

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 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. 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 such as angular oversampling, and (c) 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.
- (3) **Technology Innovation:** This research thrust focuses on the exploration of phased array technology merged with novel signal processing techniques. 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. For example, a novel scanning scheme termed beam multiplexing (BMX) is developed to optimize the scan time and data quality. In addition, the refractivity on surface, which can serve as a proxy of humidity, can be measured from the radar returns from ground clutter. The impact of these technology innovations on numerical prediction can be evaluated and quantified using the OSSE and OSE.
- (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.

WORK COMPLETED

Note that the project was ended on April 30, 2010 and a final report was submitted. The team had been focused on wrapping up the project, but we also obtained some interesting results from a couple additional research areas and are reported here.

- (1) **Robust Storm Identification with Strong Point Analysis:** In this work, an image segmentation algorithm using an alternating erosion/dilation technique called Strong Point Analysis (SPA) was developed for general-purpose feature detection (i.e., storm identification). Our results have shown that SPA can provide robust storm identifications that are coherent and consistent over time. These characteristics are critical for reliable storm tracking because abrupt changes to the apparent position of a storm cell from one time-step to the next greatly hinder a tracking algorithm's ability. Specific accomplishments are highlighted in the following.
 - *Development of SPA engine for storm identification:* A novel storm identification algorithm termed SPA was developed, which can be applied to radar reflectivities from either PAR or NEXRAD. The SPA takes erosion/dilation in an alternating and iterative manner. The erosion process would erode the image, revealing the presence of multiple distinct regions instead of one large region. The dilation process then rebuilds or grows those regions, while maintaining their newly discovered distinctions. With this approach, thresholds were determined dynamically, rather than using predetermined quantities. This allowed for incremental changes to the thresholds in regions where the image values did not change much, while still being able to make larger changes to the thresholds when the region contained variations.
 - *Test and verification of SPA:* The quality of SPA was tested using radar reflectivity images from three S-band weather radars. The algorithm was proven to identify storm features fairly consistently over a time-series of images, as well as exhibiting well-behaved changes to its output with respect to changes to the algorithm's input parameters.
 - *Demonstration of SPA with PAR images:* We successfully applied the SPA to fast updated PAR reflectivities from a relatively complicated squall-line case. Reliable and consistent identification of embedded storm cells was achieved.
- (2) **Clutter Mitigation With Spatial and Frequency Diversity:** Range IMaging (RIM) was developed in 1999 to improve range resolution by transmitting multiple frequencies for vertically pointing profiler radar. Since then, the capability of RIM for resolving fine atmospheric layer

embedded in the conventional range gate has been demonstrated by a number of VHF and UHF atmospheric radars around the world. Nevertheless, like conventional radar, RIM is susceptible to clutter contaminations that are contributed from antenna sidelobes. This work addresses this important issue in RIM the first time by capitalizing the capability offered by multiple receivers and multiple frequencies with the goals of maintaining resolution gained by RIM and simultaneously, suppressing clutter contamination. Note that although the techniques have been applied to clear-air observations with profiler radars (a phased array system), the same technique is suitable for weather observations if the future MPAR has the provision of multiple frequencies and multiple receivers. This work with multi-receiver and multi-frequency is summarized in the following.

- *Statistical analysis of the developed techniques:* The three techniques were first demonstrated and verified using numerical simulations, where atmospheric signals were contaminated with various non-stationary clutter. Statistical comparisons of the three techniques were made and their associated errors were quantified.
- *Demonstration with real data:* The feasibility of the three techniques was further demonstrated using real data collected by the Middle and Upper (MU) radar in Japan. It has shown that atmospheric layer at scale smaller than the range gate can be revealed through the three developed techniques, while only a gross structure was observed using conventional scheme with single frequency and receiver. In addition, two of the techniques have superior performance in suppressing clutter. The results agree with those from number simulations.

