Meteorological Studies with the Phased Array Weather Radar and Data Assimilation Using the Ensemble Kalman Filter

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LONG-TERM GOALS

The long-term goal of this project is to integrate two state-of-the-art technologies, the phased array weather radar (PAR) and the emerging Ensemble Kalman Filter (EnKF) data assimilation method, to optimize the radar performance and improve coastal and marine numerical weather prediction (NWP).

OBJECTIVES

This project leverages on the new PAR in Norman, Oklahoma to exploit phased array technology and its applications to improve NWP through EnKF data assimilation with the goal of improving environmental characterization and forecast to optimize naval operation. This project will further enhance the existing collaboration among ONR, National Serve Storms Laboratory (NSSL), and the University of Oklahoma (OU) to achieve the four specific research objectives: (1) develop an EnKF framework for optimally assimilating quantitative observations of the atmosphere including the PAR data, (2) design a sophisticated radar emulator which will be used to validate innovative processing techniques developed in the project and to design accurate and efficient forward observation operators

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14. ABSTRACT
The long-term goal of this project is to integrate two state-of-the-art technologies, the phased array weather radar (PAR) and the emerging Ensemble Kalman Filter (EnKF) data assimilation method, to optimize the radar performance and improve coastal and marine numerical weather prediction (NWP).

15. SUBJECT TERMS

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for assimilating PAR data, (3) advance phased array radar technology through the development of novel signal processing techniques and integration of current state-of-the-art technologies to provide high-quality and high-resolution weather measurements, and (4) evaluate the impact of scanning strategies including SPY-1 tactical and non-tactical waveforms on data assimilation and NWP using the Observing System Simulation Experiments (OSSE) and Observing System Experiments (OSE). Optimal scanning strategies of PAR for NWP model initialization will be developed and tested.

APPROACH

Our multidisciplinary team is comprised of scientists with academic and industrial expertise in radar engineering, radar signal processing, EnKF data assimilation, numerical modeling, and weather prediction. Our approach is to exploit these complementary talents to achieve the goals of the proposed research. The five main research thrusts are discussed in the following.

(1) **Design of the PAR Emulator**: A sophisticated PAR emulator is designed to take in high-resolution three-dimensional meteorological fields and to generate synthetic radar time series data. The output of the emulator is then processed to produce the three spectral moments (reflectivity, mean radial velocity and spectrum width). The emulator is flexible enough to produce radar data for various waveforms, sensitivity, and sectoring. Artifacts such as ground clutter, point target, radar system noise, attenuation, range and velocity folding can also be simulated. The emulator will serve as a vehicle for developing accurate and efficient forward observation operators for PAR data assimilation. Moreover, error characterization can be obtained in the emulation and will be fed into the EnKF system.

(2) **Establish the EnKF system**: The existing EnKF-based OSSE framework for radar data developed by our group will be extended (a) to use much more realistic, yet efficient, forward observation operators that will be derived from the full-scale PAR emulator discussed in (1), (b) to handle PAR data collected in various non-conventional manner including those used in the SPY-1/TEP (Tactical Environmental Processor), (c) to assimilate cross-beam winds potentially available through spaced antenna (SA) method, and (d) to effectively account for model errors. The availability of an accurate and realistic radar emulator will allow us and the Navy to evaluate the impact of various simplifications (needed for efficient) in the observation operator on the quality of analysis and the subsequent forecast. The varying PAR scanning strategies will require much greater flexibility in the filter code design. Concerted efforts will also be made to parallelize the filter code for distributed memory processors because of the potentially large volume of radar data to assimilate.

(3) **Technology Innovation**: This research thrust focuses on the exploration of phased array technology merged with novel signal processing techniques to develop optimal scanning strategies. An agile beam phased array radar has the potential to not only increase the scanning rate, but also to measure meteorological variables not currently available and to enhance data quality. Two focus areas are proposed to address these issues. (a) A novel scanning scheme termed beam multiplexing (BMX) is developed to optimize the scan time and data quality. (b) The application of SA method on weather radar to measure the cross-beam wind component will be tested and verified using the PAR emulator. The impact of additional cross-beam wind measurement on numerical prediction will be evaluated and quantified using the OSSE.

(4) **Observing System Simulation Experiment (OSSE):** A comprehensive simulation system is being designed to integrate the processes of designing radar scanning strategies, making observations, assimilating data, and producing forecasts with the goal of improving short-term weather prediction and better understanding the relationships among all involved processes. The SPY-1 waveform with 1-pulse (reflectivity only) in clear mode, 3- or 4-pulse in Moving Target Indicator (MTI) mode, 16-pulse, and 32-pulse will be simulated and their impact on data assimilation and weather forecasting will be evaluated and quantified. Moreover, a framework for developing an optimal scanning strategy is being established based on a feedback design in the simulation. In other words, the information of the difference between the forecast and high-resolution model outputs can be used to adjust scanning patterns until optimal results are achieved.

