34th Conf. on Radar Meteorology
October 5-9, 2009

P5.6

IMPROVING PERFORMANCE OF STAGGERED-PRT CLUTTER FILTERING FOR LONGER PRTS VIA SHREWD WINDOWING

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ABSTRACT – The data acquisition strategy named Staggered Pulse Repetition Time (SPRT) with stagger ratio 2/3 is used to mitigate range-velocity ambiguity in weather radars. SPRT has a problem: it requires an intricate procedure for spectral clutter filtering due to the non-uniform spacing of SPRT data samples. Although the SPRT clutter filtering procedure was developed, tested and named Spectral Adaptive Harmonic Identification (SACHI), it only provides acceptable performance for pairs of PRT with shorter duration (i.e., 1 ms and 1.5 ms). Pairs of PRT with longer duration (i.e., 2 ms and 3 ms) are desirable to extend range coverage. There is no benefit in mitigating range-velocity ambiguity if only short ranges can be achieved. This paper shows a trick for improving the performance of SPRT for longer PRTs via shrewd windowing.

1. BACKGROUND

The National Weather Service (NWS) maintains a network of 166 mechanically steerable S-band weather Doppler radars, also referred to as NEXRAD. Pulse Repetition Time (PRT, T) determines maximum range (R_a) and maximum velocity (v_a) that radar can measure unambiguously: $R_a = cT/2$, $v_a = \lambda/(4T)$, where c is the speed of light, λ is the radar wavelength. From these equations, one can find the Range-velocity (R-v) ambiguity trade-off rule: $R_a v_a = c\lambda/8$. Larger range coverage limits the range of detectable unambiguous velocities, while larger velocities come at a cost of reduced unambiguous range. NEXRAD can mitigate the R-v ambiguity using staggered PRT (SPRT) data acquisition strategy [Sachidananda and Zrnic 2000, Torres et al 2007]. This data acquisition strategy utilizes two PRTs such that $2T_1 = 3T_2$, and transmits a series of PRT pairs for R-v mitigation. SPRT allows observation of farther ranges and larger velocities than possible with a uniform PRT. An example of this is presented in Fig. 1 [Bachmann 2005]. The uniform PRT velocity field (Fig. 1a) requires two separate scans: surveillance scan to locate storms, and Doppler scan to assign velocities to the located echoes. The purple color in Fig. 1 indicates regions where algorithm was not able to assign velocities.

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The staggered PRT velocity field (Fig. 1b) has less purple and extends to further ranges. SPRT is a promising technique that expands radar capabilities and saves resources. However, it has one problem: due to the non-uniform spacing of the SPRT data samples, an intricate procedure is required to filter ground clutter (GC). The intricate filtering procedure, Spectral Adaptive Harmonic Identification (SACHI), exits and was recently modified to utilize NEXRAD's adaptive clutter filter, which has shown to be very effective [Bachmann 2008]. Nonetheless, evaluation of SACHI indicated that an acceptable performance is only possible for pairs of PRT with shorter duration (i.e., T_1 = 1 ms and T_2 = 1.5 ms). Pairs of PRT with longer duration (i.e., T_1 = 2 ms and T_2 = 3 ms) are desirable to extend range coverage. The problem could be mitigated at the expense of increased dwell time; however, increasing the dwell time is not an acceptable option. Therefore the NWS is not using SPRT at lowest elevation tilts.

Recently, a "simplified" SPRT clutter filtering procedure was presented [Hubbert and Meymaris 2009]. The procedure involves separating samples from T_1 and from T_2, transforming each sequence into frequency domain, clutter filtering, transforming back to time domain, and putting the filtered sequences back together. Though straight forward, the procedure has a major flaw: due to the required Blackman windowing, the sequences become distorted and thus cannot be re-assembled in a simple manner. The "simplified" procedure was demonstrated only for short PRTs, a range of PRTs where the SACHI technique already shows excellent performance.

2. THE ROOT OF THE PROBLEM

SACHI performs conventional spectral analyses on staggered PRT data. To create an artificial uniformly-spaced sequence from staggered data, zeros are inserted between samples in a pattern [1 0 1 0 0]. The modified sequence is then processed using conventional spectral analyses. An example of a weather Doppler spectrum from such modified data is shown in Fig. 2b. An example of a weather Doppler spectrum for uniform PRT is given in Fig. 2a. The SPRT spectrum has 5 replicas of the uniform PRT spectral features. The power level of the replicas can be estimated using a kernel obtained by transforming the sequence [1 0 1 0 0] into the frequency domain. The main peak, or the largest replica, is located at the true Doppler velocity of the observed phenomenon in a given unambiguous velocity interval. Other replicas are equidistant and symmetric from the main replica.

