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Research and Development of Advanced Radar Data Quality Control and Assimilation for Nowcasting and Forecasting Severe Storms

Qin Xu
CIMMS, University of Oklahoma
120 David L. Boren Blvd.
Norman, OK 73072
phone: (405) 325-3041 fax: (405) 325-3098 email: Qin.Xu@noaa.gov

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LONG-TERM GOALS

Advance the state of the art in radar data quality control (QC) and assimilation for nowcasting and forecasting severe storms and other high-impact hazardous weather by attacking outstanding problems and addressing basic science and applied research issues in radar data QC and assimilation that are important and yet very challenging for nowcasting and forecasting high-impact hazardous weather not only over US homeland but also in US Navy's battle spaces worldwide, especially over oceans and in remote areas where conventional observations are very limited.

OBJECTIVES

Develop automated high-standard radar data QC techniques for nowcasting severe storms and operational data assimilation. Explore and develop new concepts and formulism for ensemble-based radar data assimilation with enhanced dynamic balances on multiple scales to improve nowcast and forecast of high-impact weather.

APPROACH

Upgrade the radar-based wind analysis system (RWAS, Xu et al. 2013a, 2015c) for nowcasting severe storms and use it to test new QC techniques. Use model predictions and analyses to improve the adaptive radar velocity dealiasing techniques (Xu and Nai, 2012, 2013; Xu et al. 2013a, 2014a) for various weather conditions scanned by operational WSR-88D radars, Terminal Doppler Weather Radar and the phased array radar at the National Weather Radar Testbed.

Extend and use the spectral formulations for measuring information content from observations for data assimilation (Xu 2011; Xu and Wei 2011) to develop efficient data compression and multistep incremental analysis strategies adaptively for different radars and data assimilation systems to minimize data redundancy and information loss.

Explore and develop new concepts and formulism for probabilistic-deterministic hybrid approaches in data assimilation with enhanced dynamic balances to improve nowcast and forecast of high-impact weather. Optimize the sampling time interval and covariance inflation and localization in the time-

expanded sampling (Xu et al. 2008a,b; Lu et al. 2011) for time critical applications of ensemble-based data assimilation with the Navy's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®, Hodur 1997).

The PI, Dr. Qin Xu, is responsible for designing the overall approaches for the proposed objectives and providing 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 and his colleagues at NRL Monterey will perform pre-operational tests as the radar data QC and assimilation packages are upgraded and delivered.

WORK COMPLETED

The recently upgraded radar-based wind analysis system (RWAS, Xu et al. 2015c) was used to run and test the radar data QC package for difficult cases in more than 2000 volumes of Doppler velocity data scanned by 10 operational WSR-88D radars under various weather conditions. The model-based variational dealiasing method (developed in FY 14 by using a model-produced wind field as the first guess for the alias-robust variational analysis) was further tested and improved with fine-tunned threshold conditions.

By extending the spectral formulations previously derived to measure information content from observations for data assimilation (Xu 2011; Xu and Wei 2011), a breakthrough was made in addressing the important issue on how to optimally assimilate high-resolution observations (especially remotely sensed observations from radars and satellites) on the mesoscale and storm scale. In particular, a two-step variational method for analyzing observations of different spatial resolutions was developed based on Bayesian estimation theory. Three theoretical formulations and related properties were established [see (2)-(10) of Xu et al. 2015a] for efficiently estimating the analysis error covariance and thus making the two-step analysis more accurate than the single-step analysis of observations of different resolutions when the number of iterations is not sufficiently large.

In collaboration with Dr. Allen Q. Zhao and colleagues at NRL Monterey, the time-expanded sampling (TES) method (Xu et al. 2008a,b) was tested with conventional and satellite data for operational applications constrained by computational time or resource. The tests used the recently developed ensemble Kalman filter (EnKF) at NRL for mesoscale data assimilation with the Navy's mesoscale numerical weather prediction (NWP) model. The test results further confirmed that the TES method can improve the effectiveness and efficiency of ensemble-based data assimilation and subsequent forecast with reduced ensemble size, and the TES method was shown to be particularly useful for ensemble-based data assimilation when the ensemble size cannot be sufficiently large due to operational constraints in situations where a time critical environment assessment is needed or the computational resource is very limited. The detailed results were published in Zhao et al. (2015).

