

Signal Design and Processing Techniques for WSR-88D Ambiguity Resolution

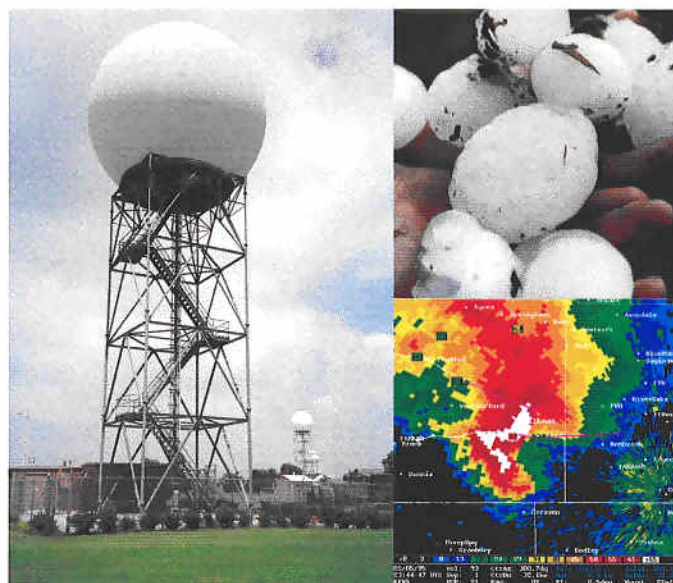
Further Investigation

National Severe Storms Laboratory Report

prepared by: M. Sachidananda

with contributions by: D. S. Zrnić and R. J. Doviak

Part 5
October 2001



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FOR WSR-88D AMBIGUITY RESOLUTION**

PART – 5: Further Investigation

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Part-4: Some Investigations.**

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**SIGNAL DESIGN AND PROCESSING TECHNIQUES
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Part-5: Further Investigation**

1. Introduction

The Radar Operations Center (ROC) of the National Weather Service (NWS) has funded the National Severe Storms Laboratory (NSSL) to address the mitigation of range and velocity ambiguities in the WSR-88D. This is the fifth report in the series that deals with range-velocity ambiguity resolution in the WSR-88D. The first two reports mainly dealt with the uniform PRT transmission and phase coding techniques to resolve the range ambiguity. Although the phase coding techniques do not directly address the velocity ambiguity problem, their capability to separate overlaid echoes allows the use of shorter PRTs which, in turn, diminishes the occurrence of ambiguous velocities. In the third report, we considered the staggered PRT technique and its variants. A significant outcome of the work is a new staggered PRT sequence processing technique in the spectral domain with significantly improved spectral moment estimates, and a clutter filtering technique that recovers velocity information over the entire extended unambiguous velocity interval without any drop-out regions. The only assumption made in the algorithm is that there are no overlaid signals. This necessarily restricts the selection of T_1 (the short PRT segment) to be sufficiently large for a given elevation so that the probability of overlay is small.

After the third report was submitted in July 1999, some more ideas were explored in an effort to further improve the staggered PRT scheme. Specifically, we tried to reduce the velocity estimate errors by optimizing the window weights. We also examined the possibility of extending the unambiguous range from r_{a1} to r_{a2} , by resolving one-overlay situation. The one-overlay situation is one in which only the short PRT can generate

overlaid echoes in the long PRT interval. Exhaustive simulations were carried out to evaluate the performance of the staggered PRT decoding scheme, and determine the limits of spectral moment recovery within acceptable range under various conditions. This information is very useful in developing a data censoring strategy to discard or flag the bad data. The results from all these studies are in Report 4.

There are several points that were left out during the course of the study of the range-velocity ambiguity problem in the WSR-88D. Some of these are addressed in this fifth report. In the SZ phase coding technique, suggested for low elevation angle scans of the WSR-88D radar, an alternative to the magnitude deconvolution, called the substitution method, is proposed by Frush (1999). A comparative study was carried out to evaluate its performance vis-à-vis the magnitude deconvolution proposed by Sachidananda and Zrnic (1999). These results are discussed in Section 2 of this report. Apart from the Section 2, which pertains to the SZ coding technique, the rest of the report is concerned with the staggered PRT technique.

During one of the review meetings concerning the range-velocity ambiguity work, Jim Evans (2001) suggested to examine the possibility of estimating the aliased velocity from the autocorrelation R_1 and de-alias it using R_2 , for the staggered PRT technique. On examination, it is found that this indeed is possible in the absence of clutter, and the estimate variance is much lower than using other methods. We have evaluated this technique using simulation and compared it with other methods. The results are presented in Section 3.

