P10R.5 IMPROVED RADAR SENSITIVITY THROUGH LIMITED SECTOR SCANNING: THE DCAS APPROACH

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1. INTRODUCTION

Distributed Collaborative Adaptive Sensing (DCAS) is being developed to provide solutions to many existing limitations of operational weather radar. DCAS makes use of large numbers of distributed short-range (30 km) radar to monitor the first 3 km of the Earth's atmosphere. DCAS includes the ability to rapidly adjust individual radar operating parameters in a collaborative manner. Included in these parameters is the ability to adjust individual node volume coverage pattern (VCP) in accordance with meteorological events. By adjusting VCP to maximize time on target measurement precision may be improved (McLaughlin et al. 2005).

DCAS radars are operated as a network and collaboratively make use of neighboring radar capabilities in order to improve data quality. In this paper we examine the expected theoretical improvement in reflectivity measurement by employing limited sector scanning.

Operational radars employ VCPs that include full azimuth rotations as well as multiple tilts in elevation. During a storm event, targets of interest may be located in a limited sector of the full VCP. By limiting the scanning sector, time which would have been spent completing a full volume scan, including volume of limited data utility, is spent observing the targets of interest. By dynamically adjusting a DCAS radar's VCP to the limited sector of interest, measurement precision may be increased by increasing dwell time. Sensitivity may be improved for a given measurement precision by decreasing the required signal to noise ratio.

Dynamic adjustment of a radar's VCP will require high speed beam scanning via high torque mechanical pedestals or electronic beam scanning. The initial DCAS testbed radars have the capability to scan in azimuth at 120 deg/s and elevation at 30 deg/s (Juyent et al. 2005). Such high scan systems will enable the interlacing of general full volume scans with higher precision limited sector scans.

This paper will analyze the theoretical improvements from limited sector scanning in detail. A review of fading theory will be presented followed by both single and multiple node limited sector scanning.

2. BACKGROUND

Pulsed, Doppler radars transmit fixed length pulses of electromagnetic energy which is measured following reflection by targets in the atmosphere. The distributed nature of meteorological targets causes the received power to fluctuate as targets move, a phenomenon referred to as fading. Fading may be reduced by averaging successive pulses resulting in a reduction in the standard deviation of the target's reflectivity. By combining fading with the radar equation one is able to estimate radar sensitivity.

2.1. *Fading*

When estimating reflectivity in the presence of noise, the standard deviation of the reflectivity estimate σ_z, assuming an equal number of signal and noise samples and removal of the noise, in linear units is (Doviak and Zirić 1993; Ulaby et al. 1986):

$$\sigma_z = 1 + \sqrt{\frac{1}{N_I}\left(\left(1+\frac{1}{S_n}\right)^2 + \left(\frac{1}{S_n}\right)^2\right)} \qquad (1)$$

where N_I is the number of equivalent independent samples and S_n is the signal to noise ratio.

Figure 1 illustrates the impact of an increased number of averaged independent pulses has on the standard deviation of the reflectivity σ_z. While significant, the trade-off between the number of pulses and the signal-to-noise ratio allows for improvement in radar sensitivity by increasing dwell time. It is this trade-off that limited sector scanning seeks to take advantage of.

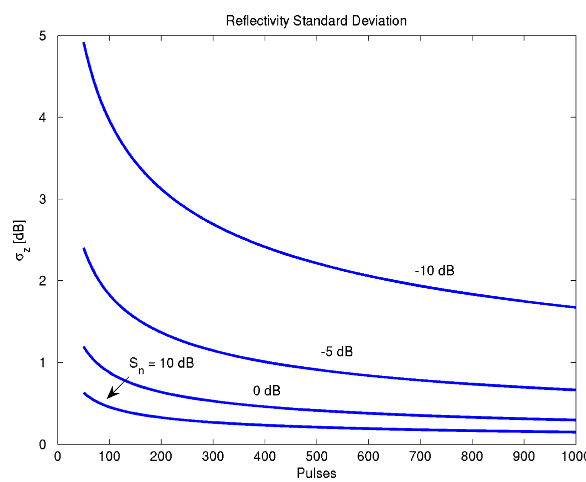

Figure 1: Reflectivity standard deviation σ_z assuming perfect whitening.

The number of equivalent independent pulses may be increased by whitening the data signal through post pro-

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cessing methods as suggested by Koivunen and Kostinski (1999); Torres and Zrnić (2003). Data whitening may also be accomplished by "dithering" transmitted frequency from pulse to pulse (Choudhury et al.). Perfect whitening will increase the equivalent number of independent samples until it is equal to the number of pulses transmitted. The remainder of this paper will assume that perfect data whitening has been accomplished using time or frequency techniques. That is $N_I = N$, the number of pulses transmitted.

