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JOINT MEETING OF
CBS EXPERT TEAM ON SURFACE-BASED REMOTELY-SENSED OBSERVATIONS
(Second Session)
AND
CIMO EXPERT TEAM ON OPERATIONAL REMOTE SENSING
(First Session)

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WEATHER RADAR OPERATIONS, STATUS, ISSUES, REQUIREMENTS FOR DATA EXCHANGE AND PLANS

Operational Developments

Application of Doppler Velocity
(Quality Control Method and Application of Doppler Velocity of Weather Radar)

(Submitted by Richard Ice, WSR-88D Radar Operations Center, Norman Oklahoma USA)

SUMMARY AND PURPOSE OF DOCUMENT

Provides a review of some recent advances in the Next Generation Radar (NEXRAD) program signal processing and algorithm developments that have improved the accuracy and utility of Doppler data and also summarizes current use of Doppler velocity in WSR-88D operational algorithms.

ACTION PROPOSED

1. The Joint Meeting is invited to review the information contained in the document.

INTRODUCTION

The WSR-88D Radar Operations Center (ROC), working in concert with the National Severe Storms Laboratory (NSSL), and the National Center for Atmospheric Research (NCAR), has supported the implementation of several capabilities that have enhanced the quality of Doppler velocity estimates from the radar.

The enhancements in Doppler velocity quality and utility include the following items: (1) Range Velocity Ambiguity Mitigation, (2) Improved range and azimuth data resolution, (3) Improved clutter filtering, and (4) enhanced algorithms.

RANGE-VELOCITY AMBIGUITY MITIGATION

The Radar Operations Center entered into a partnership with the National Severe Storms Laboratory and the National Center for Atmospheric Research in 1995 for the purpose of developing and implementing methods of mitigating the classical "Doppler Dilemma" associated with the tradeoff between maximum unambiguous range and maximum non-aliased velocity estimates. The full history of the effort is documented in a series of reports available at the NSSL and NCAR web sites. The links below provide access to the full complement of reports:

NSSL Reports:
http://cimms.ou.edu/rvamb/home.htm

NCAR Reports:
http://www.eol.ucar.edu/rsf/NEXRAD/nexrad_publications_links.html

This effort presented considerable challenges, not just from a technical aspect, but from the practical issue of hosting sophisticated signal processing on the original baseline hardware. It was not until the mid-2000's that methods became mature enough, and a new signal processing system became available, for the first mitigation reduction to be practical. This platform was a result of the Open Radar Data Acquisition (ORDA) project managed by the National Weather Service, Office of Science and Technology NEXRAD Product Improvement Program. This project incorporated a modern digital IF receiver and signal processor. The following is a summary of the project around the time of deployment:

Gregory S. Cate, NOAA/NWS, Norman, OK; and R. W. Hall, 2005, "NEXRAD Product Improvement—Current Status of WSR-88D Open Radar Data Acquisition (ORDA) Program and Plans for the Future", 21st International Conference on Interactive Information Processing Systems for Meteorology, Oceanography, and Hydrology.
http://ams.confex.com/ams/pdfpapers/85593.pdf

The following papers available on the ROC web site detail some of the early benefits of that project:

Ice, R. L., Rhoton, R., Saxion, D., Patel, N. K., Sirmans, D., Warde, D. A., Rachel, D. & Fehlen, R. G., 2004: Radar Operations Center (ROC) Evaluation of the WSR-88D Open Radar Data

Acquisition (ORDA) System Signal Processing. 20th International Conference on Interactive Information Processing Systems for Meteorology, Oceanography, and Hydrology.
http://www.roc.noaa.gov/WSR88D/PublicDocs/Publications/20th_IIPS_Jan04_Ice_ORDA_ROCEvalSigProc.pdf