(5) **Data Collection and Observing System Experiments (OSE):** The findings and lessons learned through radar emulator and OSSEs will then be demonstrated using the PAR at NWRT. Various scanning strategies tested with the OSSEs will be implemented with the PAR. We will leverage on a suite of existing weather radars including the research NEXRAD (KOUN), the mobile SMART radars, the nearby operational NEXRAD (KTLX) radar to validate the PAR measurements and retrieved variables. For example, the two mobile SMART radars will be strategically deployed to perform dual-Doppler analysis to estimate the three-dimensional wind field that can be used to verify the retrieved wind field and transverse wind measured by the SA method. Moreover, the co-located KOUN will be operated simultaneously using conventional scanning pattern in contrast to the irregular but strategic sampling patterns used by the PAR. Observations from these two radars will be assimilated individually using an EnKF which will allow effective assessment and quantification of the impact of PAR sampling strategies, for real weather.

About the Team: A multidisciplinary team including 6 OU professors and two postdoctoral fellows has been assembled to execute the project. The principal investigator, Prof. Yu is responsible for providing technical expertise and project management, including planning and coordination, monitoring the progress, and reporting to the program manger. Prof. Xue is in charge of data assimilation, numerical models, and NWP. He has been providing the high-resolution model data to be used for the PAR emulation. Prof. Yeary brings his expertise of adaptive signal processing, Kalman filtering, and clutter filtering to develop optimal scanning strategies. Prof. Palmer has been working on the development of PAR emulators and SA algorithms. Prof. Torres who also holds an adjunct faculty position in ECE is involved in the evaluation and quantification of the impact of the PAR scanning strategies on data assimilation and numerical prediction. Prof. Biggerstaff is strongly engaged in the design and coordination field experiments to exercise and validate the results.

WORK COMPLETED

The team has been continuously working toward project goals. The following specific tasks are completed.

1. The PAR emulator has been enhanced to incorporate additional features as follows. (a) The PAR emulator is now capable of simulating time series data as well as moments for agile beams on a pulse-by-pulse basis. As a result, the newly developed beam multiplexing as well as other flexible/adaptive scanning strategy can be simulated. (b) The PAR emulator is now capable of generating spatially correlated measurement errors that are derived from the high-resolution true fields of the Advanced Regional Prediction System (ARPS) model. These errors can be used in the EnKF assimilation to

study the impact of errors on the prediction performance. (c) The PAR emulator is now capable of simulating a monopulse system with a flexible configuration. Time series signals from the sum and two difference (azimuth and elevation) channels are now available.

2. To fully take advantage of the PAR at NWRT, we have applied monopulse processing technique to weather observations. This capability has been demonstrated using the PAR emulator. Strong linear shear embedded within radar resolution volume can be retrieved using the monopulse processing of weather signals that cannot otherwise be resolved by conventional weather radar.

3. In this year, the ARPS's EnKF data assimilation system has been modified to use more realistic radar observational operators such as the antenna beam patterns and range weighting function. Moreover, we have developed a scheme to directly assimilate radar data on individual radials, which has the potential to effectively assimilate spatially spare data from adaptive sensing.

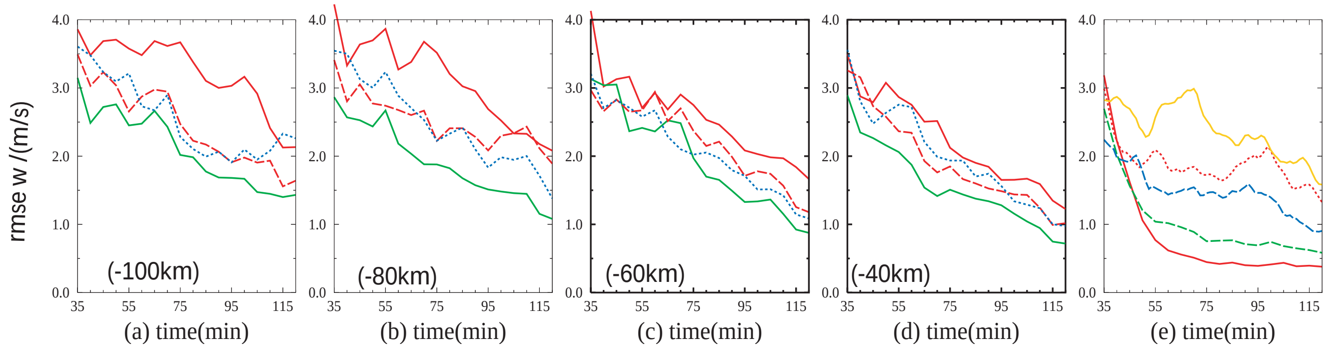
4. A series of OSSE experiments based on the enhanced ability of ARPS EnKF has been conducted to assess the impact of angular over-sampling and high data rate provide by the PAR on weather prediction. In those OSSE, both the truth simulation and the analysis processes use the same resolutions of 1 km horizontal mesh size and stretched vertical mesh. Higher resolution OSSE are being carried out with 500 m horizontal mesh size. They are expected to provide more realistic and accurate study base. Their preliminary results have been analyzed.

