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PERFORMANCE TESTING OF THE WSR-88D PRECIPITATION ADJUSTMENT ALGORITHM

Richard Fulton, Dong-Jun Seo, Jay Breidenbach, and Edward Johnson
Hydrologic Research Laboratory, Office of Hydrology
NOAA National Weather Service
Silver Spring, Maryland U.S.A.
20910

ABSTRACT

The National Weather Service of the United States is progressing in its modernization activities, the hallmark of which is the installation of an extensive network of 164 Doppler weather radars, WSR-88D (Weather Surveillance Radar-1988 Doppler), with advanced technological and computing capabilities. The deployment is about 70% complete. Survey results from weather forecasters using this new system over the past several years have indicated that, of the nearly 40 diverse hydrometeorological products generated by the radar, the most extensively used ones include the derived rainfall products.

The Hydrologic Research Laboratory is responsible for developing, evaluating, and optimizing the performance of the WSR-88D operational software that processes the reflectivity measurements and generates these rainfall products. This software package is called the Precipitation Processing Subsystem (PPS) and is composed of five major component algorithms: Preprocessing, Rate, Accumulation, Adjustment, and Products (Seo and Johnson, 1995). HRL has been performing validation tests of all the PPS algorithms, and this paper will discuss some results from the testing of the Adjustment algorithm using reflectivity data collected and archived by the WSR-88D radar and archived, operationally-available raingage data. The Adjustment algorithm uses real-time raingage data to calibrate the rainfall estimates derived from radar reflectivity measurements.

1. INTRODUCTION

The Adjustment algorithm of the Precipitation Processing Subsystem is the fourth in a series of five algorithms which make up the PPS. The purpose of this algorithm is to quantitatively compare the hourly raingage accumulations with corresponding hourly radar rainfall accumulation estimates derived from reflectivity measurements at 5-6 minute volume scan intervals using a Z-R relationship (currently $Z=300R^{1.4}$).

Currently the National Weather Service (NWS) is not ingesting real-time raingage data into the WSR-88D for use in the Adjustment algorithm. The necessary computer processing and communications hardware are just now beginning to be implemented in a testing mode at a limited number of operational radars. Within a year, about half of the radars in the U.S. will be receiving gage data from existing gage networks.

This paper will briefly review the mathematical design and functionality of the Adjustment algorithm, present some results derived from off-line testing at the Hydrologic Research Laboratory (HRL) for one rainfall event in the central U.S., and finally discuss some challenges associated with real-time operational implementation of the algorithm for use by the weather forecasters and hydrologists in the U.S.

2. ALGORITHM DESIGN

The Adjustment algorithm adjusts the radar estimated rainfall by multiplying by a mean field bias estimated using a Kalman filter technique (Ahnert et. al., 1986). This is performed once an hour, and the computed bias is applied for that hour until a new one is calculated. This bias adjustment is intended to collectively correct the radar rainfall estimates caused by a variety of errors such as improper Z-R coefficients, poor radar calibration, etc.

There can be a maximum of 50 gages defined for each radar, although the software is currently being enhanced to increase that number to 200 for those rare, data-rich areas. There is currently a time window of approximately 45 minutes for the gage observations to be sent to the WSR-88D radar for use in the algorithm. The algorithm uses hourly radar rainfall estimates on a polar grid 2 km in range and 1 degree in azimuthal increment. Gage-radar data are paired for each available hourly gage observation using the numerically-closest radar rainfall estimate from the 9 polar gridpoints surrounding the gage location to account for possible gage location and/or radar navigational inaccuracies.

There are two quality control steps executed once the hourly gage-radar pairs have been assembled. The first one is called the "two standard deviation" test which throws out gage-radar pairs in which the gage-radar difference is more than two standard deviations away from the normalized mean. The second step is the "0.6 mm threshold" test which throws away pairs in which both the hourly radar and gage accumulation are less than 0.6 mm.