This symmetry creates conditions for accurate and un-biased velocity estimation from SPRT spectra.

When both GC and weather signals are present, the situation becomes more complicated. Figs. 2c and 2d show an example of a Doppler spectrum with weather and clutter for uniform PRT and SPRT, respectively. Note that clutter and weather replicas overlap in Fig 2d. As a result, the largest replica is at zero Doppler, which is not good for the weather parameters estimation. SACHI removes all five clutter contributions as shown in Fig. 2e. If the clutter is notched precisely, the largest replica will still be located at the correct weather Doppler velocity. Sometimes due to excessive clutter filtering, an incorrect weather replica can end up larger and be chosen as indicated by the arrow in Fig. 2f. This problem is referred to as “catastrophic velocity errors.” The problem comes from the fact that aggressive window weighting increases the spectral width of GC contribution and this increase happens five times – once in each replica. A slight round-off error in adaptive clutter width identification leads to either under filtering – algorithm picks up clutter instead of weather, or over filtering – algorithm might pick up a wrong weather replica.

NEXRAD has a requirement for range coverage which dictates the use of long PRTs at low elevations. A limited dwell time and long PRTs allow for only a small number of transmitted stagger pairs. A small number of pairs in turn leads to inaccurate clutter filtering and a choice of the wrong replica. When the wrong replica is used, accurate estimates of power and spectral width are accompanied by an incorrect velocity estimate thus creating catastrophic velocity errors. This paper presents a scheme for reducing these catastrophic velocity errors without increasing the dwell time or reducing the range coverage.

3. MITIGATING THE PROBLEM

In general, catastrophic velocity errors can be mitigated by 1) increasing the dwell time (which is equivalent to increasing the number of pairs), 2) reducing the PRT (which means reducing the range coverage), and 3) using a less aggressive window weighting function (which means that clutter residuals will be spilled all over the spectrum).

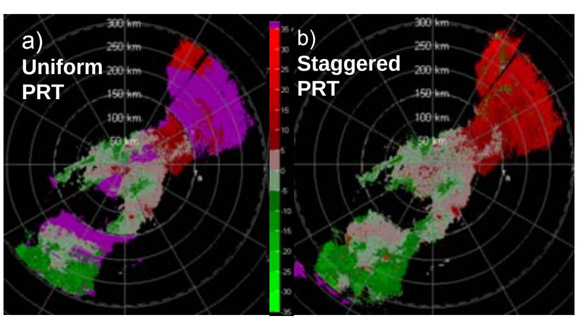

Fig.1. Example of velocity field from (a) uniform PRT data and (b) staggered PRT data. Data: 06/26/03 03:24 GMT. (This figure is taken from [Bachmann 2005] to exemplify benefits of staggered PRT)

