P13R.9 CHANGES IN THE PRECIPITATION PROCESSING SUBSYSTEM (PPS) OF THE WSR-88D (NEXRAD) IN 2004-2009

Daniel S. Berkowitz*
NOAA/NWS NEXRAD Radar Operations Center, Norman, Oklahoma

1. INTRODUCTION

In early 2004, changes were implemented to the Precipitation Processing Subsystem (PPS) that operates within the Weather Surveillance Radar 1988 Doppler (WSR-88D, also known as NEXRAD) Radar Product Generator (RPG) computer to incorporate recent scientific and operational enhancements of that system into the rainfall estimation process. These changes include (1.) use of more accurate and higher resolution terrain data in determination of radar beam blockage; (2.) utilization of a technique for identification and removal of Anomalous Propagation (AP) and clutter on a bin-by-bin basis; (3.) incorporation of what had been an external process for determination of the onset and termination of defined precipitation events, known as the Precipitation Detection Function (PDF), directly into an enhanced version of the first algorithm of the PPS, known as the "Enhanced Precipitation Preprocessor" (EPRE); and (4.) a greater versatility for assembling the composite-elevation, "Hybrid Scan" output of EPRE from any (pre-existing or new) NEXRAD Volume Coverage Pattern (VCP). This paper summarizes (1.) the major algorithm changes and (2.) the observed impact of these changes on radar rainfall estimates. It is an update on the presentation by O'Bannon and Ding (2003).

2. OVERVIEW OF THE WSR-88D PRECIPITATION PROCESSING SUBSYSTEM

The PPS of the WSR-88D is the first stage of a process that estimates areal rainfall from radar and other sensors. This rainfall estimate is computed from radar data, but it may be adjusted by application of a rain gauge-based bias correction. The second stage of processing is based on a combination of rain gauge data and radar data for a single radar. The third stage is a mosaic of data from adjacent radars, adjusted by rain gauge reports, satellite data, and subjective corrections by experienced hydrometeorologists, typically at River Forecast Centers. This paper only deals with the first stage: the PPS.

Here are the simplified steps in the PPS: (1.) base reflectivity data are collected and, at the discretion of the RPG operator, can be filtered to remove or reduce echoes due to ground return ("clutter"); (2.) preprocessing constructs a composite-elevation pattern of reflectivity, called the Hybrid Scan, by using, at each azimuth and range location (az/ran), the elevation considered most representative of precipitation reaching the ground without being contaminated by ground returns or being blocked by terrain; (3.) the total areal extent of reflectivity that is assumed to constitute rainfall is compared to a site-adaptable threshold to determine whether a defined precipitation event is starting, continuing, or ending; (4.) an empirical relationship is applied to convert the reflectivity at each az/ran to a rainfall rate; (5.) this rainfall rate is applied over various time periods to determine accumulations; (6.) these accumulations can be adjusted at the discretion of the RPG operator by application of a multiplicative gauge/radar bias; and (7.) rainfall accumulation estimates are formulated into graphical and digital WSR-88D products.

*Corresponding author address:
Dan Berkowitz, Radar Operations Center (ROC),
1200 Westheimer Dr., Norman, OK 73069;
e-mail: Daniel.S.Berkowitz@noaa.gov

3. BRIEF HISTORY OF MAJOR CHANGES IN THE PPS

The set of algorithms in use from 1991 until 2004 (that is called the legacy PPS) is very well described by Fulton et al. (1998). That paper explains how a "sectorized" Hybrid Scan was constructed from the lowest elevation angles (namely, 0.5°, 1.5°, 2.4°, and 3.4°). In the original software, the Hybrid Scan was constructed to operate on data with a nominal (target) altitude of 1.0 km above ground level, but it also needed to have the bottom of the half power beam width clear the terrain by at least 150 m at each polar grid bin.[1]

The first major change in the PPS occurred in 1998, with the introduction of "terrain-based" occultation data. The new procedure forced the use of the lowest elevation angle that would clear the terrain by at least 1 m at each polar grid bin. The lowest elevation angle requirement eliminated the "optimum altitude" and was particularly helpful where radars were located on mountain tops.

