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Waveform design considerations for CASA radar network

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1 Introduction

The Center for Collaborative Adaptive Sensing of the Atmosphere (CASA) is embarking on a paradigm of network of small radars to sample the atmosphere at high resolution. A fundamental physical limit imposed by transmission from single radar is the problem of decreasing resolution as a function of range. In addition the lowest coverage altitude increases with range due to earth curvature. As an alternate solution, a networked radar environment concept has been proposed by Chandrasekar and Jayasumana, 2001 and McLaughlin, 2001. The basic principle of the networked radar environment is to provide good coverage, in terms of accuracy and resolution to a large area through a network of radars. In order to provide a more economically feasible solution to this approach, meteorological radar operation must change from S-band operation to higher frequencies (X-band). Chandrasekar *et al* (2004) describes the various challenges that arise for radars operating at X-band. CASA will deploy its first generation network of four low-powers, short-range, X-band, dual-polarized Doppler weather radars known as NETRAD. Doppler weather radars transmitting pulses with uniform pulse repetition frequency (PRF) have a fundamental limitation on maximum unambiguous range (r_{max}) and maximum unambiguous velocity (v_{max}) governed by $r_{max}v_{max} = c\lambda/8$, where λ is radar wavelength and c is the velocity of light. The $r_{max}v_{max}$ limit reduces by a factor of three when the wavelength is changed from S-band to X-band. There is always a trade off between r_{max} and v_{max} (Range-velocity ambiguity). Precipitation particles can be distributed over a large area and the dynamic range of the radar reflectivity can be as high as 80 dB which results in range overlay. Velocity measurements can span 100 m/s in severe storms resulting in velocity folding. NETRAD is primarily for"targeted applications" such as tornado detection, flash flood monitoring, and hydrological applications. Such applications will have range overlay and velocity folding problems with conventional pulse pair processing. A testbed of smaller X-band radar systems is being developed within CASA (Junyent *et al*, 2005). X-band radars have a low unambiguous velocity due to their short wavelength, and increasing the PRF will result in multiple trip overlays since storms can extend over a large distance. It can be observed that range-velocity ambiguity is more severe for X-band radars compared to the conventional S-band. Several range-velocities ambiguity mitigation schemes have been proposed in the past. Staggered pulse-repetition-time (PRT) and multi-PRF waveforms can be used to increase the unambiguous. Random phase coding of the transmitted pulse was proposed by Siggia (1983) to mitigate range overlay, and a systematic phase code and associated processing was suggested in Sachidananda and Zrnic (1999). A systematic phase code has been known to give better performance than random phase codes but requires a coherent transmitter such as a klystron or solid-state transmitter. This paper describes the adaptive waveforms for the individual radar nodes based on NETRAD operational requirements such as scan speeds, volume coverage pattern and system/hardware limitations to resolve range and velocity ambiguities.

2 Design Considerations

2.1 Operational requirements

In addition to the basic requirements on the spectral moments there are several spatial and temporal aspects in the data specifications based on weather detection algorithms. Bharadwaj and Chandrasekar (2006) describe the requirements based on detection algorithms, namely system heartbeat and surveillance mode, feature identification and anticipation and coordinated scanning. Such scan strategies place limitations on the PRF and dwell times. The dwell time and PRF are directly related to the scan speeds and must be adaptively changed based on the feature of the weather event. The meteorological command and control (MC&C) sends out the scan strategies to the individual radar sites where they are instantiated to a new volume coverage pattern.

