Experimental Evaluation of SZ(8/64) Phase Coding with Censoring for Range-Velocity Ambiguity Mitigation

J.C. Hubbert, S. Ellis, M. Dixon, and G. Meymaris
National Center for Atmospheric Research, Boulder CO, 80307 USA

Abstract: The Doppler Dilemma or range-velocity folding of echoes from uniformly spaced transmit pulse trains of weather radar poses a fundamental limit on radar data quality: there is a limited unambiguous range for echoes and there is a maximum unambiguous velocity. The radar pulse repetition time may be adjusted to increase either the unambiguous range or the maximum unambiguous velocity but the other necessarily will decrease. Phase coding of the transmit pulses is one technique that can mitigate the Doppler Dilemma. Experimental results using S-Pol, NCAR’s research S-Band radar, illustrate the technique.

Keywords: weather radar, phase coding, Doppler Dilemma, range folding, velocity folding

1. Introduction

The Doppler Dilemma or range-velocity folding of echoes is expressed by and is expressed by the following equation,

\[ r_a v_a = c\lambda/8 \]  \hspace{1cm} (1)

where \( r_a \), \( v_a \) are the unambiguous range and velocity, respectively, for wavelength \( \lambda \) and where \( c \) is the speed of light. Since the product \( r_a v_a \) is a constant for a particular wavelength, increasing either one \( (r_a, v_a) \) necessarily decreases the other. For \( \lambda = 10 \) cm (S-band) and a typical pulse repetition time (PRT) of 1 ms, \( r_a = 150 \) km and \( v_a = 25 \) m/s. Weather phenomena routinely exceed both of these limits. Phase coding of the transmit pulses for single polarization radars has been shown to be an effective method for the separation of range overlaid echoes thus extending \( r_a \) without compromising \( v_a \) [1]. A systematic phase code is applied to the transmit pulses so that the simultaneous received echoes from different trips (i.e., range overlaid echoes) will have distinct and separate phase codes. This allows for the separation of the estimates of the moments of the overlaid echoes up to about a 40 dB power ratio. This paper discusses the SZ(8/64) phase coding algorithm and its implementation using a new state-of-the-art receiver/processor in S-Pol, NCAR’s S-Band radar. An important aspect of the algorithm is the censoring of data. The data quality of the radar moments that result from phase code processing are limited by power ratios, clutter power, spectrum width, SNR and spectra shapes. Censoring algorithms are discussed and experimental results are given. Detailed theory of SZ(8/64) phase coding can be found in [1]. In [1] the technique was evaluated using numerically simulated data while [2] demonstrated the technique using experimental data from S-Pol. The technique was further statistically evaluated with experimental data in [3][4]. Since the implementation of SZ phase coding is computationally intensive, the experimental evaluation of SZ the algorithm has been done by post processing data and not in real time; however, recent advances in radar processor technology have now made possible real time execution of phase coding algorithms. One such state-of-the-art receiver/processor was recently installed in parallel with the existing processor on S-Pol. The systematic SZ(8/64) phase code is applied to the transmit pulses. When the first trip (considered the strong trip here) echoes are made coherent (i.e., by subtracting the applied phase code) the second trip becomes phase shifted by the SZ(8/64) modulation code (time series considered here are 64 in length). The spectrum of the phase modulated second trip echo consists of eight replicas of the spectrum of the unphased coded second trip echo. To recover the moments of the weak trip signal, at least two of these replicas need to be preserved. Thus, 3/4 of the modulated weak trip spectrum may be “notched” or zeroed and this 3/4 notch is typically centered at the mean velocity of the coherent overlaid first trip. An attractive feature of the SZ phase code is that the auto covariance function of the phase code sequence is 1 for lags 0, 7, 15 etc., and zero otherwise. Thus velocity estimates of the first trip coherent signal are unbiased by the overlaid modulated second trip echo. Overlaid echoes in effect behave as if they were white noise and do not bias the velocity estimates for the cohered trip. The signal processing steps in executing the SZ(8/64) algorithm on unphased coded data are as follows: (moments with “∗” are recovered while others without “∗” are “truth” calculated from the original time series): 1) Phase code two time series, one as first trip the other as second trip and combine the sequences, 2) Create two sequences by cohering the combined sequence for the first and second trip echoes, 3) Calculate \( R(1) \) (first lag autocovariance) for both sequences; the greater one determines which trip is stronger; or the strong trip can be determined from a long PRT scan; 4) Calculate the power \( P_1 \), velocity \( V_1 \) and width \( W_1 \) for the stronger trip (always referred to with the subscript “1” but not necessarily the first trip), 4) Apply a Hanning window to the combined time series and correct for the power loss, 5) Transform into the frequency domain via an FFT algorithm, 6) Apply 3/4 notch filter centered at the \( V_1 \) estimated velocity, 7) Calculate the weaker trip power, \( P_2 \), from the notched spectrum and multiply by 4 to account for the effects of the 3/4 notch, 8) If the recovered power ratio \( P_1/P_2 < 20 \) dB, \( P_1 \) is corrected by subtracting \( P_2 \), 9) Transform the notched spectrum back to the time domain (via an IFFT) and cohere to the weaker trip, 10) Calculate \( V_2 \), and 11) Estimate the weaker trip spectrum width via the deconvolution method given in [1]. In May of 2003 the new receiver/processor (RV8 and associated IFDs) was installed in parallel to the existing S-Pol system. A simple block diagram of the S-Pol system is shown in Fig. 1. The blocks in red (or gray) are part of the newly installed RV8 system. Both the integrated moments and the
times series are output on a gigabit Ethernet connection to a gigabit switch that makes the data available to two workstation PCs called IRIS and IQ which further process and display the data. The time series data are stored on a terabyte RAID. The IQPC is used to develop real time signal processing algorithms such as SZ(8/64) algorithm and subsequently the developed algorithm is programmed on to the RVP8. The SZ(8/64) algorithm has been developed in this way and now runs in real time on the RVP8. Clutter filtering is an important aspect of data quality. Typically ground clutter power is removed via the use of IIR (infinite impulse response) filters which effectively remove the power around zero velocity but which also impart a phase delay which is non-linear. This phase delay will degrade the performance of the SZ algorithm causing unacceptable biases in \( \hat{V}_2 \). To overcome this, either spectral clutter filters or FIR clutter filters need to be used.

