11B.2 UPDATE ON DEPLOYMENT OF STAGGERED PRT FOR THE NEXRAD NETWORK

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1. INTRODUCTION

In the NEXRAD network, the range and Doppler velocity ambiguity problems are coupled such that trying to alleviate one worsens the other. Operationally, this is evidenced by the obscuration of overlaid weather echoes and/or the aliasing of measured Doppler velocities, both of which impair the effective observation of weather phenomena. Identified as one of the highest technical needs for the NEXRAD program, the Radar Operations Center (ROC) of the National Weather Service has sponsored the National Severe Storms Laboratory (NSSL) to develop signal processing methods for mitigating the effects of velocity and range ambiguities on the US weather radar network (Zrnić and Cook 2002). The first stage of this development was completed during 2007 with the operational deployment of a technique based on systematic phase coding termed as SZ-2 (Torres 2005). However, SZ-2 was designed to run only at the lower antenna elevation angles. Recently, NSSL recommended a staggered pulse repetition time (SPRT) algorithm for the second stage of deployment. This algorithm is based on a transmission sequence with two alternating pulse repetition times (PRT) and is suggested for intermediate to higher elevation angles of the antenna beam.

Comparisons with existing “legacy” algorithms have demonstrated the ability of SPRT to effectively mitigate range and velocity ambiguities (Torres 2006). However, the performance of this algorithm is limited by the accuracy of Doppler velocity estimates obtained for each PRT set. Large errors of estimates lead to dealiasing errors that cannot be effectively mitigated by the baseline NEXRAD velocity dealiasing algorithm (VDA). This paper presents a review of the SPRT algorithm, describes the performance of the algorithm in terms of velocity dealiasing errors, and illustrates the performance of a modified VDA to mitigate this particular class of errors. Finally, the status and plans for the operational deployment of the SPRT algorithm are outlined.

2. THE STAGGERED PRT ALGORITHM

The staggered PRT technique was first proposed in the context of weather surveillance radars by Sirmans et al. (1976). With this technique, transmitter pulses are spaced at alternating PRTs, T_1 and T_2, and pulse-pair autocorrelation estimates are made independently for each PRT. These estimates are suitably combined so that the effective maximum unambiguous velocity can be extended to $v_a = m\lambda/4T_1 = n\lambda/4T_2$, where the stagger PRT ratio is given by $T_1/T_2 = m/n$ (m and n are integers) and λ is the transmitter wavelength. In addition, the maximum unambiguous range is $r_a = cT_1/2$, corresponding to the shorter PRT (c is the speed of light). At the core of this technique is the generalized velocity dealiasing algorithm (Torres et al. 2004); to determine the Nyquist interval of the true velocity, it uses the fact that Doppler velocities obtained from the short and long PRTs alias in different ways.

The implementation of the staggered PRT technique on weather radars had been precluded from use mainly due to the difficulties in designing efficient ground clutter filters. However, a few years ago, Sachidananda and Zrnić (2002) proposed an efficient spectral clutter filter for staggered pairs that achieves clutter suppressions on par with those obtained for uniformly spaced samples. The recommended algorithm incorporates both the generalized velocity dealiasing algorithm and the spectral ground clutter filter.

3. VELOCITY DEALIASING ERRORS

The generalized velocity dealiasing algorithm at the core of SPRT fails if the variances of the short- and long-PRT velocity estimates are large. In such cases, the algorithm employs the wrong dealiasing rule and the resulting “dealiased” velocity is significantly different from its true value. These types of dealiasing errors are termed “catastrophic” errors (Torres et al. 2004) because they may result in completely incorrect velocity estimates. “Catastrophic” errors are usually evident as speckle noise in the Doppler velocity image and can be easily removed by velocity dealiasing algorithms based on field continuity as will be demonstrated later. Still, the rate of catastrophic errors should be kept to a minimum to ensure that the speckling nature of these errors is preserved and that continuity-based velocity dealiasing algorithms can detect and correct these problems effectively.

Figure 1 shows the rate of catastrophic velocity errors expected for a volume coverage pattern (VCP) similar to VCP 11, but using staggered PRT. To get the required coverage in range, longer PRTs are needed at lower elevation angles resulting in larger velocity

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variances. Hence, the rate of “catastrophic” errors is larger for the lower elevation angles. Also, wider spectrum widths lead to larger variance of Doppler velocity estimates and, as a result, to higher rates of “catastrophic” errors. However, “catastrophic” errors are almost negligible for all elevation angles if the spectrum widths are less than about 4 m/s.

