4R.5 DEMONSTRATION OF RANGE OVERSAMPLING TECHNIQUES ON THE WSR-88D

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1. INTRODUCTION

Among the planned upgrades for the NEXRAD network of weather surveillance radars are super-resolution (1/4 km reflectivity and 0.5 deg radials) and polarimetric capabilities. In either case, keeping current update times (i.e., same antenna rotation rates) results in meteorological variable estimators with unacceptable large errors. A family of methods to reduce errors in estimates of spectral moments and polarimetric variables beyond those achievable with standard estimators has been proposed (Torres and Zrnić 2003a, 2003b, Torres et al. 2004) and is scheduled for inclusion in future upgrades of the WSR-88D Open Radar Data Acquisition (ORDA) subsystem. These techniques consist of oversampling echo signals in range, applying linear transformations to the samples, processing the sequences in time at fixed range locations to obtain covariance estimates, averaging these covariances in range, and finally combining them to compute the variables. This paper demonstrates the enhanced performance of estimators based on range oversampling techniques.

2. RANGE OVERSAMPLING IN THE WSR-88D

Traditional sampling of weather radar in-phase (*I*) and quadrature (*Q*) signals occurs at a rate of τ^{-1}, where τ is the duration of the transmitted pulse. In a typical receiver system, the effective sampling rate can be accomplished by hardware only or by a combination of hardware and software (e.g., filtering and decimation performed at the front end of the processing chain). Oversampling in range entails acquiring (polarimetric) time series data at increased rates so that *L* complex samples are collected during time τ. This has become feasible with the advent of commercial, single-board digital receivers (Ivić, Zahrai, and Zrnić 2003) and digital signal processors (Torres and Zahrai 2002).

Fig. 1 depicts ideal (rectangular pulse and infinite receiver bandwidth) resolution volumes using traditional sampling (range gate spacing is $c\tau/2$, where *c* is the speed of light) and oversampling (range gate spacing is $c\tau/2L$). Note that oversampling increases the number of range gates by a factor of *L*, but does not increase the dwell time (which is dictated solely by the number of transmitted pulses and the pulse repetition time). Because the width of the transmitted pulse is τ, the resolution volumes corresponding to the oversampled signals are overlapped. Hence, oversampled signals are correlated, and their degree of correlation is dictated by the extent of the “shared” volumes. An analytical expression for the correlation of range-oversampled signals was derived by Torres and Zrnić (2003a). It was shown that if scatterers are uniformly distributed in the resolution volume, the range-time correlation of oversampled signals only depends on the transmitted pulse shape and the receiver impulse response.

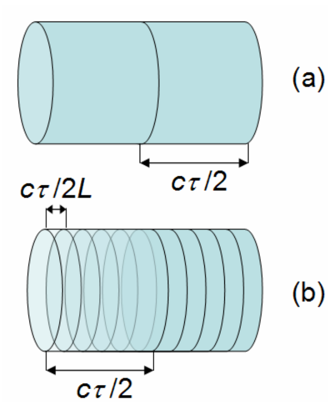

Figure 1. Depiction of ideal radar resolution volumes corresponding to (a) traditional sampling and (b) oversampling by a factor of *L*.

It is important to mention that whereas the transmission bandwidth remains the same, to benefit from oversampling, the receiver bandwidth should be increased. That is, for an oversampling factor of *L*, a receiver bandwidth that is about *L* times larger than the matched filter bandwidth is needed. As a result, there is an increase in the receiver noise total power, which is equivalent to a reduction of the signal-to-noise ratio (SNR) by a factor of *L*.

3. PROCESSING OF OVERSAMPLED SIGNALS

Oversampled signals in range can be used to improve the quality of meteorological variable estimates without increasing volume acquisition times. Because the objective is not to improve the radar’s range resolution, a set of signals at *L* oversampled range gates are suitably combined to produce better-quality estimates for the traditional (non-oversampled) range gate spacing. Next, we describe three oversampling

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techniques that have been proposed for implementation in future upgrades of the upcoming ORDA.

3.1. *Oversampling and Averaging*

One of the simplest approaches to processing oversampled signals is termed as "oversampling and averaging". With this technique, covariances are estimated at each of the L oversampled range gates. These L covariance estimates are averaged to produce one covariance estimate with reduced statistical errors. As with traditional sampling, averaged covariances are used to compute the spectral moments (and the polarimetric variables in a dual-polarization radar.) However, because oversampled signals are correlated, the variance reduction through averaging is at most a factor of two (regardless of the oversampling factor used). Thus, oversampled data are "underutilized."

