An Assessment of TDWR Rainfall Estimates for Flash Flood Forecasting

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1 Introduction

The utility of Terminal Doppler Weather Radar (TDWR) reflectivity observations (Fig. 1) for flash flood forecasting has been examined through analyses of TDWR observations from the Baltimore-Washington International (BWI) radar for a series of storms during the warm season of 2004. Analyses included: 1) rainfall estimation from TDWR reflectivity observations, 2) implementation of attenuation correction algorithms for the TDWR reflectivity observations (and rainfall estimation using the resulting reflectivity fields), 3) intercomparison of TDWR observations with drop spectra measurements from a Joss-Waldvogel disdrometer, 4) intercomparison of TDWR rainfall estimates with WSR-88D rainfall estimates (from the KLWX radar), 5) intercomparison of TDWR rainfall estimates with rain gage and discharge observations from the Dead Run watershed in Baltimore County, Maryland (Fig. 2).

The principal conclusions and recommendations of this study are the following:

1) The TDWR can provide reflectivity observations at 1 minute time scale and spatial scales finer than 1 km^2 that accurately represent the fluctuations at the surface (see Fig. 3). Consequently, the TDWR provides a critical resource for flash flood forecasting in small urban watersheds.

2) WSR-88D reflectivity observations do not capture the fine scale fluctuations in rainfall rate that are resolved by the TDWR reflectivity fields (see Fig. 4).

3) Attenuation correction algorithms will be required for operational utilization of TDWR reflectivity fields for rainfall estimation. Calibration studies for algorithm parameters are needed for algorithm implementation.

4) Rainfall estimation algorithms that combine TDWR and WSR-88D reflectivity observations should be explored. A combined algorithm could exploit the temporal and spatial resolution of the TDWR, while minimizing the adverse impacts of attenuation on TDWR reflectivity fields.

5) Utility of the TDWR reflectivity observations for flash flood forecasting is greatest for rapidly moving, high rain rate convective systems over small urban catchments. In this setting, the 1 minute time resolution resolves the spatial distribution of reflectivity associated with storm motion far better than the 5-6 minute time resolution of the WSR-88D.

6) Accurate rainfall rate estimates for rapidly moving, high rain rate convective systems will also benefit substantially from polarimetric measurements. For small urban watersheds, (Z, Z_{DR}) rainfall estimation algorithms are of particular importance for resolving the fine scale distribution of extreme rainfall rates.

2 Methodology

Analyses of TDWR rainfall estimates are based on observations from the BWI radar for 10 storms during the period April - September 2004. Data sets were provided by

NWS in two formats, a “raw” format, which included full volume scan reflectivity and Doppler velocity data (23 April, 25 May, 7 July and 4 August) and a processed format, which included reflectivity observations for low tilts (11 August, 12 August, 13 August, 8-9 September, 17-18 September and 28-29 September). A major task was development of software to decode and process the volume scan data sets (software can be provided to any NWS units with interest in analyses of volume scan TDWR data sets).

Volume scan reflectivity data sets from the KLWX WSR-88D were obtained for each of the 10 storm events. During the period from 1 July - 31 August, a Joss-Waldvogel disdrometer was deployed at the University of Maryland Baltimore County (UMBC), which is located 4 km southeast of the Dead Run watershed (see fig. 2). Drop spectra data sets were collected for the 7 July, 4 August , 11 August, 12 August and 13 August storm events. A network of 19 rain gages (locations are denoted by stars in Fig. 2) which provide storm total accumulations was monitored for the July - August events.

Stream gaging stations DR1 - DR4 (Fig. 2) were installed in the Dead Run watershed during the summers of 2003 and 2004. The drainage area of the Dead Run watershed above the USGS gaging station at Franklintown (Fig. 2) is 14.3 km^2. Stations DR3 and DR4 were installed during the summer of 2004 and discharge data sets (based on provisional rating curves) are available for the 4 August, 11 August, 12 August and 13 August events. The DR3 and DR4 subbasins have drainage areas between 4 and 5 km^2. Extensive property damage and numerous rescues took place in the reaches near DR3 and DR4 during the 7 July 2004 flood, which was the flood of record on Dead Run.

