Radar Data Quality Control and Assimilation at the National Weather Radar Testbed (NWRT)

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

Award Number: Grant N000140410312

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 new variational methods to improve the existing radar wind analysis system so it can be applied to any radar scans to produce real-time vector wind displays and monitor data quality. Study radar data quality problems and develop statistically reliable quality control (QC) techniques. Explore new data assimilation techniques to optimally utilize the PAR scan capabilities.

APPROACH

Continue testing the radar data QC packages (delivered to NRL and NCEP) with raw level-II data collected in different regions (especially along the coasts of the United States) under various weather conditions (especially high-impact weather conditions). Collect difficult cases in which quality problems cannot be well detected or corrected by the existing automated QC techniques. Examine the detailed features in each type of data quality problems, and find proper solutions to improve the existing QC techniques.

Extend the recently derived entropy measure of information content from observations (Xu 2007), so it can be applied not only to 3D analyses (produced by the 3dVar and Kalman filter) but also to 4D ananlyses (produced by the 4dVar and Kalman smoother). By analysing the singular-value form of the entropy measure, some guiding principles can be derived to design optimal observation strategies (such as PAR scan strategies at NWRT) for a given data assimilation system.

Develop a new proto-type ensemble hybrid filter to combine the merits of the ensemble-based filters (such as the ensemble Kalman filter) and variational data assimilation (such as the 3.5dVar delivered to NRL) for flow-dependent covariance estimation and high-resolution radar data assimilation. Toward

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2009**	2. REPORT TYPE	3. DATES COVERED **00-00-2009 to 00-00-2009**

4. TITLE AND SUBTITLE **Radar Data Quality Control And Assimilation At The National Weather Radar Testbed (NWRT)**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Oklahoma, CIMMS,120 David L. Boren Blvd.,Norman,OK,73072**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
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.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

this goal, the first step is to explore new ideas and sampling techniques to improve the covariance estimation and computational efficiency of the existing ensemble-based filters.

The PI, Dr. Qin Xu, is responsible to derive basic formalisms and 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. Collaborations between this project and the development of the NWRT PAR is coordinated by Douglas Forsyth, Chief of NSSL's Radar Research and Development Division. Dr. Allen Q. Zhao at NRL Monterey and Drs. Shun Liu and David Parrish at NOAA/NCEP (and their colleagues) perform pre-operational tests as the radar data QC algorithms and assimilation packages are further upgraded and delivered.

WORK COMPLETED

The theoretical formulations (Xu 2007) based on singular-value decomposition for using the relative entropy and Shannon entropy difference to measure information content from observations for 3-dimensional variational data assimilation were further extended for 4-dimensional variational data assimilation (Xu et al. 2009d) and ensemble-based data assimilation. The theoretical formulations can provide not only qualitative guiding principles for designing phased-array radar (PAR) scan configurations through numerical experiments (Lu and Xu 2009) but also quantitative criteria for measuring the optimality of the designed scan configurations in terms of maximizing observarion information contents for PAR data assimilation.

An aliasing operator was introduced to mimic the effect of aliasing that causes discontinuities in radial-velocity observations, and to modify the observation term in the costfunction for direct assimilations of aliased radar radial-velocity observations into numerical models. It is found that if the aliasing operator is treated as a part of the observation operator and applied to the analyzed radial velocity in a conventional way, then the analysis is not ensured to be aliased (or not aliased) in consistency with the aliased (or not aliased) observation at every observation point. Thus, the analysis-minus-observation term contains a large alias error whenever an inconsistency occurs at an observation point. This causes fine-structure discontinuities in the costfunction. An unconventional approach was introduced to apply the aliasing operator to the entire analysis-minus-observation term at each observation point in the observation term of the costfunction. With this approach, the costfunction becomes smooth and concave upwards in the vicinity of the global minimum. This unconventional approach was shown to be useful for directly assimilating aliased radar radial-velocity observations under certain conditions (Xu et al. 2009b).