Once the quality controlled gage-radar pairs are assembled, they are passed to a discrete Kalman filter. It assumes that the mean multiplicative bias follows a random walk process, i.e., the bias is equally likely to increase or decrease over the next hour. Based on this model, the best forecast bias for the next hour is simply the best current estimate. If enough gage-radar pairs exist, the forecast from the last execution of the procedure is updated based on those data. The gage-radar pairs are also used during each execution to estimate the measurement error covariance matrix in real-time. If enough pairs are not available, the forecast bias from the previous hour becomes the new bias and the estimation error variance also increases each hour by an additive system noise variance. Once the bias is computed, it is multiplied by the radar rainfall estimates on the polar grid.

3. GAGE DATA

HRL has examined a number of rainfall cases in the Oklahoma area of the central U.S. as well as other regions. The case presented here is a heavy rainfall event in Oklahoma observed by the Frederick, Oklahoma (FDR) WSR-88D radar. This rain was associated with a very strong line of thunderstorms and associated trailing stratiform rain which swept across the area during the spring convective season on 9 May 1993 over an 11 hour period producing local storm total rainfall amounts exceeding 15 cm.

Figure 1 shows the reflectivity factor at 0.5 degrees elevation during the storm passage. A narrow leading squall line extends southwest to northeast and is moving eastward. A trailing stratiform rainfall region is located to the north of the radar.

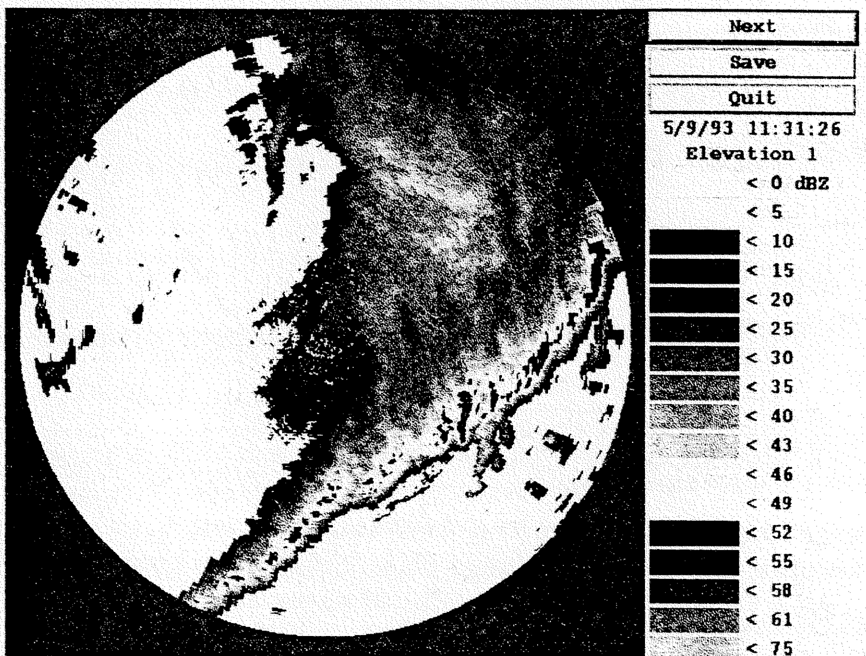

Figure 1. Reflectivity display at 0.5 degrees elevation at 11:31 UTC on 9 May 1993.

The available gage data were collected from the NWS's Arkansas-Red Basin River Forecast Center (RFC) in Tulsa, Oklahoma which is one of 13 RFCs in the U.S. that receive automated raingage reports in near-real-time into their computer databases. This same gage information will be supplied to WSR-88Ds in real-time for use in the PPS Precipitation Adjustment algorithm in the near future. The gages include a number of different types from several different networks. The total number of available gages located within the 230 km range of the rainfall processing in the PPS for the FDR radar was about 40. Not all of these gages sent reports quickly enough to be used by the Adjustment algorithm (see Section 5 below). We have assumed, however, in our post-processing that all gage reports were received instantaneously for testing purposes. The gage locations are shown in Figure 2. Unfortunately the gages are not distributed uniformly across the radar umbrella. In the testing described here, a minimum threshold of 6 gage-radar pairs was required to compute a bias. This threshold can be changed.