Ice, R. L., G. T., McGehee, R., Rhoton, D., Saxion, N. K., Patel, D., Sirmans, D. A., Warde, R. G., Guenther & D., Rachel, 2005: Radar Operations Center (ROC) Evaluation of New Signal Processing Techniques for the WSR-88D. 21st International Conference on Interactive Information Processing Systems for Meteorology, Oceanography, and Hydrology.
http://www.roc.noaa.gov/WSR88D/PublicDocs/Publications/21st_IIPS_Ice_DSP_Eval.pdf

Chrisman, J. N. & Ray, C. A., 2005: A First Look at the Operational (Data Quality) Improvements Provided by the Open Radar Data Acquisition (ORDA) System. Preprint-CD, 32nd Conference on Radar Meteorology, AMS, Albuquerque, NM.
http://www.roc.noaa.gov/WSR88D/PublicDocs/Publications/DQ_Improvements_ORDA_Chrisman_Ray.pdf

One of the major benefits of the Open RDA and use of a commercial digital receiver and signal processor was the availability of an adaptive, spectrally based clutter filtering method. The papers listed above detail the superior performance of this method over the legacy Infinite Impulse Response (IIR) time domain filters deployed with the baseline WSR-88D.

The first Range Velocity Mitigation method deployed relied on the Sachidananda-Zrnic 64 Phase Coding Method (SZ-2). This method employs a custom phase code wherein the relative phase of each transmitted pulse is shifted per a predetermined pattern. This pattern is then used to coherently process returns from multiple trips. The algorithm can extract useful Doppler data from the two strongest of up to four trips. The algorithm description is found on the NSSL web site at:
http://cimms.ou.edu/rvamb/Documents/SZ2_Algo_2007.pdf

Development of the production version of this code is documented in the following papers available on the ROC web site:

Saxion, D. S., Rhoton, R., McGehee, G. T., Ice, R. L., Warde, D. A. & Sirmans, D., 2005: “Radar Operation Center (ROC) Production Software Status for RV Ambiguity Mitigation”, 21st International Conference on Interactive Information Processing Systems for Meteorology, Oceanography, and Hydrology.
http://www.roc.noaa.gov/WSR88D/PublicDocs/Publications/IIPS21_P17_ROCSZ2_Saxion.pdf

Saxion, D. S., Rhoton, R., Ice, R. L., McGehee, G. T., Warde, D. A., Boydstun, O. E., Zittel, W. D., Torres, S. & Meymaris, G., 2007: New Science for the WSR-88D: Implementing a Major Mode on the SIGMET RVP8. 23rd International Conference on Interactive Information Processing Systems for Meteorology, Oceanography, and Hydrology.
http://www.roc.noaa.gov/WSR88D/PublicDocs/Publications/IIPS23_P2%209_SZ2MM_Saxion.pdf

The SZ-2 feature was deployed to the WSR-88D network in 2007.

The next range velocity ambiguity feature to be implemented is Staggered Pulse Repetition Time (SPRT). In this method, pulses with two distinctly separate PRT’s are interleaved, producing a non-uniform pulse spacing. The ratios of the PRT’s are chosen to provide maximum unambiguous range while allowing for acceptable performance of the SPRT de-aliasing process. A down side of this approach is that spectrally based clutter filters are not possible due to the non-uniform sampling approach. Considerable effort was devoted toward developing a clutter filtering approach. This resulted in a method called SACHI after the inventor, Prof. Sachidananda and is described in the following paper:

M. Sachidananda, Indian Institute of Technology, Kanpur, India and D. S. Zrnic, 2002, “Improved Clutter Filtering and Spectral Moment Estimation Algorithm for Staggered PRT Sequences”, Journal of Atmospheric and Oceanic Technology, December 2002.
http://cimms.ou.edu/rvamb/Documents/JTECH122002.pdf

The resulting algorithm has been implemented in WSR-88D code in an engineering test mode only. Deployment of this capability will occur in the near future. A description of the algorithm including the SACHI filter is found at the NSSL web site at:
http://cimms.ou.edu/rvamb/Documents/SPRT_Algo_2010.pdf