2.2 Hardware requirements

In order to make a network of radars affordable, one of the drivers is to work with smaller cheaper radars, which dictates

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the hardware requirements. The first generation CASA radar systems are magnetron based with limited agility on duty cycle and supported waveforms. Junyent *et al* (2005) gives a complete description of the radar system along with its features. The transmitter can deliver a maximum peak power of 25 kW at a duty cycle of 0.1%. The CASA radars operate at a range resolution of 100 m. Hence only a PRF of 1.5 kHz can be used at the peak power of 25 kW. The transmitter can be tuned below its maximum peak power allowing one to increase the duty cycle, which is used to accommodate the higher PRF bursts. There will be significant frequency drifts in the magnetron due to increased temperature if the PRF is very high. Based on tests conducted on the magnetron it is concluded that high PRFs are suitable only in conjunction with a low PRF and the high PRF waveform is limited to 2.4 kHz when used with a lower PRF. There is also a limitation on the ability to phase code the transmit pulses because a magnetron based system has a random start-up phase. Therefore, random phase coding is the only scheme that can be implemented.

3 Ground clutter filtering

Radar observations at short ranges are contaminated by ground clutter. Ground clutter is the radar return from non-meteorological targets that bias the reflectivity and velocity estimates. Ground clutter at close range could come from side lobes or main lobe of the antenna, depending on the radar altitude or the phenomena being observed. Specifically, designing radars for short-range operation needs extensive emphasis on clutter mitigation. Ground clutter filtering is performed by applying a notch filter centered at zero Doppler velocity. Elliptic filter have been traditionally used for clutter filtering. The advent of high speed digital processors enables clutter filtering in spectral domain. Siggia and Passarelli (2004) suggest an adaptive filtering technique called Gaussian Model Adaptive Processing (GMAP) wherein the clutter spectral coefficients are notched with a spectral clipper using a Gaussian model for the clutter spectral density. A Gaussian weather spectral density is recursively fit to the remaining points and the notched spectral coefficients are interpolated with the model. GMAP requires an a priori knowledge of the clutter spectral width, and it performs the notch filtering. The clutter contaminated weather echo can be modeled with a spectral density given by

$$S(\mathbf{\mu}) = \frac{S_c}{\sqrt{2\pi\sigma_c^2}}\exp\left\{-\frac{v_k^2}{2\sigma_c^2}\right\} + \frac{S_0}{\sqrt{2\pi\sigma_v^2}}\exp\left\{-\frac{(v_k - v_m)^2}{2\sigma_v^2}\right\} + N \qquad (1)$$

Where $\mathbf{\mu} = [S_c\ \sigma_c\ S_0\ \sigma_v\ v_m\ N]^T$ with the subscript"c" indicating clutter parameters and N is the noise power density. The notched region is recursively interpolated with a Gaussian spectral density fitted to the remaining signal to obtain the filtered signal. The standard deviation, bias in reflectivity and velocity is shown in Fig. 1. respectively for a weather signal with $\sigma_v = 2$ m/s and $\sigma_v = 4$ m/s. The bias in reflectivity is within 1 dB and the bias in velocity is within 1 m/s for clutter-to-signal ratios up to 50 dB.

A PPI plot of reflectivity and velocity before and after ground clutter filtering are shown in Fig. 2 through Fig. 5 respectively. The data for this PPI scan is from one of the radars in the first generation magnetron based four-node radar network deployed by CASA in Cyril, Oklahoma. The radar operated with PRF =2 kHz and N=40 samples were used in an integration cycle. It can be observed in Fig. 2 and Fig. 3 that reflectivity on the order of 45 dBZ due to ground clutter is suppressed. However, there are region from 25 to 30 km around an azimuth of 265 degrees where the performance of the clutter filter appears to be degraded. This is due to the presence of a wind-farm that contaminates the received signal with wind turbine returns, that is not centered at zero velocity.

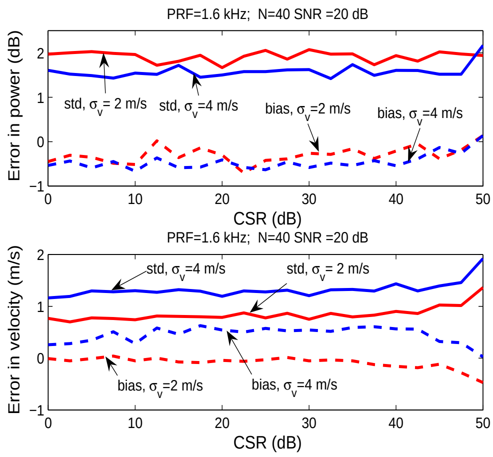

Fig. 1. Bias and standard deviation of reflectivity and velocity after ground clutter filtering with PRF=1.6 kHz and N=40.