The global minimization problem for directly assimilating aliased radial velocities was derived in terms of Bayesian estimation by folding the domain of the original Gaussian non-aliased observation probability density function (pdf) into the Nyquist interval. By truncating the folded tails of the observation pdf, the observation term in the costfunction recovered the aliased observation term formulated previously by an unconventional approach. This established the theoretical basis for the above unconventional approach and quantified the involved approximation (Xu 2009).

An efficient method was developed for fitting VAD winds to aliased radar radial-velocity observations based on the above unconventional approach (Xu et al. 2009a). The method solves a global minimization problem in the presence of multiple local minima caused by the zigzag-discontinuities of the aliasing operator. This alias-robust VAD method was used to provide reliable reference to improve the dealiasing algorithm in the upgraded radar data quality control package. The alias-robust VAD method was also used to improve the background wind estimation for the automated radar-based wind analysis system (RWAS). The RWAS was upgraded for monitoring low-level wind conditions at high spatial and temporal resolutions in real time (Xu et al. 2009c). The environmental wind produced by the RWAS was used as the first-step reference for PAR velocity dealiasing. The improved dealiasing algorithm was then adapted for PAR velocity dealiasing. The adapted method has been tested with a large number (180) of aliased sector-scans of tornadic storms (collected by the PAR at NWRT on 02/10/2009 and 05/14/2009).

Built on the previously reported progress (Qiu et al. 2007; Xu et al. 2008a,b), a new scheme was designed to improve the ensemble-based 4D variational data assimilation (En4DVar). In this scheme, leading singular vectors are extracted from 4D ensemble perturbations in a hybrid space and then used to construct the analysis increment to fit the 4D innovation (observation minus background) data. The hybrid space combines the 4D observation space with only a gridded 3D subspace at the end of each assimilation cycle, so its dimension can be much smaller than the dimension of the fully gridded 4D space used in the original En4DVar and the background covariance matrix only needs to be constructed in the 3D subspace. This improves the computational efficiency and reduces the rank deficiency of the ensemble-constructed covariance matrix (Shao et al. 2009).

RESULTS

The above alias-robust VAD method (Xu et al. 2009a) and upgraded radar data quality control package have been tested extensively and successfully with real-time radial velocities scanned by the KTLX radar under various weather conditions. The dealiasing algorithm in the upgraded radar data quality control package can use the radial velocities estimated by the alias-robust VAD analysis for the reference check in most cases, except for severe winter storms scanned by using the VCP31 mode with the Nyquist velocity reduced below 12 m s^{-1}. In the latter case (VCP31), the alias-robust variational analysis (Xu et al., 2009b; section 3.2) was used in place of the alias-robust VAD analysis for the reference check. This makes the new scheme VCP-adaptive and free of false dealiasing even for VCP31 with a small Nyquist velocity. As shown by the example in Fig. 1, the new scheme can correct the alias errors in the raw radial velocities without any false dealiasing, even though the raw data were severely aliased. The operationally used algorithm, however, performed very poorly.