The original Digital Elevation Model ("native DEM") from U.S. Geological Survey (USGS) was replaced by Digital Terrain Elevation Data (DTED) from National Imagery and Mapping Agency (NIMA) in 1998. (NIMA is now the National Geospatial-Intelligence Agency, NGA.) This enabled greatly improved terrain blockage determination, which, from 1991 to 2004, was used to

[1] Due to precision limitations of the elevation data and the method of calculation, the terrain clearance was actually 1.0 km.

define site specific elevation/azimuth/range sector tables and occultation data files that, in turn, defined the construction of the sectorized Hybrid Scan of the legacy PPS (O'Bannon, 1997a).

About the same time "terrain-based" method was introduced, the NEXRAD program (at the suggestion of Tim O'Bannon) promoted the use of four relationships in addition to the default (convective) one for converting reflectivity to rainfall (known as Z-R, R(Z), or Z/R relationships). These included the Marshall-Palmer relationship, the Rosenfeld tropical relationship, a cool stratiform relationship for the eastern U.S., and a cool stratiform relationship for the western continental U.S. Along with this, guidance was provided to RPG operators on the maximum precipitation rate allowed (also known as the "hail cap"), which could vary with the weather environment.

The second major algorithm change was in WSR-88D Build 5 software, which began deployment in spring of 2004. The most significant change in that software was replacement of the original preprocessing algorithm by EPRE (first described by O'Bannon, 1997b). The primary motivation for this change was the introduction of VCPs that did not necessarily contain the same four elevation angles as the original VCPs used by the legacy PPS.

Accompanying this was a major change in how terrain blockages were applied. A Beam Blockage Algorithm (BBA) computed blockages for any elevation angle, thus replacing fixed occultation data files with more dynamic blockage maps. The Hybrid Scan is still constructed to be "terrain-based" as described above.

These changes enabled the deep convection VCP 11 (Figure 1) to be replaced in some weather situations by VCP 12 (Figure 2). VCP 12 had better vertical continuity than VCP 11, especially at elevation angles below 4° (i.e., 0.5°, 0.9°, 1.3°, 1.8°, 2.4°, and 3.2°). It also had better temporal resolution than VCP 11, completing an entire volume scan (from 0.5° to 19.5°) in 4.1 minutes rather than 5 minutes.

Initiation of precipitation accumulations, which was originally determined by the PDF, was incorporated into EPRE. The area threshold became a single EPRE adaptable parameter, Area with Reflectivity Exceeding Significant Rain Threshold (RAINA), instead of a combination of Nominal Clutter Area and Precipitation Area Threshold. RAINA must be adjusted for each site based on the detected Total Rain Area as reported in the Supplementary Precipitation Data product (SPD) during a period with no precipitation.

Contamination of reflectivity has always been a problem for radar rainfall estimation (Hunter, 1996). Even though some forms of contamination (such as hail, bird, and bright band contamination) will remain until dual polarization is utilized, contamination by ground returns can be greatly reduced or eliminated by a combination of clutter suppression and a scheme that recognizes ground return and determines whether or not a particular sample bin can be used for precipitation estimation.

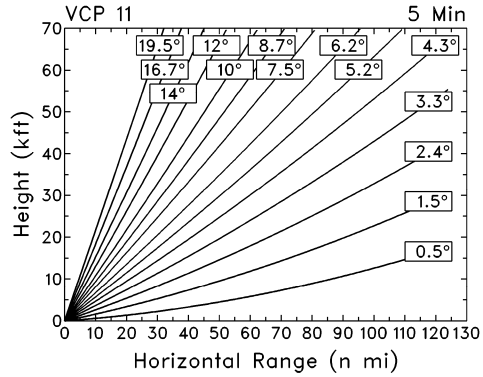

Figure 1 – Legacy VCP 11 (for deep convection).