The previously formulated vortex-flow-dependent background error covariance functions for vortex wind analyses (Xu et al. 2013b) were refined with improved asymptotic properties toward the vortex center. In particular, the Gaussian correlation function was modified by subtracting its mirror image obtained by mirror-reflecting the two correlated points with respect to the vortex center in the radial direction, so the correlation function can have the desired property to ensure the analyzed radial and tangential velocities always approach to zero toward the vortex center [see (6b) of Xu et al. 2015d]. The square root of the associated error covariance matrix was also derived analytically to pre-condition the cost-function and thus enhance the computational efficiency [see (7)-(14) of Xu et al. 2015d].

A multi-step method was developed to estimate the vortex center locations and movements in four-dimensional space from radar observed tornadic mesocyclones (Xu et al. 2015f). In this method, the vortex center location is estimated as a continuous function of height and time by fitting a smooth-function form constructed by B-spline basis functions to the vortex center locations estimated on each tilt in each volume scan. This provides the critical information for vortex wind analyses performed with vortex-flow-dependent background error covariance functions.

RESULTS

The model-based variational dealiasing method were tested with 1510 volumes of Doppler velocities scanned by the KDFR, KINX, KSRX, KTLX and KVNX radars for severe storms over the periods from 20:00 UTC 5/19/2013 to 300 UTC 5/20/2013 and from 1900 UTC 5/31/2013 to 1200 UTC 6/1/2013. With the fine-tuned threshold conditions, model-produced wind fields can be used safely (without false dealiasing) as the first guesses for the alias-robust variational analyses to improve the dealiased data coverage significantly. The improved coverage ranges from 75% to 93% for the tested 1510 volumes. An example is shown in Fig. 1.

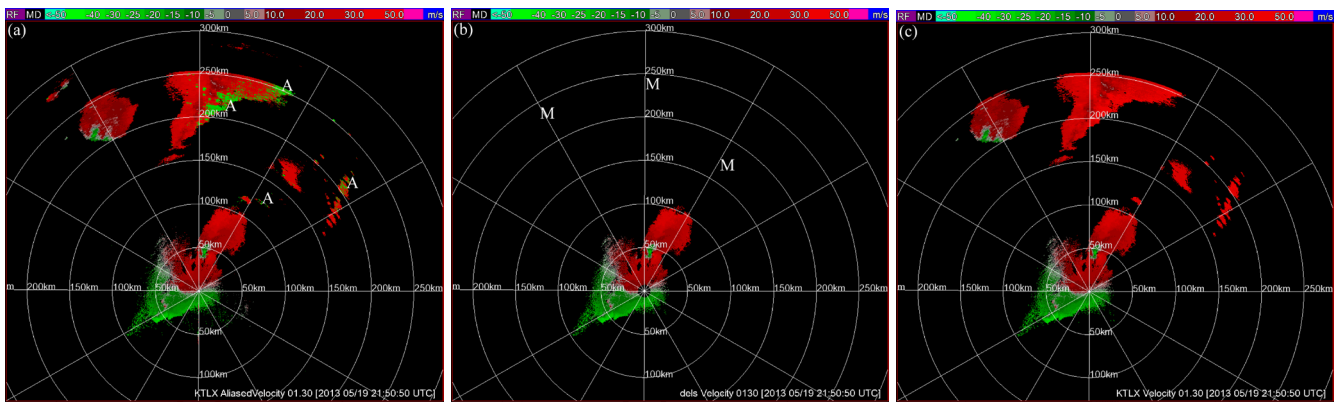

Fig. 1. (a) Image of raw radial velocity scanned from KTLX radar on 1.3^o tilt at 2050 UTC on 19 May 2013. (b) Image of dealiased radial velocity produced by the previous method (Xu et al. 2013a) without using model-produced wind field. (c) Image of dealiased radial velocity produced by using model-produced wind field as the first guess for the alias-robust variational analysis. The white letters "A" in (a) mark the aliased-velocity areas. The white letters "M" in (b) mark the locations of major isolated data areas not covered by the dealiased radial velocities.