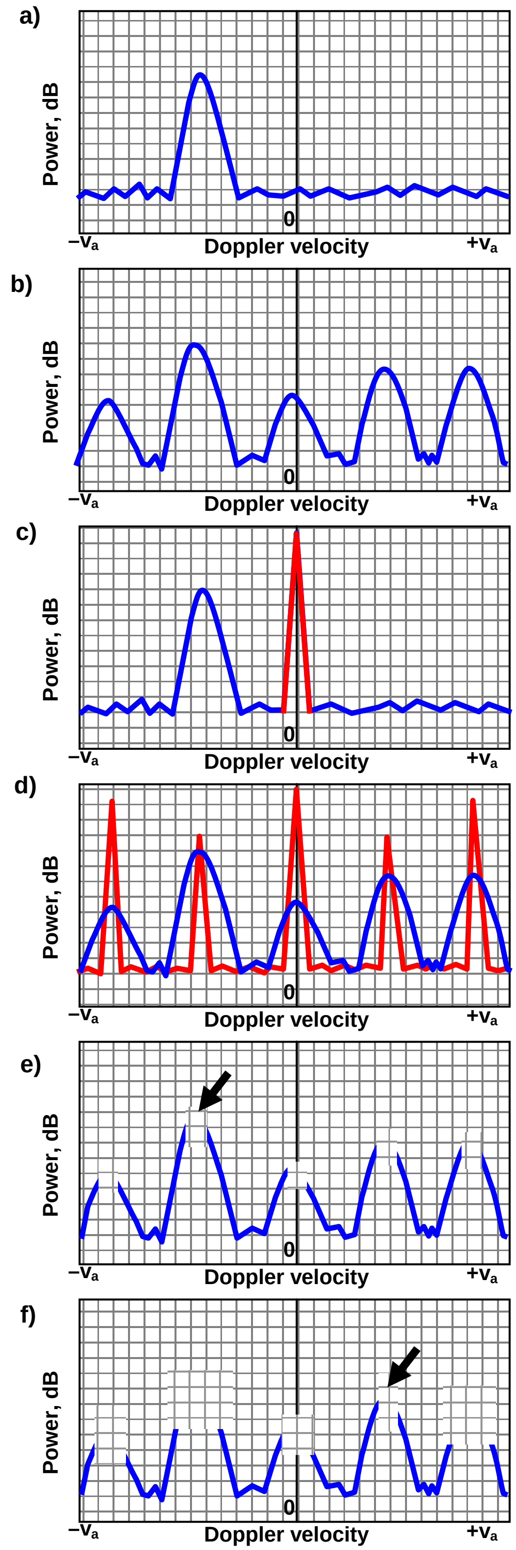

Fig.2. Doppler spectra of a) weather for uniform PRT, b) weather for staggered PRT, c) weather and ground clutter for uniform PRT, d) weather and ground clutter for staggered PRT, and e, f) same as d with notched clutter contributions.

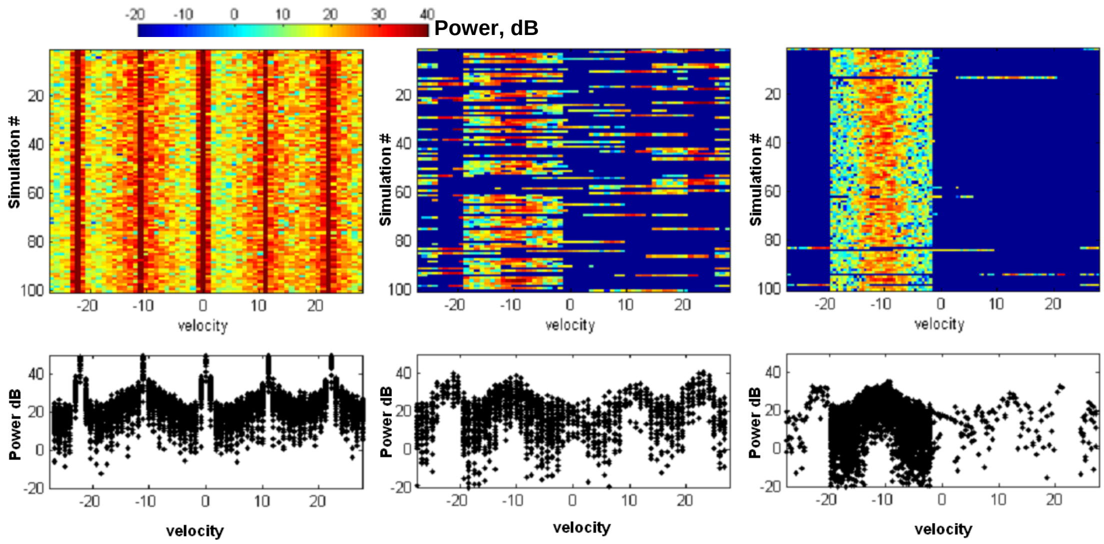

Fig. 3: Example of a,d) SPRT Doppler spectra containing weather and ground clutter: 5 replicas of clutter and 5 replicas of weather are visible; b,e) SPRT spectra after conventional windowing and SACHI clutter filtering: horizontal lines centered at -10 m s^{-1} indicate correct choice of weather contribution, other lines indicate incorrect choice; and c,f) same as b,e, but data was bootstrapped on the edges prior to windowing: only 5 wrong replicas are chosen out of 100. Data: dwell time 60 ms, T1= 2ms, 12 pairs, SNR=20dB, CNR=40 dB.