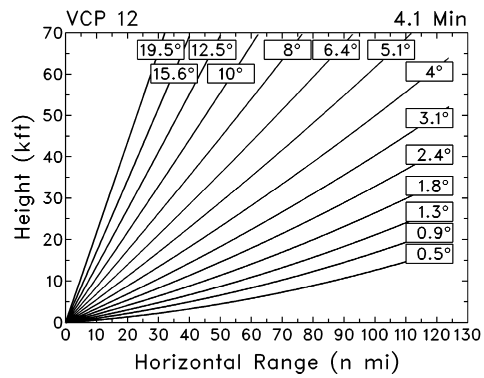

Figure 2 – New VCP 12 (for deep convection but with improved vertical continuity and shorter time intervals).

Clutter suppression has been done primarily through invoking a filter, eliminating reflectivity bins where radial velocity is near zero. A clutter bypass map is generated by the Radar Data Acquisition (RDA) signal processor to identify ground returns during Normal Propagation (NP) weather conditions. Additional clutter suppression regions can be created by an operator to handle Anomalous Propagation (AP) ground returns.

Typically, AP ground returns develop for brief periods (especially during early morning temperature inversions or when cold air outflow from thunderstorms pass over the radar vicinity). The legacy PPS handled these anomalous ground returns through the use of a "tilt test," which compared the coverage of significant reflectivity at the lowest elevation angle (0.5°) with the coverage in the next elevation angle (1.5°) and would use the higher elevation instead of the lowest one whenever a set threshold was exceeded. This method made the assumption that a major reduction between these elevations was related to ground returns. However, precipitation detected only at the low elevation could be lost in this process.

A fuzzy logic scheme, the Radar Echo Classifier AP Detection Algorithm (REC-APDA; Kessinger et al., 2003), to recognize such returns, was developed by the

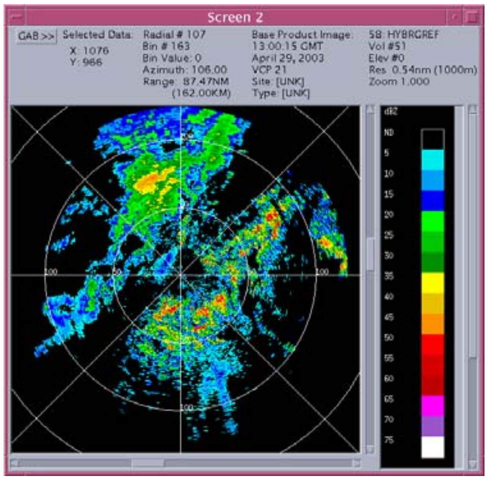

Figure 3 – KLWX Build 4 Hybrid Scan Reflectivity (HSR).

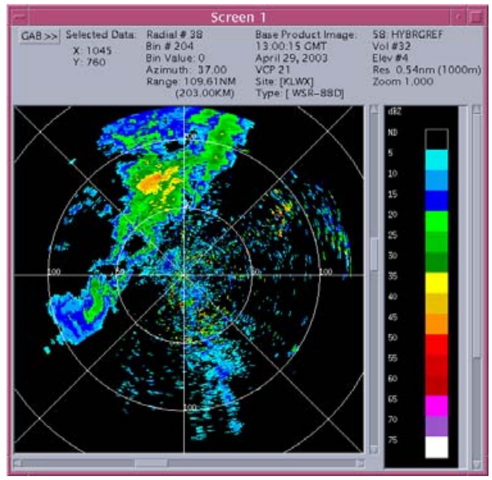

Figure 4 – KLWX Build 6 HSR.

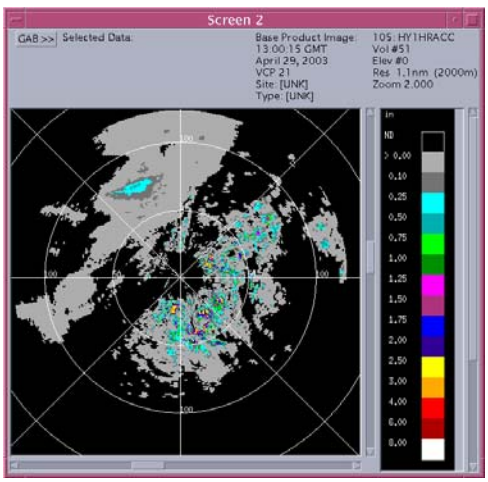

Figure 5 – KLWX Build 4 One-Hour Precipitation (OHP).

