168 RESOLUTION ENHANCEMENT SYSTEM FOR NETWORKED RADAR SYSTEM

Nitin Bharadwaj[1]*and V. Chandrasekar[2]
1 Pacific Northwest National Laboratory, Richland, WA.
2 Colorado State University, Fort Collins, CO.

1 INTRODUCTION

The resolution of Doppler weather radars is primarily dependent on the transmit pulse length and antenna beam width. The resolution has two independent components namely, range resolution and cross-range resolution. Range resolution corresponds to the pulse length while cross-range resolution is a function of beam width and the range to the resolution volume. Obtaining good range resolution for Doppler weather radars has not been a very serious problem because a short transmit pulse provides very good range resolution. However, obtaining good cross-range resolutions at farther ranges requires the use of larger antennas, which is not a viable solution.

The resolution along range can be improved by transmitting shorter pulses. A typical $1\ \mu s$ pulse will provide a range resolution of 150 m. Pulse compression waveforms (Mudukutore et al., 1998; Bharadwaj and Chandrasekar, 2011) can be used to improve range resolution. Other techniques using deconvolution methods have been suggested to improve range resolution (Galati et al., 1996; Yu et al., 2006) and a technique using interferometry has been proposed (Zhang et al., 2005). The resolution obtained along range in current pulsed Doppler weather radar is on the order of 100 m and is within acceptable limits. However, the cross-range resolution is a function of antenna size and its impractical to have a physically very large aperture antenna. Therefore, the spatial resolution of a pulsed Doppler weather radar is limited by the antenna beam width. In this paper a novel methodology to improve the spatial resolution is presented.

A networked radar environment concept was proposed by Chandrasekar and Jayasumana (2001); McLaughlin (2002) to mitigate the many of the limitations of single radar using a large antenna. Chandrasekar and Lim (2008) used the concept of different view angles in a networked radar environment to perform attenuation correction. In this paper we use the concept of different view angles in a networked radar environment to enhance the spatial resolution of reflectivity. This paper presents a methodology for the retrieval of radar reflectivity at high resolution for volume targets. Results are presented from data collected with an X-band radar network. The data collected are from the Engineering Research Center (ERC) for Collaborative Adaptive Sensing of the Atmosphere (CASA) radars deployed in southern Oklahoma.

*Corresponding author address: Nitin Bharadwaj, 902 Battelle Blvd, MSIN K4-28 , Richland, WA-99352. Email: nitin@pnnl.gov

2 Received signal from volume targets

A pulse Doppler radar transmits a pulse train with a pulse repetition time (PRT) T_s. The received voltage from a resolution volume at range r corresponds to the back-scattered signal from particles within a volume extending radially from r to $r+\Delta r$, as illustrated in Fig.1. The back-scattered signals from all the particles within a single resolution volume sum to a resultant voltage sample at the receiver at time t (range, r) and is given by

$$v_r(t) = \sum_k a_k(\tau_k;t) e^{-j2\pi f_0 \tau_k} g_(t-\tau_k) \tag{1}$$

where a_k is the scattering amplitude of the k^{th} particle in the resolution volume. $g(t)$ is the complex envelope of the transmit pulse operating at a frequency f_0 and $\tau_k = 2r_k/c$ where c is the speed of light. A more detailed description of the properties of the received voltage can be found in Bringi and Chandrasekar (2001). The mean power received from the resolution volume is given by

$$\bar{P}_r(t) = \langle |v_r(t)|^2 \rangle = \sum_k \langle |a_k(\tau_k)|^2 \rangle |g_(t-\tau_k)|^2 \tag{2}$$

$$= \frac{\lambda^2 P_t}{(4\pi)^3} \sum_k \left\langle \frac{G_k^2 4\pi |S_k|^2}{r_k^4} \right\rangle |g_(t-\tau_k)|^2 \tag{3}$$

where $\langle . \rangle$ indicates ensemble averaging. G_k is the antenna gain in the direction of the k^{th} particle.

