

Adaptive Radar Data Quality Control and Ensemble-Based Assimilation for Analyzing and Forecasting High-Impact Weather

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LONG-TERM GOALS

Study and develop advanced approaches for radar data quality control (QC) and assimilation that will not only optimally utilize Doppler wind information from WSR-88D and Terminal Doppler Weather Radar (TDWR) but also take full advantage of rapid and flexible agile-beam scans from the phased array radar (PAR) at NWRT.

OBJECTIVES

Develop advanced methodologies for radar velocity data QC and assimilation that will not only optimally utilize observations from operational Weather Surveillance Radar-1988 Doppler (WSR-88D) and Terminal Doppler Weather Radar (TDWR) but also take full advantage of rapid and flexible agile-beam scans from the phased array radar (PAR) at the National Weather Radar Testbed (NWRT).

APPROACH

Use the automated radar-based wind analysis system (RWAS, Xu et al. 2009a) to monitor and record various data quality problems in operational WSR-88D and TDWR radar observations as well as NWRT PAR observations. Investigate and classify outstanding data quality problems, and develop advanced adaptive data QC techniques for various scan modes to satisfy data assimilation needs.

Extend the theoretical formulations derived for measuring information content from observations for data assimilation, so efficient data compression strategies and optimal PAR scan strategies can be designed based on the modern information theory to maximize the information content from observations and minimize data redundancy for ensemble-based radar data assimilation.

Explore and develop new hybrid sampling approaches based on Bayesian probability theory for ensemble-based radar data assimilation to improve real-time analysis and forecast of high-impact weather.

The PI, Dr. Qin Xu, is responsible to derive basic formalisms and provide technical guidelines for the implementations. The data collections and QC algorithm developments are performed by project-supported research scientists at CIMMS, the University of Oklahoma. Dr. Allen Q. Zhao at NRL

Monterey and Dr. Shun Liu at NOAA/NCEP perform pre-operational tests as the radar data QC and assimilation packages are upgraded and delivered.

WORK COMPLETED

By using real-time dual-polarization observations from the operational WSR-88D radars, a fuzzy-logic technique was developed to identify contaminated Doppler velocities by birds, especially migrating birds. As a necessary and important part of the radar QC, this technique is new in terms of using newly available dual-polarization observations, and it replaces the previous technique developed by the PI's group (Zhang et al. 2005; Liu et al. 2005) from a past ONR-funded project before the operational WSR-88D radars in the US were upgraded with dual-polarization. Without dual-polarization observations, the previous technique could only crudely detect bird-contaminated velocities volume-wise or tilt-wise (for each sweep), so it would reject the entire volume (or tilt) of velocity observations even if only a fraction of the volume (or tilt) were contaminated by migrating birds. By using the dual-polarization observations, the new technique can detect and remove bird-contaminated velocities pixel-by-pixel. This new technique will be incorporated into the radar data QC package delivered to NRL Monterey and NCEP for radar data assimilation applications (Zhao et al. 2008; Liu et al. 2009).

An alias-robust least-squares method was developed to estimate the maximum tangential velocity V_M and its radial distance R_M from the hurricane vortex center by fitting a parametric vortex model directly to raw aliased velocities scanned from a hurricane. In this method, aliasing-caused zigzag-discontinuities are formulated into the cost-function via the unconventional approach of Xu et al. (2009b) rooted in the Bayesian estimation theory (Xu 2009) to ensure the cost-function to be smooth and concave around the global minimum. Simulated radar velocity observations were used to examine the cost-function geometry around the global minimum in the space of control parameters (V_M, R_M). The method was successfully tested with more than 600 volumes of severely aliased raw velocity data scanned from three hurricane cases by four operational radars (KLIX, KMOB, KHGX, KMHX).