3.2. *Oversampling and Whitening*

A whitening transformation on oversampled I and Q can be used to decorrelate these signals before averaging. That is, through a linear transformation, a set of L correlated complex samples is transformed into a set of L decorrelated (or whitened) complex samples. Because data are uncorrelated, averaging covariances from whitening oversampled signals reduces the variance of estimates by a factor of L. The assumption here is that powers are uniformly distributed in the resolution volume so that a whitening transformation can be pre-computed exactly from the measured pulse shape and receiver filter characteristics. Deviations from this assumption are tolerated but penalized with a sub-optimal performance (Torres and Zrnić 2003a).

A weakness of the whitening transformation is that its design ignores the presence of additive noise. As a result, when the L oversampled signals are decorrelated, the noise is enhanced due to the transformation. Hence, the whitening transformation is useful only in cases of relatively large SNR (Torres and Zrnić 2003a,b).

3.3. *Oversampling and Pseudowhitening*

Pseudowhitening techniques were introduced as practical solutions that achieve a suboptimal compromise between variance reduction and noise enhancement (Torres et al. 2004). Processing is identical to oversampling and whitening, except that pseudowhitening linear transformations do not decorrelate the signals completely. Instead, a partial degree of decorrelation is traded for a smaller amount of noise enhancement (compared to pure whitening). This family of transformations is more suitable for the operational environment as it is possible to extend the range of SNRs for which oversampled signals provide better estimates than their counterparts employing traditional sampling.

4. IMPLEMENTATION ON THE WSR-88D

Implementation of all oversampling techniques described in the previous section can be accomplished using the same framework as shown in Fig. 2. Oversampled time-series signals are transformed via matrix multiplication (note that in case of oversampling and averaging no transformation is necessary, so the transformation matrix is the identity matrix.) Next, signals at each oversampled range gate go through the traditional processing pipeline. The minimum required processing consists of ground clutter filtering and computation of auto (and cross) covariance estimates. For a single-polarization radar, autocovariances are estimated at lags 0, 1, and possibly 2, depending on the chosen algorithm for spectrum width computation. For a dual-polarization radar, cross covariances at lag 0 are added. As described before, L covariance estimates are averaged and used to compute the spectral moments (and the polarimetric variables in a dual polarization radar.) It is evident that the majority of computations (i.e., ground clutter filtering and covariance estimation) are increased by a factor of L.

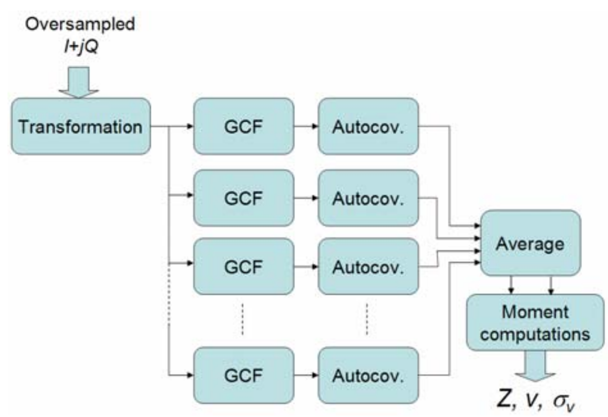

Figure 2. Implementation of oversampling techniques on the WSR-88D (single polarization radar). The majority of computations (i.e., ground clutter filtering and covariance estimation) are increased by a factor of L.

A real-time implementation of oversampling techniques was completed on NSSL's KOUN research WSR-88D (RRDA). NSSL's RRDA uses open-system standards and replaces most of the legacy WSR-88D RDA, especially the functions associated with the signal processor (Zahrai el. al. 2002). The bulk of the signal processing is performed by an array of PowerPC 7400 processors linked by a high-speed interconnect. The resulting system replicates the functionality of the legacy RDA, and its expandability characteristics make it the perfect platform to implement new algorithms.

The RRDA was upgraded with a digital receiver from Echotek corp. (ECDR-GC814), and this receiver was configured to collect I and Q signals using sampling rates of $1/\tau$, $5/\tau$, and $10/\tau$ (Ivić, Zahrai, and Zrnić 2003); i.e., oversampling factors of 1 (traditional sampling), 5, and 10 are possible.

Previously, Ivić, Zrnić, and Torres (2003) reported a demonstration of oversampling techniques on Sigmet's RVP-7 digital processor. Whereas the RVP-7 was passively coupled to the RRDA, the Echotek receiver used here is actively connected to the RRDA providing more flexibility for data collection. Still, these techniques are proposed for future upgrades of the upcoming ORDA, which will use Sigmet's RVP-8 digital processor.

Preliminary evaluations have shown that oversampling is a feasible candidate for future upgrades of the ORDA. Sample spacing on the RVP-8 can be as low as 15 m; i.e., a maximum oversampling factor of about 16 is possible. However, our recommendation is to use oversampling factors of about 5. In this regard, the computational load is increased approximately by a factor of 5; the additional processing being: (1) oversampled data transformation (L-by-L matrix multiplication), (2) L times ground clutter filtering and covariance estimation, and (3) averaging of L covariance estimates. Note that implementation of larger oversampling factors may be precluded by the available CPU computational power, but are actually not needed.

