2.4 QUANITATIVE ANALYSIS OF THE SZ(8/64) PHASE CODE FOR THE MITIGATION OF RANGE AND VELOCITY AMBIQUITIES IN THE WSR-88D

Gregory Meymaris, John Hubbert, and Scott Ellis
NCAR, Boulder, Colorado

1 INTRODUCTION

The mitigation of the range-velocity ambiguity problem is a high priority in the data quality effort for the WSR-88D. A fundamental problem of any pulsed Doppler radar is that the unambiguous range increases with increasing pulse repetition time (PRT), while the unambiguous, or Nyquist, velocity decreases. Therefore, in the case of the WSR-88D, adjusting the PRT to obtain a desirable unambiguous range, like 460km, results in a small Nyquist interval, ±8m/sec, and thus severe velocity folding. Conversely, a PRT that provides an adequate Nyquist interval, ±50m/sec, delivers unacceptably short unambiguous ranges, 75km, resulting in inadequate area coverage and increased multiple trip contamination (Sachidananda and Zrnić 1999).

The current WSR-88D strategy for minimizing the effects of range and velocity ambiguities is to scan separately for power (reflectivity) and the Doppler fields (radial velocity and spectrum width). The power, or surveillance, scan uses a long PRT with an unambiguous range of 460 km, and a Nyquist velocity near ±8 m/s. The Doppler scan uses shorter PRT's resulting in Nyquist velocities near ±25 m/s and typical unambiguous ranges of 150 km. The surveillance scan is then used to sort first and second trip echoes in the Doppler scan. If one trip's power exceeds the other by a predetermined threshold (typically 5 dB), the weaker trip's signal is censored and the computed velocity is assigned to the stronger trip. However, if the power difference between the two trips is less than the threshold, both signals are censored. While allowing Doppler measurements beyond the unambiguous range in the case of strong second trip echoes, this method results in large amounts of data, in both trips, being censored.

Phase coding the transmitted pulse allows separation of multiple trips with appropriate decoding of the received signal (Sachidananda and Zrnić 1999). This strategy allows recovery, rather than censoring, of overlaid echoes and will greatly increase the area of coverage compared to the current WSR-88D processing.

The SZ(8/64) code (Sachidananda and Zrnić, 1999; Frush and Doviak 2002) allows the resolution of signals from up to four trips in a wide variety of conditions. Notch filter and spectrum reconstruction techniques have been developed and tested for suppressing the out of trip contamination, while preserving the desired trip's signal. It is also important to objectively identify regions that are not well recovered by the SZ(8/64) phase coding method and censor them automatically.

Section 2 discusses the SZ(8/64) code, an explanation of the trip separation technique used in this paper. Section 3 describes the quanitative analysis techniques and presents preliminary results of the quantitative analysis performed on experimentally obtained non-phase coded I&Q data from the Memphis, TN WSR-88D (KNQA).

2 ALGORITHM

2.1 SZ(8/64) Code

Briefly, the code developed by Sachidananda and Zrnić, called the SZ(8/64) code, is a particular sequence, ψ_k, of 32 phase shifts applied to the transmitted radar pulses in a rotating fashion, so that after 32 pulses the code repeats. If the received echo samples are phase corrected by $-\psi_k$, the first trip signal will be coherent, the second trip signal will be modulated by $\phi_k=\psi_{k-1}-\psi_k$, and the third trip by $\phi_k+\phi_{k-1}$. The SZ(8/64) code defines the modulation code $\phi_k=8\pi k^2/64$ and $\psi_0=0$ (Sachidananda and Zrnić 1999).

*Corresponding author address: G. Meymaris NCAR, P.O. Box 3000, Boulder, CO 80307
meymaris@ucar.edu

This code has several nice properties that make it useful for unwrapping overlaid signals. When cohered to the first trip, the power from the other trips (up to the 8th trip) is distributed into evenly spaced replicas in the power spectrum so that the bias from the out of trip echoes is removed (in the ideal case) from the mean velocity estimate. In the case of a signal in an adjacent trip, 8 spectral replicas are formed. The phases of these spectral power replicas differ by known phase shifts. Because of this property, only 2 spectral replicas are necessary to recreate the signal which allows the recovery of the spectrum width.