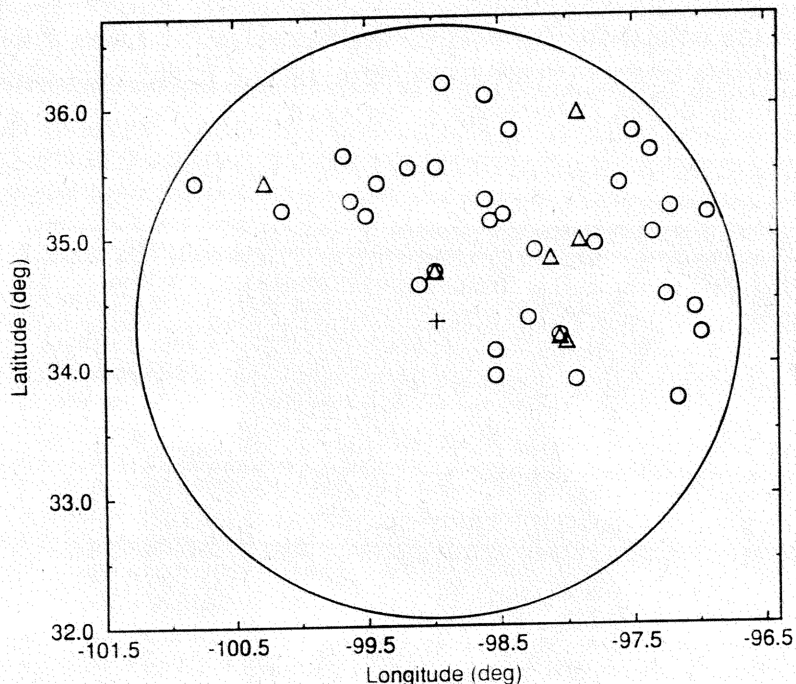

Figure 2. Raingage locations for the 9 May 1993 rainfall event at the Frederick WSR-88D. The large circle represents the 230 km range ring. Small open circles are locations of gages with good data, open triangles are the locations of gages with erroneous data.

Three scenarios were tested: 1) all available gage data were used, 2) only gage data that had been manually pre-screened and quality controlled (QC'ed) were used, and 3) no gage data were used. This allowed an evaluation of the usefulness of the gage data on the resulting radar rainfall estimates and the impact of inclusion of erroneous gage data on the Adjustment algorithm. In Fig. 2 the seven gages which were manually identified as consistently sending erroneous reports are indicated by the triangles. The circles indicate locations of the remaining 33 gages sending good data.

4. ADJUSTMENT ALGORITHM PERFORMANCE

Figure 3 illustrates the number of actual gage-radar pairs used in the Adjustment algorithm for the second scenario (QC'ed gages only). The top line shows that during the 10 hour period examined, there was a maximum of about 33 gage-radar pairs available. That was reduced by 2 or 3 after the two-standard-deviation test which removes suspect gage-radar pair outlier. The lower curve shows the number of pairs remaining after the 0.6 mm threshold test. This removes any pairs where both hourly gage and radar accumulations are less than 0.6 mm. It is clear that the rainfall event peaked in areal extent under the FDR radar umbrella about 6 hours into the period shown when the number of pairs going into the actual bias calculation peaked at about 24.