As shown next, these sporadic dealiasing errors (i.e., the “catastrophic” errors) occurring in the WSR-88D Radar Data Acquisition (RDA) subsystem can be easily mitigated by velocity dealiasing techniques based on field continuity which are implemented in the Radar Product Generation (RPG) subsystem.

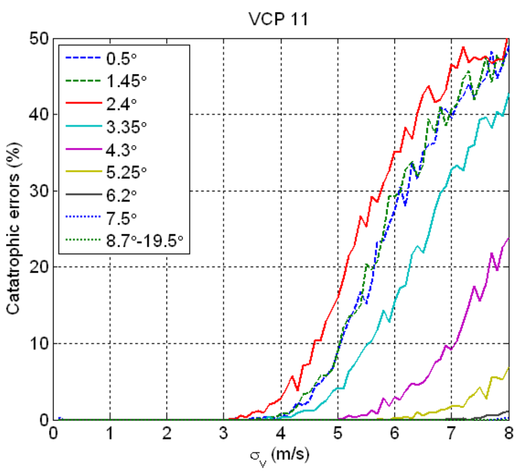

Fig. 1. Rate of catastrophic errors as a function of the spectrum width for all the tilts in the staggered PRT-based VCP 11 “clone”.

4. THE VELOCITY DEALIASING ALGORITHM

In addition to the “catastrophic” errors described above, the SPRT algorithm may not fully resolve (dealias) velocities under strong wind conditions (i.e., the actual Doppler velocities exceed the extended unambiguous velocity). Therefore, further velocity dealiasing may be required. The WSR-88D RPG velocity dealiasing algorithm and its modifications to handle the “catastrophic” errors from SPRT are described next.

4.1. *General description*

The Velocity Dealiasing Algorithm (VDA) for the NEXRAD system is an efficient dealiasing technique that processes one radial at a time but uses dealiased velocity from the preceding radial when available (Eilts and Smith 1990). The VDA runs in the WSR-88D system’s RPG.

Initially, each test velocity bin is compared to a nearby bin closer in range to the radar. If the test bin is within a threshold velocity difference it is assumed to have a good value. If not, the test bin is adjusted (dealiased) by integral multiples of the Nyquist co-interval and the difference in values is again checked. If the velocity cannot be adjusted to within a threshold velocity difference, an average of the 4 preceding bins in the current radial and the 5 bins farther in range in the previous radial is computed against which the test bin (or its dealiased value) is checked. If an average of the nearby velocities cannot be computed, the VDA looks farther back along the current radial or farther in range in the preceding radial for a good comparison velocity. If a comparison velocity still cannot be found, the VDA uses environmental wind data against which to test the velocity in the current bin. For each comparison velocity, if the test bin’s velocity cannot be dealiased to within a threshold velocity difference of the comparison velocity, it is set to a below signal-to-noise flag and the velocity saved for reinsertion into the radial later. The VDA allows a threshold number of consecutive velocities (nominally 4) to be removed before it reinserts them using relaxed thresholds. The original velocity value may be reinserted if, after dealiasing, its value cannot be adjusted to lie within a threshold velocity difference. Error-checking logic tries to correct unrealistically long runs of high azimuthal shear. Other error-checking logic looks for large gate-to-gate jumps in velocity but with opposite sign along the current radial. When found, the velocities between the large jumps are adjusted by an appropriate Nyquist co-interval. If a single large velocity jump in the current radial still exists, that radial is flagged as unusable for dealiasing velocity bins in the next radial and the previous radial’s data is retained for comparison. Otherwise, the current radial’s dealiased velocity data are saved for use by the next radial. An adaptable number of “bad” radials may be skipped before the VDA decides there is no valid previous radial.

At this point VDA has essentially completed dealiasing of the current radial but some bins may still be set to the below signal-to-noise flag. The velocities for these bins are reinserted into the radial with their original values if they cannot be adjusted by a multiple of the Nyquist co-interval using a relaxed velocity difference threshold. The velocities reinserted in this last step have no influence on future dealiasing.

