P3C.2 RANGE-VELOCITY AMBIGUITY MITIGATION SCHEMES FOR THE ENHANCED TERMINAL DOPPLER WEATHER RADAR

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1. INTRODUCTION

The Terminal Doppler Weather Radar (TDWR) radar data acquisition (RDA) subsystem is being replaced as part of a broader FAA program to improve the supportability of the system. An engineering prototype RDA is under development that will provide a modern, open-systems hardware platform and standards-compliant software. The new platform also provides an opportunity to insert algorithms to improve the quality of existing base data products, as well as support future enhancements to the aviation weather services provided by TDWR. There are several outstanding data quality issues with the TDWR. In this paper, we focus on mitigation schemes for the range-velocity ambiguity problem that is especially severe for C-band weather radars such as the TDWR.

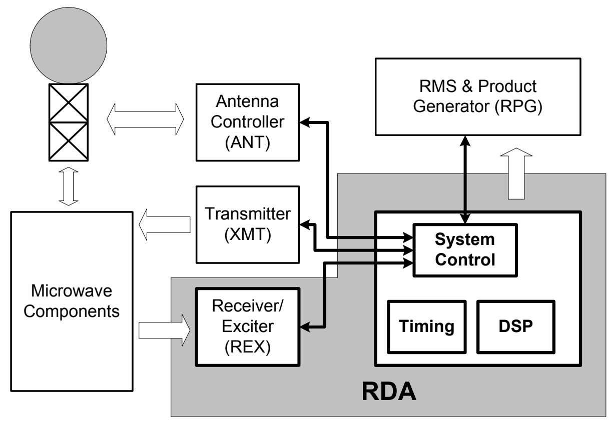

Figure 1. Legacy system block diagram.

2. ENHANCED TDWR RDA ARCHITECTURE

Figure 1 shows a simplified block diagram of the TDWR. The DSP, in addition to performing clutter filtering and generating moment data, functions as a conduit for system control between the Remote Monitoring System (RMS) and the antenna, transmitter, and receiver/exciter (REX) subsystems. The digital signal processor (DSP) hardware consists of three commercial off-the-shelf (COTS) and 19 custom cards, installed in a single 19” multibus chassis. This technology will soon be unsupportable.

A block diagram for the re-hosted RDA hardware is shown in Figure 2 (Elkin et al, 2002). Dual Intel Xeon (currently 2.4 GHz) processor compute servers running Linux perform both the signal processing and system control functions. The system control computer houses the SIGMET RVP8, which provides a COTS solution for the digital receiver, waveform trigger, and timing functions in three PCI cards (receiver, transmitter, I/O).

For the initial prototype, one dual-processor system is sufficient for the legacy signal processing, since the legacy DSP had approximately 250 Mflops of processing power. More compute nodes can be added easily to support future algorithms. Gigabit Ethernet provides ample bandwidth for sending the 5 Mb/sec in-phase and quadrature (I&Q) data stream to the compute nodes. Moment data are also output via Ethernet (instead of SCSI). This approach allows multiple users to attach to both the moment data and I&Q streams.

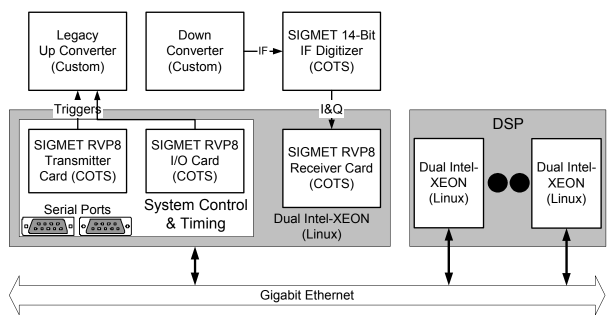

Figure 2. Re-hosted RDA hardware.