The presented solution does not require any of the above, and does not make changes to the existing SPRT clutter filtering algorithms both SACHI and "simplified". The improvement is from increased spectral resolution, which allows for more accurate clutter filtering. Better spectral resolution is from special data preparation prior to application of window weighting function.

The data preparation consists of the following steps.

1. Split the IQ sequence of SPRT data into two sequences $x(T_1)$ and $x(T_2)$. This is accomplished by combining all samples for T_1 and for T_2, similar to data preparation performed in "simplified" SPRT clutter filtering [Hubbert and Meymaris 2009].
2. Bootstrap $x(T_1)$ on both edges. If a sequence consists on N samples, it can be extended to $2N$ samples (or any other number of samples) using one of many bootstrapping techniques. Two points are important here. One, the bootstrapping is used to preserve statistical properties of data. Two, the bootstrapped data are added on both sides of $x(T_1)$ for the reason explained next. Any IQ sequence containing GC is usually weighted with an aggressive window (i.e., Blackman). In the spectral domain the benefits of weighting are easy to observe: the spectral floor drops, and the clutter powers get pushed to zero Doppler. In the time domain such weighting modifies the magnitudes of data samples: samples in the center of data sequence remain unchanged, while samples away from the center progressively become less significant in magnitude and drop to zero on the edges. If a sequence is extended in the proposed manner and an aggressive window is applied, the bootstrapped samples will be the ones to become insignificant in magnitude, allowing the original samples to maintain significance. In the evaluation presented in section 4, the authors used a fast and efficient bootstrapping technique from patent pending "System and method for increasing spectral resolution" – filed with the USPTO on March 10, 2009.
4. Bootstrap edges of $x(T_2)$.
5. Recombine bootstrapped $x(T_1)$ and $x(T_2)$. Note, a larger window weighting function is needed for a bootstrapped sequence, hence the shrewd windowing mentioned in the title of this paper
6. Perform SACHI on the extended SPRT sequence.

Extension allows achieving increased spectral resolution, and therefore a more accurate estimation of spectral width of ground clutter that is notched from all five replicas. The increased precision in clutter notching preserves weather residuals that would be over- or under-filtered without the proposed extensions. Weather residuals become more pronounced and the existing algorithm chooses the correct weather replica leading to a significant reduction in catastrophic errors. Note, the proposed bootstrapping can also be used with the "simplified" SPRT clutter filtering to improve performance.

4. PERFORMANCE EVALUATION

The example presented in Fig. 3, shows 100 Doppler spectra for SPRT simulated using 12 pairs of PRT1=2ms, PRT2=3ms. In Fig. 3a GC appears as 5 vertical lines with power exceeding 40 dB. The results of recovery of weather signal after SACHI without data preparation (Fig. 3b) and with the proposed data preparation (Fig. 3c) highlight reduction in catastrophic errors for a single Doppler velocity of -10 m s^{-1}.

To evaluate velocity errors over a range of Doppler velocities we follow the evaluation steps presented in [Bachmann 2008]. Errors are evaluated for a range of PRTs between T_1=1 ms (T_2=1.5 ms) and T_1=2 ms

(T_2=3 ms), and a range of Clutter to Noise Ratios (CNRs) between 0 dB and 65 dB for the weather Signal to Noise Ratio (SNR) of 20 dB. For each set of simulation parameters, errors for a hundred realizations at each Doppler velocity (1 m s^{-1} step size) in the unambiguous Doppler velocity interval are estimated first. Then, the velocity errors contained within the limits of acceptable error (2 m s^{-1}) are assessed. The percentage of acceptable velocity errors are shown in Fig. 4. The maroon color indicates that all velocities from 0 to the unambiguous velocity are contained within the limits of acceptable error for all cases. For colors other than maroon, a percentage of velocity errors exceed the limits. A Blackman weighting window and spectral width of weather 4 m s^{-1} are used in accordance with the error requirement of the current WSR-88D GCF procedure specification.

Figs. 4a-b depict results for conventional windowing. A maroon color for the shortest PRT=1 ms indicates that there are no velocity errors exceeding 2 m s^{-1} for this PRT. For longer PRTs, the percentage of acceptable velocity errors is unsatisfactory. Figs. 4c-d depict results for the same data modified by shrewd windowing after bootstrapping. The maroon region extends to 1.3 ms. Note that these examples are prepared for a very short dwell time of 40 ms. An increase in the dwell time would increase the maroon area in both images. Fig. 4 shows that shrewd windowing after bootstrapping can be used to improve performance of SACHI.