The mean radar cross-section per unit volume, $\eta(r,\theta,\phi)$, is defined by

$$\eta(r,\theta,\phi)\Delta V = \sum_k \langle 4\pi |S_k|^2 \rangle \tag{4}$$

where ΔV is the elemental volume and $|S_k|^2$ is the element of the scattering matrix. The mean received power from range r_0 can be expressed as an integrals of weighted $\eta(r,\theta,\phi)$ over the resolution volume of the

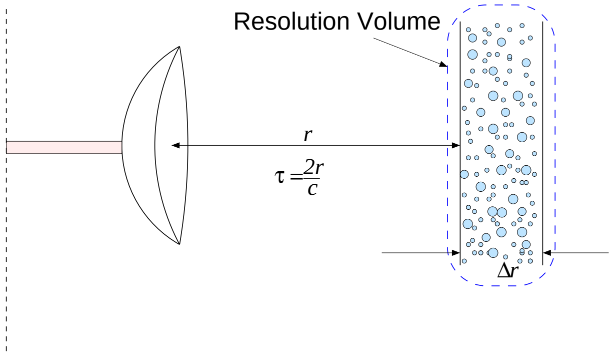

Figure 1: Received voltage due to scattering from particles located within a shell extending from $(r, r+\Delta r)$.

beam

$$\bar{P}_r(t) = \frac{\lambda^2 P_t}{(4\pi)^3}\int_V \frac{G^2(\theta,\phi)}{r^4}\eta(r,\theta,\phi)|g(t-\tau)|^2 dV \quad (5)$$

$$= \frac{\lambda^2 P_t}{(4\pi)^3}\int_\Omega \int_{r_0+\Delta r/2}^{r_0-\Delta r/2} \frac{G^2(\theta,\phi)}{r^2} \eta(r,\theta,\phi)|g(t-\tau)|^2 dr d\Omega \quad (6)$$

Where $G(\theta, \phi)$ is the two-way antenna power pattern and Ω is the elemental solid angle subtended by the resolution volume. The antenna power pattern is expressed in terms of peak power pattern G_0 and normalized power pattern $f(\theta, \phi)$ as $G(\theta, \phi) = G_0 f(\theta, \phi)$. Then the mean received signal is given by

$$\bar{P}_r(t) = \frac{\lambda^2 P_t G_0^2}{(4\pi)^3}\int_\Omega \int_{r_0+\Delta r/2}^{r_0-\Delta r/2} \frac{f^2(\theta,\phi)}{r^2}\eta(r,\theta,\phi) |g(t-\tau)|^2 dr d\Omega \quad (7)$$

3 Resolution Enhancement System (RES)

The networked radar system provides measurements of the inherent reflectivity distribution from different look angles using N radar nodes. Doppler weather radars operate with very good spatial resolution in range and poor cross range resolution at farther ranges. In this paper we present a novel methodology to retrieve higher resolution reflectivity data from a network of radars. In a networked radar environment each radar observes a common reflectivity distribution with different spreading function. The principle that the underlying reflectivity distribution should remain identical for all the nodes is used to improve the resolution. Figure 2(a) shows an illustration of the the reflectivity distribution being measured by two radars as the two radars scan across the volume. Figure 2(b) shows a common resolution volume observed by two radars. The measurements in the radial direction have high spatial resolution but the cross-range resolution is degraded by the effective antenna pattern. The reflectivity in the cross-beam direction is smeared by the effective antenna pattern a shown in Fig. 2(c).

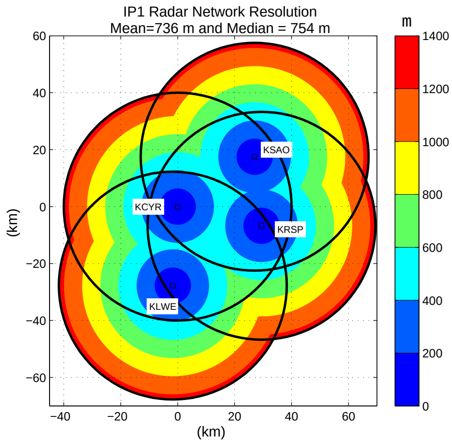

Figure 3: Composite networked resolution for CASA's IP1 radar network.

4 Implementation with CASA radar network data

The IP1 testbed is a networked radar system with four radars operating at X-band. Measurements at X-band suffer the effect of attenuation due to propagation in precipitation. The IP1 radars perform attenuation correction (Liu et al., 2006) on a real-time basis and a attenuation corrected reflectivity product is provided operationally (Junyent et al., 2009). The data used to apply RES is attenuation corrected reflectivity distribution. The four radars are separated by approximately 25 km and make measurements up to 40 km. The radars transmit a short pulse resulting in a range resolution of 60 m. A 1.2 m antenna with a $1.8°$ beam-width has a mean cross range resolution of 837 m in the coverage region of a single radar. However, mean resolution in a networked radar environment is less than the mean range resolution of an individual radar. The resolution in a networked environment is obtained by selecting the minimum resolution among the radars within the common coverage. The resolution in the CASA's IP1 radar network is shown in Fig. 3 (Junyent and Chandrasekar, 2009). A mean resolution of 736 m can be obtained by selecting the best resolution from the four IP1 radars. The reflectivity obtained corresponds to a $1°$ integration cycle which provides oversampled data in azimuth with oversampling factor ~ 2. In this paper we are not considering the retrieval of the three dimensional reflectivity distribution and hence only scans at lower elevation angle $(\leq 2°)$ are used. The RES is solved for a grid resolution of 100 m using a $6 \times 6\, km^2$ area tile. The origin is arbitrarily chosen to coincide with the Cyril radar and each radar GPS locations is translated to this new