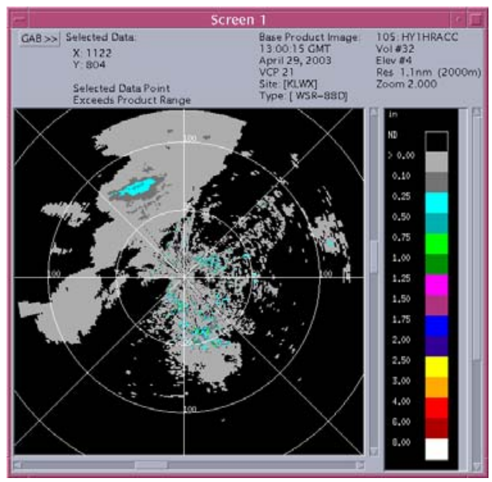

Figure 6 – KLWX Build 6 OHP.

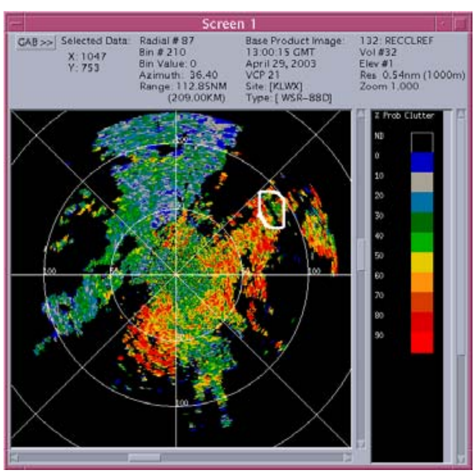

Figure 7 – KLWX Build 6 Clutter Likelihood (CLR) at 0.5°. Some of the residual ground clutter is encircled.

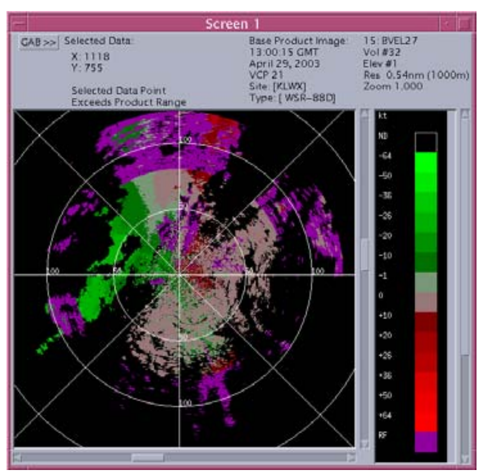

Figure 8 – KLWX Base Velocity at 0.5° indicating the region of range folding (in purple).

National Center for Atmospheric Research (NCAR) and was employed within EPRE during the construction of the Hybrid Scan. The REC-APDA fuzzy logic utilizes characteristics of reflectivity, radial velocity, and spectrum width to determine the likelihood that a particular sample bin is contaminated by ground returns. The clutter likelihood threshold (CLUTTHRESH), if set too high, causes the bin being examined to be retained as precipitation even when it is clutter; if it is set too low, it causes the bin to be rejected even if it is precipitation. The entire elevation is rarely rejected.

The legacy PPS (Build 4 software) that was in use at Sterling, VA (KLWX) on April 29, 2003, produced a Hybrid Scan Reflectivity (HSR) product (Figure 3) that differs greatly from the EPRE-based Build 6 software's HSR (Figure 4). The resulting Build 4 One-Hour Precipitation (OHP) is shown in Figure 5, while the Build 6 OHP is shown in Figure 6. The reflectivity reduction from 0.5° to 1.5° was not sufficient (i.e., it was <75%) to force 1.5° to be used in place of 0.5°. Therefore, ground returns contaminated the precipitation accumulations in Figure 5.