The effectiveness of the two-step variational method for analyzing observations of different spatial resolutions was demonstrated for idealized one-dimensional cases. By using the three theoretical formulations and related properties established in (2)-(10) of Xu et al. (2015a), the analysis error covariance matrix can be estimated very efficiently. As shown in Fig. 2, the estimated analysis error covariance matrix is very close to the benchmark analysis error covariance matrix computed accurately from the matrix formulation that is impractically expensive for operational applications [see (1b) of Xu et al. 2015a]. The estimated analysis error covariance matrix can be used to update the background error covariance matrix after the coarse-resolution observations are analyzed in the first step. The two-step analysis can be more accurate than the single-step analysis of observations of different resolutions when the number of iterations is not sufficiently large and thus the single-step analyses is not truly optimal (see Figs. 7 and 10 of Xu et al. 2015a).

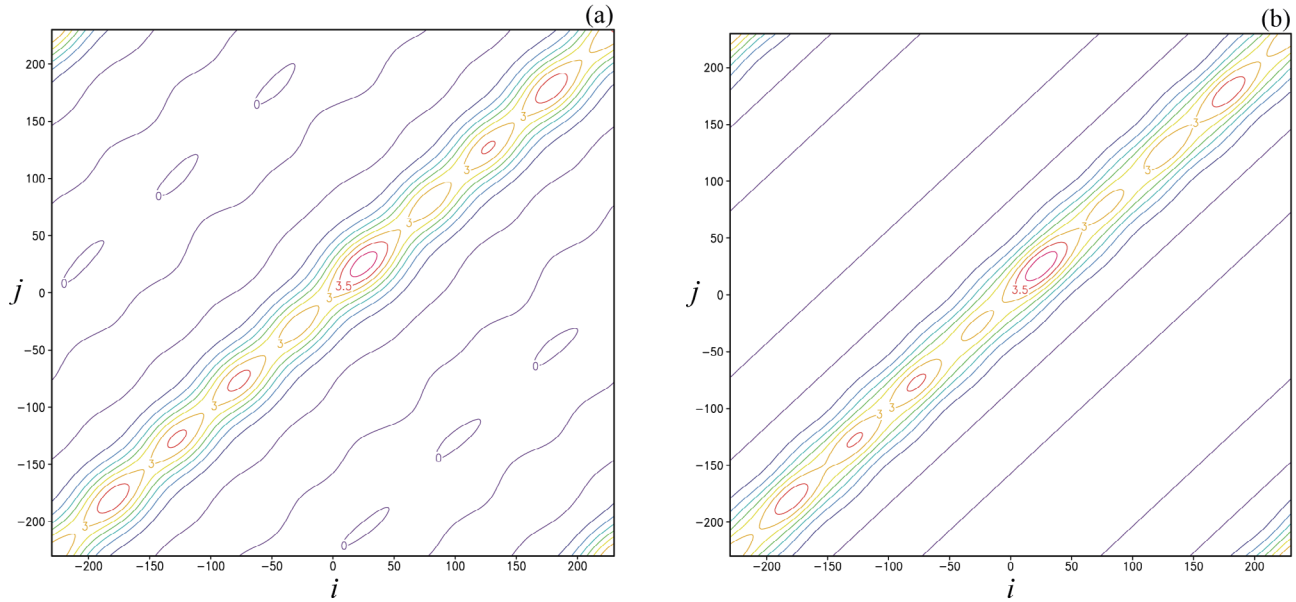

Fig. 2. (a) Structure of the analysis error covariance matrix computed accurately from the matrix formulation that is impractically expensive for operational applications. (b) Structure of analysis error covariance matrix estimated very efficiently by using the three theoretical formulations and related properties in (2)-(10) of Xu et al. (2015a). In each panel, the matrix column index i and row index j both range from -229 to 229, and the matrix element values are plotted by color contours in the unit of m^2s^{-2} (for squared velocity errors).