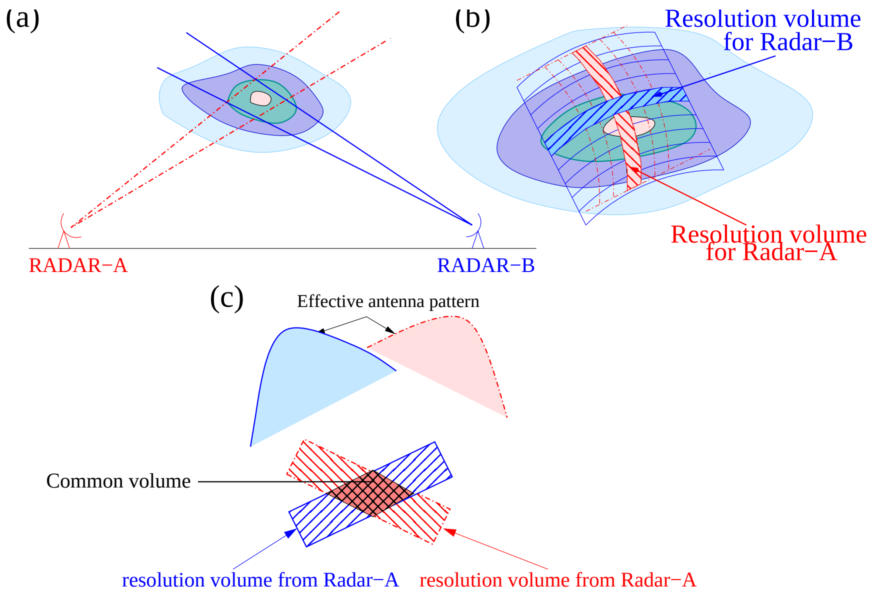

Figure 2: Illustration of networked radar system for resolution enhancement (a) Underlying reflectivity distribution being observed by two radar nodes. (b) Resolution volume with different cross-range resolution with higher resolution common volume.

origin. A constrained linear least-squares solution is obtained to provide the RES reflectivity distribution.

A hook echo associated with a tornado was observed by the IP1 radar network on Feb 10, 2009 at 21:13 UTC. The position of the hook echo within the network is shown in Fig.4 and its clearly out of range for Rush Springs and Lawton. The hook echo was observed by only two radars located at Cyril and Chickasha as shown in Fig.5(a) and (b). The networked resolution enhancement system is applied to this data set. In addition composite reflectivities based on range weighted averaging was also estimated. The range weighted averaging of reflectivity from multiple radars uses the fact that the resolution and signal-to-noise ratio degrades with range. Reflectivity from individual radars are relatively weighted such that measurements from the closest radar is assigned the highest weight while measurement from the farthest radar is assigned the least weight. The weight for the i^{th} radar to obtain a range weighted mosaic is given below.

$$w_i = \frac{R_i^{-p}}{\sum_{j=1}^{N} R_j^{-p}} \tag{8}$$

In the above equations R_j is the range of the resolution volume from the individual radar nodes and p is an integer selected to adjust the dependence on range. The range weighted mosaic is obtained as given below.

$$Z_{rmean}(x,y) = \sum_{j=1}^{N} w_j(x,y) Z_j(x,y) \tag{9}$$

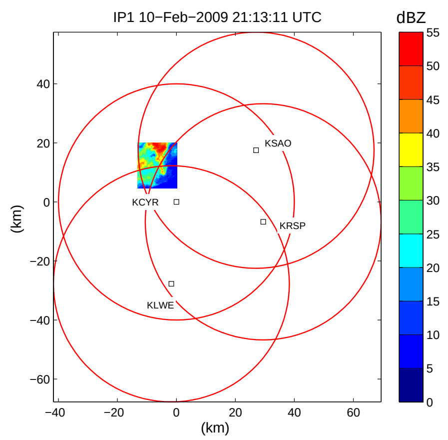

Figure 4: Location of the precipitation event in the radar network for data collected with IP1 radar network on Feb 10, 2008 at 21:13:11 UTC.