The development status was reviewed in 2009 at the 34th Radar Conference:
Darcy S. Saxion, NEXRAD Radar Operations Center, Norman, OK; and R. D. Rhoton, R. L. Ice, J. C. Krause, O. E. Boydstun, W. D. Zittel, S. M. Torres, and D. A. Warde, 2009, “New science for the WSR-88D: staggered PRT implementation on the SIGMET RVP8”, 34th Conference on Radar Meteorology, Williamsburg PA.
http://ams.confex.com/ams/pdfpapers/155158.pdf

IMPROVING RANGE AND AZIMUTH DATA RESOLUTION

The research teams at the NSSL and ROC determined that velocity based algorithms such as mesocyclone and tornado vortex signature detection could be vastly improved by increasing the range resolution of the data bins from 1km to 250 m and the radial resolution from 1.0 degree to 0.5 degree. The basic research and performance features can be found in the following references:

Rodger A. Brown, Vincent T. Wood, Dale Sirmans, 2002, “Improved Tornado Detection Using Simulated and Actual WSR-88D Data with Enhanced Resolution”, Journal of Atmospheric and Oceanic Technology, Volume 19, Issue 11, November 2002.
http://journals.ametsoc.org/doi/pdf/10.1175/1520-0426%282002%29019%3C1759%3AITDUSA%3E2.0.CO%3B2

Vincent T. Wood, Rodger A. Brown, 2000, “Oscillations in Mesocyclone Signatures with Range Owing to Azimuthal Radar Sampling”, Journal of Atmospheric and Oceanic Technology, Volume 17, Issue 1, January 2000.
http://journals.ametsoc.org/doi/pdf/10.1175/1520-0426%282000%29017%3C0090%3AOIMSWR%3E2.0.CO%3B2

The ROC investigated performance of some of the super resolution methods, focusing on the performance of the aggressive windowing employed to mitigate the overlapping sample volumes due to the nearly one degree wide antenna beam:

David A. Warde, SI International, Inc., Norman, OK; and D. Sirmans, R. L. Ice, R. D. Rhoton, and D. S. Saxion, 2005, "Radar Operations Center (ROC) Evaluation of Proposed Super Resolution Techniques for the WSR-88D", 21st Conference on Interactive Information Processing Systems. http://ams.confex.com/ams/pdfpapers/85894.pdf

IMPROVING CLUTTER FILTERING

The ORDA hosted GMAP filtering provided improved data quality as documented in the first section of this report covering the ORDA basic signal processing. Further evidence of operational improvements is found in the following papers:

Ray, C. A. & Chrisman, J. N., 2007: A Data Quality Comparison of the WSR-88D Legacy Radar Data Acquisition (RDA) to the Open RDA (ORDA) in a Challenging Clutter Regime. 23rd International Conference on Interactive Information Processing Systems for Meteorology, Oceanography and Hydrology, AMS, San Antonio, TX..
http://www.roc.noaa.gov/WSR88D/PublicDocs/Publications/Phoenix_RDA_vs_ORDA_Clutter_DQ.pdf

Chrisman, J. N. & Ray, C. A., 2007: A Method to Reduce the Clutter Filter Induced Data Bias by Improving the Vertical Application of the WSR-88D Bypass Maps. 23rd International Conference on Interactive Information Processing Systems for Meteorology, Oceanography, and Hydrology, AMS, San Antonio, TX.
http://www.roc.noaa.gov/WSR88D/PublicDocs/Publications/Increased_Segments_Paper_Final_10-31-06.pdf

More recently, the ROC deployed automatic detection and clutter filtering as detailed in the following paper:

Richard L. Ice, Wyle Information Systems, Norman, OK; and R. D. Rhoton, J. C. Krause, D. S. Saxion, O. E. Boydstun, A. K. Heck, J. N. Chrisman, D. S. Berkowitz, W. D. Zittel, and D. A. Warde, 2009, "Automatic clutter mitigation in the WSR-88D, design, evaluation, and implementation", 34th Conference on Radar Meteorology, Williamsburg PA.
http://ams.confex.com/ams/pdfpapers/155409.pdf