2.2 Trip Separation

In the event of a single strong echo with no competing echoes from other trips, it is enough to cohere the signal to that trip and perform the standard methods, like pulse pair (Doviak and Zrnić 1993), to estimate the power, mean velocity, and spectrum width. The phase coding does not affect these estimates, assuming that the transmitted phase shifts are exactly known. In this case, the only advantage to the SZ(8/64) code over a traditional non-phase coding scheme is that it is possible to determine the correct trip of the signal, without using the long PRT scan.

The SZ(8/64) phase coding technique is more advantageous when the signal consists of two overlaid echoes because the moments from both trips are recoverable (Sachidananda and Zirnić 1999). The results in this paper were obtained using a slightly altered version of the trip separation algorithm described by Sachidananda and Zrnić 1999, and so it is worth describing the algorithm used.

First a windowing function is applied to the time series I&Q data. The trip 1 power is calculated by first cohering to trip 2 and then calculating the mean velocity using the pulse pair algorithm. An unbiased estimate of the mean velocity can still be made because of the property of the SZ(8/64) code that the power of the out of trip signals in the spectrum is distributed into evenly spaced replicas. The spectrum is computed and then notched, centered at the mean velocity. The notch width, in the case of SZ(8/64), should be either 1/8, 1/4, 1/2, or 3/4 of the Nyquist interval. This allows for at least two whole replicas from the first trip to remain since, as mentioned above, the first trip echo is replicated 8 times in the second trip. In this paper, a notch width of 3/4 was used. If the notch is wide enough to remove the power from trip 2, the remaining power after the notch is applied, is 7/8, 3/4, 1/2, or 1/4, respectively, of the total trip 1 power. Thus first trip power is calculated by multiplying the remaining power by 8/7, 4/3, 2, and 4, respectively. The second trip's power is computed in the analogous way.

The estimation of the trips' powers is important, because the moments of the stronger trip (i.e. the trip with more power), are largely unaffected by the presence of the weaker trip, while the moments of the weaker trip are strongly affected by the stronger trip. Thus, the next step is to calculate the stronger trip's mean velocity and spectrum width, which can be calculated by using the standard pulse pair techniques on the windowed I&Q data cohered to that trip.

To recover the weaker trip's mean velocity, a notch is applied, in the manner described above, to the spectrum of the stronger trip, centered at the mean velocity of the stronger trip. Then, an inverse Fourier transform is applied to the new spectra (the signal is now in the time domain), and the result is cohered to the weaker trip. The mean velocity of the weaker trip can now be calculated by performing pulse-pair on this new time series data. However, the spectrum width estimate, at this point, is biased high because of sidebands produced from the notch (Sachidananda and Zrnić 1999). To mitigate this, magnitude deconvolution is performed as described in Sachidananda and Zrnić 1999, and in Frush and Doviak 2002.

This algorithm was coded into NCAR's Improved Matlab Archive 1 Tool (IMAT). This tool provides a flexible environment for writing I&Q time series data processing algorithms.

3 QUANITATIVE ANALYSIS

3.1 Methods

The difficulty in performing a quantitative analysis on experimentally obtained data for the phase coding technique is the lack of truth for comparison. It is not possible for the radar to simultaneously collect data of both overlaid and non-overlaid signals for the same range gate. The current solution has been to scan the same region twice: once to collect overlaid data (transmitting SZ(8/64), short PRT) and once for non-overlaid (transmitting no phase shifts, long PRT). The temporal discrepancy in measurements is a source of error that unfairly degrades the evaluation of the algorithm.

A broad quantitative analysis has been preformed on this moment recovery technique using purely simulated I&Q time series data. (Sachidananda and Zrnić 1999) and another performed using experimentally obtained data (Frush and Doviak 2002). In the case of the latter, the truth fields were obtained by human experts.

