5.6 A METEOROLOGICAL RADAR EMULATOR FOR EDUCATION AND RESEARCH

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1. INTRODUCTION

Teaching radar meteorology involves both theoretical treatment of the interaction of electromagnetic (em) energy with hydrometeors and practice interpreting and applying radar information to the study of atmospheric processes. With the availability of data from the National Weather Service's (NWS) operational radar network and tools developed by Unidata to display that information, there are numerous opportunities to illustrate theoretical concepts for the em frequency (~3 GHz) represented by the operational network. Beyond the operational frequency, however, opportunities are scarcer.

Operational radar networks are also intended to provide high-quality data using a somewhat fixed sampling strategy. For greater flexibility and to extend the students' experience to include more troublesome data over a greater range of the em spectrum, educators typically rely on unedited research data that are difficult to access and less than optimal for classroom instruction. Moreover, educational use of research data is often limited to those with personal knowledge of the data and familiarity with the tools used to display and analyze them.

To facilitate student exploration and to provide a tool to quantify the impact of weather radar design on the ability to detect atmospheric circulations, we have developed a weather radar emulator. The emulator takes high-resolution output from a numerical simulation and scans the simulated atmosphere using radar characteristics and scanning strategies specified by the user. Input into the emulator can be held constant while the radar characteristics are changed, permitting a direct assessment of the impacts of radar design and scanning strategy on the diagnosis of atmospheric phenomena.

Using the emulator, a vast number of artificial data sets over a wide range of radar characteristics can generated, limited only by the number and type of numerical simulations available. The artificial data can aid in algorithm development as well as the investigation of radar performance necessary for the detection of meteorological phenomena. For example, the emulator documented here has been used to determine a baseline for detection of tornadic circulations by a fixed-site broad-beam low-power Doppler radar. This application is one element of the design process for a network of inexpensive radars that will be fielded in Oklahoma as part of the Center for Adaptive Sensing of the Atmosphere (CASA), an engineering research center supported by the National Science Foundation (NSF). This application underscores the potential for using the emulator to address research in both engineering and the atmospheric sciences.

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2. EMULATOR DESIGN

One of the major differences between this emulator and those based on analytic airflow (e.g. Wood and Brown 1997) or homogeneous rainfall characteristics (e.g. Capsoni and D'Amico 1998) is that input to this radar emulator is from a high-resolution numerical simulation of the atmosphere. The basic variables required are the three-dimensional winds and hydrometeor content. Temperature, pressure, and humidity are also required if computing the beam's path from the simulated index of refraction. This allows for investigation of anomalous propagation. Otherwise, a standard index of refraction is assumed.

The emulator also requires a radar configuration file, in which the user lists the fundamental characteristics of the virtual radar (Table 1), and a scanning strategy request to apply in sampling the input airflow and hydrometeor fields. The scanning strategy states the pulse repetition time, the number of pulses to average to compute a radial of data, and the position of the antenna as a function of time. Expressed in these general terms, the scanning strategy can accomplish Plan Position Indicator (PPI) sweeps, sector scans, Range Height Indicator (RHI) cross-sections, pointing mode, or adaptive scanning similar to phased array antenna systems.

Table 1. User specified radar characteristics

Frequency of emitted radiation
Peak power transmitted
Nominal half-power beamwidth
Antenna gain function
Pulse duration
Sample gate spacing
Minimum detectable signal of receiver

To allow for differential attenuation across the radar pulse and to apply the antenna gain function, the emulator breaks each transmitted pulse volume into hundreds of individual elements at each sample gate in range. The back-scattered power of an element and the signal loss due to attenuation depends on the transmitted power in the beam element at that range and the hydrometeor content of the closest numerical model grid cell to the location of that radar beam element. The nearest neighbor grid cell estimate is sufficient since the radar elements are purposely much smaller than the grid spacing of the input hydrometeor field. The return from each beam element is weighted by the antenna gain and accumulated attenuation for that beam element and then summed to yield the total returned power for that pulse.

Radial velocities are used as a proxy for differences in phase shift between successive pulses. For each range gate, the radial velocity of each radar beam element is computed as a projection of the three-dimensional wind and hydrometeor fall-speeds from the nearest neighbor grid cell. Each radial velocity is weighted by the returned power for its beam element. The recorded Doppler velocity for each transmitted pulse at a range gate is the sum of the power-weighted radial velocities of all the beam elements across the pulse volume at that range.

The average of the returned power and Doppler velocity from a sequence of pulses equal to the number specified in the scanning strategy is used to calculate the recorded beam of data. Application of the Nyquist velocity (Doviak and Zrnic 1993) to imitate velocity aliasing is performed after the summation of all the beam elements and the summation of the individual pulses. In other words, velocity aliasing is applied at the scale of a range gate for each computed beam.