The adaptive dealiasing technique based on variational analysis (Xu and Nai 2012) was incorporated into the radar data QC package in the automated radar-based wind analysis system (RWAS, Xu et al. 2009a). This technique has been used effectively with the RWAS to correct severely aliased radial velocities in severe winter ice storms scanned by the operational WSR-88D radars with the Nyquist velocity reduced below 12 m s^{-1} . The RWAS has been running continuously with real-time radar data (including dual-polarization data) to monitor data quality problems in radar observations. From the real-time run of RWAS, the adaptive dealiasing technique was found to be capable of correcting alias errors without false dealiasing, but the dealiased data still often have less or sometimes even much less coverage than the raw data, especially in isolated data areas far away from the radar or in localized areas of strong and complex winds such as those around mesocyclones. Dedicated efforts were made to further improve the dealiasing technique, so the dealiased data can have increased coverage but remain to be completely free of false dealiasing, especially over storm-scale areas threatened by intense mesocyclones and their generated tornados. Substantial improvements were made in both the first-step reference check and the second-step continuity check, and the details are presented in Xu et al. (2013b). The improved technique will be incorporated into the radar data QC package and delivered to NRL Monterey for radar data assimilation applications.

Automated algorithms were developed to detect mesocyclones imbedded within severe thunderstorms scanned from radars and to estimate their key parameters, such as the vortex center location and moving speed and direction, maximum rotational winds and radius of maximum wind. From the

estimated key parameters, vortex-flow-dependent background covariance functions were formulated in terms of stream-function and velocity-potential for the flow field around each detected mesocyclone. By applying the convolution theorem to the formulated covariance functions in discrete forms, the square root of background covariance matrix was derived analytically and used to transform the control variables for preconditioning the cost-function. Using this preconditioned cost-function, a new and efficient variational method was developed in an incremental form for analyzing tornadic vortex winds from radar radial-velocity observations in a nested vortex-following domain on each tilt of radar scan. The method was successfully tested with tornadic mesocyclones observed by operational radars in Oklahoma on 24 May 2011 and 19-20 May 2013, and it can be either used independently or incorporated into the RWAS as an adaptive incremental step for real-time applications.

RESULTS

The automated fuzzy-logic technique for identifying contaminated velocities by birds performs two steps: In the first step, the hydrometeor classification algorithm (HCA) for dual-polarimetric WSR-88D radars developed at the NSSL is simplified and used to differentiate biological scatterers from meteorological scatterers. In the second step, a new fuzzy logic method is developed to differentiate bird echoes from insect echoes among the biological scatterers. The technique was tested with polarimetric data collected from the operational KVNK and KICT radars during several spring and fall migrating seasons. The results are presented in Jiang et al. (2013). An example is shown in Fig. 1.

The results from the alias-robust least-squares method are summarized below: (a) The global minimum point of the cost-function can be found by an efficient descent algorithm to estimate the maximum tangential velocity V_M and its radial distance R_M if the initial guess is in the concave vicinity of the global minimum and the hurricane vortex center location is known. (b) The estimated (V_M, R_M) are not sensitive to errors in the vortex center location (estimated from operationally issued hurricane location information). (c) With elaborated refinements, the method can produce reliable reference radial-velocity fields to improve the automated dealiasing (Xu et al. (2011) adaptively for severely aliased velocities scanned from hurricanes. The detailed method and results are presented in Xu et al. (2013a).

In the improved dealiasing technique (Xu et al. 2013b), the alias-robust variational analysis (Xu and Nai 2013) is modified adaptively and used in place of the alias-robust velocity azimuth display (VAD) analysis (Xu et al. 2010a) for all scan modes (including WSR-88D VCP31 with the Nyquist velocity reduced below 12 m/s and TDWR Mod80 with the Nyquist velocity reduced below 15 m/s), so more raw data can pass the stringent threshold conditions used by the reference check in the first step of Doppler velocity dealiasing. This improves the dealiased data coverage without false dealiasing, as required by radar data assimilation. The dealiasing technique is then further improved by adding new procedures to the continuity check in the second step to increase the dealiased data coverage over storm-scale areas threatened by intense mesocyclones and their generated tornados. The technique has been successfully tested with more than 400 volumes of severely aliased raw radial-velocity data scanned from tornadic storms and is being continuously improved. An example is shown in Fig. 2.