Figure 3 illustrates the prototype software. System control paths between the RMS, transmitter, antenna, and DSP/REX are provided by a message passing process. It provides scan strategies to the antenna, and waveform data and scan commands to the IQ Master (IQM). The IQM sends transmit instructions to the RVP8, accesses the received I&Q data, and serves the I&Q data to the DSP algorithms running on IQ Slave (IQS) processes. Algorithms will be implemented using the VSIPL portable vector-processing library. Each IQS process operates on a subset of the received range gates, and sends moment data to a collector process, which re-assembles the range slices and outputs the data to the legacy RPG.

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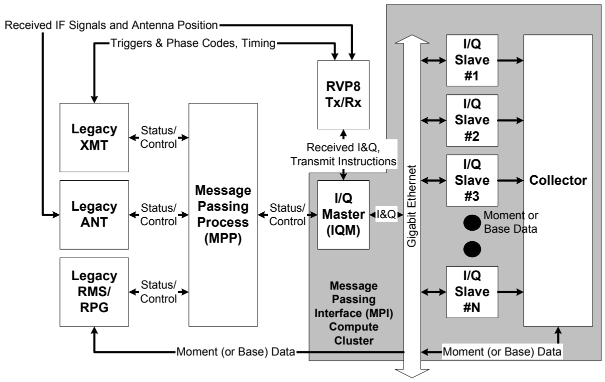

Figure 3. Re-hosted RDA software.

The engineering prototype will be installed in July 2003 at FAA's Oklahoma City Program Support Facility (PSF) site. FAA personnel will evaluate and test an initial configuration that provides hardware replacement of the RDA platform and implements the existing DSP algorithms in software. In 2004, this initial configuration will be fielded at one or two operational TDWR sites. This will provide an opportunity to record I&Q data to facilitate the algorithm development effort. Algorithmic improvements such as those discussed in this paper will then be inserted into the platform in 2004-2006.

3. RANGE-VELOCITY AMBIGUITY MITIGATION

The fundamental constraint is defined by the ambiguity relation, $r_a v_a = c\lambda/8$, where r_a is the unambiguous range, v_a is the unambiguous velocity, c is the speed of light, and λ is the radar wavelength. The FAA requirement for the TDWR is radial wind speed measurement up to 40 m/s with coverage out to 89 km. If these values are plugged into the ambiguity relation, we see that the radar wavelength must be at least 10 cm to satisfy the specification. However, the TDWR operates at 5 cm, so it is impossible to perfectly meet the requirement with a single-wavelength radar. In fact, the actual situation is much worse, since at the lowest tilts the TDWR can detect weather much farther than 89 km. It is possible for strong signals from beyond 400 km (5th trip for an 89-km 1st trip) to fold into the first trip. It is also possible for wind speeds to exceed 40 m/s.

Fortunately, there are tricks that allow us, at least partially, to resolve this inherent ambiguity. We will briefly review the process currently used, then discuss alternative techniques that we have been examining.

3.1 *Current Operational Scheme*

For the lowest elevation tilt, where the range-velocity ambiguity problem is worst, the operational TDWR system transmits three consecutive scans. During the first scan a pulse repetition frequency (PRF) of 326 Hz is used to provide unambiguous reflectivity coverage out to 460 km. This corresponds to the approximate range limit of weather returns at the lowest elevation. Of course, such a low PRF waveform does not allow velocity estimation. However, the reflectivity data from the low-PRF scan is then used to choose a much higher PRF for the following scan that minimizes range-folding obscuration of the areas noted for attention (ARENAs), which are associated with the active runways (Crocker, 1988). Another PRF is selected for the third scan, which optimizes the velocity dealiasing (Wieler and Hu, 1993). Range gates that are still obscured after this procedure are blacked out for display.

The problem with this technique is that only one pair of PRFs is applied to the entire scan. This means that although the ARENA gates in one radial may be saved from range-aliased obscuration, ARENA cells in other radials (and non-ARENA cells in any radial) may be obliterated. Even within a radial, there is a trade-off to be decided between optimization for different range gates. Furthermore, since the choice of the second PRF is dictated by velocity-dealiasing criteria, it may be a bad one with respect to range folding.