2. SZ Censoring

An important part of the SZ(8/64) algorithm is data censoring. There are two distinct types of SZ algorithms and accompanying censoring algorithms: 1) SZ-1 and SZ-2. SZ-2 is used for lowest elevation angles (below about 1.5°) where long PRT scans are followed by phase coded short PRT scans. Information from the long PRT scan is used to sort the overlaid echoes of the short PRT scan. Short PRT data which is range unambiguous assuming maximum cloud tops of 18 km. The long PRT powers are used to estimate velocity and strong trip spectrum widths. Only moments from the strongest two trips are estimated, i.e., velocities from the third and fourth strongest trips are not estimated since it is difficult and recovery would be limited. Censoring of SZ-2 data is accomplished by four criteria: 1) SNR 2) SWR signal to sum of weak trip powers ratio 3) \( P_1/P_2 \), the ratio of strong trip to weak power as a function of strong trip and weak trip widths and 4) SCR, the signal to clutter ratio. Criteria 1 simply requires that the received signal be above some power threshold based on the sensitivity of the radar. Criteria 2 uses the ratio of the in trip power to out of trip powers as calculated from the long PRT. For the strongest trip power \( P_1 \), the second strongest trip power \( P_2 \), these criteria are

\[
P_1/(P_2 + P_3 + P_4) \geq THRES1 \\
P_2/(P_3 + P_4) \geq THRES2
\]

The thresholds are typically set to \( THRES1 = 0 \) dB, \( THRES2 = 5 \) dB in order to maintain acceptable variance of velocity estimates. Criteria 3 is based upon theoretical and experimental statistical plots such as shown in Fig. 2. Fig. 2 shows the standard deviation of the errors of the recovered weak trip velocity \( \hat{V}_2 \) as a function of the power ratio \( P_1/P_2 \) and the width of the stronger trip signal, \( W_1 \).