In this paper, two non-phase coded, experimentally obtained time series I&Q data are phase-coded offline and then added together; one is phase coded for trip 1 and the other to trip 2. The moment recovery techniques can be performed on this hybrid data and compared to the moments calculated using standard techniques on the original data.

Figures 1 a and b show power (I^2+Q^2) and radial velocity, respectively, from a WSR-88D in a short PRT mode. The data was collected on KNQA in Memphis, TN during the summer of 1997 using NCAR's Archive 1 Data Acquisition unit (A1DA). The scan is comprised of 2 separate PPI scans that are concatenated in range simulating a long PRT scan. Note that there is a threshold of –45dB on the raw power. To create the simulated phase coded data, the two separate scans that comprise the truth dataset are phase coded at the I&Q level, the bottom scan for trip 1 and the top for trip 2, and then added together. The new combined dataset can be processed using the trip separation algorithm and compared to the moments from the original scans. An advantage of such an approach is that, unlike the case where the radar is transmitting the SZ(8/64) phase code, both the overlaid and pre-overlaid signals are available for processing. Another advantage is that there is more non-phase coded I&Q data available than phase coded.

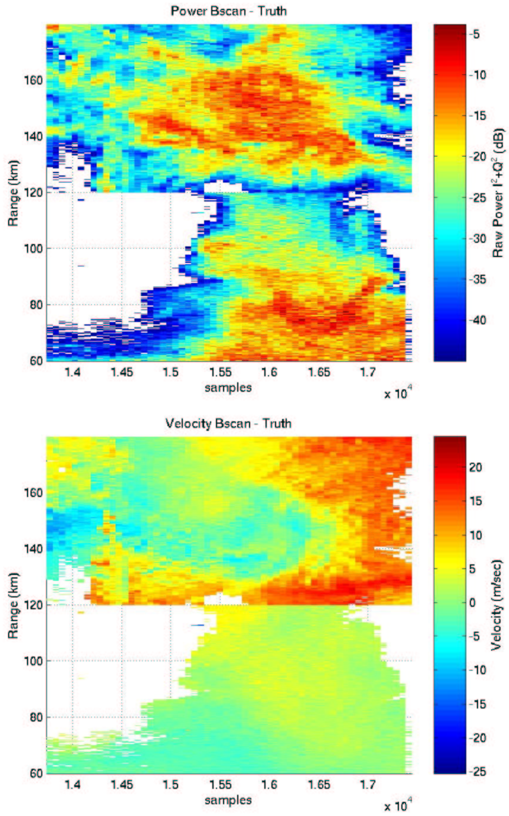

Figure 1 a, b: B-scans of the truth dataset: 1a shows the raw power and 1b shows the radial velocity. The data is comprised of 2 separate scans appended in range. The seam between the 2 separate scans can be seen at the 120KM range gate.

Additionally, phase transmit errors can be included or not, as desired.

An alternative to overlaying 2 scans is to overlay individual gates of I&Q time series data. Using this technique, it is possible to pick and choose the characteristics of the overlaid data with more control than by overlaying entire scans.

More than 5000 I&Q data blocks (64 pulses each) were selected from 2 short-PRT PPI scans, categorized by hand, and then stored in a database. The existence of clutter, weather, and multi-modal weather signals were established by a human expert and stored with the I&Q data. All the data blocks were then paired with every other data block to create another database with over 12.5 million data blocks. Each of these data blocks was created by phase coding the first of the pair for trip 1, the other for trip 2, and then combining the pair, thus simulating overlaid echoes.

3.2 Results from Overlaid PPI Scans

Figures 2a and 2b show the recovered power and radial velocity, respectively, from the trip separation algorithm described above, on the overlaid scan shown in Figures 1a and b. The same power threshold was applied to the recovered data. The recovery is quite good wherever there is significant power in both trips. However, if there is little or no power in the weaker trip, and the stronger trip has a wide spectrum width the stronger trip can leak through to the weaker trip. This can be seen in the lower left quadrants of Figures 2a and 2b.

Note that this recovery was done without using a long PRT scan for reference on the power, which would improve the results. No censoring was done on the data other than the estimated power threshold. The “speckle” in the mean velocity field should give an excellent indication of where there is leakage from the stronger trip so that the data can be censored, automatically.