RESULTS

The results are highlighted in the following two areas, denoted by 1 and 2 below.

1. **Investigation of the impact of radar sampling using enhanced ARPS EnKF system**

A series of OSSEs was conducted to investigate the impact of radar sampling on numerical weather prediction. The APRS EnKF system has been modified to assimilate radar data on a radial basis. This approach is desirable because radar data are intrinsically in polar format and collected radial by radial. The root-mean-square (rms) errors of the analyzed vertical velocity through the analysis cycles are shown in Fig. 1 for various radar locations. The radar is located at 100, 80, 60, and 40 km west of the domain in (a)-(d), respectively. The PAR beamwidth is 2 degrees and the data update time is 5 min. In each subplot, various angular sampling of 0.5, 1, and 2 degrees in both azimuth and elevation are denoted by blue-dotted, red-dashed, and red lines, respectively. In addition, results from WSR-88D with a 1 degree beamwidth and the lowest elevation scan of 0.5 degree are denoted by green lines. Note that for the PAR experiments, the lowest elevation scan is 1 degree limited by the beamwidth. Present experiments have shown that angular over-sampling with a factor of two (red dashed lines) can improve analysis results for all the four radar locations compared to those without over-sampling (i.e., 2 degree angular sampling, red lines). However, no evident improvement can be obtained if a higher oversampling rate is employed.



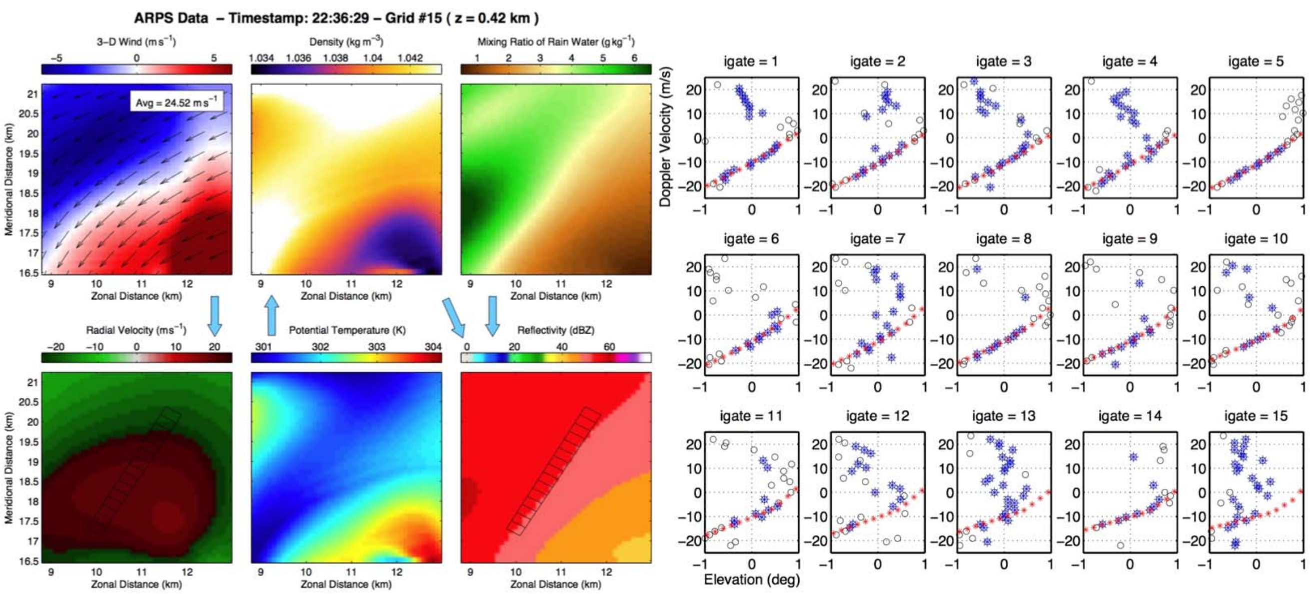
[Figure 1. The rms errors of ensemble mean analyses of vertical velocity averaged over those regions where the true reflectivity is greater than 5 dBZ for various radar locations (a) (-100, 0), (b) (-80, 0), (c) (-60, 0) and (d) (-40, 0) km. In (a)-(d), the green lines are for experiment with WSR-88D with 1 degree beamwidth and 0.5 degree the lowest elevation angle, the blue-dotted, red-dashed and red lines denote results from the PAR with angular oversampling of 0.5, 1, and 2 degrees, respectively. The data update is 5 min. In (e), benchmark experiments for radar located at (0,0) km and (-100, 0) km are denoted by red-solid and green dashed lines, respectively. Experiments with high data update rate of 1.25 min and 1 degree angular oversampling are denoted by blue-dashed and red-dotted lines for radar location of (-60, 0) and (-100, 0) km, respectively. The worst performance is obtained for the case of high data rate, non-oversampling, and largest distance, which is denoted by yellow-solid line.]