RESULTS

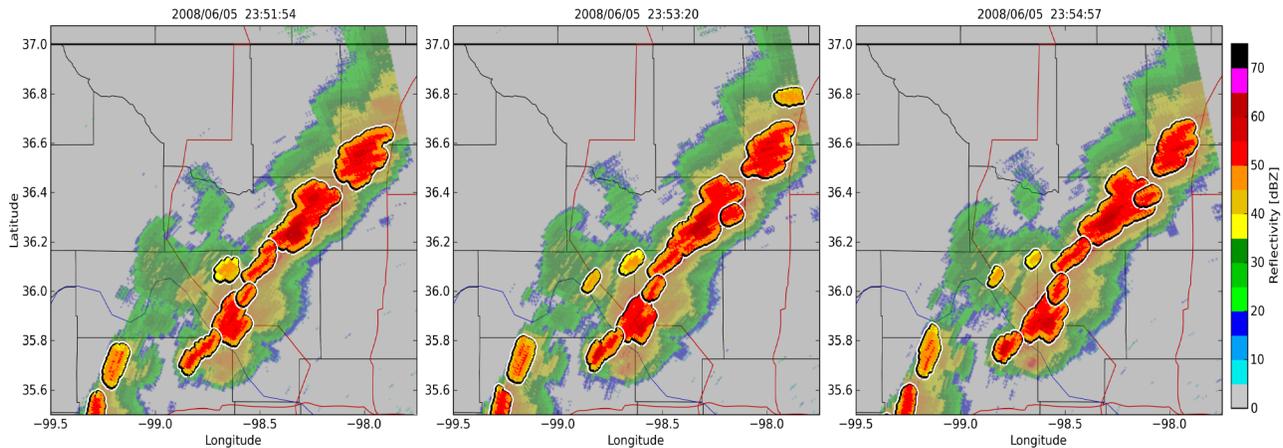
The results are highlighted in the following two areas.

(1) **Robust Storm Identification with Strong Point Analysis:**

One of the prerequisites for reliable tracking of storms in complex weather scenarios is to identify storm cells in consecutive radar images in a reliable and consistent fashion. In this work, we focused on developing a reliable and robust storm identification with the provision for adaptive weather sensing. The design is modular so it can be easily integrated into existing or future storm tracking algorithm implemented on the WSR-88D or MPAR, respectively.

It has been shown that the two morphological operations of “erosion” and “dilation” on a radar image can improve the detection skill of an existing algorithm. Erosion is, essentially, the process of reducing the area of a region, while dilation is the process of increasing the area of a region. In this work, a novel clustering algorithm termed strong point analysis (SPA) was developed to take erosion/dilation in an alternating and iterative fashion. Rather than erode the image once to break up false mergers and then dilate the regions to produce a final result, SPA erodes the image slightly, then dilates those regions, and then repeats the process. As a result, the SPA can produce robust and consistent storm cell identification over a sequence of radar images. At the most fundamental level, the algorithm of SPA can be reduced down to the following description: (1) Identify and network together neighboring pixels that are ‘Strong Points’ -- an isolated network is a cluster, (2) Grow each cluster's region with neighboring pixels that are ‘Weak Points’, (3) Repeat within each cluster, (4) Go to step one for each cluster. The erosion is an implicit byproduct of the recursion described in the engine, while dilation is explicitly performed by the region-growing step. This process is repeated until a defined stop condition is satisfied.

The SPA was tested and verified by radar images from both WSR-88Ds and PAR. Figure 1 shows the reflectivities and cluster results from the PAR at NWRT on June 5, 2008 at 2352, 2353, and 2355 UTC. In this time series, the storm is rapidly moving and changing. This image series is more complicated, with less distinct features. There is a strong squall line extending from the southwest to the northeast, with the storm motion predominately to the northeast. Much of the weaker features are ignored, as expected. The stronger features are segmented appropriately into individual storm cells. More importantly, the features are consistently identified across the time series of images.



[Figure 1. Time series of radar images from NWRT in Norman, Oklahoma on June 5, 2008 at 2352, 2353, and 2355 GMT. Storm cells identified by SPA are indicated by the undimmed reflectivities within the white outlines.]

In this work, we have demonstrated the benefit of using the image statistics and recursion in SPA. Simply speaking, SPA determines thresholds dynamically, rather than uses predetermined values. This allowed for incremental changes to the thresholds in regions where the image values did not change much, while still being able to make larger changes to the thresholds when the region contained variations. Those identified storms can be subsequently fed to the storm tracking algorithm.