4 Waveform selection

4.1 Random phase coding

Since the magnetrons have random startup phase, the transmitted pulses are naturally coded by random phases (ψ_k) on a pulse-to-pulse basis. Therefore, random phase processing (Siggia, 1983) will be performed to suppress range-overlaid echoes. The received signal is phase corrected (cohered) to account for the transmitted phase. Only the selected trip, e.g., the first trip signal, is cohered; the second trip is then random phase modulated by the phase sequence $\phi_k = \psi_{k-1} - \psi_k$. Let $V_1(k)$ and $V_2(k)$ be the two distinct weather echoes from the first and second trip respectively. The received signal after recohering for the first trip echo is written as

$$S_r(k) = V_1(k) + V_2(k)\exp\{j\phi_k\} \qquad (2)$$

The second trip signal $V_2(k)$ is phase modulated by the polyphase sequence. With a random modulation code the modulated second trip signal $V_2(k)\exp\{j\phi_k\}$, is like white noise (the spectral distribution is close to being flat or white). Hence, the second trip signal will only appear as white noise which results in a degradation of the effective signal-to-noise ratio (SNR). This reduction in SNR will increase the variance of the Doppler spectral moments. The spectral moments of the second trip signal can also be recovered with additional processing. The region of recovery

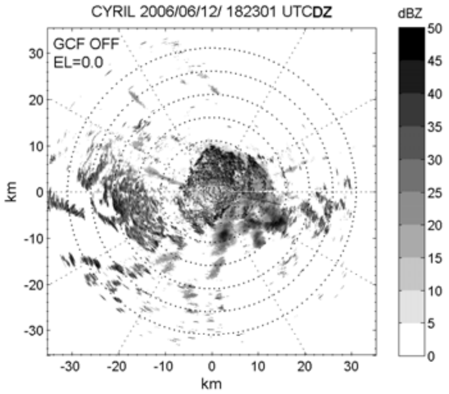

Fig. 2. Reflectivity before ground clutter filtering.

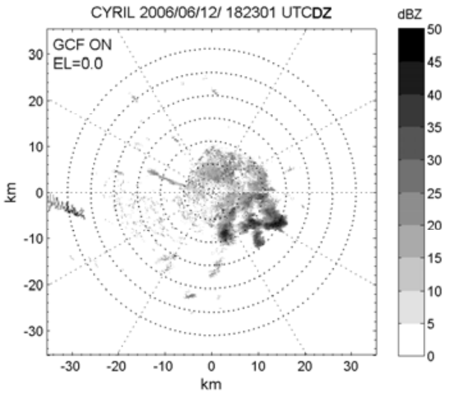

Fig. 3. Reflectivity after ground clutter filtering

for the second trip echo is determined by the first trip parameters and the PRF. Although the echo beyond 30 km is not of interest in NETRAD, the principle is used to suppress the impact of overlaid echoes for the first 30 km. The concept of random phase processing was explained in terms of first/second trips, but it can be interchanged to strong/weak trip echoes without the loss of generality. The performance in recovery region for the second trip signal is presented in Bharadwaj and Chandrasekar (2005) and the second trip echo can be recovered well for lower spectral widths even when the overlaid power ratio is more than 40 dB.