In the course of examination of the suggested spectral domain ground clutter filtering technique for the staggered PRT sequence, the theoretical analysis showed a possibility of exact complex reconstruction of the lost signal components. The theory and conclusions arrived at after testing the procedure using simulations is presented in Section 4.

A fifth section deals with the recovery of spectral moments of weather signals that have very narrow spectrum widths overlapping a very strong ground clutter return. Most of our results presented in Report 3 and 4 dealt with weather signals of width 4 m s^{-1} . The specific case of a very narrow width signal ($w < 1 \text{ m s}^{-1}$) overlapping the clutter requires a

window function with much lower side lobes than that used for larger widths. This is discussed in Section 5.

A new Sigmet processor has been connected (in a passive mode) to the WSR-88D research radar at NSSL. Thus we were able to record some time series data using uniform PRT transmission. Although the staggered PRT is not programmed in yet, we can derive a staggered PRT time series from the uniform PRT sequence by dropping appropriate samples. Further, the uniform sample set can be processed by standard algorithms and the spectral moments compared with those of the staggered set. A comparative study of different data sets has been carried out and some statistics of the standard error has also been generated using the actual radar data. All these results are presented in Section 6.

Finally, there were some lacunae in the suggested vcp-11 scan strategy for the WSR-88D in Report 4. These recommendations are reviewed and revised tables with additional inputs are given in the last section.

2. Magnitude deconvolution and the substitution in SZ-1: a comparison of performance

Sachidananda et al. (1997) proposed the SZ-1 algorithm for retrieving the mean velocity and spectrum width of the weaker of the two overlaid signals from the SZ(8/64) phase encoded sequence of returned echoes. The algorithm uses recohering and magnitude deconvolution. First the stronger signal is removed by a spectral domain notch filter of width equal to $\frac{3}{4}$ of the total number of spectral coefficients, centered on the stronger signal mean velocity. The remaining $\frac{1}{4}$ of the spectrum contains two replicas of the weaker signal, which when recohered produce the original signal and symmetrically spaced side bands. The mean velocity, obtained from this time series, is a very good estimate in spite of the side bands presence. There is no bias in the velocity estimate because side bands are symmetric. Nonetheless, the spectrum width is affected by the side bands. To reincorporate the power from the side bands into the main spectral lobe, a magnitude domain deconvolution is carried out before the spectrum width is computed.

Frush (1999) proposed an alternative, called the substitution method. In it, the phase difference between the two replicas available in the remaining $\frac{1}{4}$ of the spectrum (after notch filtering) is used to reconstruct the deleted replicas of the weaker signal

spectral coefficients. Because the spectrum is a convolution of the signal spectrum with the code spectrum, the sequence of the phase shifts for the replicas progress in predetermined increments, each of which is unique. For the SZ(8/64) coded time series these unique increments can be derived from the code spectrum. The spectrum thus reconstructed by substitution, is transformed to the time domain and recohered to reconstruct the original signal without any side bands. Therefore, both the mean velocity and spectrum width can be computed from it.

The deconvolution operation is a matrix multiplication (i.e., pre-multiply the spectrum matrix with the deconvolution matrix). We also need to compute the autocorrelation $R(1)$ twice, once before the deconvolution to obtain the mean velocity and again after the deconvolution to obtain the spectrum width. This repetition is because the deconvolution procedure increases the estimate variance whenever the spectrum is not “narrow” (see Sachidananda et al. 1998), hence to get a better mean velocity estimate it is necessary to compute the velocity before the deconvolution. The substitution method requires computation of phase differences, comparisons with the code spectrum sequence of phase differences to determine the match, then shift the phase of the spectral replicas by the successive phase difference sequence, and substitution of these replicas in the place where the notch filter was applied. The rest of the computations are the same for the two algorithms.

Both these procedures are developed based on the assumption of a “narrow” spectrum as defined by Sachidananda et al. (1998). If the spectrum is “narrow” both methods are exact and give the same results. The difference in the performance in terms of the estimate variances arises because the “narrow” spectra criterion is not exactly satisfied in actual weather signals, and the noise is always present along with the signal. If the spectral spread is more than $1/8^{\text{th}}$ of the Nyquist interval, the replicas in the SZ coded signal spectrum overlap, and the reconstruction is not exact. It is this aspect that is compared here using simulation procedure to generate the statistics of velocity and spectrum width recovery. The SZ-1 decoding algorithm is reproduced here from Sachidananda et al. 1998) to conveniently compare the two methods. The details of the substitution procedure used in this simulation study are also presented before the results are discussed.