Output from the emulator is stored in a netCDF format (Rew et al. 1997) and can be viewed using Unidata's Integrated Data Viewer (Unidata).

3. EXAMPLE— DETECTION OF TORNADOES

Output from a non-hydrostatic three-dimensional Advanced Regional Prediction System (ARPS; Xue et al. 2003) simulation of a tornadic supercell storm was used to evaluate the range dependency of detecting tornadic circulations for a low-power, two-degree half-power beamwidth radar. The simulation employed only bulk warm rain microphysical parameterizations (Kessler 1969) with a Marshall-Palmer (1948) drop-size distribution. The horizontal spacing in the simulation was 50 m. Vertical spacing was stretched with 20 m between the first two levels. For the purposes of this study, only one time step of the model was used.

Radar signatures associated with tornadoes include the maximum velocity differential (ΔV) between the inbound and outbound radial velocities and a vorticity parameter, S, defined as $2(\Delta V)/L$ where L is the distance between the centers of the gates having the maximum inbound and outbound velocities (Wurman 2002). Using these metrics, the simulated storm (not shown) had a velocity differential of 160 m s^{-1} and a vorticity parameter of 1.6 s^{-1}. The peak wind speed was about 80 m s^{-1}, which placed this circulation in the range of a F3 tornado (Fujita 1971).

Assuming no ground clutter, at ten kilometers from the tornado, a two-degree beamwidth radar with matched spacing (i.e. two degrees) between adjacent radar beams and 100 m range gate spacing would be able to diagnose a velocity differential of 57 m s^{-1} and a vorticity parameter of 0.31 s^{-1} with a 0.5° elevation angle PPI (Fig. 1). Even at this relatively close range, averaging across the radar beam significantly reduces the diagnosed circulation of the tornado. Over-sampling by 50 percent in azimuth (i.e. one degree between adjacent radar beams) increased the diagnosed velocity differential to 62 m s^{-1} and the vorticity parameter to 0.35 s^{-1} (Fig. 2).

At 30 km from the tornado (Fig. 3), the vorticity parameter is only 0.09 s^{-1}. A value of 0.1 s^{-1} is thought to be a lower-limit on being able to distinguish between tornadic and non-tornadic circulations (Alexander 2004).

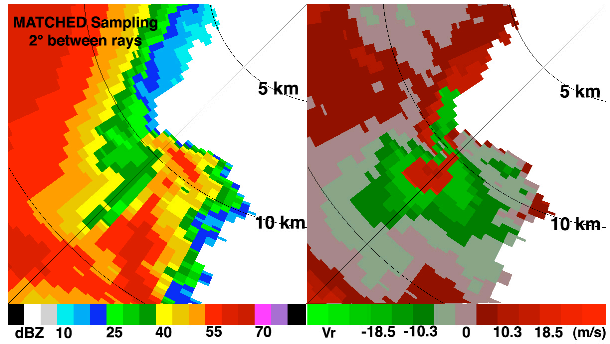

Fig. 1. Radar reflectivity assuming Rayleigh scattering and no attenuation (left panel) and Doppler velocity (right panel) for the hook echo region of the tornadic storm as determined by the radar emulator for a radar located 10 km from the tornado. The azimuthal beam spacing is matched with the 2° beamwidth of the radar. The PPI is taken at 0.5° elevation.

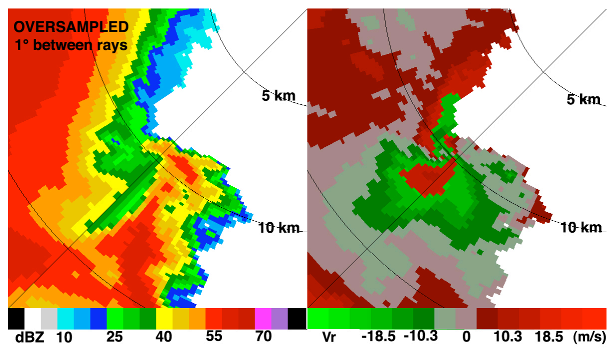

Fig. 2. Same as Fig. 1 except for 50% over-sampling, i.e. one degree azimuthal spacing between adjacent radar beams.