The Clutter Likelihood of Reflectivity (CLR) product from the REC-APDA identified nearly all of the ground returns (Figure 7). There is still some residual seen, mainly around 56° at 161 km (87 nm), which is in a region of range folding.[2] Figure 8 indicates the region of range folding in purple. Because of the ambiguous velocity and spectrum width, the REC-APDA does not identify clutter very well where there is range folding.

An additional feature of Build 5 software that did not exist in the legacy PPS is the option of creating and using exclusion zones. These zones alter the Hybrid Scan reflectivity to block out small locations that would not be identified as clutter by the REC-APDA due to relatively high radial velocity and/or high spectrum width. The best examples are wind farms, highways, and coastal locations with high sea spray. They only affect precipitation accumulation products from the PPS and Snow Accumulation Algorithm.

A wind farm located around 245° at 41 km (22 nm) from the Dodge City WSR-88D (KDDC) caused strong reflectivity (Figure 9) in the early morning of 31 May 2005. Because of high spectrum width, the CLR did not indicate high likelihood that it was clutter contamination. As a result, the Storm Total Precipitation (STP) product (Figure 10) indicated over 38 cm (15 inches) of rainfall. When an exclusion zone was invoked (Figure 11), the erroneous rainfall was eliminated. Caution must be used to ensure that the exclusion zone is used only for conditions that are not adequately handled by the REC-APDA. When meteorological conditions change, such as AP development or dissipation, the exclusion zone (like clutter suppression regions) may need to be adjusted.

[2] Range folding refers to echoes from a previous pulse being indicated at a close range as though they were from a current pulse even though they are from a much greater range (e.g., second-trip echoes).

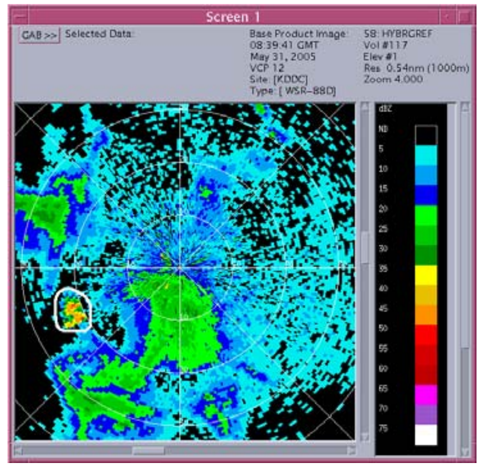

Figure 9 – Hybrid Scan Reflectivity at the Dodge City WSR-88D (KDDC) at 08:39 UTC 31 May 2005. The wind farm location is encircled.

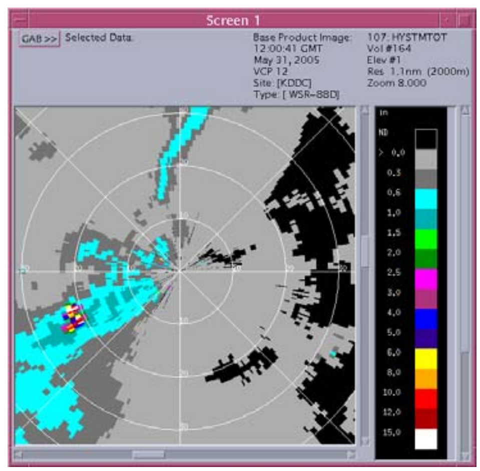

Figure 10 – KDDC Storm Total Precipitation (STP) for 12 hours ending at 12:00 UTC 31 May 2005.

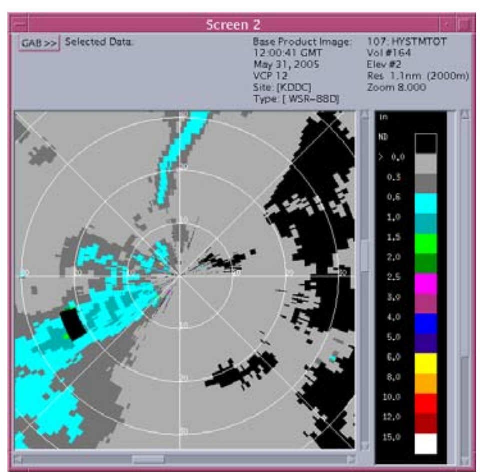

Figure 11 – KDDC STP with an exclusion zone applied.

