The NEXRAD Rainfall Estimation Processing System: A radar tool to improve rainfall estimation across the Tennessee River Valley

P. N. Gatlin¹, Walter. A. Petersen², Lawrence. D. Carey¹, Susan. R. Jacks³.

¹ University of Alabama Huntsville-Earth Systems Science Center, Huntsville, A ² NASA-Marshall Space Flight Center, Huntsville, AL L ³ Tennessee Valley Authority, Knoxville, TN

1. Introduction

Rainfall measurement is of great hydrologic applications. importance to Knowing the rainfall distribution (where and how much) is critical in determining how to best distribute that water throughout the watershed. Rain gauges have long been the standard used by water resource management organizations to provide their rainfall measurements across watershed. However, maintaining a large rain gauge network can be rather costly and budget cutbacks driving are water management organizations to investigate other, less expensive means for measuring rainfall.

The Tennessee Valley Authority (TVA), the nation's largest public power provider, is responsible for managing the Tennessee River and some of its tributaries. The Tennessee River watershed stretches from southwestern Virginia, southwest through Tennessee and Alabama and north into western Kentucky, where the Tennessee River discharges into the Ohio River (Figure 1). TVA maintains a network of 189 rain gauges to measure precipitation across the Tennessee River watershed, which results in annual maintenance costs around \$1 million. Precipitation measurement is critical to TVA's River Scheduling division, which manages the water storage and flow within the Tennessee River in order to support TVA's power plants, the public's



Figure 1. Map of the Tennessee River watershed with subbasins controlled by TVA (highlighted) and region covered by AREPS (dotted line).

recreational activities and the local ecosystem. The long term expenses associated with maintaining a large rain gauge network along with the improvement of weather radar's capability in mapping rainfall motivated TVA to investigate the feasibility of replacing rain gauges with weather radar rainfall estimates.

2. Dual-polarimetric radar demonstration project

The ARMOR Rainfall Estimation Processing System (AREPS) was developed to provide TVA with radar-derive rainfall estimates. The Advanced Radar for Meteorological Operational Research (ARMOR) is a C-band dual-polarimetric radar located in Huntsville, AL (Petersen etl al. 2005). It operates continuously 24 hours

Corresponding author address: Patrick N. Gatlin, Earth Systems Science Center, Univ. of Alabama Huntsville, 320 Sparkman Dr, Huntsville, AL, 35805. E-mail: gatlin@nsstc.uah.edu

a day, 7 days a week conducting rain volumetic scans, which consists of 360° scans at three antenna elevations, at least every 5 min. These rain scans are ingested by AREPS so that an hourly rainfall estimate can be determined. AREPS first cleans up the data using horizontal reflectivity, the correlation coefficient and the variance of differential propagation Once quality controlled, specific phase. differential phase is computed and used to correct the power variables for attenuation (using locally modified code originally developed by V.N. Bringi, Colorado State University). The attenuation corrected data is then used to calculate the rain rate. The methods for calculating the optimal rain rate, which include checking for the presence of ice and precipitation intensity, are well-known relationships described in Bringi and Chandrasekar (2001). The rain rate field gets transformed to a Cartesian grid with 1 km spacing and then summed over an hour. During the demonstration project, the average hourly rainfall estimate for each sub-basin in the central part of the watershed (see area enclosed by dotted line in Figure 1) is sent to TVA in real-time for use in their hydrologic streamflow model.

After several months of collecting data, estimates AREPS rainfall the were against rain compared the gauge measurements. A scatter plot of 6 hr rainfall measurements taken from 27 rainfall events that occurred from October 2007 through June 2008 is shown in Figure 2a. The radar estimates show a -10% normalized bias relative to the gauge measurements and normalized error of 12%. Since TVA uses areal rainfall estimates in their streamflow model, we also compared the average radarderived rainfall for each sub-basin with the gauge-derived rainfall for the respective sub-basin. The results show the radar underestimated the 6 hr rainfall by 8% on the sub-basin scale, but the standard error was larger (20%) than that of the point comparison. This higher error is largely attributed to the Thiessen polygon method (Thiessen 1911) used to determine spatially



Figure 2. Scatterplots of 6 hour rainfall estimates for (a) 1km² radar pixel versus rain gauge ("point "comparisons) and (b) radar-derived sub-basin average versus rain gauge derived sub-basin amount (areal comparison).

distributed rainfall from a coarse rain gauge network, which can result in unrepresentative sub-basin rainfall (i.e., the rain gauge network is too coarse to capture isolated rainfall events). Regardless of this error, AREPS performed rather well relative to the rain gauge network and the statistics are well within the range of those shown in other dual-polarimetric radar rainfall studies (e.g., Bringi et al. 2000; Brandes et al. 2001; Ryzhkov et al. 2005).

3. Extending the radar rainfall estimates across the entire watershed

Although the AREPS demonstration proved that radar could take the place of rain



Figure 3. The number of WSR-88Ds within 200 km of any point in the Tennessee River watershed. Also shown are sub-basin boundaries and rain gauge locations (yellow and red gauges are owned and maintained by TVA).

gauges for TVA's rainfall mapping needs, it only provided coverage over a small portion of the watershed (11 sub-basins and 42 rain gauges). In order to remove additional rain gauges, and further reduce the rainfall measurement costs. the radar-derived rainfall data must be provided across a much larger portion of the watershed. Thus we utilized the network of WSR-88D radars. There are at least two WSR-88D radars within 200 km of any location for 98% of the watershed (Figure 3). Furthermore, some portions of the area are even covered by 4-5 radars. As a result, the NEXRAD Rainfall Estimation Processing System (NREPS) was developed to take the WSR-88Ds measurements and provide an hourly rainfall accumulation map of the watershed.