4.2. *VDA changes to support SPRT*

The baseline VDA cannot dealias the velocities resulting from “catastrophic” errors introduced by the SPRT but instead, places them back in a radial with their original values. Because many of the velocity difference thresholds used by the VDA are derived from the Nyquist velocity, notably for the final reinsertion step, a simple solution is to allow the VDA to use the Nyquist velocity corresponding to $v_a = \lambda/4T_1$ which is half the extended Nyquist velocity. It is appropriate to use v_a for T_1 because dealiased velocity estimates provided by the SPRT algorithm are computed from T_1.

In regions of weak signal, more than 4 consecutive bins may have “catastrophic” errors. These bins would have been filled in by the VDA with their original values during the first reinsertion process and so would not be dealiased using v_a for T_1. However, the number of consecutive bins that may be flagged as missing may be increased thus allowing for more recovery of "catastrophic" errors. The following figures will illustrate the improvements from these simple changes. Figure 2 shows a small region of velocity data dealiased using the baseline VDA. While the overall field has been dealiased correctly, there are numerous bins that do not fit the strong outbound flow. Figure 3 shows that the noisy velocities can be greatly mitigated by allowing the VDA thresholds to be rescaled using half the extended Nyquist velocity. Some remaining regions of noisy velocity may be further "cleaned up" by increasing the number of consecutive bins that may be removed from 4 to 9 as shown in Figure 4. However, care must be taken to not remove too many bins. Figure 5 shows the reflectivity field corresponding to the velocity images. A strong storm core is seen at 70 nautical mile (nmi) range, 75 deg azimuth and also just beyond 50 nmi, about 130 deg azimuth. These cores may act as a barrier to the outbound velocities. The near-zero velocities just upstream of them may, therefore, be entirely realistic.

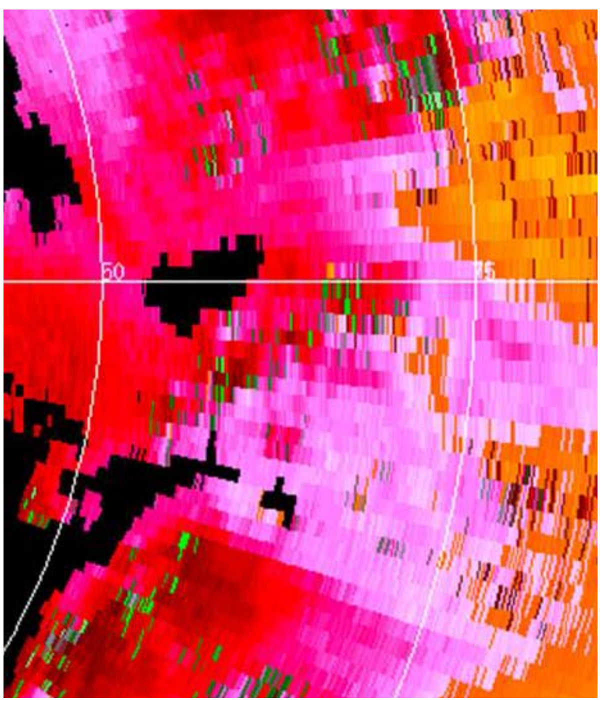

Fig. 2. SPRT velocity field from March 31, 2008, 1951Z at 3.1 deg elev. dealiased using baseline VDA. Range rings are every 25 nmi. Note numerous bins with velocities that do not fit the general flow. Warm colors show flow away from the radar; cool colors show flow towards the radar. See legend in Fig. 8 for corresponding velocities.

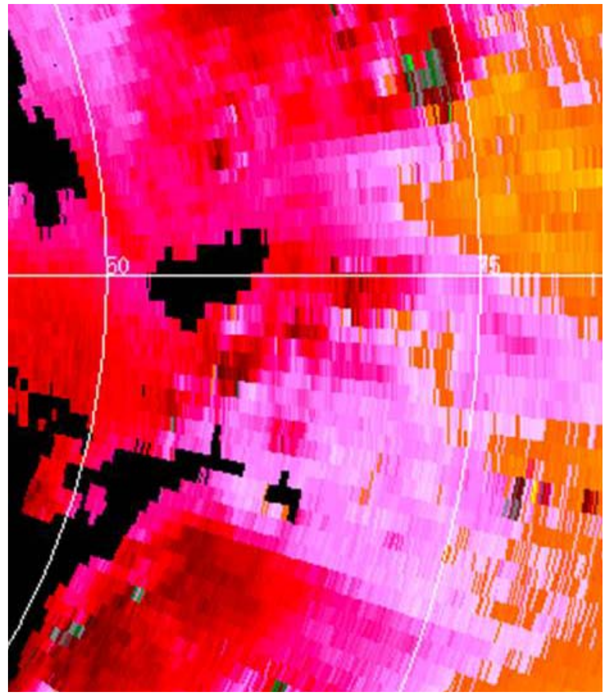

Fig. 3. Same as Fig. 2 but the final bin reinsertion for VDA uses the Nyquist velocity corresponding to the shorter PRT.