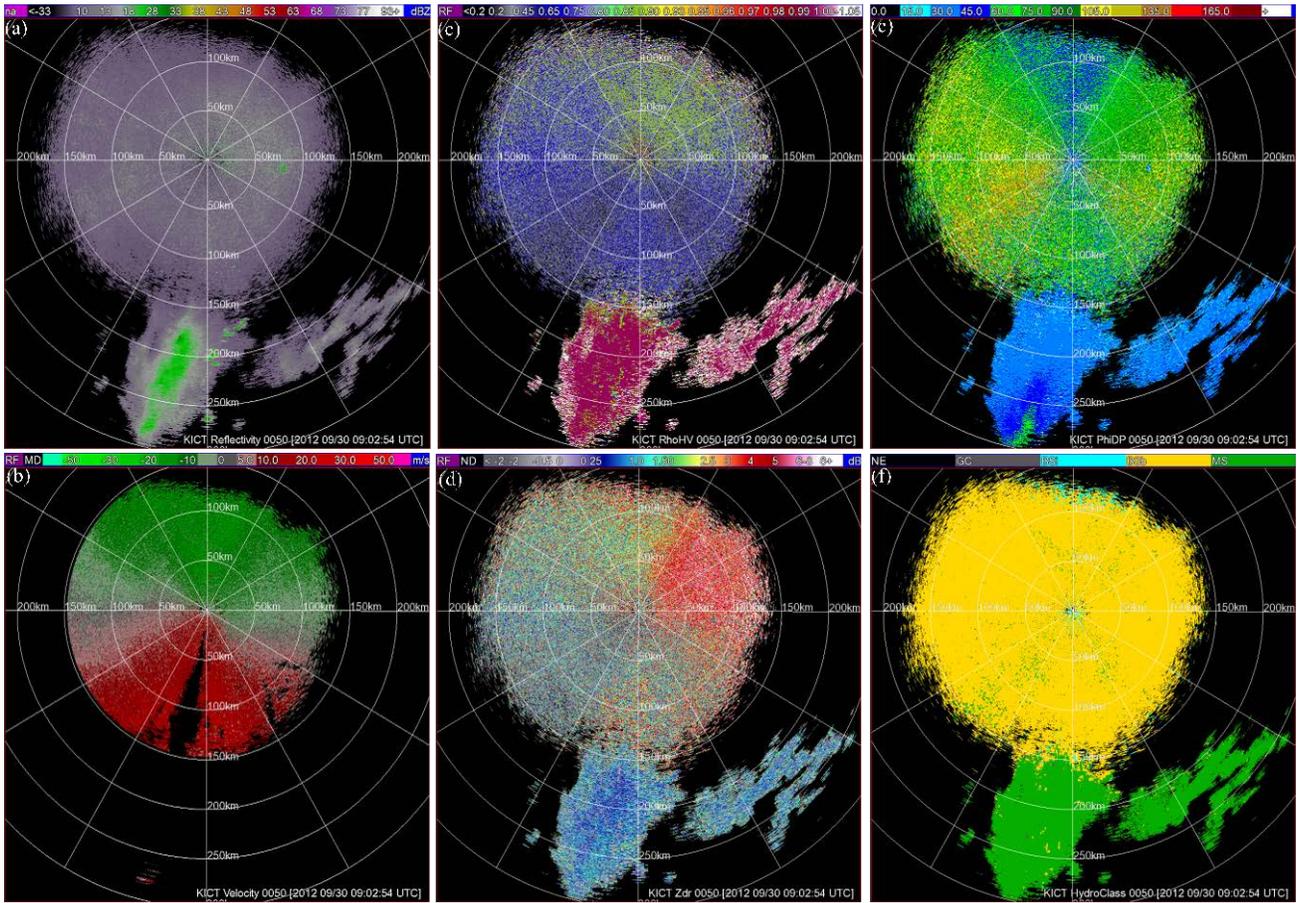


Figure 1. Images of (a) reflectivity Z , (b) radial velocity v_r , (c) cross-correlation coefficient ρ_{hv} between horizontally and vertically polarized radar returns, (d) differential reflectivity Z_{DR} , (e) differential phase Φ_{DP} , and (f) classification results produced in the second step from the KICT radar 0.5° scan at 09:01:42 UTC (local time around 4 am) on 30 September 2012. In panel (f), the three types of pixels for meteorological scatterers (MS), bird scatterers (BSb) and insect scatterers (BSi) are colored in green, yellow and cyan, respectively. The classification results in panel (f) are consistent with those identified by human expertise.