4. CURRENT AND IMMINENT PPS CHANGES

4.1 *Blockage File Improvements*

In February 2000, the Space Shuttle Endeavor (mission STS-99) generated highly detailed elevation measurements in connection with the Shuttle Radar Topography Mission (SRTM). Due to availability of this very high resolution SRTM DTED, improved terrain data are being generated within 50 km of each radar site that is south of 60° N. latitude (the northern limit of the SRTM data).

In addition, the Radar Operations Center (ROC) obtained high resolution Global Positioning System (GPS) readings for numerous sites. The combination of more accurate geolocation of the radars and better resolution terrain data ensures more accurate blockage calculations and, therefore, more accurate rainfall estimates.

4.2 *Open-System RDA*

Deployment of the Open-System RDA (ORDA) has just begun. Potentially, the biggest impact on the PPS is the change in the method of clutter suppression. Instead of removing bins with very low radial velocity (utilizing a notch width clutter filter), ORDA utilizes a spectral processing method called Gaussian Model Adaptive Processing (GMAP), developed by Sigmet Corporation for deployment with Sigmet's RVP8 signal processor. Testing by the Radar Operations Center in 2004 and 2005 indicated that GMAP is very effective at clutter suppression. Like legacy clutter filtering, it can be applied to a clutter bypass map or to clutter suppression regions (Chrisman and Ray, 2005).

The calibration procedure is faster and more accurate than the one used for legacy RDAs. This will cause a major improvement in reflectivity and, therefore, rainfall estimates. The ORDA has a GPS server that rectifies two problems that often occur on legacy systems: erroneous product times and erroneous locations (which impact blockage determination).

An enhancement to ORDA software is planned for Build 9 software (2007) that will help mitigate range and velocity ambiguity (i.e., reduce range folding and improve radial velocity estimates). This will help the performance of fuzzy logic clutter mitigation software (such as the REC-APDA).

4.3 *Improved Graphical User Interface*

The Human Computer Interface (HCI) used to monitor and control the RDA and the RPG is about to undergo some changes in Build 8 software (to be released in 2006). It includes a way to readily determine when the system can be switched from precipitation mode to clear air mode (the top of Figure 12) and a precipitation status display that indicates whether or not precipitation is in the process of being accumulated. It also has a Precipitation Status window (Figure 13) that uses information from EPRE rather than the old PDF (which no longer has relevance to precipitation accumulation).

5. LONG-TERM PPS CHANGES

5.1 *Super-resolution PPS Products*

Build 10 software (to be deployed in 2008) is expected to include super-resolution base products (reflectivity, radial velocity, and spectrum width), all with 0.5° by 0.25 km sample bins. WSR-88D PPS products from super-resolution data are planned for Build 11 software (to be deployed in 2009). These are expected to be helpful in localized flash flood situations and in places that have rough terrain, where rainfall estimates for hydrologic forecasts can be isolated to a small river basin.

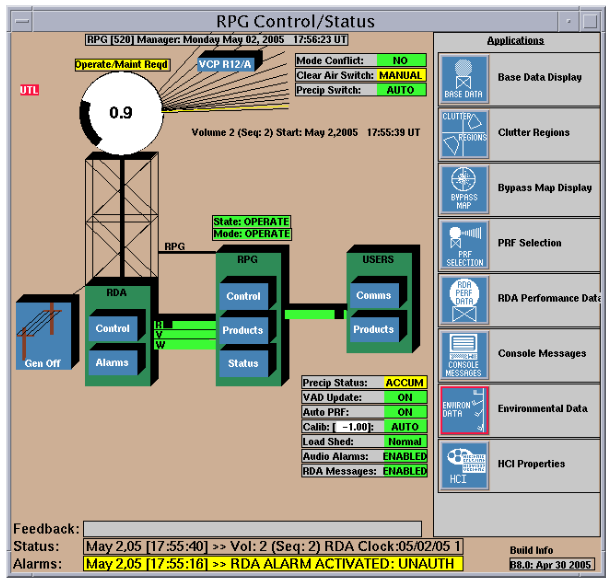

Figure 12 – Build 8 Human Computer Interface (HCI).