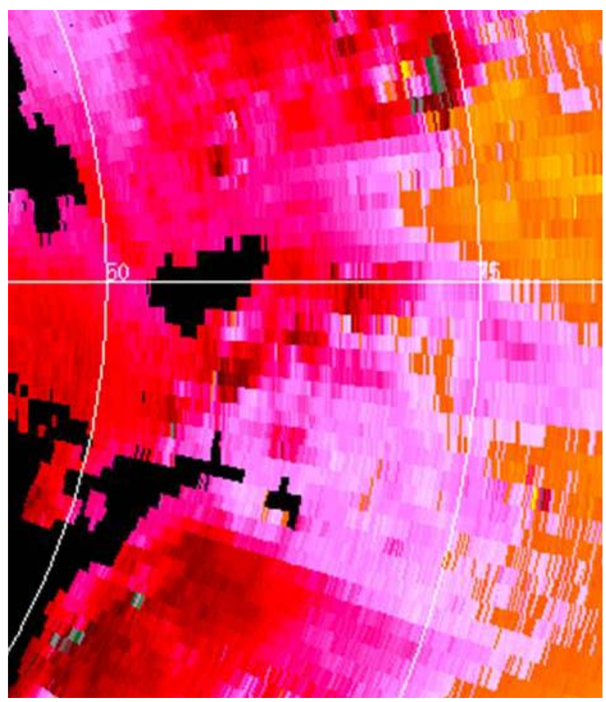

Fig. 4. Same as Fig. 3 but the number of bins VDA may initially remove is changed from 4 to 9. Note further reduction in bins with velocities that do not fit the overall flow.

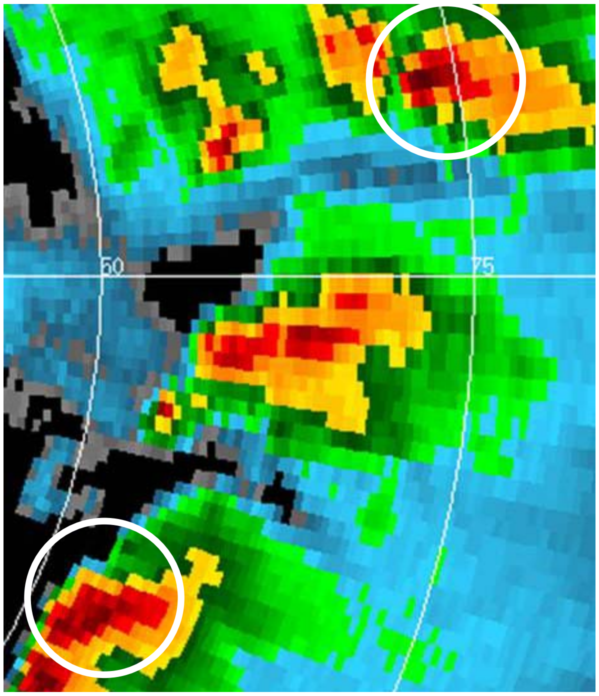

Fig. 5. Reflectivity corresponding to the velocity fields in Figs. 2-4. Note the juxtaposition of near zero velocities with strong cores upper right and lower left (circles). See legend in Fig. 7 for dBZ values.

5. OPERATIONAL STATUS AND PLANS

The ROC is responsible for implementing and integrating new science into the NEXRAD network. A good example of this process is given by ongoing effort to implement signal processing techniques for the mitigation of range and velocity ambiguities. Both the SPRT algorithm for the RDA subsystem and the modified VDA for the RPG subsystem are in the process of being incorporated into the WSR-88D. As mentioned in the introduction, staggered PRT is only one part of an overarching effort to improve the mitigation of range and velocity ambiguities on the NEXRAD network.