It is interesting to point out that WSR-88D case can produce the best results because not only it has a narrow beam but also it scans lower level of the storms. The benchmark experiments with radar positions at (-100, 0) and (0, 0) km in Fig. 1 (e) exhibit, not surprisingly, the best performance because of the absence of horizontal interpolation or volume average error. In addition, experiments with higher data update rate of 1.25 min were also conducted and is shown in Fig. 1 (e). The results show that higher update time can improve the data analysis, especially in the early and middle stages of data analysis. This is especially helpful for the analysis and prediction of newly developed thunderstorms that have not had radar data available for long.

2. **Application of a monopulse phased array system to weather observations**

Monopulse radar has been widely used in military application for tracking hard target such as airplanes and missiles. The angular location of the target can be determined with accuracy much finer than the radar beamwidth by processing the sum and difference of signals from spatially separated antennas. In this work, the monopulse processing is exploited for distributed targets of weather. As a result, angular distribution of radial velocities in both azimuth and elevation directions can be obtained at sub-beamwidth resolution, while a conventional weather radar cannot resolve them. This is especially important if the region of interest is located far from the radar such that the smoothing effect of radar volume is significant. As a result, variation of the velocities within the radar volumes cannot be resolved.

Our PAR simulator has been upgraded to generate signals from a monopulse system (i.e., signals from the sum, and elevation and azimuth difference channels). An example of ARPS generated fields are presented on the left panel of Fig. 2. The 3D field is shown on the upper left with color contouring for vertical velocity. The resulted radial velocity is shown on the lower left panel and the reflectivity field is also shown on the bottom panel of the third column. Raw time series signals from 15 range gates, denoted by black boxes, were generated. These gates are *indexed* from 1 to 15 and are denoted by *igate* in the figure. Note that only a single velocity estimate would have being obtained at each gate if signals only from the sum channel are used (i.e., conventional processing). As a result no information about the variation of the wind field within the radar volume can be obtained. However, for this case strong vertical shear is present within the radar volume which is indicated by red asterisks in the subplots on the right panel of Fig. 2. For each subplot, the x-axis represents the elevation angle at a sub-beamwidth scale with respect to the center of the beam point direction, which is 3 degrees. Radial velocity estimates derived from reliable monopulse ratio are denoted by blue crosses. It is evident that strong vertical shear can be reconstructed at a scale finer than the radar beamwidth using monopulse processing such as those results from gates 1-6 and 8-9. It is also found that the performance of these cases is limited if the azimuthal shear is also presented in the resolution volume. For example, those from igate=13 and 15.



[Figure 2: Fields generated from ARPS. The 3D wind field and a field of radial velocities observed from the PAR are presented in the first column. Raw time series data from the monopulse PAR were generated at 15 range gates along one radial, which is depicted by black boxes in the field of reflectivity and velocity fields. Using the ratio of signals from the sum and elevation delta the variation of radial velocity can be reconstructed at a sub-beamwidth resolution as demonstrated in the right panel. The true velocity variation from the ARPS is denoted by red asterisk and the estimated radial velocity from monopulse processing with reliable monopulse ratio is denoted by blue cross. Note that only one radial velocity estimate is obtained at each gate if a conventional processing is used.]

IMPACT/APPLICATIONS

The APRS EnKF system has been modified to assimilate radar data on a radial basis. In other words, it has the potential to assimilate radar data after the collection data at each radial. This will allow us to effectively assimilate PAR data for the scenario of adaptive sensing where meteorological data could be only available at a few radials. Therefore, the radar can allocate more resources for tactical operations. Moreover, the application of monopulse technique to weather observations can increase the functionality of a phased-array system. In addition, this is compatible to the spaced antenna technique to estimate the cross-beam component of the wind field. As a result, it has the potential to timely access high-resolution wind and shear (at a sub-beamwidth scale) information in both azimuth and election directions in a tactical environment.

RELATED PROJECTS

There is no related DoD project.

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