3.2 *Multistaggered Pulse Processing*

A logical extension of exploiting PRF diversity for range-velocity ambiguity mitigation is to transmit not just two but *M* PRFs. We can also do this within each radial instead of for the entire scan. Figure 4 shows a schematic of an example multi-PRF waveform.

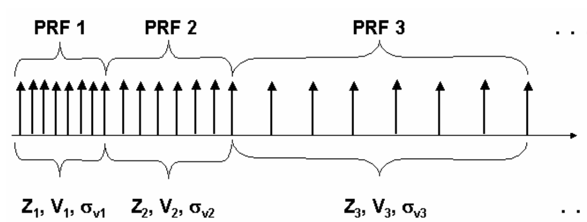

Figure 4. Schematic of multistaggered pulse train.

The advantage of a multi-PRF waveform is that for a given range gate, each set of PRF pulses corresponds to different out-of-trip range gates. Thus, one needs to only use the base data estimates resulting from the PRF sets with no range folding present. (The estimates can be generated using standard pulse-pair processing techniques, then the median of the "clean" estimates taken for more robustness.) Since there are *M* PRFs to choose from for every cell, this is a big improvement in first-trip protection capability compared to the legacy mode.

Velocity dealiasing can be performed within each radial using the "clean" estimates. Either a least-squares fitting approach can be used, or, if the PRFs are chosen to be simple integral ratios, then the Chinese remainder technique could also be applied. Clearly, velocity dealiasing within the radial is preferable to velocity dealiasing between scans.

There are two disadvantages to this method, which we call multistaggered pulse processing (MSPP). The first, also common to the legacy approach, is that range-extensive out-of-trip signals could contaminate all of the PRFs transmitted. In this case, the first-trip protection mechanism fails for those particular range gates. Second, although effective ground clutter filters can be designed for multi-PRF waveforms (Chornoboy, 1993), their application destroys the independence of each