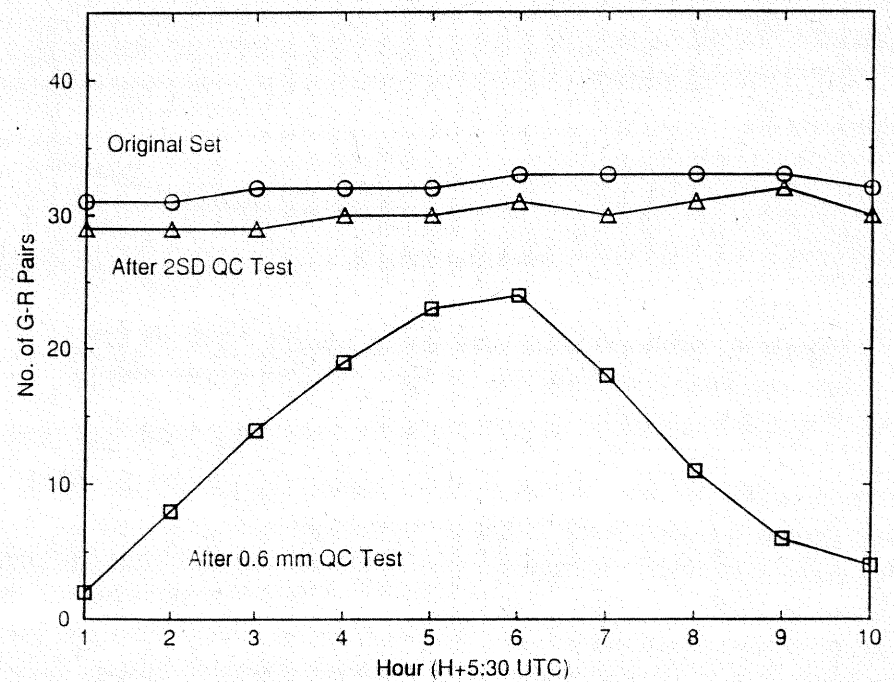

Figure 3. Number of gage-radar pairs used in the PPS Adjustment algorithm as a function of time on 9 May 1993 (QC'ed gages only).

Figure 4 plots the computed bias estimate (a multiplicative factor such that a bias of 1.0 means no bias of the radar estimate relative to the gage accumulation) and predicted mean square error of the bias estimate as a function of time on an hourly timestep for the test case using only the QC gages. The computed bias estimate is what each radar rainfall estimate bin (on a 2 km range by 1 degree azimuth grid) would be multiplied by to get an adjusted rainfall estimate. For all hours the bias estimate was greater than 1.0 indicating that the Adjustment algorithm determined that the radar was underestimating the rainfall compared to the gages.