The ROC is developing SPRT in three phases. The first phase was an investigation and decision phase. It was completed in August of 2007. During that time, the ROC compared the NSSL SPRT algorithm with the Vaisala/SIGMET Dual PRT (DPT2) algorithm. While the DPT2 is a very good algorithm, the NSSL approach provided additional flexibility for any form of PRT ratio and an approach to manage overlaid signals. During phase I, the Vaisala/SIGMET DPT2 major mode was enabled so that we could transmit staggered PRT pulse sequences as part of engineering tests. ROC engineers recorded time series data from those tests which were used later for analysis and testing.

The ROC implemented the NSSL SPRT algorithm during the second phase of development. SPRT was implemented in a user major mode on the RDA signal processor, the Vaisala/SIGMET RVP8. The initial implementation of SPRT uses a DC removal clutter filter. The performance of this filter does not meet WSR-88D clutter suppression requirements; therefore, the new user major mode is non-operational at this time. However, the second phase established the architecture and basic algorithm on which improved clutter filtering can be added. The second phase of SPRT is nearly complete.

Phase II algorithm implementation also allowed for some preliminary comparisons between the current ORDA batch mode and SPRT. On May 07, 2008, a widespread rain event with embedded convective cells passed through central Oklahoma. KTLX, the Oklahoma City radar, was running VCP 12 which runs batch mode signal processing at the mid-level tilts. KCRI, the ROC test radar, was running engineering test VCP 15, which is a “clone” of VCP 12 except that it runs SPRT at the mid-level tilts. Figures 6 and 7 show the reflectivity and Doppler velocity fields from KTLX at an elevation of 1.8 deg obtained with batch processing. The reflectivity is estimated from pulses transmitted at a PRT of 3140 μsec; which provide a maximum unambiguous range of 252 nmi. The velocity is estimated from pulses transmitted at a PRT of 1000 μsec, which gives a maximum unambiguous range of 80 nmi and a maximum unambiguous velocity of 24 m s^{-1}. Note the areas of overlaid echoes (purple haze) that are typical when using shorter PRTs. Figure 8 shows KCRI’s Doppler velocities obtained with SPRT processing at nearly the same time and at the same elevation angle. SPRT used a 2/3 PRT ratio of 1740 μsec/2160 μsec. This combination of PRTs provides a maximum unambiguous velocity of 28 m s^{-1} and a maximum unambiguous range of 141 nmi. Note the increased coverage in range with similar maximum unambiguous velocities. Both the KTLX and KCRI velocity products have been processed by the improved VDA algorithm on the RPG described in the previous section.

The ROC is beginning the third phase of SPRT. During this phase the ROC will add NSSL’s Spectral Algorithm for Clutter Harmonics Identification and removal (SACHI) clutter filter. In addition, the ROC will analyze SPRT-derived base moments to verify that they meet WSR-88D requirements. Another task of phase three is to define optimal PRTs so that both SPRT and the clutter filter have the best performance while maintaining the fastest possible scan rate for minimal Volume Coverage Pattern (VCP) update times. The ROC envisions a VCP that mitigates both range folding and velocity dealiasing by enabling SZ-2 on the lower split-cuts and SPRT on all the remaining upper cuts. The target build for SPRT is Build 13.

The changes to the VDA have been made in a parallel effort with the development of the SPRT Major Mode. The completed upgrades to the VDA will be available in Build 12 whenever SPRT Major Mode is enabled. During the implementation and testing of the SACHI clutter filter, the ROC will perform more testing, data collection, and analysis including changes to the VDA.