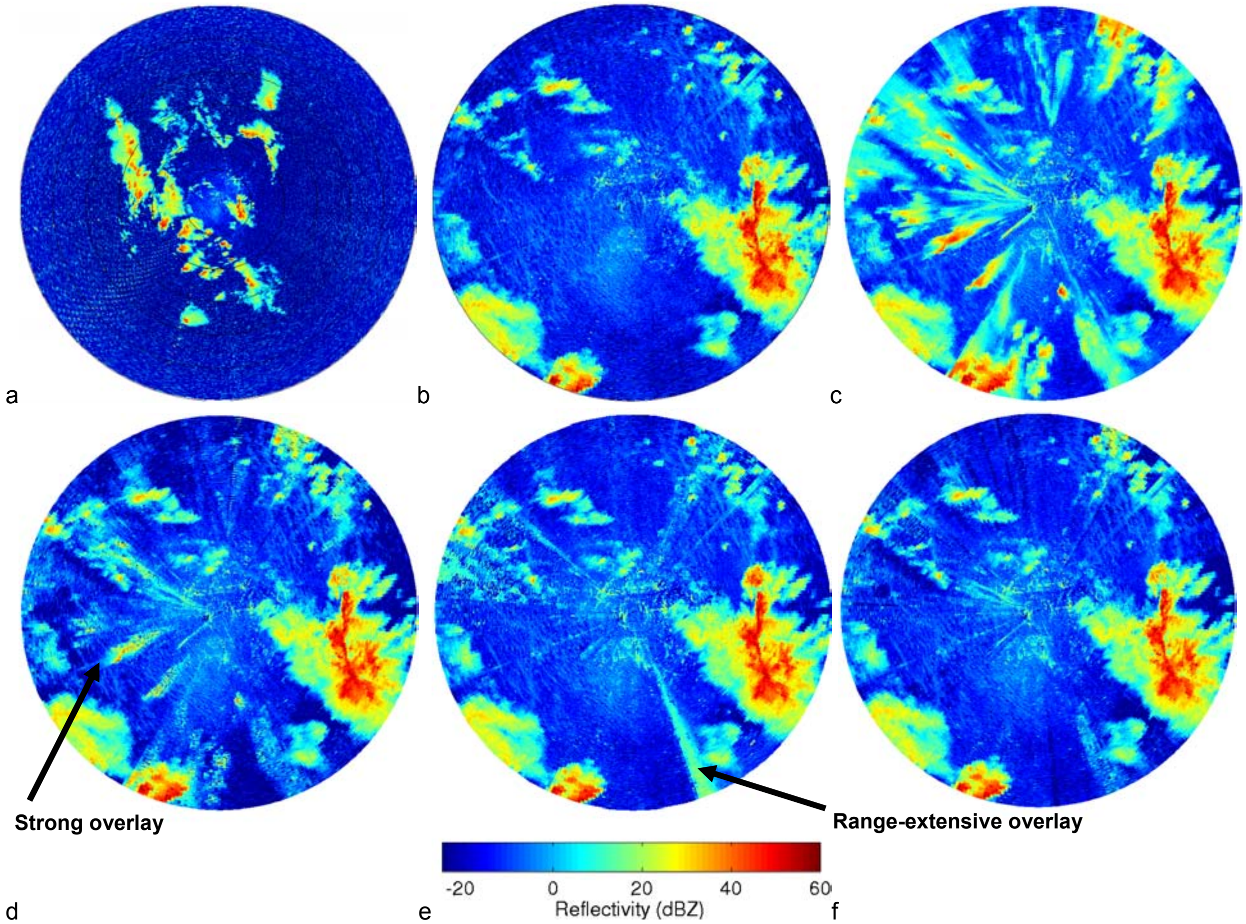

Figure 5. First-trip protection comparisons of reflectivity from 2040 UT, 17 March 2003, 0.3° elevation. a) Low PRF to 460 km, b) low PRF, c) single PRF, no phase code processing, d) single PRF, random phase code processing, e) MSPP, f) optimized radial-by-radial combination of MSPP and random phase code processing. See text for details.

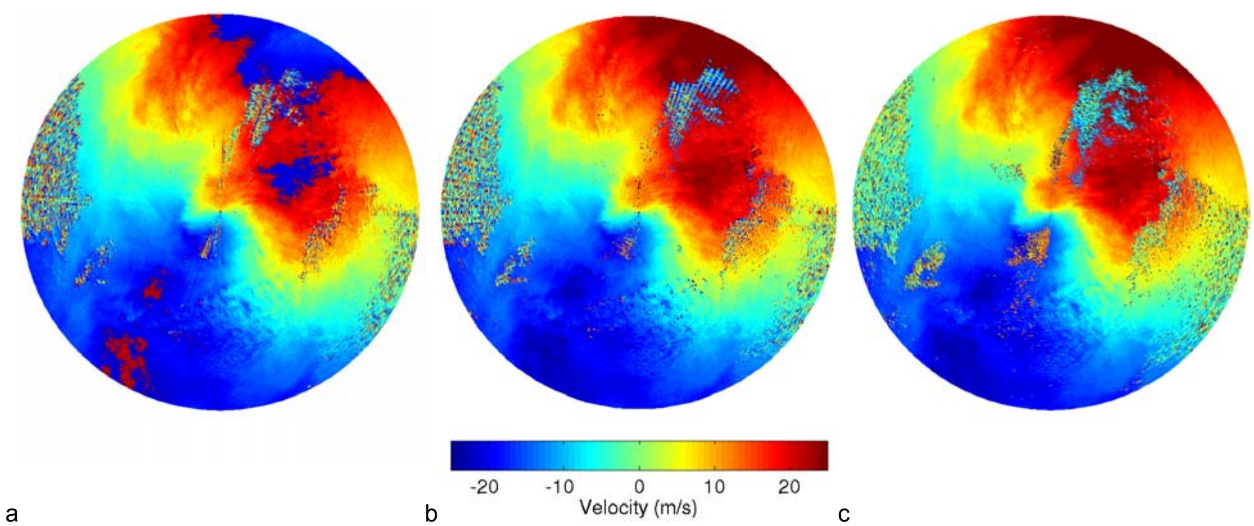

Figure 6. Velocity dealiasing comparisons from 1821 UT, 3 April 2003, 2.6° elevation. a) Single PRF, b) alternating radial dual PRF, c) MSPP. See text for details.