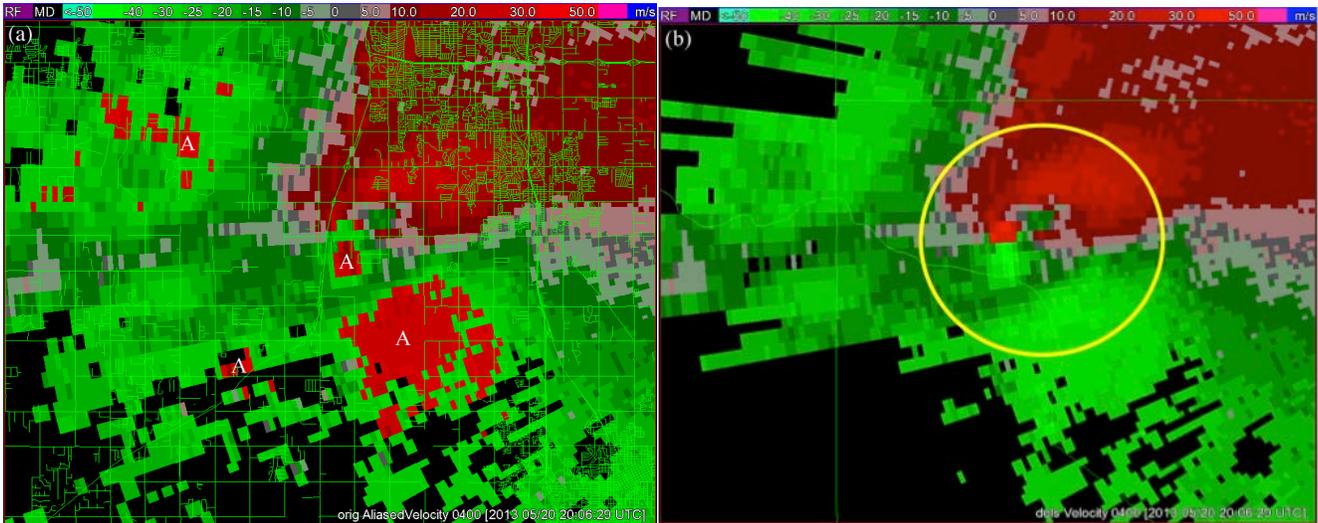


Fig. 2. (a) Image of raw radial velocity (superimposed on the Moore city street map plotted by bright green lines) scanned from KTLX radar on 4.0° tilt at 20:06:29 UTC on 20 May 2013 for the Moore, Oklahoma tornadic storm. (b) Image of dealiased radial velocity produced by the improved method. The white letters “A” in (a) mark the aliased-velocity areas. The yellow circle in (b) encircles the mesocyclone and its produced EF5 tornado.

The new variational method for tornadic vortex wind analysis has the following attractive features. (a) The analysis domain is centered at and moving with the detected vortex center on each tilt of radar scan. (b) Vortex-flow-dependent background error covariance functions are formulated for the control variables (stream-function and velocity-potential) in the moving frame. (c) The square root of the background covariance matrix is derived analytically from each covariance function and is used to transform the control variables and formulate the cost-function in a concisely preconditioned form. (d) The control variables are discretized adaptively based on the background de-correlation length scales to achieve the desired high-computational efficiency and accuracy. The detailed method and test results are presented in Xu et al. (2013c). An example of analyzed vortex winds is shown in Fig. 3 for the mesocyclone and its produced EF5 tornado that struck the city of Moore, Oklahoma in the afternoon on 20 May 2013. The method can be further extended to analyze three-dimensional vortex winds from either single-Doppler or multi-Doppler scans of intense atmospheric vortices (such as tornadic mesocyclones and hurricanes). This capability is being developed and will be incorporated as an adaptively nested incremental-analysis step into the 3.5dVar radar data assimilation package (Xu et al. 2010b) delivered to NRL Monterey.