2.2. *Radar Sensitivity*

Radar sensitivity (in units of $Z_e\left(mm^6/m^3\right)$) may be expressed by rearranging Equ. (4.35) of (Doviak and Zirić 1993) as[1]:

$$Z_{min} = \frac{CP_rR^2\lambda^2L}{P_tG^2\tau\theta^2|K_w^2|} \quad (2)$$

where the variables are listed with their units in Table 1 and C is the numerical constant equal to:

$$C = \frac{6.75\times 2^{14}\left(\ln 2\right)}{1000\pi^5 10^{-17}} = 2.5\times 10^{16}. \quad (3)$$

The received power, P_r, may be related to the signal to noise ratio discussed above by the expression:

$$P_r = S_n P_{min} \quad (4)$$

where P_{min} is the minimum detectable signal due to thermal noise.

Rearranging (1) and solving for S_n as a function of N_I and σ_z yields:

$$S_n = \frac{\sqrt{2}}{\sqrt{N_I\left(\sigma_z - 1\right)^2 - 1}}. \quad (5)$$

Substituting (5) and (4) into (2) yields Z_{min} as a function of N_I and σ_z:

$$Z_{min} = \frac{CP_{min}R^2\lambda^2L}{P_tG^2\tau\theta^2|K_w^2|}\times\frac{\sqrt{2}}{\sqrt{N_I\left(\sigma_z - 1\right)^2 - 1}} \quad (6)$$

This expression allows for the relation between radar sensitivity, precision and dwell time.

3. LIMITED SECTOR SCANNING

A radar node may reduce its scan volume to follow targets of interest. Assuming that the time per scan remains a constant while the volume of the scan reduces, dwell time and hence the number of pulses to integrate will increase.

The number of pulses N to be averaged per range bin may be approximated as:

$$N = \frac{T_v\theta\phi f_p}{\delta\theta\delta\phi} \quad (7)$$

where T_v is the volume scan time, $\delta\theta$ is the width of the scan in degrees of the azimuth, $\delta\phi$ is the height in degrees of elevation, θ is the antenna beamwidth (assumed to be symmetric), ϕ the elevation step in degrees, and f_p is the pulse repetition frequency.

Parameter	Symbol	Value	Unit
Wavelength	λ	3	cm
Antenna Beamwidth	θ	1.8	deg
Antenna Gain	G	38	dB
Maximum Range	R	30	km
Range Resolution	Δr	100	m
Pulse Repetition Frequency	f_p	3	kHz
Transmitter Power	P_t	25	kW
System Losses	L	20	dB
Minimum Detectable Signal	P_{min}	-106.2	dBm
Pulse Length	τ	1	μs
Dielectric Constant of Water	$\lvert K_w^2\rvert$	0.93	
Volume Scan Time	T_v	5	min

Table 1: Radar Node Specifications

Table 1 includes the radar node parameters which have been assumed for the remainder of this analysis[2]. These parameters are based on those outlined by McLaughlin et al. (2005); Juyent et al. (2005) for networked radar systems. The default full-volume scan is assumed to be six, $2°$, elevation tilts from 0-12° with a full 360° azimuthal scan at each elevation and a volume scan time of 5 min. It is assumed that the volume scan may be limited to any sub-sector of the full volume scan and is not impeded by scanning inertia which will be neglected. The volume scan time will be treated as a constant for this analysis.

E \ A	$360°$	$270°$	$180°$	$90°$	$45°$
$12°$	750	1000	1500	3000	6000
$10°$	900	1200	1800	3600	7200
$8°$	1125	1500	2250	4500	9000
$6°$	1500	2000	3000	6000	12000
$4°$	2250	3000	4500	9000	18000

Table 2: Number of Pulses Available for Integration

Table 2 includes the approximate number of pulses available for integration as both the azimuthal width and elevation height are varied. As illustrated by the table a full volume scan of $360°$ azimuth by $12°$ yields 75 pulses for averaging. By reducing the volume scanned to $45°$ azimuth by $4°$ elevation the yield increases to 18000 pulses.

By utilizing Equ. (6) we are able to determine the sensitivity of the radar as a function of the required precision and the number of pulses available. Figure 2 illustrates the improvement of minimum sensitivity as the number of pulses increases. Figure 3 relates this sensitivity to the limited sector scans listed in Table 2. Reducing the

[1] The gain (g^2g_s) and loss terms (l^2l_r) listed in (Doviak and Zirić 1993) have been combined into single terms G and L.

[2] System losses include a 15 dB rain attenuation margin.

volume coverage pattern from a full volume scan , 360° azimuth by 12° elevation, to a scan of 45° azimuth by 4° elevation improves the sensitivity by 8 dB. Greater improvements may be achieved with smaller sectors below 45° azimuth or 4° elevation.