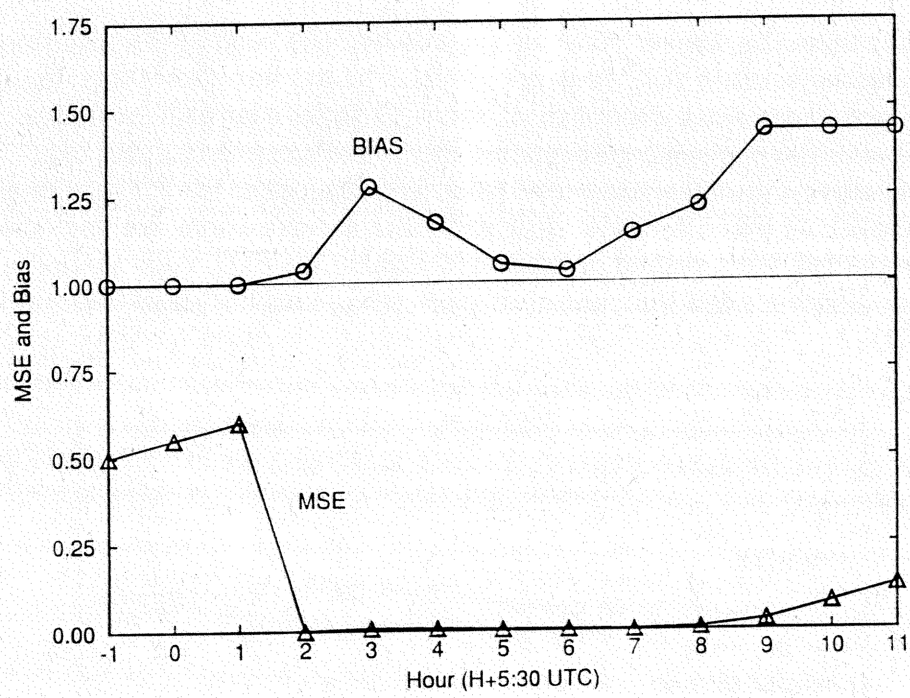

Figure 4. Bias estimate and mean square error of the bias estimate as a function of time (QC'ed gages only).

The Adjustment algorithm was initialized with default values of bias of 1.0 and mean square error of 0.5. It was not until hour 2 that enough gage-radar pairs (six or more) with non-zero hourly rainfall were available to compute a bias estimate. At this time the mean square error of the bias estimate sharply drops to less than 0.01. Similarly, after hour 9 the number of gage-radar pairs drops below the threshold, and the most recent bias estimate is propagated forward while the mean square error increases by a constant additive value of 0.05 to account for system noise.

When all available gage reports were used, including the ones which were obviously in error, the resulting bias estimates were similar (not shown). The trend of the bias matched the case when only the QC'ed gages were used, but there were small differences in the computed bias estimate. So the quality control procedures used within the Adjustment algorithm were able to remove some of the bad data, but some of it did get through and was used in the algorithm. However, the algorithm was not very sensitive to the inclusion of bad gage data, at least for this case.

Figure 5 is a plot of the gage-radar pairs after summing the gage accumulations and radar estimate accumulations for the entire 11 hour storm event. The closed circles represent the gage-radar pairs when no adjustment is performed, and the open circles represent the pairs after the bias adjustment has been applied to the radar rainfall estimates. A linear least square fit was made to each set of data, and the resulting best fit lines are shown. The results show that for all pairs the adjusted radar estimate is larger than the corresponding unadjusted value (recall from Fig. 4 that the computed bias estimate was greater than 1.0 for all hours). For the majority of the points, this causes the adjusted radar estimate to move closer to the no-bias (i.e., bias=1.0) line shown in the plot. For some of the pairs to the right of the no-bias line, the adjustment has moved the radar estimates farther to the right compared to the unadjusted pairs. This is a degradation in the radar rainfall estimates compared to the unadjusted case. However, since many more pairs fall to the left side of the unbiased line, on the average the radar estimates have been improved relative to the gage accumulations. The net result is a best fit line for the adjusted case which is closer to the no-bias 1:1 line than the unadjusted case.