Analyses of radar rainfall estimates for both the TDWR and WSR-88D utilize the convective Z-R relationship (Fulton et al. [1998] and Baeck and Smith [1998]). A bias correction algorithm (Baeck and Smith [1998]) based on the Dead Run rain gage network is also utilized for several analyses.

An attenuation correction algorithm was implemented for the TDWR reflectivity observations. The algorithm employed a specific attenuation coefficient in power law form

$$K_r = aR^b \tag{1}$$

where K_r is the one-way specific attenuation in $dB\ km^{-1}$ and R is the rainfall rate in $mm\ h^{-1}$. A range of parameter values was used to examine sensitivity of algorithm performance to parameter values (based on values reported in Doviak and Zrnic [1993] and Rinehart [1997]). Results below for "algorithm 1" use parameter values $a = 0.01$ and $b = 1.00$. "Algorithm 2" results are based on parameter values $a = 0.0018$ and $b = 1.05$.

3 Analyses

In this section analyses of the 7 July, 4 August, 11 August and 13 August events are presented. Each of these events produced flash flooding in the Dead Run watershed, ranging from modest overbank flows in portions of the watershed to record flooding throughout the basin from the 7 July storm. Each of these events has complete TDWR and WSR-88D observations, as well as disdrometer and stream gage data. The other six events had major data gaps and were also of less interest in terms of occurrence of flash floods.

The 7 July storm produced record flooding in the Dead Run watershed and in other basins in the Baltimore metropolitan area. The duration of heavy rainfall in Dead Run was two hours (Fig. 1). During the final period of heavy rainfall over Dead Run, the system organized into a line of convection and moved rapidly from west to east over the Baltimore region (Fig. 1).

TDWR reflectivity observations capture the temporal variability of surface reflectivity (as reflected in Joss-Waldvogel disdrometer observations) at the 1 minute time scale (Fig. 3). As the line of convection passed over the disdrometer after 2030 UTC and significant rainfall appears in the beam between the BWI radar and UMBC (the location of the disdrometer; see Fig. 1), attenuation results in severe underestimation of reflectivity by the TDWR. Disdrometer estimates of reflectivity are generally larger than TDWR reflectivity estimates, suggesting that radar calibration problems may result in systematic underestimation of reflectivity by the TDWR.

In contrast to the TDWR-disdrometer analyses, small-scale fluctuations in reflectivity from the WSR-88D do not match those of the TDWR (Fig. 4). In this case, the temporal variability of reflectivity is compared for the TDWR bin and WSR-88D bin containing the Woodlawn High School rain gage (see Fig. 2). The contrasting representations of temporal variability of reflectivity are tied both to the contrasting spatial and temporal sampling of the two radars. The WSR-88D does not resolve the spatial structure of intense convection nor the spatial gradients of reflectivity that are tied to storm motion (note, in particular, the period around 2030 UTC, when the system has assumed a linear organization and begun to propagate rapidly from west to east). It should also be noted that the TDWR shows severe attenuation problems after 2040 UTC. Combined rainfall estimation algorithms that utilize WSR-88D and TDWR reflectivity observations could potentially exploit the strengths of the two systems, while mitigating the individual weaknesses. Additional analyses of the 7 July storm are presented at the end of the section.

The 4 August storm was a rapidly moving line of thunderstorms (Fig. 5) that produced extreme rainfall rates over Dead Run for a period of less than 15 minutes. As the line passed over Dead Run, there was rapid transformation of the structure of the line with convective elements that passed over Dead Run propagating rapidly ahead of the line (Fig. 5). TDWR - disdrometer intercomparisons (Fig. 6) again show: 1) excellent agreement in the temporal pattern of the reflectivity variation at 1-minute time scale and 2) significant attenuation of reflectivity. Fluctuations in disdrometer reflectivity are generally bracketed by the TDWR reflectivity values that are obtained without attenuation correction (denoted by circles in Fig. 6) and those derived using the attenuation correction algorithm with parameter set 1 (denoted by the symbol "x" in Fig. 6 and referred to as "algorithm 1").

TDWR rainfall estimates over Dead Run (Fig. 7) for the 4 August 2004 storm vary by a factor of 3 to 4 from the attenuation-corrected algorithm to the uncorrected algorithm. In both cases, the storm total rainfall estimates reflect storm motion and evolution at fine spatial scales. These elements of rainfall variability are not captured by the WSR-88D rainfall estimates (Fig. 8).