PRF set, because the filter convolves information from the entire pulse sequence. Consequently, for a given range gate, MSPP can either deal with ground clutter or first-trip protection, but not both simultaneously.

3.3 *Phase Codes + Alternating-Radial Dual PRF*

Another parameter that can be varied to achieve separation of signal from different trips is the transmitted pulse phase. By tagging each pulse with a characteristic phase, one can cohere on reception to the desired trip signal (Laird, 1981), or, more effectively, cohere to the unwanted signal and filter it out before recohering to the wanted signal (Siggia, 1983). There are different ways of performing this filtering operation, as well as a variety of phase codes that can be used, such as random or periodic phase codes (Sachidananda and Zrnić, 1999). Although periodic phase codes can yield superior performance relative to random codes, we concluded that they have limited applicability to the TDWR because of two factors: the failure to provide first-trip protection against certain trips (e.g., the 5th trip for the SZ(8/64) code), and the need for accurate knowledge of the spectral widths for both the desired and unwanted signals for effective data quality censorship. These two factors are problematic, in particular, for C-band radars and do not necessarily apply to S-band radars such as the NEXRAD. For details, see Cho (2003).

Phase code processing does not provide velocity dealiasing. However, by alternating the PRF on consecutive radials, one can dealias velocity between radials. Such a scheme is already implemented in the SIGMET RVP8.

The main disadvantage of phase code processing compared to MSPP is that strong or spectrally wide out-of-trip signals cannot be completely filtered out. Furthermore, if more than one out-of-trip signal is overlaid, the process fails. The advantage is that range-extensive overlays are okay.

4. DATA EXAMPLES

To compare the performance of MSPP vs. phase code processing, we collected I&Q data with the FAA's PSF TDWR in Oklahoma City. For the MSPP waveform we transmitted 8 blocks of PRFs varying from 1066 to 1930 Hz with 8 pulses in each block. Another scan was made using PRFs of 1254 and 1672 Hz alternating on consecutive radials with the random phase code waveform. A low-PRF scan at 326 Hz was also included in the set. The antenna rotation rate was 21.6°/s.

Figure 5a is a low-PRF reflectivity scan showing strong returns up to the 5th trip of the highest PRF (1930 Hz) used (indicated by the dark concentric rings). Figure 5b is a blow up of the same plot to show only the range of the high-PRF first trip. This plot can be taken to be "truth" as there are presumably no range-folded signals. Figure 5c is a single-PRF scan with no phase-code processing. Note the range-folding occurring on many radials. Figure 5d is the result of random phase-code processing, while Figure 5e is the product of MSPP. Neither technique works perfectly (see arrows indicating examples of failure regions). However, their relative strengths are complementary; therefore, a selection from the two processes yielding the better result would be best. Such an optimized combination, chosen on a radial-by-radial basis, is shown in Figure 5f. The velocity comparisons (not shown due to limited space) are similar in nature to the reflectivity comparisons, although in this case a "truth" plot is not available.

An example of the velocity dealiasing performance of the two mitigation techniques is shown in Figure 6, and we see that both techniques yield good results. Figure 6a is a single-PRF scan, while Figure 6b is a phase-coded alternating-radial dual-PRF scan, and Figure 6c is an MSPP scan.

5. CONCLUSIONS

We see that MSPP and phase-code processing have complementary strengths with respect to first-trip protection. Therefore, the best strategy is to adaptively select from both. The revamped RDA system will allow us to do this on a radial-by-radial basis in real time. At the lowest tilt, a low-PRF scan can be conducted first then the reflectivity information obtained can be used to set up a pattern of MSPP and phase-coded dual-PRF waveforms for the radials in the subsequent scan. A third scan will not be needed, because velocity dealiasing can be performed within the second scan. With this framework, it will be straightforward to add other waveforms to the roster that we might devise in the future, ensuring flexibility in devising further data quality improvement schemes.

6. REFERENCES

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