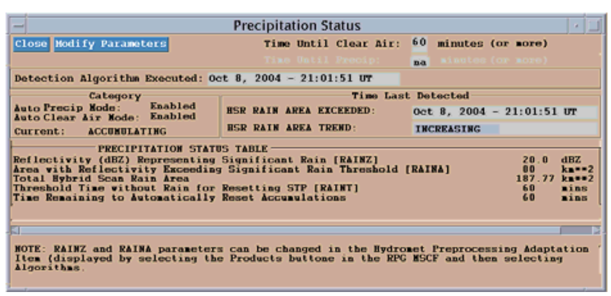

Figure 13 – Build 8 Precipitation Status window.

The FAA's Terminal Doppler Weather Radar (TDWR) has higher spatial and temporal resolution than the legacy WSR-88D, even though its range is not as great. It has been used as a "test bed" for super-resolution PPS development. The Supplemental

Product Generator (SPG) that is expected to be installed with AWIPS sites in 2006 will create products from the TDWR, and, possibly as soon as 2007, may include a high resolution version of the PPS.

5.2 RDA-based Ground Clutter Mitigation

To enhance clutter suppression, a fuzzy logic methodology that discriminates clutter from precipitation return within the spectral domain of the RDA, called Clutter Mitigation Decision (CMD), is under development by NCAR (Dixon et al., 2005). Once it identifies an echo as ground return, the GMAP filter is applied to that range bin. Range bins that contain identified precipitation returns will not be filtered by GMAP. The CMD should mitigate the reflectivity bias introduced by clutter filter application in regions of stratiform precipitation having near zero velocity and low spectrum width. In this manner, GMAP could eliminate ground clutter contamination from base data before the radar moments (reflectivity, radial velocity, etc.) are calculated, whether the clutter occurred from normal radar beam propagation or from AP. Tentatively, this will be part of Build 10 (2008) or Build 11 (2009) software.

5.3 Dual Polarization

Dual polarization WSR-88Ds may be deployed as early as 2009. In addition to the three base moments in the current system (i.e., horizontal reflectivity (Z_h), radial velocity, and spectrum width), it will provide horizontal-vertical differential reflectivity (Z_{DR}), differential phase (Φ_{DP}), specific differential phase (K_{DP}), and horizontal-vertical correlation coefficient (ρ_{hv}). Of these, the most important inputs to the polarimetric quantitative precipitation estimate (QPE) being developed by the National Severe Storms Laboratory (NSSL) are Z_h, Z_{DR}, and K_{DP}.

The current design of polarimetric QPE uses a set of empirical relationships based on these inputs, described as the “synthetic algorithm.” Each one of these equations is selected based on output from the default convective Z/R relationship being used in the WSR-88D, $Z=300R^{1.4}$ (Ryzhkov et al., 2005a).

In addition, a fuzzy logic Hydrometeor Classification Algorithm (HCA; Ryzhkov et al., 2005b) identifies the nature of the echoes. The HCA should be able to distinguish hail, snow, biological scatterers (esp. birds and insects), light rain, heavy rain, etc., thus reducing contamination by non-meteorological echoes, the bright band (melting snow), and hail.

6. SUMMARY

The PPS has been undergoing improvement as the technology has developed. Improved blockage calculation was enabled by better site location data from a GPS and better digital terrain data from the SRTM. Major changes (such as spectral processing at the RDA, the use of fuzzy logic, super-resolution, and dual polarization) were enabled by faster, more powerful computers.

The most dramatic change in the PPS occurred in 2004, with the introduction of EPRE to replace the legacy preprocessing algorithm. EPRE and its accompanying Beam Blockage Algorithm enable the use of new VCPs. These, in turn, can result in better rainfall estimation due to improved vertical continuity and greater temporal resolution. The REC-APDA helps to identify ground return, which can then be rejected during construction of Hybrid Scan reflectivity. Hybrid Scan data is then used as input to the Flash Flood Monitoring and Prediction (FFMP) program, which is frequently the tool used to determine the need for flash flood warnings.