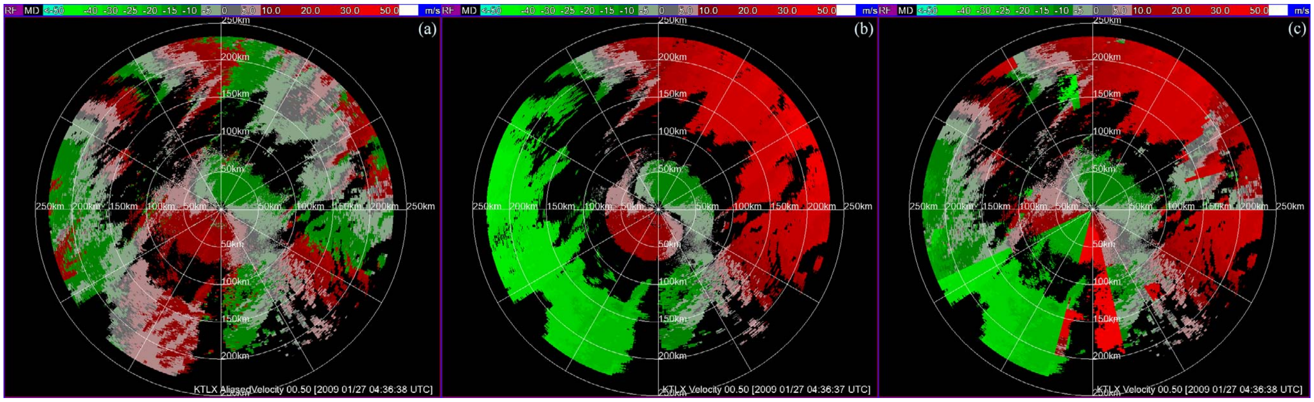

Fig. 1. (a) Raw radial-velocity image scanned by the KTLX radar with VCP31 mode and Nyquist velocity = 11.51 m s^{-1} at 0.5^{o} tilt for the Oklahoma ice storm at 043637 UTC on 27 January 2009. (b) Dealiased radial-velocity image by the new scheme. (c) Dealiased radial-velocity image by the operational algorithm.

The automated RWAS (Xu et al. 2009c) performs the following steps:

I. Use the alias-robust VAD analysis to estimate the vertical profile of the environmental wind above the KTLX radar, and then use the estimate profile as the background to assimilate observations from the NOAA Profiler Network (available hourly from four profiler stations in the ±200 km vicinity of KTLX radar) by using the optimal interpolation technique at each vertical level.

II. Use the wind field produced in step-I as a new background to assimilate the Oklahoma Mesonet winds at the lowest vertical level (10 m above the ground) of the analysis grid.

III. Use the wind field produced in step-II as a new background to assimilate the super-observations that consolidate the dealiased radial velocities in three batches with the resolution coarsened to 30, 21, and 13 km (in both the radial and azimuthal directions) on each tilt over the radial ranges of $r > 80$ km, 40 km $< r \leq 80$ km, and 5 km $< r \leq 40$ km, respectively. The error standard deviation is estimated for each super-observation based on the amount and distribution of the dealiased radial velocities within the area represented by that super-observation. The optimal interpolation technique (Xu et al. 2006) was extended and used to assimilate each batch and to update the background. The background error de-correlation length (or depth) is empirically tuned to 25 (or 2), 18 (or 1) and 11 (or 0.3) km for the first, second and third updates with the first, second and third batches, respectively.

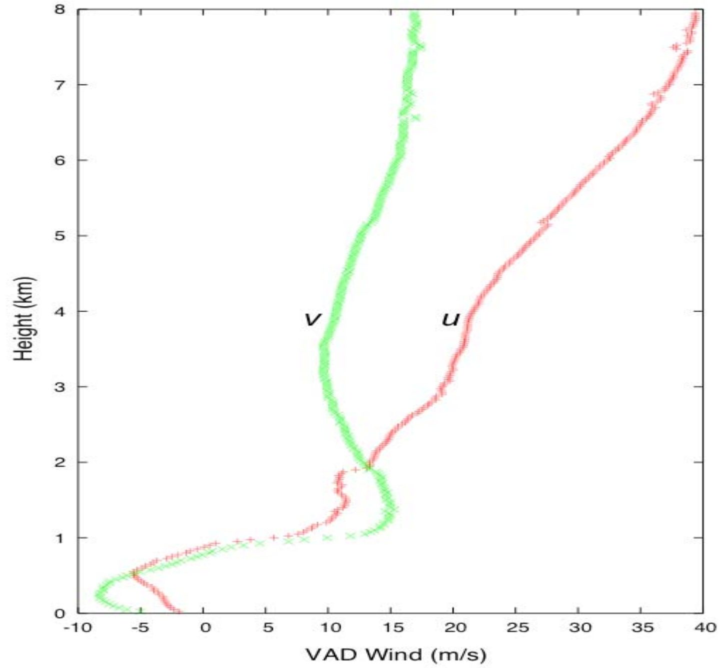

Fig. 2. Vertical profiles of zonal and meridional components, (u, v), of VAD wind produced from the dealiased radial velocities for the ice storm case in Fig. 1.