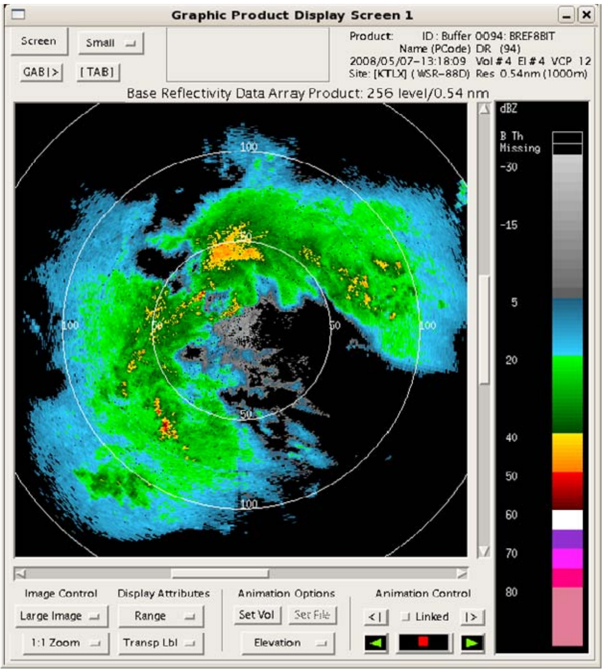

Fig. 6. KTLX reflectivity, elevation 1.8º, batch mode processing, Surveillance PRT 3140 µsec, unambiguous range 252 nmi.

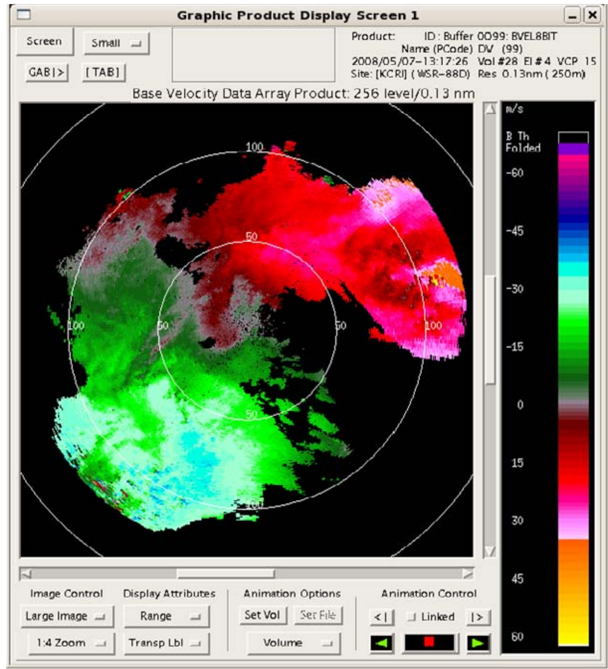

Fig. 8. KCRI Doppler velocity, elevation 1.8º, SPRT mode processing, PRT Ratio 2/3, PRT 1740 µsec/2160 µsec, unambiguous range of 141 nmi, unambiguous dealiased velocity of 28 m s^{-1}.

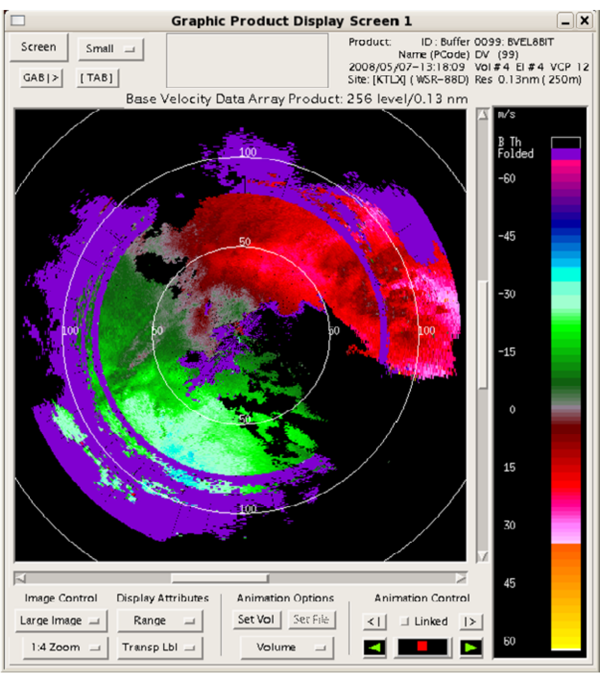

Fig. 7. KTLX Doppler velocity, elevation 1.8º, batch mode processing, Doppler PRT 1000 µsec, unambiguous range of 80 nmi, unambiguous velocity of 24 m s^{-1}.

6. CONCLUSIONS

In an effort to improve the effective observation of weather phenomena, the ROC and the NSSL are working together to develop and implement SPRT with clutter filtering as a velocity aliasing mitigation technique. That, in conjunction with VDA upgrades that will correct for the occasional "catastrophic" SPRT dealiasing error, will greatly mitigate velocity aliasing on the WSR-88D. The ROC is working towards having SPRT with clutter filtering and VDA upgrades operational by Build 13.

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