Exclusion zones enable elimination of artifacts, such as wind farms and highways, which might not be identified as clutter by the REC-APDA. ORDA with GMAP enables clutter suppression that is based on spectral processing instead of velocity notch width. The CMD will enable all base data to have ground return removed without requiring operator interaction to handle AP returns and should minimize reflectivity bias within precipitation that is caused from clutter filter application.

Super-resolution PPS will enable better resolution hydrologic forecasts and warnings, particularly important in rough terrain and urban areas. This development will probably be applied to data from both WSR-88D and TDWR radars.

With the introduction of polarimetric QPE, contamination by hail, birds, and bright band (the leading causes of overestimation) will be greatly reduced. Also, better and more timely empirical relationships will be applied to convert returned radar energy to rainfall.

All of these changes lead to better rainfall estimates at the first stage of processing. Denser rain gauge networks will lead to better bias corrections, which will then lead to better estimates of mean areal precipitation for hydrologic forecasts and warnings.

7. ACKNOWLEDGMENT

I am particularly indebted to the late Tim O’Bannon, who pioneered flexibility in the PPS by development of EPRE along with the beam blockage algorithm and the use of the REC-APDA. Thanks go to Randy Steadham, of the ROC Applications Branch, who chairs the Site-Specific Scan Strategies working group and related groups that developed new VCPs and more user-friendly HCI features. Finally, thanks go to the many reviewers of this paper, including George Smith, Pedro Restrepo, Dennis Miller, and Dave Kitzmiller (OHD); Cathy Kessinger (NCAR); LtCol Randy George, Ron Guenther, and Rich Rasmussen (ROC); and Terry Schuur (NSSL).

8. REFERENCES

Chrisman, J. N., and C. A. Ray, 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.

Dixon, M., C. Kessinger and J. Hubbert, 2005: Echo classification and spectral processing for the discrimination of clutter from weather. Preprint-CD, 32nd Conference on Radar Meteorology, AMS, Albuquerque, NM.

Fulton, R., J. Breidenbach, D.-J. Seo, D. Miller, and T. O'Bannon, 1998: The WSR-88D rainfall algorithm. *Wea. Forecasting*, **13**, 377-395.

Hunter, S., 1996: WSR-88D radar rainfall estimation: capabilities, limitations and potential improvements. *NWA Digest*, **20** (4), 26-36.

Kessinger, C., S. Ellis, and J. Van Andel, 2003: The radar echo classifier: A fuzzy logic algorithm for the WSR-88D. *Preprint-CD, 3rd Conference on Artificial Applications to the Environmental Science,* AMS, Long Beach CA

O'Bannon, T., 1997a: Using a 'terrain-based' hybrid scan to improve WSR-88D precipitation estimates. Preprints, *28th Int. Conf. on Radar Meteorology,* Austin, TX, Amer. Meteor. Soc., 506–507.

O'Bannon, T., 1997b: The Enhanced Precipitation Pre-processing Subsystem (PPS) algorithm, Preprints, 14th International Conference on Interactive Information and Processing Systems (IIPS) for Meteorology, Oceanography, and Hydrology, American Meteorological Society, January, Phoenix, AZ.

O'Bannon, T., and F. Ding, 2003: Continuing enhancement of the WSR-88D precipitation processing subsystem. *Preprints, 31st Int'l Conf. on Radar Meteorology*, AMS, 6-12 August 2003.

Ryzhkov, A. V., S. E. Giangrande, and T. J. Schuur, 2005a: Rainfall Estimation with a Polarimetric Prototype of the WSR-88D Radar, *J. Appl. Meteor.*, **44**, 502-515.

Ryzhkov, A. V., T. J. Schuur, D. W. Burgess, P. L. Heinselman, S. Giangrande, and D. S. Zrnic, 2005b: The Joint Polarization Experiment: Polarimetric rainfall measurements and hydrometeor classification, *Bull. Amer. Meteor. Soc.*, **86**, 809-824.