The multi-step method for estimating the vortex center location was applied to the tornadic mesocyclone case observed by operational KTLX radar in Oklahoma on 20 May 2013. The trajectory of the estimated vortex center at the ground level ($z = 0$) is plotted by the dashed green curve in Fig. 3, where the nine differently colored line segments attached to the trajectory show how the estimated vortex center location changes as the height z increases from 0 to 5 km at nine different times. The estimated vortex center location provides the critical information for analyzing the three-dimensional vortex winds in the slantwise cylindrical coordinate system that is co-centered with the mesocyclone at each vertical level. The vertical cross-section of the axi-symmetric part of vortex winds analyzed in the slantwise cylindrical coordinates (z', r) is shown by the inserted panel on the left (or right) side below the dashed green trajectory curve in Fig. 3, where z' is the slantwise vertical coordinated along the vortex center estimated by the dash-dotted cyan (or red) segment at 1955:59 (or 2025:43) UTC.

The refined vortex-flow-dependent background error covariance formulations were used to improve the vortex wind analysis. Examples of analyzed vortex winds are shown in the two panels of Fig. 4 for the tornadic mesocyclone observed by operational KTLX radar in Oklahoma on 20 May 2013 at the same times (that is, 1955:59 and 2025:43 UTC) as those for the two vertical cross-sections below the dashed green trajectory curve in Fig. 3.

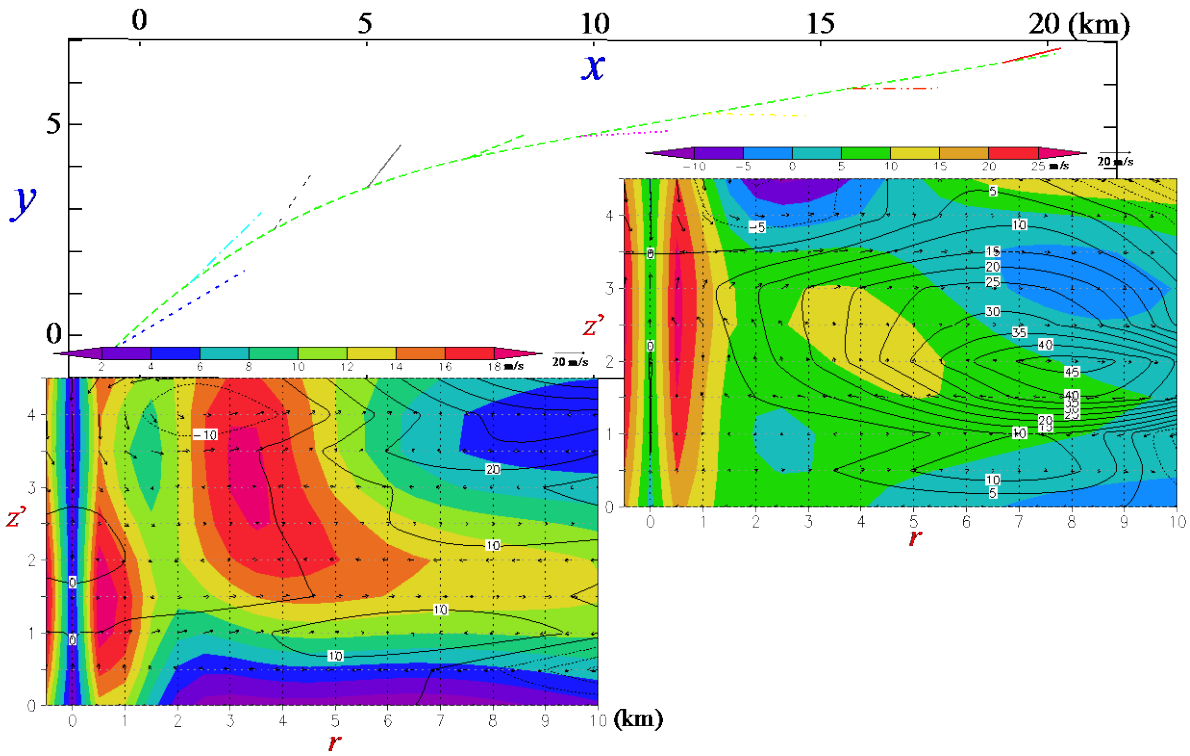

Fig. 3. Trajectory of the estimated vortex center at z = 0 plotted by the dashed green curve. Vertical variations of the vortex center from z = 0 to 5 km at nine different times plotted by the nine colored line segments attached to the trajectory. The two vertical cross-sections below the dashed green trajectory curve show the analyzed axi-symmetric part of the vortex in the slantwise cylindrical coordinates (z', r), where the color scale is for the tangential velocity, and black arrows (or contours) plot the velocity (or streamfunction) of the vertical circulation.