Figure 4 illustrates the design of NREPS and the data flow through the system. WSR-88D level II formatted data is received via Unidata's Internet Data Distribution (IDD) using their Local Data Manager (LDM) software. The NEXRAD data latency via the IDD is around 5-7 min. NREPS is run every 6 min to check for the most recent data received from each of the radars, and then it organizes these data by time. Utilizing the Data Quality Assurance algorithm developed by MIT/Lincoln Labs for the NEXRAD ORPG Build 3 (Smalley et al. 2003), anomalous propagation and sun strobes are removed (notch width filter using Doppler velocity) from the data so not to



Figure 4. The NEXRAD Rainfall Estimation Processing System.

contaminate the rain rate. A very simple, vet fast, convective-stratiform partitioning is which the equivalent performed in reflectivity factor greater than or equal to (less than) 37 dBZ is classified as convective (stratiform). This allows for the more appropriate Z-R relation to be applied. The standard NEXRAD Z-R relation, $Z = 300 R^{1.4}$ (Woodley and Herndon 1970), is applied to convective elements and the Marshall-Palmer relation, $Z = 200 R^{1.6}$, (Marshall et al. 1955) is applied to the stratiform elements. Once the rain rate is calculated, a melting level correction is applied if the 0°C isotherm is near the radar altitude. This correction assumes an 8:1 snow to liquid water equivalent ratio (Baxter et al. 2005) across the Tennessee Valley region. The rain rates are then gridded with a 2 x 2 x 0.5 km (x, y, z) resolution and merged by assigning each grid point a rain rate derived from the closest available NEXRAD. The merged rain rate grid is summed to produce an hourly rainfall accumulation.

If an outage of the primary radar feed (LDM/IDD) occurs, NCEP's Stage II precipitation product (Lin and Mitchell 2005) is used as a backup. The NCEP Stage II product provides an hourly rainfall accumulation, but it is derived from rain adjusted radar estimates. gauge А coordinate transformation of the Stage II data is conducted and the Tennessee Valley domain is extracted (domain shown in Figure 3). Each hour, the average rainfall within each sub-basin is extracted from the radar-derived hourly accumulation product (primary or backup) and put into an ASCII formatted text file that can be easily read and used in the TVA hydrologic stream flow model. The frequency at which NREPS can provide hourly rainfall accumulation can be much higher, but the needs of TVA only require an hourly rainfall total once each hour.

4. NREPS performance

A comparison between NREPS hourly rainfall estimates (R) and hourly rain gauge accumulations (G) for January through May 2009 (226 hours of rainfall) is shown in Figure 5. The data were filtered by removing zero value radar and gauge samples and choosing the radar pixel value that most closely matches (of the 9 pixels surrounding the gauge location) gauge This method resulted in 15,596 value. radar-gauge pairs to compare. The results show that NREPS underestimatees hourly rainfall by 4% with a normalized error $(|R-G|/\langle G \rangle)$ of 16% relative to the rain gauges. These statistics are also well within the range of other radar rainfall studies similar Z-R employing power law relationships, which have found biases of -38% to +16% and errors of 31-69% (Ryzhkov and Zrnic 1995; Ryzhkov et al. 1997; Brandes et al. 2001).



Figure 5. Scatterplot of 1 hr rainfall accumulations estimated by NREPS (radar) vs rain gauge network measurements (226 hours).



Figure 6. An example of the NREPS 1 hr rainfall image across the western half of the Tennessee River watershed that is provided to TVA.

5. Summary

A radar-based rainfall processing system has been developed for a water resource management organization, TVA, to reduce costs associated with measuring rainfall across the Tennessee River watershed. During a demonstration project, dualpolarimetric rainfall estimates across the southwestern portion of the watershed (11 sub-basins) were created and provided to TVA for comparison with their rain gauge network. Favorable results (-10% bias and 12% error) demanded the rainfall estimates be extended to the rest of the watershed (all 48 sub-basins) to further reduce costs. The NEXRAD Rainfall Estimation Processing System (NREPS) was developed to provide the additional coverage. NREPS utilizes ten NEXRAD radars that provide coverage across the watershed to create hourly rainfall products for TVA in real-time. The NREPS products used by TVA include 1-hr and 24hr rainfall accumulation images (Figure 6), which are used for situation awareness, and 1-hr sub-basin rainfall text files, which are ingested into the TVA stream flow model to predict the response of streams and rivers within the watershed.

TVA has implemented NREPS into their River Scheduling operations and already removed 18 rain gauges, saving TVA a projected \$100K per year as a result. Although the NREPS versus rain gauge results are comparable to the of dualpolarimetric rainfall estimates of AREPS, we need to expand our comparison dataset into the summer months when conventional *Z-R* relationships do not perform as well as the dual-polarimetric rainfall estimators due to the more intense rainfall events (e.g., typical summertime pulse thunderstorms).

The next big step in this project will come as the NEXRADs are upgraded to dual-polarimetric capability. We then plan on utilizing the ARMOR rain rate algorithm in NREPS to take advantage of the improved rainfall estimating capability of dual-polarimetry. In the mean time, ARMOR's dual-polarimetric rainfall estimates will be compared with a neighboring NEXRAD in order to improve upon the standard Z-R-derived rainfall estimates. If errors are not too large then we will continue this method, propagating the results to adjacent NEXRADs and thereby improve the NREPS rainfall estimates provided to TVA.

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