The reflectivity mosaic and networked retrieval is shown in Fig. 6(b) and (c) respectively. The formation of the hook echo is much more clearly visible in the networked retrieval. Also, as observed with previous data sets the peak reflectivity observed in the the storm is much more prominent in the networked retrieval.

5 Summary

A methodology called the Resolution Enhancement System (RES) was presented for improving the resolution of observations in a networked radar system. A

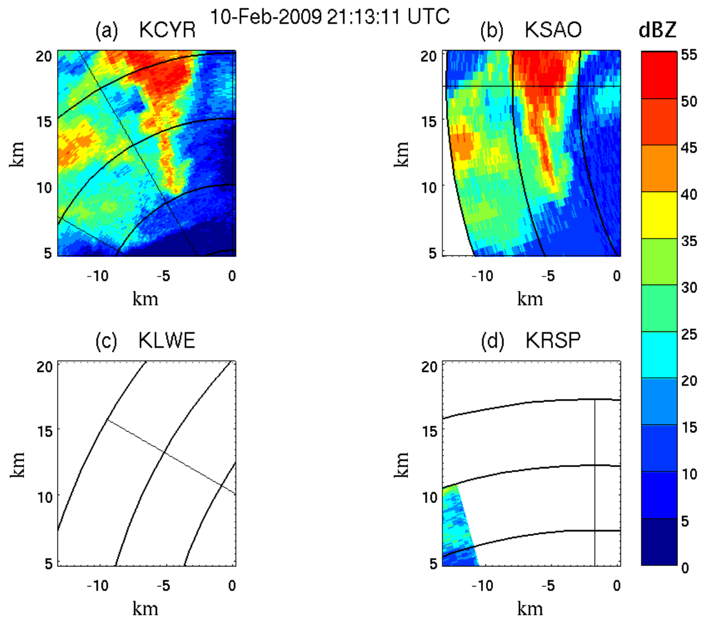

Figure 5: Data collected with IP1 radar network on Feb 10, 2008 at 21:13:11 UTC: (a) KCYR (b) KSAO (c) KRSP, and (d) KLWE.

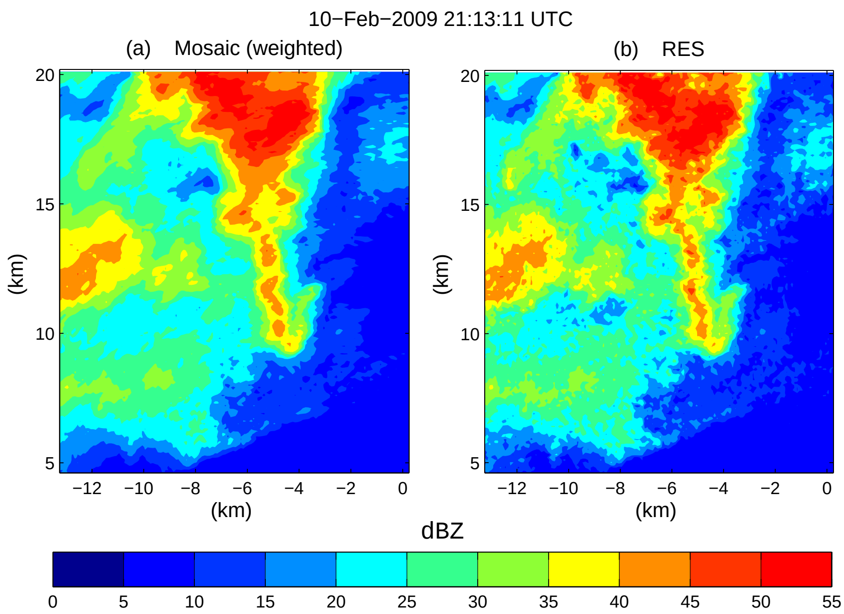

Figure 6: Reflectivity retrieval from the IP1 radar network with data collected on Feb 10, 2008 at 21:13:11 UTC (a) Range weighted reflectivity mosaic and (b) RES reflectivity retrieval.

networked radar approach is used in RES to undo the effect of range variant smoothing. The methodology was applied to data collected by CASA's IP1 radar network. Attenuation corrected reflectivity was used as inputs from each of the four radar. The RES reflectivity retrievals from IP1 radar network were compared with the range weighted reflectivity mosaic. Similar to the results obtained with simulated data it is observed that RES is better than reflectivity mosaic in capturing small scale features. However, RES is not able to provide the identical resolution as the true reflectivity distribution but a cursory examination shows that RES still provides better resolution than a simple mosaic.

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