The 11 August 2004 (Fig.. 9) storm consisted of a broken line of convective elements, which moved rapidly from northwest to southeast over the Baltimore metropolitan region. The storm exhibited even more pronounced spatial variability in reflectivity than the 7 July or 4 August storms (Figs. 9 and 10). The higher resolution of the TDWR provides a different picture of rainfall distribution over Dead Run than the WSR-88D. The TDWR shows striking contrasts in the timing of basin-averaged rainfall rate for the DR3 and DR4 subbasins of Dead Run (Figs. 11 and 12). This variability is missed by the WSR-88D due to the coarser time and spatial sampling. Attenuation correction plays a significant role in TDWR rainfall estimates for the 11 August storm (Fig. 13). There are large differences in TDWR rainfall estimates between the two attenuation algorithm parameter sets. Operational implementation of TDWR rainfall estimation algorithms would benefit from parameter estimation studies of attenuation correction algorithms.

The 13 August 2004 storm (Fig. 14) consisted of a line of weak convection that moved slowly from southeast to northwest over the Dead Run watershed. As with the 11 August storm, there was large spatial variability in storm structure that is reflected in TDWR rainfall estimates for DR3 and DR4, but not in the WSR-88D rainfall estimates (Figs. 15 and 16). For the 13 August storm, the attenuation algorithm is of less significance for TDWR rainfall estimates and the contrast between the two algorithm parameter sets is diminished (Fig. 17)

Storm total rainfall estimates from the TDWR for the 7 July 2004 storm (Fig. 18) exhibit several notable similarities to the rainfall estimates for the 4 August storm . Rainfall estimates vary by a factor of 2-3 between attenuation corrected rainfall estimates (algorithm 1) and uncorrected rainfall estimates. The structure of the storm total field strongly reflects storm structure and motion at the 1 minute time scale of the TDWR rainfall estimates. Although the WSR-88D and TDWR show similar structure in the southeast to northwest gradients of storm total rainfall (compare Figs. 19 and 20), the WSR-88D does not resolve the spatial details linked to fine-scale spatial structure of convection or the short time scale evolution and motion of storm elements. To resolve the distribution of heavy rainfall over small urban watersheds with reflectivity measurements, the spatial and temporal resolution of the TDWR can be extremely valuable.

High resolution reflectivity observations are not a panacea for developing high-resolution rainfall rate estimates for flash flood forecasting. There are significant sources of errors in short-term estimates of extreme rainfall rates from reflectivity observations. The problems are illustrated through analyses of rainfall estimates for the 7 July storm. Both the WSR-88D and TDWR agree on the broad spatial details of rainfall distribution for the 7 July storm, but they are both wrong (Fig. 20). Rain gage observations (and flood evidence) indicate that heavy rainfall was distributed more uniformly over the basin.

The fundamental problem in estimating peak rain rates for the 7 July storm concerns microphysical controls of the raindrop size distribution. Using drop spectra measurements from the disdrometer, rainfall rate was estimated directly and after first computing reflectivity then estimating rainfall rate using the convective Z-R relationship. The results show that there is systematic overestimation with the convective Z-R on the leading edge of the storm and underestimation on the trailing edge.

To capture the microphysical controls of rainfall rate variability requires polarimetric measurements (Figs. 22 and 24). Differential reflectivity, which was computed for the drop spectra data using the method of Ulbrich and Atlas [1984], illustrates the "large drop" domination of the leading edge of the line of convection (Fig. 22). A combined (Z, Z_{DR}) rainfall estimation algorithm (modified from Brandes et al. [2004]) provides accurate rainfall rate estimates for the 7 July storm (compare the results in Figs. 23 and 24). (Z, Z_{DR}) algorithms are of particular importance for estimating rainfall rate at the finest spatial resolution; algorithms based on specific differential phase shift may also be of utility but the range-averaging inherent in these measurements will limit the capability for resolving the spatial distribution of extreme rain rates.

The TDWR can play an important role in providing marked advances in rainfall estimation for flash flood forecasting in small catchments. Combined algorithms that utilize TDWR and WSR-88D reflectivity (and ultimately differential reflectivity) fields are an especially promising avenue for developing high-resolution rainfall rate products. These developments are the first critical step in enhancing flash flood forecasts, especially for small, high-hazard, urban watersheds.

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