For comparison, see Figure 3 which shows the results from an algorithm very similar to that currently implemented on the WSR-88D. Since the pulses are not phase coded, both trips simply add together. A long PRT scan is then used to sort the mean velocity field, using the method described in the introduction. The censoring results in “purple haze” which can devastate the scan.

3.3 Results from Overlaid Range Gates

Because of the availability of truth, statistics can be generated by comparing the results of the trip separation algorithm to the moments from the data before the pair was combined. Figures 4a and b show the standard deviation of the recovered weak trip velocity as a function of the ratio of the trips’ powers and the strong trip’s spectrum width. The data used contained no clutter, was not multi-modal, and the weaker trip true SNR was at least 5dB. These plots are analogous to those shown in Sachidananda and Zrnić 1999, which were generated using simulated weather spectra with no background noise, but a random phase error is included. Sachidananda and Zrnić, also use a Nyquist velocity of 32 m/sec whereas the data in this paper has a Nyquist velocity of 25m/sec. To directly compare the results,

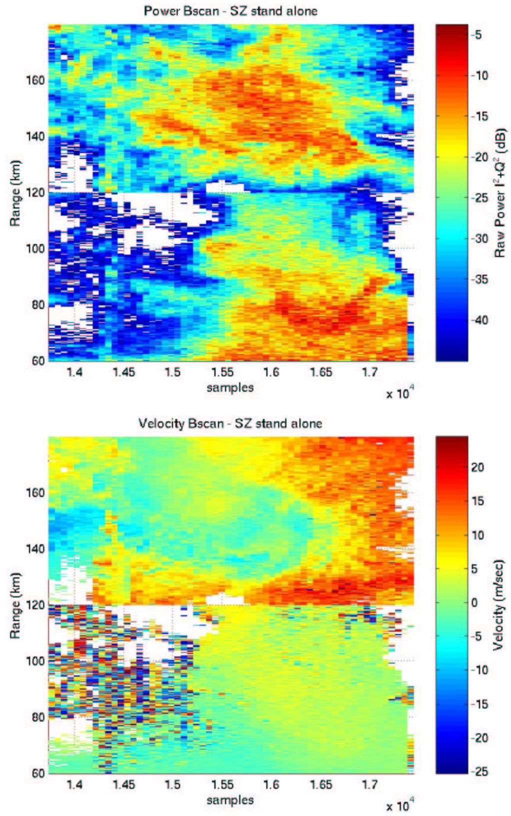

Figure 2 a, b : The recovered raw power field (2a) and recovered radial velocity(2b) from the moment recovery algorithm using IMAT.

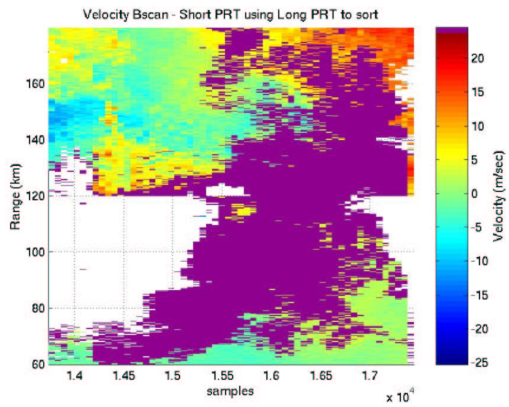

Figure 3: B-scan of the mean velocity field as computed by the current algorithm implemented on the WSR-88D

the mean velocities and the spectrum widths in this paper should be multiplied by 32/25. The white areas in Figures 4a and 4b indicate a lack of data that satisfy the criteria for that pixel.