5. PRELIMINARY RESULTS

Oversampled data was collected using NSSL's KOUN radar in Norman, OK. Data was collected in two modes: (a) with a stationary antenna for statistical analysis (shown here), and (b) with a rotating antenna (PPI fields will be shown during the presentation). The oversampling factor was 5 and data was processed off-line with MATLAB.

Figures 3 and 4 show the performance of traditional matched filter (MF), oversampling and averaging (OA), whitening transformation (WT), and pseudowhitening transformation (PT) techniques. The pseudowhitening transformation on these examples is based on the sharpening filter with parameter α = 0.8 (the reader is referred to Torres et al. 2004 for a detailed discussion of this transformation.) Reflectivity and differential reflectivity estimators are shown here. It can be verified in both cases that all estimators are unbiased (mean curves are on top of each other) and the statistical performance in terms of standard errors of estimates is as predicted by the theory. The greatest variance reduction is achieved by the whitening transformation. However, the price to pay for this is a large noise enhancement factor. Suboptimal performance is achieved by oversampling and averaging and pseudowhitening, although the latter is closer to optimum. Difference in performance for these techniques is more apparent for large SNRs; for medium SNRs (e.g., range gates 350 to 400 in Fig. 3 and 4), all oversampling techniques seem to perform similarly (this more evident for the differential reflectivity estimator since it is more sensitive to noise). As the SNR decreases, performance of the pseudowhitening technique deteriorates. This is even worse for the whitening transformation due to a larger noise enhancement factor.

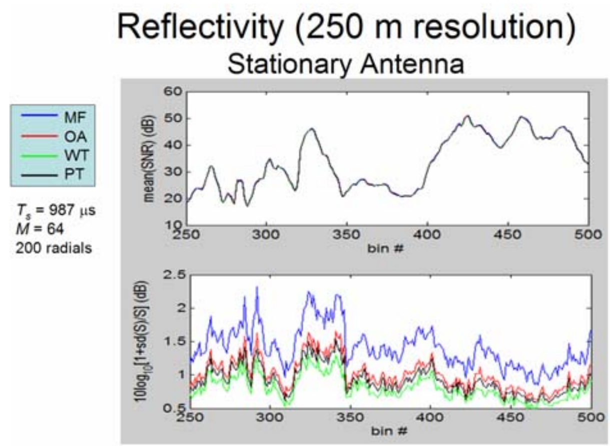

Figure 3. Mean SNR (top) and normalized standard deviation of reflectivity estimates (bottom) using traditional sampling (MF), oversampling and averaging (OA), a whitening transformation (WT), and a pseudowhitening transformation (PT) for 200 radials collected with a stationary antenna.

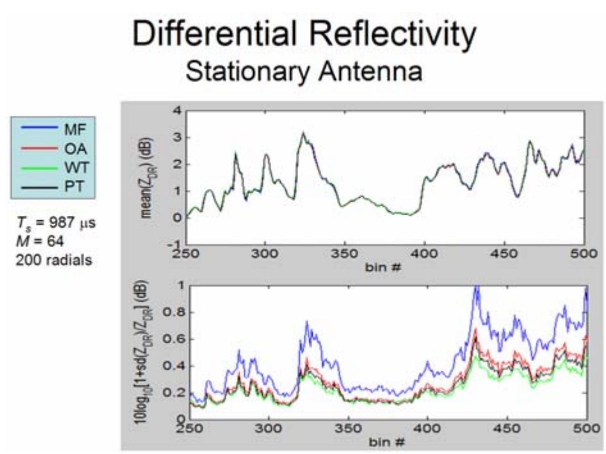

Figure 4. Same as Fig. 3 for differential reflectivity estimates.

6. CONCLUSIONS

Results on weather data collected with the NSSL's research WSR-88D confirm both simulations and analytical formulas (Torres and Zrnić 2003a, 2003b, Torres et al. 2004). Compared to standard processing of signals using a matched filter, a reduction in variance by a factor equivalent to the number of samples within the pulse is achieved. Of the three techniques considered, we recommend implementation of oversampling and pseudowhitening. Compared with oversampling and averaging, pseudowhitening achieves better utilization of oversampled signals (almost optimal) with much less noise enhancement than pure whitening.

Oversampling techniques are fully compatible with super-resolution, dual polarization, staggered PRT, and SZ phase coding, to name a few. In addition, the ORDA signal processor can accommodate oversampling factors of about 5, providing a variance reduction of almost 5 times at large SNRs with an additional computational complexity well within the expected capabilities of the next generation ORDA (at least in the single polarization mode).

Preliminary results included in this work demonstrate that techniques employing range oversampling are feasible candidates to maintain data quality without sacrificing acquisition time in future enhancements of the national network of weather surveillance radars.

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