4.2 Dual-PRF waveform

Dual-PRF techniques for extending the unambiguous velocity have been known for more than two decades and are available on many operational Doppler weather radars, especially longer wavelength radar systems. The unfolding is performed by comparing the difference in the two velocity estimates corresponding to the two PRFs. However, there are unfolding errors that occur due to the inherent uncertainty in the folded velocity estimates. A dual-PRF waveform with 1.6 kHz and 2.4 kHz can to provide a maximum unambiguous velocity of 38 m/s. The errors in velocity for a dual-PRF scheme after clutter filtering (SNR =10 dB, CSR =50dB) is shown in Fig. 6 respectively. Results obtained from simulations show that large velocities can be measured even in the presence of a strong clutter signal.

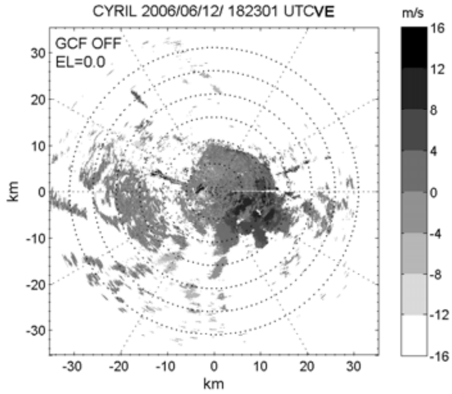

Fig. 4. Velocity before ground clutter filtering.

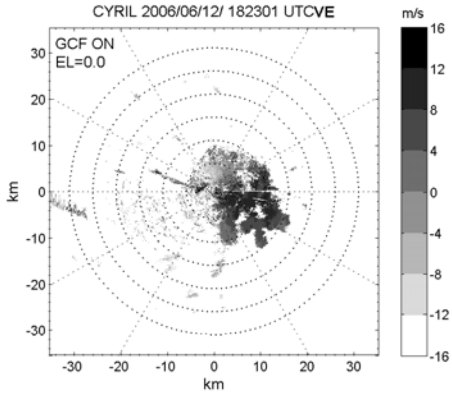

Fig. 5. Velocity after ground clutter filtering.

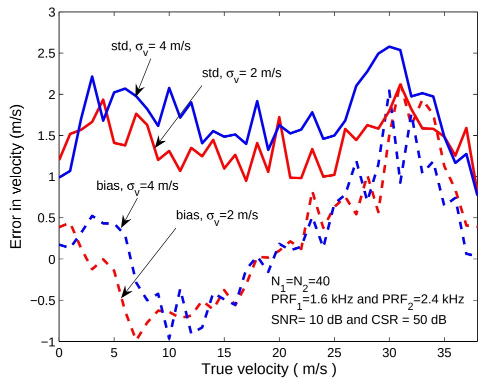

Fig. 6. Bias and standard deviation of velocity after ground clutter filtering for a dual-PRF waveform.

4.3 Surveillance mode

In surveillance scan mode the radar operates at PRF=1 kHz with a maximum range of 150 km. The radar can scan at a very high speed of 50 deg/s (>8 rpm). This is more than twice the maximum operating speed of NEXRAD. There are N=20 pulses in each dwell for 1 degree azimuthal sampling. The radar can provide a VCP with 4 tilts of 360 degrees sweeps in the 30s system "heartbeat" and only reflectivity measurements are made in the surveillance mode. The bias is within a 1dB while the standard deviations on the order of 4 dB. Higher standard deviations are acceptable in a surveillance mode.

4.4 Feature detection mode

Waveform with 1.6 kHz and 2.4 kHz with 40 and 54 samples respectively will able to provide a maximum unambiguous velocity of 38 m/s. Since the higher PRF signal can be easily contaminated by second trip echoes, random phase processing is performed on the higher PRF signal. The velocity measurements extend to ±38 m/s even with a clutter-to-signal ratio of 45 dB and an overlaid second trip echo (Bharadwaj and Chandrasekar, 2005).