(2) Clutter Mitigation With Spatial and Frequency Diversity:

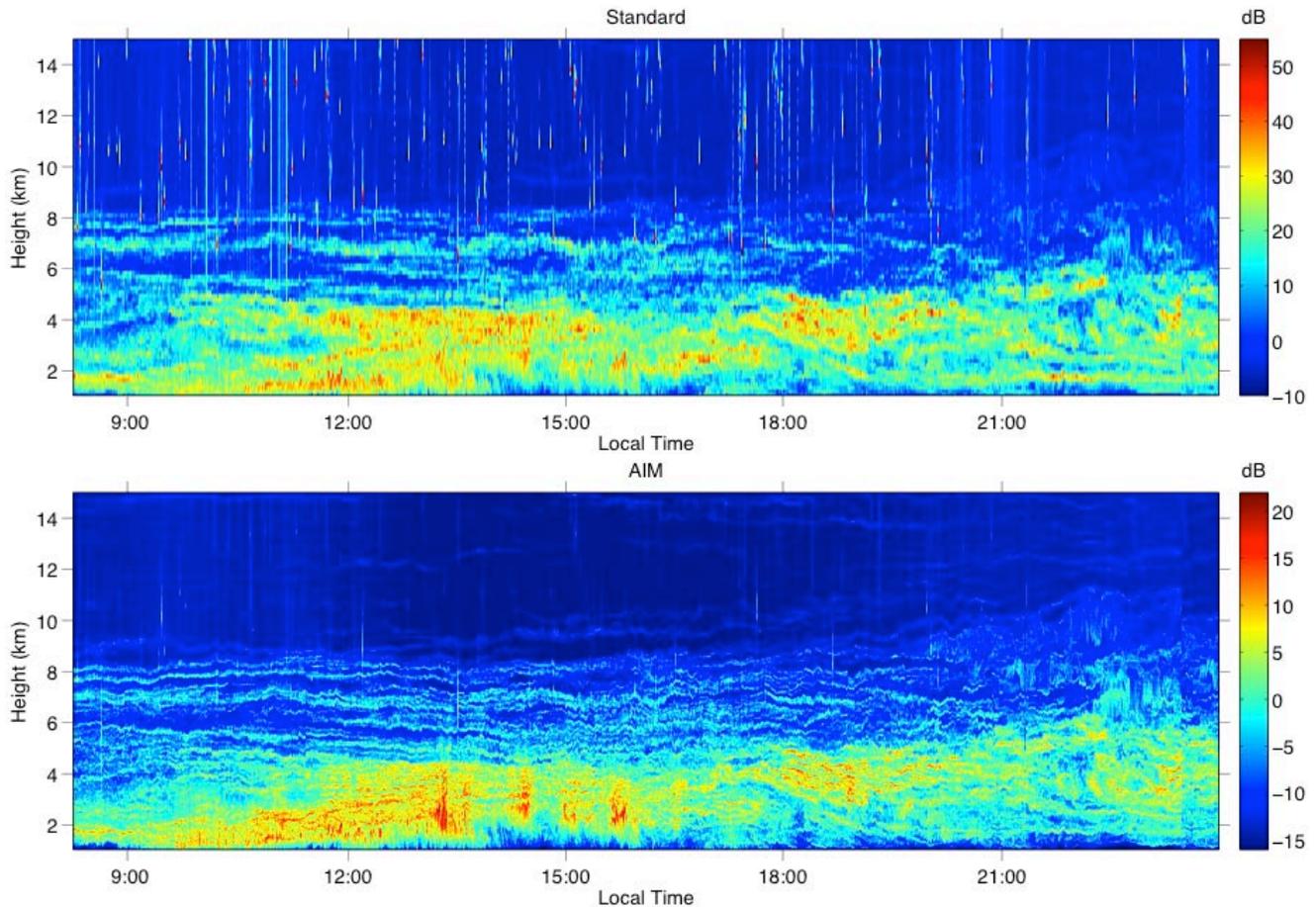
Although RIM has become mature, the technique is susceptible to clutter contamination, which hinders its applicability. We have developed some clutter suppression techniques for the PAR at NWRT using sidelobe canceller. By capitalizing our experience from the PAR, here we developed three novel imaging techniques to address this important issue by exploiting additional signals from spatially separated antenna subarrays to achieve the goal of improving range resolution and suppressing clutter contamination. It should be noted that the proposed techniques have the potential to apply to meteorological observations using a phased array system with frequency agility. Two techniques were developed where multi-receiver signals from the same frequency are initially combined using Fourier or Capon beam-forming technique for clutter suppression, and subsequently, these combined signals from multiple frequencies are processed using RIM for resolution enhancement. The two techniques are abbreviated by FB-RIM and CB-RIM. The mathematical representation of FB-RIM and CB-RIM was derived. Moreover, the 3-D atmospheric radar imaging (AIM) was applied to the multi-receiver and multi-

frequency signals to image in the vertical direction. The feasibility of the three techniques were demonstrated and their performances were compared using numerical simulations of moving target with different flight paths and clutter-signal-ratios. A detailed description of the three techniques and the statistical comparisons of their performance are provided in the paper Here only some selected results from real data are presented.