2.1 The SZ-1 decoding algorithm

This algorithm was developed for SZ($n/64$) coded transmission in the short PRT mode (i.e., the shorter of two PRTs used in the successive scans at the lowest two elevations). The step by step procedure follows (for details of the algorithm and description of math symbols, see Sachidananda et al. (1998), depending on the context = is often used as in a programming language to indicate substitution of a variable into a memory register).

<<< **START** of algorithm (*stand alone mode; does not use long PRT data*)

1. Input raw time series E_{Ik} ; $k=1,2, \dots M$.
 - ▶ The phase switching sequence ψ_k ; SZ(n/M) code.
2. Cohere the 1st trip signal.
 - ▶ $E_1 = E_{Ik} \exp \{-j\psi_k\}$.
 - ▶ 1st trip is coherent; 2nd trip is phase coded by a sequence
 $\varphi_k = n\pi k^2/M$; $k=0,1,2,\dots M-1$.
3. Multiply by von Hann window weights, h_k .
 - ▶ $E_1 = E_1 h_k$.
4. Filter the ground clutter.
 - ▶ $E_1 = \text{GCF}(E_1)$.
5. Cohere the second trip.
 - ▶ $E_2 = E_1 \exp \{-j\varphi_k\}$.
6. Autocovariance process E_1 and E_2 to get $\hat{\rho}_1, \hat{\rho}_1', \hat{\rho}_2, \hat{\rho}_2'$ and $\hat{\rho}_2, \hat{\rho}_2', \hat{\rho}_1, \hat{\rho}_1'$
(for the computation of $\hat{\rho}_1', \hat{\rho}_2'$ use Eq. 6.27 of Doviak and Zrnic, 1993, and
for the computation of $\hat{\rho}_1, \hat{\rho}_2$ use Eq. 6.32 of Doviak and Zrnic, 1993).
7. Compute $\hat{\rho}_1'/\hat{\rho}_2'$ ratio.
 - ▶ if $\hat{\rho}_1'/\hat{\rho}_2' > 1$, trip=2, second trip is stronger - process E_2 .
 - ▶ if $\hat{\rho}_1'/\hat{\rho}_2' < 1$, trip=1, first trip is stronger - process E_1 .

8. If trip=2, interchange E_1 & E_2 , and all the parameters in step number 6.
 - ▶ with this interchange, E_1 is the time series with stronger signal coherent.
 - ▶ we need to recover \hat{p}_2, \hat{v}_2 and \hat{w}_2 of the weaker signal.

[Note: The processing steps 9 to 17 are the same for the two cases in step 7 with E_1 replaced by E_2 . This is accomplished by step 8, and the trip numbers are restored in the step 18.]
9. Compute spectrum of E_1 .
 - ▶ $S_1' = \text{DFT} [E_1]$.
10. Notch ($n_w M$) coefficients centered on \hat{v}_1 to get S_1 from S_1' .

Note: (a) n_w is not to exceed the maximum permissible value, $(1-2n/M)$.

(b) for SZ(8/64) & SZ(12/64) optimum PNF center location to be computed if trip=1 (i.e. 1st trip stronger) and GCF is applied.
11. Compute the mean power p from the remaining coefficients.

Multiply p by $1/(1-n_w)$ to get mean power estimate \hat{p}_2 .
12. Compute power ratio $pr = 10 \log_{10}(\hat{p}_1/\hat{p}_2)$ dB.
13. If $pr < 25$ dB, correct error in \hat{p}_1 estimate.
 - ▶ $\hat{p}_1' = \hat{p}_1 - \hat{p}_2$.
 - ▶ compute corrected power ratio $\hat{pr} = \hat{p}_1'/\hat{p}_1$.
14. Cohere the weaker signal in S_1 .
 - ▶ $e_1 = \text{IDFT} [S_1]$
 - ▶ if trip = 1, $e_2 = e_1 \exp\{-j\varphi_k\}$.
 - ▶ if trip = 2, $e_2 = e_1 \exp\{j\varphi_k\}$.
15. Compute autocorrelation $R(1)$ for e_2 , and compute mean velocity, \hat{v}_2 .
16. Magnitude deconvolution. (for SZ(8/64) and SZ(16/64) only)
 - ▶ compute magnitude spectrum, $s_2' = | \text{DFT}(e_2) |$.
 - ▶ multiply by the deconvolution matrix, $s_2 = D s_2'$.

[The deconvolution matrix, D , is a part of the program. D is pre-computed and supplied to the algorithm, or stored as a

part of the program.]