4.5 Waveform table

The final goal of NETRAD however, is to dynamically assign the scan strategy based on the features detected. These high-level features are used to generate tasks that are passed to a resource allocation module that combines the tasks and end-user priorities to generate new scan strategies. The maximum PRF is limited by the duty cycle as described in Section 2. The minimum number of samples is limited by the clutter suppression ability and the maximum is limited by the dwell time. The azimuthal sampling resolution of the data is dependent on the scan speed. Decisions to dynamically change the waveform can only be made in a NETRAD environment and thus optimally use the capability of the radar system. The waveform look-up table (see Table.1) provides the MC&C the necessary tool to adaptively select the waveform and efficiently use the radars in a NETRAD environment.

5 Summary

The combination of smaller wavelength, low cost hardware and adaptive scan strategy enforce a stringent constraint on the waveform to mitigate range-velocity ambiguities. An adaptive Gaussian spectral fit is used for clutter filtering which provides good clutter suppression. The clutter suppression of 50 dB is achieved with $N = 40$ samples as shown in Fig.2 and Fig.3 from data collected by the first generation CASA radars. However, the algorithm must be evaluated with more data sets. Based on simulated data it is observed that the dual-PRF waveform is able to measure velocities up to 38 m/s even in the presence of a strong clutter signal (45 dB clutter-to-signal ratio). The NETRAD system can adaptively change the scan strategy based on the features detected by using a look-up table of waveforms. The look-up table consists of waveforms with random phase processing, dual-PRF and a combination of both. The waveform is chosen from a look-up table based on the features detected and end-user priorities.

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(a) Dual-PRF with Phase Coding (includes GMAP clutter filtering)						Beam width = 1.8 deg
Scan Speed (deg/s)	PRF_1 (kHz)	PRF_2 (kHz)	~Velocity (m/s)	N_1	N_2	Azimuthal resolution (deg)
20	1.60	2.40	38.00	40	54	0.95
22	1.60	2.40	38.00	40	54	1.05
24	1.60	2.40	38.00	40	54	1.14
26	1.60	2.40	38.00	40	54	1.24
28	1.60	2.40	38.00	40	54	1.33
30	1.60	2.40	38.00	40	54	1.43
32	1.60	2.40	38.00	40	54	1.52
34	1.60	2.40	38.00	40	54	1.62
36	1.60	2.40	38.00	40	54	1.71
(b) Dual-PRF without Phase Coding (includes GMAP clutter filtering)						Beam width = 1.8 deg
Scan Speed (deg/s)	PRF_1 (kHz)	PRF_2 (kHz)	~Velocity (m/s)	N_1	N_2	Azimuthal resolution (deg)
20	1.60	2.40	38.00	40	40	0.83
22	1.60	2.40	38.00	40	40	0.92
24	1.60	2.40	38.00	40	40	1.00
26	1.60	2.40	38.00	40	40	1.08
28	1.60	2.40	38.00	40	40	1.17
30	1.60	2.40	38.00	40	40	1.25
32	1.60	2.40	38.00	40	40	1.33
34	1.60	2.40	38.00	40	40	1.42
36	1.60	2.40	38.00	40	40	1.50
38	1.60	2.40	38.00	40	40	1.58
40	1.60	2.40	38.00	40	40	1.67
42	1.60	2.40	38.00	40	40	1.75
(c) Dual-PRF with Parametric Estimation includes CASA clutter filtering (new technique developed)						Beam width = 1.8 deg
Scan Speed (deg/s)	PRF_1 (kHz)	PRF_2 (kHz)	~Velocity (m/s)	N_1	N_2	Azimuthal resolution (deg)
20	1.50	2.00	48.00	25	25	0.71
24	1.50	2.00	48.00	25	25	0.86
28	1.50	2.00	48.00	25	25	1.00
32	1.50	2.00	48.00	25	25	1.14
36	1.50	2.00	48.00	25	25	1.28
40	1.50	2.00	48.00	25	25	1.43
44	1.50	2.00	48.00	25	25	1.57
48	1.50	2.00	48.00	25	25	1.71

Table 1. Waveform table with number of pulses and PRF based on scan speeds. Technique for Part(c) is described in Nguyen *et al*, 2006.

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