An more current approach has been proposed at the NSSL and the ROC is tasked with conducting an engineering investigation. This approach uses a lag 1, autocorrelation spectral density approach utilizing phase information in the spectrum. The following paper describes the early investigations into this method:

David A. Warde, CIMMS/Univ. of Oklahoma, Norman, OK; and S. M. Torres, 2009, "Automatic detection and removal of ground clutter contamination on weather radars", 34th Conference on Radar Meteorology, Williamsburg PA.
http://ams.confex.com/ams/pdfpapers/155681.pdf

ALGORITHM DESCRIPTIONS AND IMPROVEMENTS

In addition to radar signal processing methods, the meteorological algorithms residing in the WSR-88D Radar Product Generator (RPG) have undergone systematic improvements. Some highlights are presented here.
The major algorithms that employ Doppler velocity estimates are: (1) Velocity Dealiasing, (2) Velocity Azimuth Display, (3) Mesocyclone Detection (4) Tornado Detection, (5) Storm Relative Mean Radial Velocity

Descriptions

For further details and full descriptions please refer to the Federal Meteorological Handbook Number 11, Doppler Radar Meteorological Observations, Part C WSR-88D Products and Algorithms, available from the US Federal Coordinator for Meteorology at:
http://www.ofcm.gov/fmh11/fmh11.htm

Velocity Dealiasing

The base line WSR-88D implementation of velocity dealiasing is based on the Smith-Eilts approach described in the following paper:
Eilts, M. D., and S. D. Smith, 1990, “Efficient Dealiasing of Doppler velocities using local environmental constraints”, J. Atmos. Ocean Technol., 7, 118-128.
http://journals.ametsoc.org/doi/pdf/10.1175/1520-0426%281990%29007%3C0118%3AEDODVU%3E2.0.CO%3B2

Although velocity dealiasing is part of signal processing, i.e., it is not a meteorological algorithm, this algorithm is executed in the RPG computer. The base data Doppler velocities from the radar are ambiguous. Velocities outside the region +VNyQ (Nyquist velocity) are shifted by the radar by +2n VNyQ into +VNyQ where n is an integer. These errors, or aliasing of the velocity, are corrected by using continuity of velocity along radials and between adjoining radials at the same range.
A new two dimensional velocity dealiasing algorithm has been developed at the ROC and NSSL and is described in the references listed in the improvements section below.

Velocity Azimuth Display

The Velocity Azimuth Display (VAD) Algorithm is used to obtain the vertical profile of horizontal wind speed, direction, divergence and vertical velocity for the region of the atmosphere surrounding a Doppler radar. Velocity data at different azimuths collected from a Doppler radar scanning the atmosphere at a constant elevation angle about a vertical axis is used. This algorithm performs a harmonic analysis along with a best-fit test on the Doppler velocities around the circumference of a circle at a specified slant range to obtain these parameters. The vertical wind velocity is obtained through a series of steps involving the relationship between horizontal wind speed and conservation of mass through a constant elevation surface above the radar. As mentioned above, for each horizontal wind estimate, the VAD Algorithm performs a harmonic analysis, i.e., calculates the best fit sine wave regression equation, along with a best fit test on the Doppler velocities around the circumference of a circle between the beginning and ending azimuths at a specified slant range and elevation angle. This process is done for a specific slant range, range and altitude when a specific VAD product is requested. Areas of significant blockage are not used. The best-fit test uses the calculated RMS velocity to identify outliers, and eliminates them from the regression analysis. As a final check on the quality of the wind estimates produced, tests are made on the minimum number of data points used, fit symmetry, and Root Means Square (RMS) velocity. If any one of these tests fails, the computed wind is displayed as "no data" on the VAD Wind Profile product

Mesocyclone Detection Algorithm

The MDA uses pattern recognition techniques to detect mesocyclones. These techniques define a process used for searching through Doppler velocity data for symmetric regions of large azimuthal shear. The MDA is based on the extraction of significant attributes which characterize mesocyclones. The MDA locates mesocyclones where a mesocyclone is defined as a three-dimensional region in a storm which rotates (usually cyclonically), and is closely correlated with severe weather. The MDA uses the systematic procedure described below.