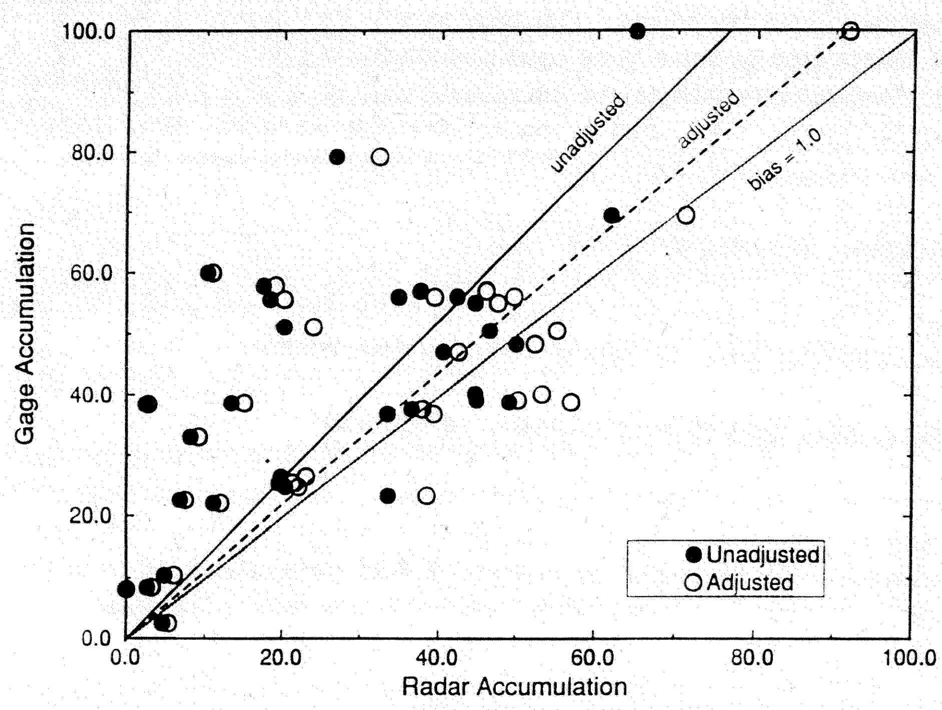

Figure 5. Storm-total gage-radar pairs for the 11 hour rainfall event. Closed circles are those pairs which have not been adjusted, and open circles are those pairs in which the bias adjustment has been applied to the radar estimated storm-total rainfall. Units in mm.

5. OPERATIONAL CONSIDERATIONS

There are a number of challenges which exist to the operational implementation of the Adjustment algorithm of the PPS in the U.S. Most of these are associated with the gage data that are needed for input:

1) *Design and installation of a number of computer and communication hardware systems and associated database software across the country to collect and supply the real-time raingage data to each WSR-88D*

A major part of the modernization plan of the NWS is the development and installation of advanced Unix-based computer workstations at each forecast office and WSR-88D site to handle local computer processing and communications. These computers will eventually have the responsibility to collect and send the real-time gage information to the WSR-88D. In the interim, other computer hardware is being developed and tested to serve that purpose.

2) *Timeliness of the receipt of gage observations for use by the algorithm*

The Adjustment algorithm requires that gage reports be supplied to the WSR-88D within about an hour of observation in order to be used to compute a gage-radar bias. The reporting and transmission characteristics of many of the operationally available gage networks which supply automated data to the NWS often do not achieve that timeliness requirement. Efforts are on-going nationwide to reprogram these gages to report more frequently.

3) *Sparsity of raingages in some parts of the U.S.*

Some parts of the U.S. that will be covered by WSR-88Ds will not have a dense enough raingage network to provide adequate data in a narrow time window.

4) *Quality control of gage data before it is passed to the radar*

The case presented in the last section demonstrated that a number of operationally available gages which supplied data for this case evaluation had problems with data quality. That is likely to be typical of other regions of the U.S. and techniques need to be developed to perform better quality control of the gage data before they are sent to the radar.

6. SUMMARY

The Adjustment algorithm of the Precipitation Processing Subsystem ingests real-time raingage data and hourly derived radar rainfall estimates to perform a correction to the radar estimates. A Kalman filter technique is used to merge the gage and radar information on an hourly timestep. Results of the performance testing for a heavy rainfall event in Oklahoma indicated that the algorithm was numerically stable and produced bias estimates which are consistent with the observed sample bias between the gage observations and the radar estimates. This resulted in an overall improvement in the agreement between the gage and radar rainfall estimates.

HRL will continue to examine other aspects of the Adjustment algorithm and improve the mathematical design and techniques. The minimum number of gages required to perform a bias will be examined. Additional gage quality control procedures will be investigated and implemented. Other improvements to existing techniques in the PPS are also being studied to improve the radar rainfall estimates before they are input into the Adjustment algorithm. In addition, as the gage data begin to flow to the radars over the next six months, additional information will be gained as the NWS gains more experience with the real-time operation and performance of the algorithm.

7. REFERENCES

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