17. Compute autocorrelation $R(1)$ for s_2 , and compute width, \hat{w}_2 .
18. If trip = 2, interchange parameters $(\hat{\phi}_1, \hat{\phi}_1, \hat{w}_1)$ and $(\hat{\phi}_2, \hat{\phi}_2, \hat{w}_2)$.
19. Output the 1st and 2nd trip parameters and go to the next sequence.

<<<-----END of algorithm

Modifications of the SZ-1 algorithm required by the substitution method.

To use the **substitution** instead of **magnitude deconvolution** in the SZ-1 algorithm, the following steps need to be modified. The steps #1 to #13 are the same. The steps #14 to #17 have to be replaced by the following steps(#14 to #16):

-
14. Reconstruct complete S_1 using substitution (for SZ(8/64) and SZ(16/64) only; details of this step for SZ(8/64) are given in section 2.2).
 15. Cohere the weaker signal in S_1 .
 - ▶ $e_1 = \text{IDFT} [S_1]$
 - ▶ if trip = 1, $e_2 = e_1 \exp\{-j\phi_k\}$.
 - ▶ if trip = 2, $e_2 = e_1 \exp\{j\phi_k\}$.

[Note: This entire step 15 can be replaced by complex deconvolution in the frequency domain, because the corresponding convolution matrix is not singular if the filter function is deleted.]

16. Compute autocorrelation $R(1)$ for e_2 , and compute mean velocity, $\hat{\phi}_2$, and width, \hat{w}_2 .
-

The substitution method is based on the observation that if the signal spectrum is “narrow”, the spectral replicas of signal modulated with the SZ(8/64) code differ in phase by the amount equal to the phase differences of the code spectral lines. This follows

from the nature of the code, because the eight replicas are obtained from the convolution of the original signal spectrum and the code spectrum. The spectrum of the modulation code $\exp(jk^2\pi/8)$, has only 8 uniformly spaced non-zero coefficients with constant amplitudes and the phases $\{\pi/4, \pi/8, -\pi/4, -7\pi/8, \pi/4, -7\pi/8, -\pi/4, \pi/8\}$. Thus for $M=64$, if the original signal components are in the first 8 coefficients, the sequence of phase difference between the consecutive spectral replicas is $\{-\pi/8, -3\pi/8, -5\pi/8, -7\pi/8, 7\pi/8, 5\pi/8, 3\pi/8, \pi/8\}$. If the original signal coefficients are in the 9th to 16th coefficients, the phase difference sequence would be $\{\pi/8, -\pi/8, -3\pi/8, -5\pi/8, -7\pi/8, 7\pi/8, 5\pi/8, 3\pi/8\}$. Note that the position of the $-\pi/8$ phase difference is the location of the original signal component, and each entry in the sequence is unique. Thus, if we have two adjacent replicas of the modulated spectrum, we can reconstruct the filtered replicas of the spectrum by adding the replicas with appropriate phase shifts. The procedure for reconstructing the spectral replicas is explained next.

2.2 The details of step 14 (substitution method for SZ(8/64))

The spectrum S_I consists of $M/4$ non-zero coefficients after applying the $3/4$ notch filter in step #10. Let the indices of these spectral coefficients be k to $(k+M/4-1)$. Note that the indices are cyclic and hence if any index exceeds M , subtract M from it to get the correct index. Of these $M/4$ coefficients, take any two separated by 8, i.e., i^{th} and $(i+M/8)^{\text{th}}$, and determine the phase of $S_I(i+M/8)/S_I(i)$. Now, compare this value with the eight values in the sequence, $\{\pi/8, -\pi/8, -3\pi/8, -5\pi/8, -7\pi/8, 7\pi/8, 5\pi/8, 3\pi/8\}$. The position of the closest match in the sequence is taken as the starting phase difference, and the rest of the entries are rotated cyclically to get the rearranged sequence. For example, if the calculated phase difference is closest to $-3\pi/8$, the rearranged sequence would be $\{-3\pi/8, -5\pi/8, -7\pi/8, 7\pi/8, 5\pi/8, 3\pi/8, \pi/8, -\pi/8\}$. Now, the coefficients at spectral indices $(i+nM/8)$; $n=0,1,\dots,7$, are constructed by adding the phases in the above sequence to $S(i)$, of which the first two are already available. The rest are computed and inserted in the appropriate spectral places in the spectrum. This procedure is repeated for $i= k$ to $k+M/8$ which will reconstruct all the filtered coefficients.

A similar procedure can be followed for SZ(16/64) code.