In the SZ-2 algorithm, powers are estimated from the long PRT data which is range unambiguous assuming maximum cloud tops of 18 km. The long PRT powers are used to sort the overlaid echoes of the short PRT scan. Short PRT data are used to estimate velocity and strong trip spectrum widths. Only moments from the strongest two trips are estimated, i.e., velocities from the third and fourth strongest trips are not estimated since it is difficult and recovery would be limited. Censoring of SZ-2 data is accomplished by four criteria: 1) SNR 2) SWR signal to sum of weak trip powers ratio 3) \( P_1/P_2 \), the ratio of strong trip to weak power as a function of strong trip and weak trip widths and 4) SCR, the signal to clutter ratio. Criteria 1 simply requires that the received signal be above some power threshold based on the sensitivity of the radar. Criteria 2 uses the ratio of the in trip power to out of trip powers as calculated from the long PRT. For the strongest trip power \( P_1 \), the second strongest trip power \( P_2 \), these criteria are

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can be defined as shown in Fig. 3 which are simply straight lines.

2.2 SZ-1 censoring

For SZ-1 censoring, long PRT data is not available and the data must be censored based on the SZ recovered moments themselves. It was found that using the SZ-2 power ratio censoring technique for SZ-1 data was unacceptable due to the possible high standard deviations of the recovered moments. To overcome this, two new censoring techniques have been developed and tested: 1) a spectral quality estimate of the weak trip recovered spectrum which measures excessive power in the modulated spectrum replicas and 2) features of the texture of the velocity field. The spectral quality estimate of the recovered weak trip signal is based on the shape of the recovered spectrum after magnitude deconvolution. If the recovery was successful, the power will likely be concentrated around the center velocity estimate. An example of a good recovered spectrum is shown in Fig. 4 while Fig. 5 shows a censored spectrum. The recovered weak trip spectrum is divided into eight segments based on the velocity estimate and the peak power in each segment is found. A ratio of the sum of the three weakest peak powers to the peak power is calculated and based on this ratio a fuzzy logic membership function is created. Poor SZ recovered velocity data quality is easily seen by the eye as high spatial velocity variance. Based on this observation, three estimates of the texture of the recovered velocity field are used for censoring: 1) a standard image texture estimator, 2) the radial spin of the velocity and 3) the azimuthal spin of the velocity. Spin is a measure of the number of inflections of a variable along a particular direction [5]. The purpose of the spin estimates is to distinguish velocity fields that have high gradients due to meteorological convergence, divergence or circulation (e.g., tornadoes) from poor quality data. For example, a velocity field with a sharp gradient can have a high texture and thus be censored. However, the spin estimate would be low indicating that the velocity should not be censored. The three texture estimates and the spectral quality estimate are all inputs to a fuzzy logic algorithm that identifies the data to be censored.

Figure 3: SZ-2 censoring boundaries based on Fig. 2.

Figure 4: An example of a good recovered weak trip spectrum.

Figure 5: An example of a bad recovered weak trip spectrum.

3. Data Analysis

3.1 SZ-1 recovered data

The following data were gathered by S-Pol using RVPS on 7 July 2003 at 0.7° elevation at the Marshall field site near Boulder, CO. A long PRT scan (PRT=2.7 ms) was followed by a short PRT (1.04 ms) phase coded scan about four minutes later. The unambiguous velocity and range for each scan are $v_a = 9.9 \text{ ms}^{-1}$, $r_a = 405 \text{ km}$ and $v_a = 25.7 \text{ ms}^{-1}$, $r_a = 156 \text{ km}$, respectively. The following plots compare the SZ recovered moments to the long PRT moments. Shown in Fig. 6 is long the PRT reflectivity and Fig. 7 shows the SZ recovered reflectivity with no censoring. By comparing the two plots, data quality problem areas are evident in Fig. 7. The ring of elevated reflectivity near 156 km range is caused by first trip ground clutter leaking through to the first few gates of the second trip. Also shown in Fig. 7 are several other regions of strong trip power leakage. These areas should be censored. In Fig. 8, SZ-1 censoring has been applied and much of the previously indicated strong trip leakage areas indeed have been censored. However, the censored image in Fig. 8 appears “rough” with data missing in some weather echo areas and with many speckles in echo free areas. The missing data areas can be filled using interpolation from surrounding pixels but this should be done only in areas where the surrounding reflectivities are reasonably smooth and the data gaps are not too large. Many speckle filters exist (e.g., in the NEXRAD spec
Shown is the SZ recovered velocity from simulated data in the recovered velocity field. This is illustrated in Figure 16. random fluctuations in the phase code can cause stripes the theoretical phase noise should be kept at a minimum. Two, small increasing the noise floor of spectra. Thus, the entire system will effectively limit the recovery of weak trip signals by the received signal. This nonlinear phase response then changes to the long PRT reflectivity in Fig. 6. There is excellent agreement between the short and long PRT scan. The second trip range begins at 100 km. This is called the SZ-2 algorithm. At higher elevation angles where the short PRT scans only have two possible overlaid powers, the long PRT scan is not required. In this case the long PRT moments can also be used to censor velocities calculated from the short PRT data. This is evident in Figure 15. The increased in the area of recovered velocity in Fig. 14 as compared to Fig. 15 is evident.