The MDA uses radial velocity and reflectivity data to detect storm-scale (1 - 10 km (0.54 – 5.4 nm)) cyclonic vortex signatures and diagnose the attributes of the detected signatures to determine if they are associated with tornadoes and/or damaging wind. The algorithm starts by identifying one-dimensional (1D) shear segments (pattern vectors) from mean radial velocity data. To help limit the search for circulations to those associated with storm cells, the algorithm only searches velocity data from sample volumes that have reflectivities above THRESHOLD (minimum Reflectivity) and are below THRESHOLD (maximum Shear Segment Height). Shear segments (pattern vectors) are an azimuthal run of velocities whose gate-to-gate shear is continuously cyclonic. Gate-to-gate means the sample volumes are from adjacent radials and at the same range. A look-ahead function, that is range dependent, mitigates problems with small perturbations in shear during shear segment construction. All shear segments must also pass strength and length criteria.

Shear segments on each elevation scan in azimuthal and radial proximity are combined into potential two-dimensional (2D) features. Using multiple strength rank thresholds, 2D vortex cores of different strength rank are isolated from broader regions of 2D azimuthal shear. Strength rank is a function of rotational velocity, shear, and range. If a potential 2D feature still has enough shear segments and meets an aspect ratio criteria, it is checked for overlap with all previously saved 2D features on the elevation scan. If weaker features overlap stronger features, the weaker features are discarded.

2D features from adjacent elevation scans are vertically correlated into potential three-dimensional (3D) features. The mesocyclone 3D features are associated with storm cells and their attributes are computed and saved.

After all 3D mesocyclone features have been identified, features are time associated. A first guess location is made, using a motion vector from the previous volume scan. 3D features within a certain radius of the first guess point become association candidates. Additional 3D features are also added as potential candidates for association as radii are increased around the first guess point. The best candidate for time association is found by sorting the candidates within each distance threshold first by strength rank and then by circulation type. The 4D detections are classified by vortex type (e.g., Mesocyclones, Low-core mesocyclones) and the classifications are saved for display purposes. Attributes of 4D detections are used to calculate time trends. Trend and time height information of tracked 4D detection attributes are saved for display purposes.
At the display device, 4D detection attributes, their classifications, and characteristics are presented in an attribute table. Graphical overlays communicate vortex type (e.g., Mesocyclones, Low-core mesocyclones), location, and strength to forecasters. Feature strength can be used by forecasters to remove weaker detections from overlay displays that become too cluttered.

Tornado Detection Algorithm

The TDA uses radar data to identify intense, small circulations that are producing or are likely to produce tornadoes. The algorithm starts by identifying one-dimensional (1D) pattern vectors from (mean radial) velocity data. To help limit the search of circulations to those associated with the lowlevels of storm cells, the algorithm only searches velocity data from sample volumes that 1) have reflectivities above a specified threshold, 2) are within a threshold range, and 3) are below a threshold height. Pattern vectors are gate-to-gate velocity differences that exceed a specified velocity difference threshold. Gate-to-gate means the sample volumes are from adjacent radials and at the same range. Next, for six (by default) differential velocity thresholds, the pattern vectors on each elevation scan that are in azimuthal and horizontal proximity and exceed the same differential velocity threshold are combined into potential two-dimensional (2D) features. Then, the potential 2D features are trimmed such that only one pattern vector remains at any range within the feature. Afterward, if a potential 2D still has enough pattern vectors and has a below threshold aspect ratio, it is checked for overlap with all previously saved 2D features on the elevation scan. If the potential 2D feature overlaps no other 2D features, it is saved as a new 2D feature. Next, the 2D features from adjacent elevation scans are vertically correlated into potential three-dimensional (3D) features. Potential 3D features with enough 2D features are saved as 3D features. Lastly in the identification process, each 3D feature is compared against thresholds to determine if it is an Elevated Tornado Vortex Signature (ETVS) or TVS or not. Finally, the TVSs and ETVSs are associated with storm cells.