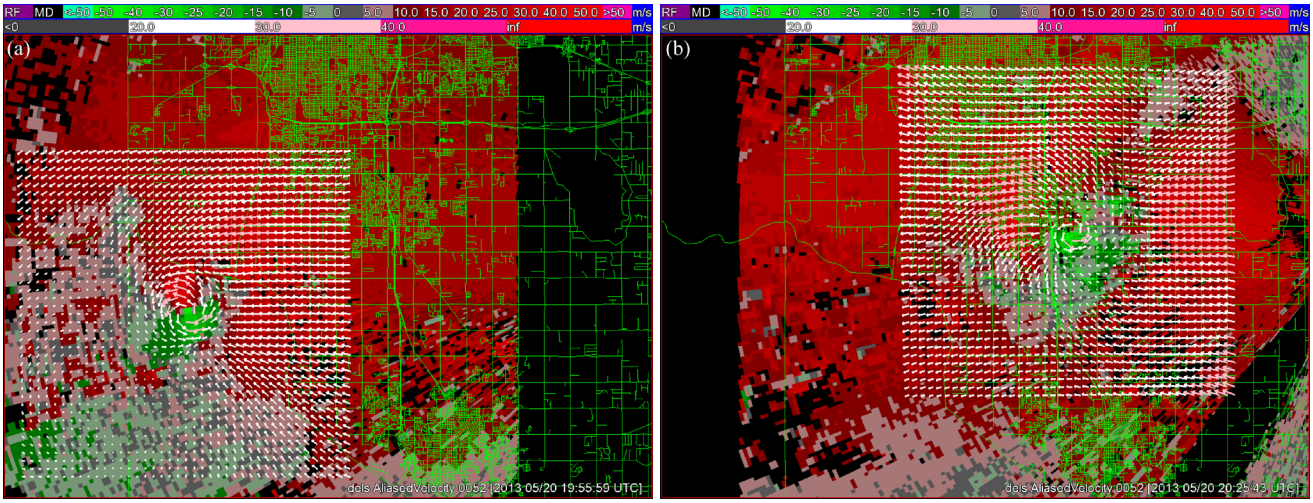

Fig. 4. Analyzed vortex winds plotted by color-scaled arrows superimposed on the images of radial-velocity innovation (that is, the dealiased radial-velocity observation minus the radial-component of the moving velocity of vortex center) from KTLX radar on 0.5^o tilt (around z = 0.67 km) at (a) 1955:59 UTC and (b) 2025:43 UTC on 20 May 2013. The thin green lines in each panel show the county boundaries and streets of city Moore.

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 various types and platforms of radar observations to improve timely and accurate analysis and prediction of severe storms and other hazardous weather. New methods and computational algorithms developed in this project will be delivered to NRL Monterey for further tests and potential operational applications.

TRANSITIONS

The radar data QC package developed and upgraded in this project will be delivered to NRL Monterey for operational tests and applications. The techniques will also be available to the science community and the National Weather Services (NWS). Based on the feedbacks from NRL and NWS, the code will be upgraded and delivered subsequently. The previously developed radar data assimilation package (delivered to NRL for nowcast applications) will be further improved with the new probabilistic-deterministic hybrid approaches explored and developed from this project, in collaboration with Dr. Allen Q. Zhao at NRL Monterey, to enhance the capabilities of assimilating nonconventional observations for nowcasting at NRL Monterey.

RELATED PROJECTS

"Ensemble Assimilation of Nonconventional Observations for Nowcasting" (funded by ONR to NRL Monterey).

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HONORS/AWARDS/PRIZES

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