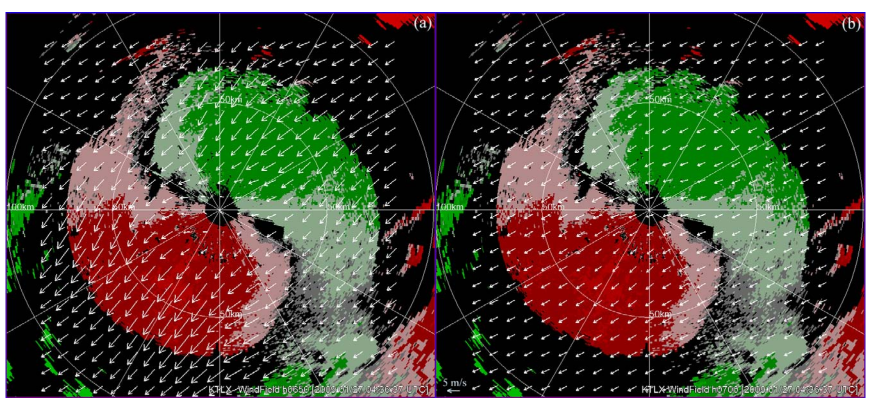

Fig. 3. Horizontal winds (shown by arrows) at z = 0.7 km produced with (a) the shear-independent vertical correlation and (b) new shear-dependent vertical correlation in background error covariance. The color images in (a) and (b) are the dealiased radial velocities at 0.5^o tilt. The vector scale is the same for the two panels and is plotted at the lower-left corner of (b).

As an example, Fig. 2 shows the vertical profiles of the (*u*, *v*) components of the VAD wind obtained in step-I by applying the traditional VAD analysis to the dealiased radial velocities for the ice storm case in Fig. 1. As shown, there was a very strong vertical shear around 1 km above the ground. Above and below this shear layer, the horizontal winds were both strong and quite uniform but in the opposite directions. Around and across the shear layer, the incremental wind field produced by the optimal interpolation can be adversely affected by the conventional shear-independent vertical correlation in the background error covariance. This can cause spurious horizontal variations in and/or near the shear layer. This problem is shown by the wind field produced at $z = 0.7$ km in Fig. 3a. To solve the problem, the background error covariance was refined and the vertical correlation was made shear-dependent by adding a new dimension measured by the integral of $|(u, v)|$ over the vertical distance between the two correlated points. With this shear-dependent feature, the spurious horizontal variations can be eliminated from the wind field produced in the vicinity of the strong-shear layer, as shown in Fig. 3b.

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 (including chemical-biological warfare environmental conditions). New methods and computational algorithms developed in this project have been and will continue to be delivered to NRL Monterey for operational tests and applications (Zhao et al. 2006, 2008), in connection with another ONR funded project entitled “Improved Doppler Radar/Satellite Data Assimilation” at NRL Monterey.

TRANSITIONS

The radar data QC package developed in this project was delivered to NRL Monterey for operational tests and applications. The QC package was also made available to NCEP for their operational applications. Based on the feedbacks from NRL and NCEP, the code was upgraded and delivered subsequently. The QC and vector wind retrieval packages in the real-time system were requested by and delivered to Pacific Northwest National Laboratory for real-time implementations over major urban areas to support and initialize their emergency response dispersion models for homeland security applications (Fast et al. 2008). The recentlly developed En4DVar will be combined with the time-expanded sampling algorithm for ensemble-based filters and used, in collaboration with Dr. Alan Q. Zhao at NRL Monterey, to develop the hybrid (combined variational and ensemble approaches) data assimilation system at NRL Monterey and applied to COAMPS (Hodur 1997). The algorithm package will be adapted and tested by the PI’s group at CIMMS and then delivered to NRL Monterey for further tests and applications.

RELATED PROJECTS

Radar Velocity Data Quality Controls (funded by NOAA/NCEP to NSSL and OU). Automated retrieval and display of phased-array radar echo movement vector field in vertical cross-section (funded by NOAA HPCC to NSSL and OU). Phased-Array Radar Data Quality Control and Adaptive Wind Retrievals (funded by NSSL internally). Improved Doppler Radar/Satellite Data Assimilation (funded by ONR to NRL Monterey).