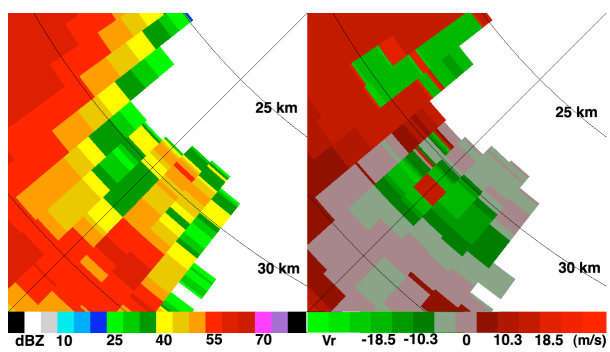

Fig. 3. Same as Fig. 1, except the radar is at a range of 30 km from the tornado.

4. FUTURE PLANS

Development of the emulator continues. Besides adding Mie (1908) scattering and attenuation, we will enable a simple form of clutter contamination for the part of the radar beam that intersects the ground. We also plan to expand the antenna gain function to include user-specified sidelobes and to fully implement the beam propagation by ray tracing from the numerical model profile of the refractive index. Moreover, we want to evaluate the impact of storm evolution on diagnosed structure by processing individual time steps of the model fields. Since each time step generates about 2 GB of model output, this will require significant computational resources. Finally, we plan to add receiver noise characteristics and to make use of the drop-size distribution and a probability distribution function of velocity to generate time series data and full power spectra.

5. SUMMARY AND CONCLUSIONS

A radar emulator has been developed for use in education and research related to radar meteorology and engineering. The emulator requires input from a high-resolution numerical simulation of the atmosphere and is able to provide moment data (radar reflectivity, Doppler radial velocity, and spectrum width) for a user-specified set of radar characteristics and a specified scanning strategy.

This tool has been used to evaluate the range dependency of detecting features associated with a strong tornado to aid in the design of a network of inexpensive low-power broad-beam Doppler radars that will be deployed in Oklahoma as part of the Center for Adaptive Sensing of the Atmosphere. We believe that the emulator can also be used to aid in the design of operating strategies for mobile radar deployments in the study of precipitating cloud systems.

Currently the emulator is housed on a dual-processor Opteron Linux-based computer with 4 GB of RAM. It takes approximately 12 hours of CPU time to generate a five-minute volume scan. Eventually we hope to install the code on a multi-processor machine. Since each radar beam can be computed independently, vectorizing the processing load would significantly improve performance.

Once the emulator has been fully developed and tested, we plan to establish an on-line digital resource complete with sample numerical simulations of severe storms for general educational use. This will allow students across the globe to investigate the impact of radar design and sampling strategies on the ability to diagnose atmospheric phenomena using weather radars.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Alexander, C. R., and J. Wurman, 2004: Comparison between DOW observed tornadoes and parent mesocyclones observed by WSR-88Ds, Preprints *22d Severe Local Storms Conf.,* Hyannis, MA, Amer. Meteor. Soc.

Capsoni, C., and M. D'Amico, 1998: A physically based radar simulator. *J. Atmos. Oceanic Technol.,* **15**, 593-598.

Doviak, R. J., and D. S. Zrnic, 1993: *Doppler Radar and Weather Observations.* 2nd ed. Academic Press, Inc., 562 pp.

Fujita, T. T., 1971: Proposed characterization of tornadoes and hurricanes by area and intensity. SMRP Research Rep. 91, University of Chicago, 15 pp.

Kessler, E., 1969: On the distribution and continuity of water substance in atmospheric circulations. *Meteorological Monograph* **10** no. 32, American Meteorological Society, 82 pp.

Marshall, J. S., and W. M. Palmer, 1948: The distribution of raindrops with size. *J. Meteor.*, **5**, 165-166.

Mie, G., 1908: Beitrage zur Optik truber Medien speziell kolloidaler Metallosungen. *Ann. Phys.*, **25**, 377-445.

Rew, R., G. Davis, S. Emmerson, and H. Davies, 1997: NetCDF user's guide for C: An access interface for self-describing, portable data, version 3. Unidata Program Center, Boulder, CO, 132 pp.

Unidata: Integrated Data Viewer (IDV) user guide. Unidata Program Center, Boulder, CO, 232 pp.

Wood, V. T., and R. A. Brown, 1997: Effects of radar sampling on single-Doppler velocity signatures of mesocyclones and tornadoes. *Wea. Forecasting*, **12**, 928-938.

Wurman, J., 2002: The multiple-vortex structure of a tornado. *Wea. Forecasting,* **17,** 473-505.

Xue, M., D.-H. Wang, J.-D. Gao, K. Brewster, and K. K. Droegemeier, 2003. The Advanced Regional Prediction System (ARPS), storm-scale numerical weather prediction and data assimilation. *Meteor. Atmos. Physics*, **82**, 139-170.