To further demonstrate the application of the three techniques to atmospheric observations, a MU radar experiment was conducted on 0817-2328 LT 15 July 2009. The MU radar is located in Shigaraki, Japan (34.85° N, 136.10° E) and is capable of transmitting 5 frequencies and receiving with a maximum of 25 digital receivers. In this experiment, two modes of imaging and wind measurements using Doppler Beam Swinging (DBS) were alternated. However, we focused on the results from the imaging mode, where 5 uniformly spaced frequencies between 46 and 47 MHz, and 25 receivers were used. Moreover, only the center 7 groups of antennas were used for transmission resulting a one-way HPBW of approximately 6.9° .

The height time intensity (HTI) plots of return power estimated from standard and one of the newly developed techniques, AIM, are shown in top and bottom panels of Figure 2, respectively. The contamination by moving clutter is apparent in standard processed results at heights above approximately 6 km. The instance of clutter manifested themselves as point-like and typically strong returns, and was caused likely by airplanes or birds from antenna sidelobes. The gain of range resolution by AIM over the standard processing is evident, with more clear and detailed layer structures revealed, such as those at heights between 2.5 and 5.0 km and 1000-1130 LT and those at 6-8 km and 1630-1900 LT. More importantly, AIM can suppress clutter contamination as demonstrated in the lower panel of Figure 2. As a result, a clearer HTI can be obtained from the novel AIM.

In addition, the statistical analysis of real data indicates that AIM provides the best performance of balancing the layer reconstruction and clutter suppression among the three techniques for most cases. The results are consistent with those from previous simulation study.



[Figure 2. The height-time-intensity plot of echo power (dB) obtained from (top panel) standard processing with 150 m range resolution, and (bottom panel) AIM processed results for 0817-2328 LT 15 July 2009.]

IMPACT/APPLICATIONS

We have designed and implemented the framework of adaptive weather sensing based on a time balance (TB) scheduling algorithm. Fast update of the storm cells without degrading data accuracy from the WSR-88D can be achieved using such approach with a PAR system. One essential component of the framework is a robust storm identification and tracking, where the newly developed SPA technique can play an important role. A team of engineers and scientists at NSSL, led by Dr. Torres, has been working on upgrading the real time control to accommodate adaptive sensing. It is of interest and recommended to demonstrate such framework of adaptive sensing with TB scheduling with the PAR at the NWRT. Moreover, in the current framework a number of simplifications have been made and no information from the numerical weather models is used. A more advanced approach of truly flow-dependent adaptive scanning can be employed based on the Ensemble Transform Kalman Filter (ETKF) approach, which chooses the scanning strategies that minimizes the forecast error variance. Although it is still computationally challenging to implement such a system for realtime radar scanning, a look-ahead study can be carried to develop an adaptive system through OSSEs.

The newly developed clutter suppression method can improve the weather data quality. Indeed, the SPY-1 antenna of the PAR at NWRT has six channels of sidelobe canceller that can allow the implementation of spatial clutter filtering. The University of Oklahoma got extra funding from the National Science Foundation to build an 8-channel receiver that will accommodate the sidelobe cancelling and monopulse processing. The receiver is currently at the final stage of testing and will be available for data collection in the near future. Therefore, the application of these advanced PAR technologies, such as monopulse processing, sidelobe cancelling, and spectral analysis, to real weather observations can be demonstrated.

RELATED PROJECTS

There is no related DoD project.

PUBLICATIONS

B. Root, T.-Y. Yu, and M. Yeary, 2010: Consistent clustering of radar reflectivities using strong point analysis: A prelude to storm tracking, *IEEE Geosci. and Remote Sens. Lett.*, [in press, referred].

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R. Reinoso-Rondinel, S. Torres and T.-Y. Yu, 2010, Task prioritization on phased-array radar scheduler for adaptive weather sensing, 14B6, *Amer. Met. Soc. 90th Annual Meeting*, Atlanta, GA, January 17-21, 2010. [accepted, nonreferred].