REFERENCES

Fast, J. D., R. K. Newsom, K. J. Allwine, Q. Xu, P. Zhang, J. Copeland, and J. Sun, 2008: An evaluation of two NEXRAD wind retrieval methedologies and their use in atmospheric dispersion models. *Journal of Applied Meteorology & Climatology*, **47**, 2351–2371.

Hodur, R. M., 1997: The Naval Research Laboratory's coupled ocean/atmosphere mesoscale prediction system (COAMPS). *Mon. Wea. Rev.*, **125**, 1414-1430.

Qiu, C., A. Shao, Q. Xu, and Li Wei, 2007: Fitting model fields to observations by using singular value decomposition – An ensemble-based 4DVar approach. J. Geophys. Res., 112, D11105, doi:10.1029/2006JD007994

Xu, Q., 2007: Measuring information content from observations for data assimilation: Relative entropy versus Shannon entropy difference. *Tellus,* **59A**,198-209.

Xu, Q., H. Lu, S. Gao, M. Xue, and M. Tong, 2008b: Time-expanded sampling for ensemble Kalman filter: Assimilation experiments with simulated Radar observations. *Mon. Wea. Rev*., **136**, 2651–2667.

Xu, Q., L. Wei, H. Lu, C. Qiu, and Q. Zhao, 2008a: Time-expanded sampling for ensemble-based filters: Assimilation experiments with a shallow-water equation model. *J. Geophys. Res*., **113**, D02114, doi:10.1029/2007JD008624.

Zhao, Q., J. Cook, Q. Xu, and P. Harasti 2006: Using radar wind observations to improve mesoscale numerical weather prediction. *Wea. Forecasting*. **21**, 502-522.

Zhao, Q., J. Cook, Q. Xu, and P. Harasti, 2008: Improving short-term storm predictions by assimilating both radar radial-wind and reflectivity observations. *Wea. Forecasting*, **23**, 373-391.

PUBLICATIONS (FY2009)

Lu, H., and Q. Xu, 2009: Trade-offs between observation accuracy and resolutions in configuring phased-array radar velocity scans for ensemble-based storm-scale data assimilation. *Journal of Applied Meteorology & Climatology*. 1230–1244. [published, referred].

Shao, A., S. Xi, C. Qiu, and Q. Xu, 2009: A hybrid-space approach for ensemble-based 4DVar. *J. Geophys. Res*., **114**, D17114, doi:10.1029/2009JD012032. [published, referred].

Xu, Q., 2009: Bayesian perspective of the unconventional approach for assimilating aliased radar radial velocities. *Tellus* [in press, referred].

Xu, Q., K. Nai, and L. Wei, 2009a: Fitting VAD wind to aliased radial-velocity observations – A minimization problem with multiple minima. *Quart. J. Roy. Meteor. Soc.* [submitted, referred].

Xu, Q., K. Nai, L. Wei, and Q. Zhao, 2009b: An unconventional approach for assimilating aliased radar radial velocities. *Tellus* [in press, referred].

Xu, Q., K. Nai, L. Wei, P Zhang, Q. Zhao and Paul R. Harasti, 2009c: A real-time radar wind data quality control and analysis system for nowcast application. *International Symposium on Nowcasting and Very Short Range Forecasting* (WSN09), Whistler, British Columbia, Canada, WMO, CD-ROM, 3.5. [published, nonreferred].

Xu, Q., L. Wei, and S. Healy, 2009d: Measuring information content from observations for data assimilations: connection between different measures and application to radar scan design. *Tellus*, **61A**, 144–153. [published, referred].

Yeary, M., J. Crain, A. Zahrai, T.-Y. Yu, R. Palmer, G. Zhang, Y. Zhang, R. J. Doviak, P. Chilson, M. Xue, and Q. Xu, 2009: An update on multi-channel receiver development for the realization multi-mission capabilities at the National Weather Radar Testbed. *25th Conference on International Interactive Information and Processing Systems (IIPS) for Meteorology, Oceanography, and Hydrology*, Phoenix, AZ, USA, AMS, CD-ROM, 8B.5.