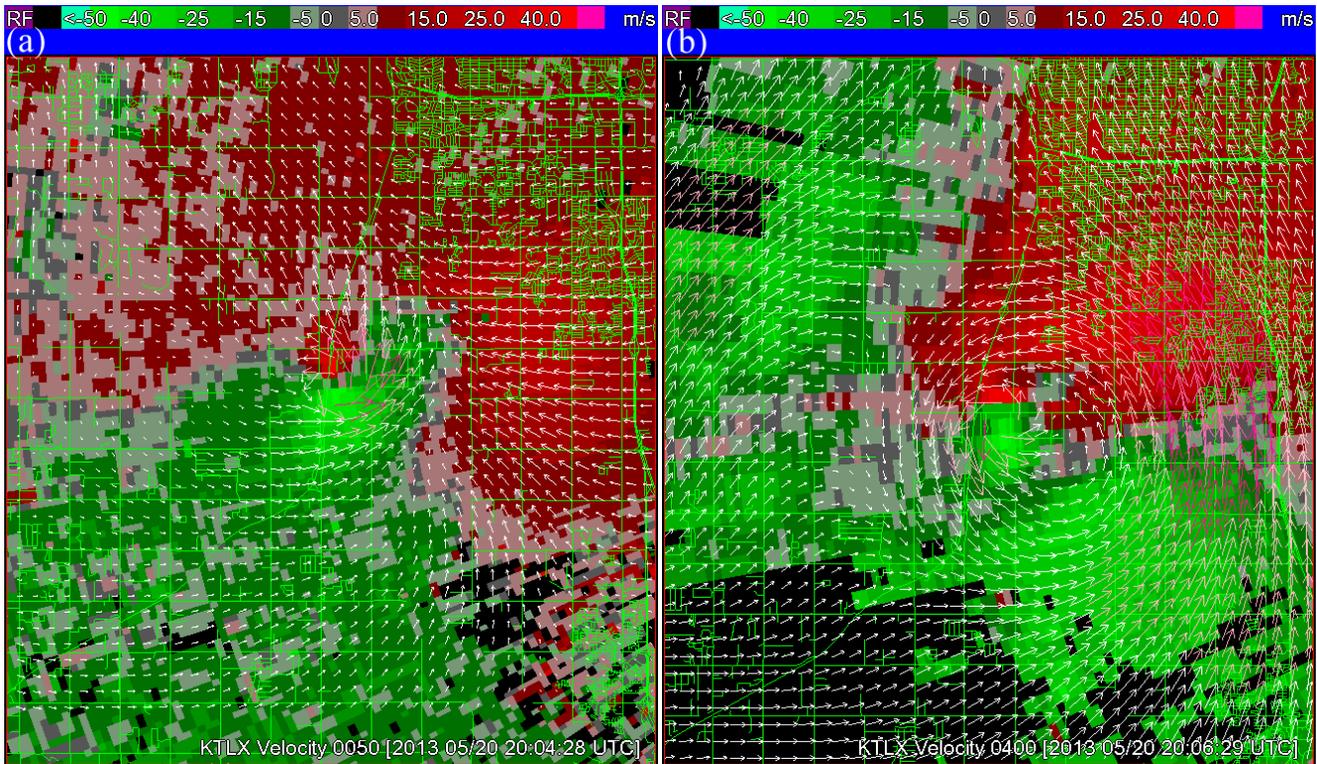


Figure 3. Analyzed vortex wind fields on (a) 0.5° tilt (around $z \approx 0.3$ km at 20:04:28 UTC) and (b) 4.0° tilt (around $z \approx 2.0$ km at 20:06:28 UTC) from KTLX radar scans of the mesocyclone and its produced EF5 tornado that struck the city of Moore, Oklahoma in the afternoon (local time between 2:45pm and 3:35pm) on 20 May 2013. In each panel, the vortex winds are plotted by the white and pink (> 30 m/s) arrows superimposed on the image of radial-velocity innovation (that is, the radar observed radial velocity minus the radial component of the moving-frame velocity) atop the Moore city street map (plotted by bright green lines).

IMPACT/APPLICATIONS

Fulfilling the proposed research objectives will improve our basic knowledge and skills in radar data QC and assimilation, especially concerning how to optimally utilize rapid-scan radar observations to improve numerical analyses and predictions of severe storms and other hazardous weather. New methods and computational algorithms developed in this project will be delivered to NRL Monterey for operational tests and applications.

TRANSITIONS

The radar data QC package developed in this project will be delivered to NRL Monterey for operational tests and applications. The QC package will be also made available to NCEP for operational applications. Based on the feedbacks from NRL and NCEP, the code will be modified and upgraded to accommodate the operational needs. The previously developed radar data assimilation package (Xu et al. 2010b) delivered to NRL for nowcast applications will be upgraded with the new vortex wind analysis capability (Xu et al. 2013c) and used, in collaboration with Dr. Alan Q. Zhao at NRL Monterey, to develop hybrid variational-ensemble assimilation capabilities of nonconventional observations.

RELATED PROJECTS

“Ensemble assimilation of nonconventional observations for nowcasting” (funded by ONR to NRL Monterey).

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