4. Data Quality Issues

There are two technical implementation issues that can affect data quality 1) ground clutter filtering and 2) phase noise. Typically, ground clutter interference is reduced by applying an IIR (infinite impulse response) filter to the time series data which will reduce clutter power by 30 dB or more. However, IIR filters also have a nonlinear phase response which will modulate the phase characteristics of the received signal. This nonlinear phase response then changes the velocity relationship among the time series members and this will cause a bias in the recovered weak trip velocity estimates. To avoid this problem, clutter filtering can be accomplished with either FIR (Finite Impulse Response) filters or with spectral domain filters that operate directly on the magnitude response of the time series leaving the phases unaltered.

To achieve the maximum recovery power ratio, \( P_1 / P_2 \), possible for separation of overlaid echoes and achieve the best data quality, the transmit burst phase pulse should be measured. Indeed this measurement is required for the RVP8 receiver. There are two issues to consider. One, phase noise will effectively limit the recovery of weak trip signals by increasing the noise floor of spectra. Thus, the entire system phase noise should be kept at a minimum. Two, small random fluctuations in the phase code can cause stripes the the recovered velocity filed. This is illustrated in Figure 16. Shown is the SZ recovered velocity from simulated data in B-scan format. The second trip range begins at 100 km. There is no weak trip signal and thus weak trip velocity estimates are solely a function of strong trip power and added phase noise. The SNR for the first trip is 60 dB and the phase code noise is 0.5°, i.e., the applied phase code has a uniform distributed random phase between -0.5° and 0.5° added to it. When recovering the weak trip velocities, the theoretical phase code (without noise) is used. These velocity stripes give the illusion of coherence in the recovered velocity field and could cause misinterpretations. Also, such velocity fields would have reduced spatial variance and thus would be difficult to censor. The methods give for SZ-1 censoring. Fortunately, this problem is alleviated by simply measuring the transmit burst phase and then using these measured phases to decode the data.

5. Summary

The SZ(8/64) algorithm has been programmed on new state-of-the-art receiver/processor which is installed in S-Pol, NCAr’s S-Band radar and is able to run in real time. The SZ algorithm makes possible the separation of overlaid echoes up to a 40 dB power ratio. At low elevations where more than two overlaid echoes are possible, a long PRT needs to accompany the short phase coded PRT (with a high unambiguous velocity) so that the location of the echoes are known unambiguously. The long PRT moments can also be used to censor the velocities calculated from the short PRT data. This algorithm is the SZ-2 algorithm. At higher elevation angles where the short PRT scans only have two possible overlaid powers, the long PRT scan is not required. In this case the recovered moments are censored using the texture of the velocity field and a estimate of the quality of the weak trip recovered spectrum. A fuzzy logic routine is used to decide censoring. This is SZ-1 algorithm. Both algorithms were test with experimental S-Pol data and evaluated with data from long PRT scans. The SZ-1 algorithm performance was compared to current NEXRAD WSR-88D censoring algorithm and a dramatic increase in the amount of recoverable velocity estimates was demonstrated.

6. Acknowledgment

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7. References


Figure 6: Reflectivity from long PRT scan.

Figure 7: SZ recovered reflectivity without censoring.

Figure 8: Same as Fig. 7 but with SZ-1 censoring applied.

Figure 9: Same as Fig. 8 but with additional signal processing to "clean up" the image.

Figure 10: Long PRT velocity corresponding to Fig. 6.

Figure 11: SZ recovered velocity corresponding to Fig. 9.
Figure 12: SZ-2 long PRT power.

Figure 13: SZ-2 recovered velocity.

Figure 14: SZ-2 censored recovered velocity.

Figure 15: WSR-88D recovered velocity.

Figure 16: SZ recovered velocity data illustrating velocity striping due to phase jitter.