5. CONCLUSION

We exposed a primary issue with clutter filtering Staggered PRT data and showed possible mitigation strategies. We showed a method for improving the performance of SPRT for longer PRTs and shorter dwell times via shrewd windowing and bootstrapping. Eith the proposed methods, pairs of PRT with longer duration (i.e., 2 ms and 3 ms) can be used at low elevation tilts. The presented method reduces catastrophic velocity errors.

AKNOWLEGEMENT

The authors acknowledge the administration of Lockheed Martin MS2 Syracuse Technical Operations for support. The authors appreciate John Winklhofer for his review.

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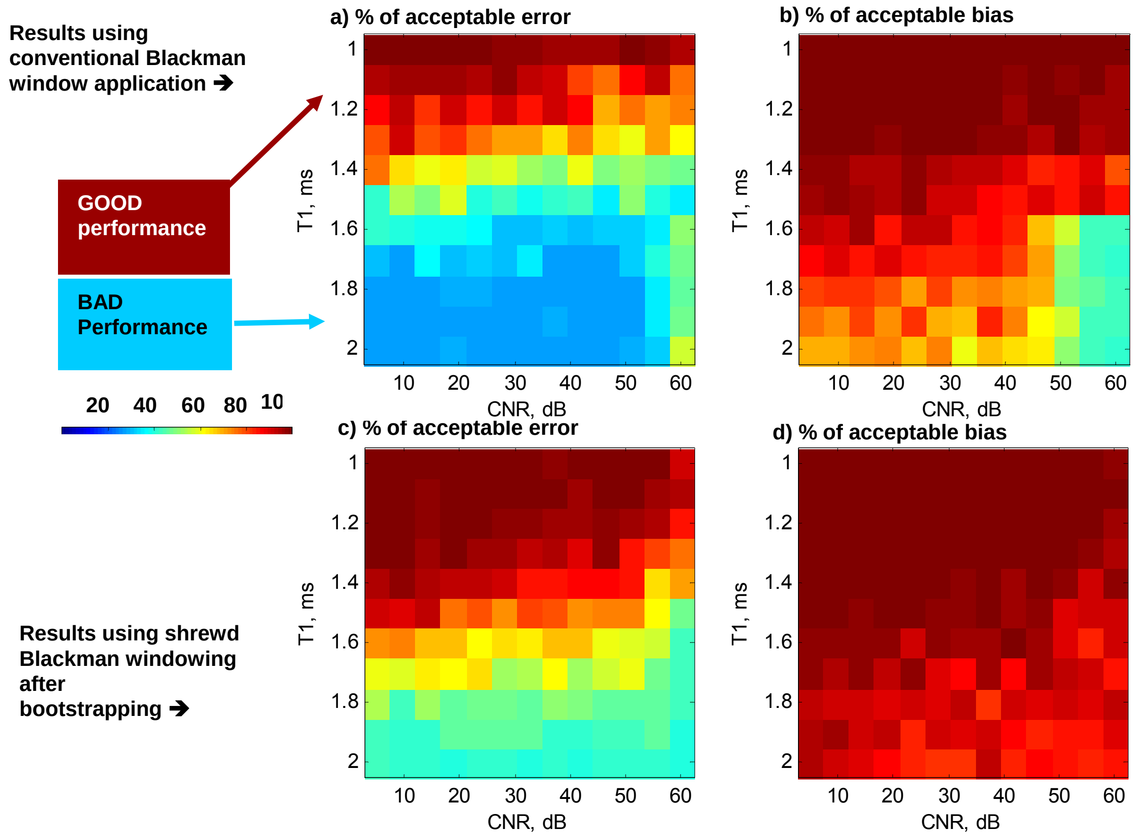

Fig. 4: Performance evaluation in terms of percent of acceptable velocity error and velocity bias for different PRTs and CNRs.: a,b) SACHI after conventional windowing; c,d) SACHI after proposed windowing. Red and maroon is good, blue is bad. Each data cell is evaluated for all weather velocities between 0 to v_a, for each velocity there are 100 simulations.