For the case where the weak trip true spectrum width is 2 ± 0.5 m/sec, Figure 4a,

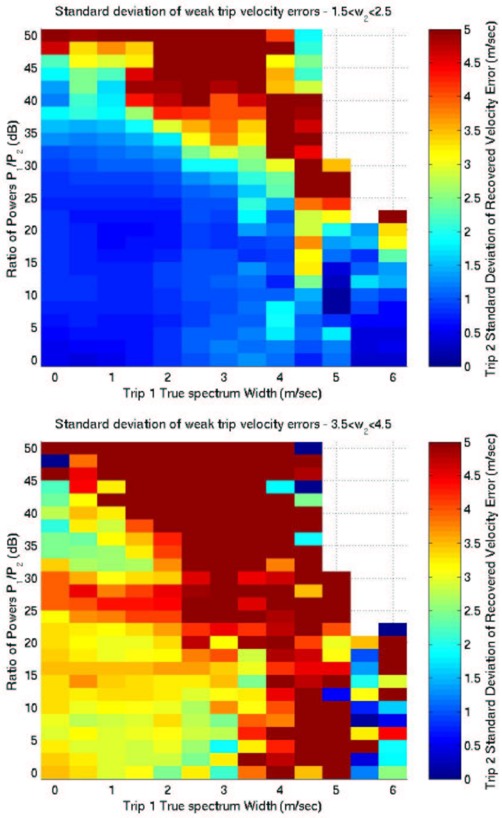

Figure 4 a, b: These show the standard deviation of the errors of the recovered weak trip velocity as a function of the true strong trip spectrum width and the true power ratio between the first and second trip signals. All data contained no clutter, no multi-modal weather spectra and the weaker trip true SNR was at least 5dB. The weak trip true spectrum width was restricted to 2 ± 0.5 m/sec for Figure 4a, and 4 ± 0.5 m/sec for Figure 4b

the errors in the recovery of the weak trip velocity appear to be quite small for smaller power ratios and smaller strong trip spectrum widths. In fact, for strong trip spectrum widths of less than 3m/sec, the separation of the trips is good up until a 30 to 35dB power difference. These results match fairly well those in Sachidananda and Zrnić 1999, although not quite as good. This is to be expected because the data in this paper contained background noise contamination and the weather signals are often not gaussian. In the case of Figure 4b, where the weak trip true spectrum width is 4 ± 0.5 m/sec, the errors are substantially worse, as expected, with standard deviations near 3m/sec in the best of cases.

4 CONCLUSIONS

While these results are still preliminary, they are consistent with the statistics generated using purely simulated data (Sachidananda and Zrnić 1999) and are encouraging. The quantitative analysis, using experimentally obtained data that is combined to create overlaid signals, shows great potential for both the evaluation of current and future moment recovery algorithms, as well as being a useful tool for deriving censorship fields. The latter is because of the ability to “data mine” for ill-behaved cases.

5 FUTURE WORK

It is crucial for the implementation of the moment recovery algorithm to recognize when the algorithm is failing and censor that data. One possible out of trip leakage indicator is the standard deviation of radial velocity computed over a small area (e.g. 3 x 3 gates). If the signal is dominated by out of trip leakage, the computed velocities tend to be uniformly distributed over the nyquist interval which results in a higher standard deviation of velocity than typical weather echoes. Similarly, the whitened, out of trip leakage will produce large spectrum width values, similar to noise. Therefore, spectrum width may also be useful as a censoring parameter.

More quantitative analysis on the variations of the algorithm described in this paper will be performed on real data. This includes simulating phase coded data from standard time series data, providing a truth field.

6 ACKNOWLEDGEMENTS

This research is sponsored by the NOAA Radar Operations Center (ROC) for the WSR-88D.

7 REFERENCES

Doviak, R. J., and D. S. Zrnić, 1993: Doppler Radar and Weather Observations. 2d ed. Academic Press, 562pp.

Frush, C., R. J. Doviak, M. Sachidananda, D. S. Zrnić, 2002: Application of the SZ Phase Code to Mitigate Range-Velocity Ambiguities in Weather Radars. *J. Atmos. Oceanic Technol.*, **19**, 413-430.

Sachidananda, M., D. S. Zrnić, 1999: Systematic Phase Codes for Resolving Range Overlaid Signals in a Doppler Weather Radar. *J. Atmos. Oceanic Technol.*, **16**, 1351-1363.