Storm Relative Mean Radial Velocity

The Storm Relative Mean Radial Velocity products (SRR and SRM) provide an estimate of the mean radial velocity for: (a) a small geographic area centered upon or near an identified storm with the storm motion removed (Region), or (b) the entire area of radar coverage (to 124 nm (230 km)) with the mean storm motion removed (Map). The velocity displayed is based on the maximum value contained in each one of the 0.25 km (0.13 nm) gates of the two or four gates, respectively, contained in the product data resolution. The product is produced upon request for any elevation angle available. The radial component of storm motion used to derive the product is the storm motion value computed for the identified cell by the SCIT Algorithm or a value input by the user. The value of storm motion used to adjust the mean radial velocity values is user-selectable at the time of product request or it defaults to the vector average of all identified storms if not selected. Each product contains 16 data levels for storm-adjusted mean radial velocity.

Improvements

The Radar Operations Center has developed a method for more efficiently scanning the radar volume during severe weather while improving radar derived wind estimates. This method employs adaptive techniques to avoid scanning empty volumes while optimizing the acquisition of data for vertical wind profile tables. A recent description of the efficient scanning method is found in the following paper:

Vincent T. Wood, NOAA/NSSL, Norman, OK; and J. N. Chrisman, 2009, “Impacts of the Automated Volume Scan Evaluation and Termination (AVSET) on the WSR-88D Velocity-Azimuth Display (VAD) Wind Profile (VWP)”, 34th Conference on Radar Meteorology, Williamsburg PA. http://ams.confex.com/ams/pdfpapers/154847.pdf

An improved method of deriving the VAD is described in the following paper:

Joe N. Chrisman, NOAA/NWS, Norman, OK; and S. D. Smith, 2009, “Enhanced Velocity Azimuth Display Wind Profile (EVWP) Function”, 34th Conference on Radar Meteorology, Williamsburg PA. http://ams.confex.com/ams/pdfpapers/155822.pdf

The ROC has also recently deployed a new two dimensional velocity de-aliasing algorithm as described in the following paper:

Arthur Witt, NOAA/NSSL, Norman, OK; and R. A. Brown and Z. Jing, "Performance of a new velocity dealiasing algorithm for the WSR-88D", 34th Conference on Radar Meteorology, Williamsburg PA.
http://ams.confex.com/ams/pdfpapers/155951.pdf

This method is based on a technique identified in 1993 as described in the following paper:

Zhongqi Jing and Gerry Wiener, National Center for Atmospheric Research, 1993, "Two-Dimensional Dealiasing of Doppler Velocities", Journal of Atmospheric and Oceanic Technology, Volume 10, Issue 6, December 1993.
http://journals.ametsoc.org/doi/pdf/10.1175/1520-0426%281993%29010%3C0798%3ATDDODV%3E2.0.CO%3B2

The following paper is a good overview of the successes in improving algorithm performance resulting in joint efforts between the ROC and NSSL over the past years:

Donald W. Burgess, CIMMS/Univ. of Oklahoma, Norman, OK; and M. A. Fresch, 2006, "The ROC/NSSL Technology Transfer MOU: A success story in radar applications technology transfer", 22nd International Conference on Interactive Information Processing Systems for Meteorology, Oceanography, and Hydrology.
http://ams.confex.com/ams/pdfpapers/104808.pdf