Figure 3 indicates, as is to be expected, that reducing the azimuth scan has a greater value than reducing the elevation scan. This said, both methods may be utilized dependening on the meteorological phenomena being observed.

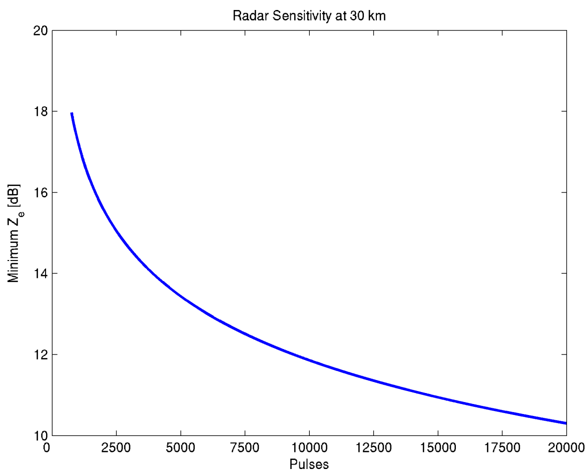

Figure 2: Sensitivity at Maximum Range (30 km), $\sigma_z = 1$ dB.

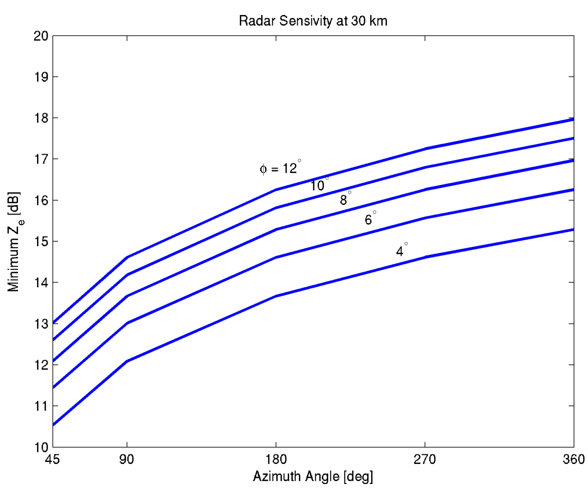

Figure 3: Sensitivity at 30 km for scan angles listed in Table 2, $\sigma_z = 1$ dB.

The improvement in measurement quality derived from limited sector scanning comes at the cost of a reduction in volume observed per scan update. Table 3 lists the percentage of volume covered relative to the full volume scan [3]. Figure 4 relates this volume coverage percentage to radar sensitivity.

E \ A	360°	270°	180°	90°	45°
12°	100	75	50	25	13
10°	96	72	48	24	12
8°	89	67	45	22	11
6°	75	56	38	19	9
4°	34	25	17	9	4

Table 3: Percentage of Coverage of Volume Below 3km

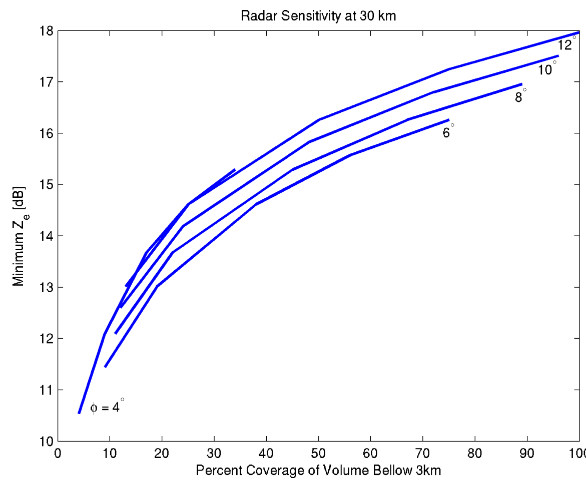

Figure 4: Sensitivity at 30 km as a function of volume coverage percentage for the 5 elevation angles in Table 2, $\sigma_z = 1$ dB.

4. SUMMARY AND CONCLUSIONS

Limited sector scanning allows an observation network to dynamically trade off volume coverage time for improved measurement quality. This would allow a network control system to take advantage of the structural variability of meteorological phenomenon during observation. Sensitivity improvements approaching 10 dB are possible when implementing limited sector scanning.

Acknowledgement This work was primarily supported by the Engineering Research Centers Program of the National Science Foundation under NSF Award Number 0313747. Any opinions, findings and conclusions or recommendations ex-pressed in this material are those of the authors and do not necessarily reflect those of the National Science Foundation.

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[3]Volume coverage only considers elevation tilts of 0° to the elevation angle listed. Other elevation scans will cover less percentage volume as the scan observes volume above the 3km altitude limit.

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