J1.17

RAINFALL ESTIMATION IN THE WSR-88D ERA FOR OPERATIONAL HYDROLOGIC FORECASTING IN THE NATIONAL WEATHER SERVICE

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1. INTRODUCTION

Since the first operational deployment of WSR-88D (Weather Surveillance Radar - 1988 Doppler version), much information and experience have been gained on WSR-88D rainfall estimation for operational hydrologic forecasting at the National Weather Service (NWS) River Forecast Centers (RFC) and Weather Forecast Offices (WFO). The purpose of this paper is to describe the current 88D-based real-time rainfall estimation stream in NWS, and to identify critical areas of improvement.

2. ESTIMATION STREAM AND PRODUCTS

The current 88D-based rainfall estimation stream in NWS consists of three stages of data processing (Hudlow 1988, Fulton 1997).

2.1 *Stage I*

Stage I is performed automatically in the Radar Product Generator (RPG) by the Precipitation Processing Subsystem (PPS) (Hudlow 1988, Fulton 1997), and produces the following products;

1) Graphical - one-hour, three-hour, storm-total, and user-selectable (between 2 and 30 hours) total rainfall accumulations, all in 16 display levels at every volume scan on the 2 km x 1° polar grid,
2) Digital - Hourly Digital Precipitation (HDP), in 256 levels at every volume scan on the HRAP (NWS 1993) grid (approximately 4x4 km^2 in mid-latitudes), and
3) Alphanumeric - Supplemental Precipitation Data (SPD), which contains the listing of PPS adaptable parameter settings and radar-gage pairs, Principal User Processor (PUP)-displayable.

Although not a 'precipitation' product, Stage I also produces Digital Hybrid-Scan Reflectivity (DHR) product at every volume scan on the 1 km x 1° polar grid. DHR, upon conversion to rainfall, can be used for flash-flood forecasting applications such as the Flash Flood Potential (FFP) system in the WFO Hydrologic Forecast System (WHFS) (Roe 1997).

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2.2 *Stage II*

Stage II is performed either automatically or manually at RFCs and WFOs. Based on the Stage I-produced HDP at the top of the hour and hourly rain gage data, Stage II currently produces, for each radar umbrella, the following products in both graphical and digital forms;

1) gage-only rainfall analysis field (Seo 1997a),
2) mean field bias-adjusted HDP field (Seo et al. 1997), and
3) radar-gage rainfall analysis field based on the mean field bias-adjusted HDP and rain gage data (Seo 1997b).

At WFOs, the Stage II products support the Areawide and the Site-Specific Flash-Flood Prediction Systems in WHFS (Roe 1997). At RFCs, they are used to produce Stage III products.

2.3 *Stage III*

Stage III, performed at RFCs, mosaics the Stage II products to produce RFC-wide rainfall analysis fields in both graphical and digital forms. A key functionality of Stage III is interactive quality control (QC) via graphical user-interface (GUI), which enables the Hydrometeorological Analysis and Support (HAS) forecasters to apply a range of human QC measures on the machine-generated rainfall analysis fields. The resulting Stage III products may then be used for river stage forecasting.

3. SOURCES OF ERROR AND AREAS OF FURTHER RESEARCH

Because HDP is the primary input to Stage II, the accuracy of Stage II (and hence that of Stage III) depends primarily on the accuracy of HDP. Among the various sources of error in radar observation of rainfall (Wilson and Brandes 1979), systematic errors, or biases, are the most important because they affect volumetric estimation of rain water at all space-time scales of aggregation. In this section, we describe the major sources of error in each stage of the current rainfall estimation stream.

3.1 *Stage I*

Sampling Geometry vs. Reflectivity Morphology

The elevation angle of the base tilt, on which WSR-88D rainfall estimation is mostly based, is nominally 0.5°. Accordingly, under normal refractive conditions, the axis of the beam reaches the atmosphere approximately 1, 2, 3, 4, and 5 km (or higher if the radar is sited higher) above the ground level (AGL) at the ranges of 60, 120, 180, 200, and 230 km, respectively. Because the vertical profile of reflectivity (VPR) of rain clouds is hardly ever uniform, radar rainfall estimates are necessarily subject to range-dependent biases.

A number of factors contribute to nonuniform VPR; nonzero vertical reflectivity gradient (e.g., bright band), incomplete beam filling, beam overshooting, etc. Given the magnitude of range-dependent biases in the current WSR-88D rainfall products particularly for heavy rainfall-producing storms (Seo et al. 1997, Smith et al. 1997), there exists a pressing need to develop and implement an algorithm for real-time adjustment of range-dependent biases due to nonzero-vertical reflectivity gradient and incomplete beam filling (Seo et al. 1997).

Z-R Relationship

Comparisons of WSR-88D rainfall products with rain gage data indicate that the current default Z-R relationship, $Z=300R^{1.4}$, tends to underestimate rainfall (Smith et al. 1997). Efforts are under way to obtain new default parameters that achieve long-term unbiasedness against gage observations. Much additional work, however, is needed to stratify Z-R parameters according to storm type and/or rainfall regime.

Combined Effects

'Tropical' storms (i.e., storms fed by tropical moisture sources, producing rainfall predominantly via liquid-phase microphysical processes through a deep cloud layer) present added difficulty in radar rainfall estimation in that not only their Z-R parameters differ significantly from those of 'nontropical' storms (currently $Z=250R^{1.2}$ is used for tropical storms), but they are also subject to strong vertical reflectivity gradient (Seo et al. 1997). Therefore, even if the Z-R parameters (which are to be estimated at a close range in order to sample raindrops rather than cloud droplets) are very accurate, significant underestimation is likely to occur at far ranges without adjustment of range-dependent biases due to nonuniform VPR (Seo et al. 1997).

Extremely heavy rainfall-producing small-scale storms offer by far the greatest challenge in WSR-88D rainfall estimation (Smith et al. 1996, Smith et al. 1997): very often they 1) are of 'tropical' nature, 2) have strong vertical reflectivity gradient, 3) are more susceptible to incomplete beam filling due to small horizontal extent, are subject to topographic control of 4) enhanced low-level growth of raindrops (which often results in rain rate for which dBZ values exceed the so-called 'hail cap') and of 5) radar beam blockage. When unadjusted for, each factor contributes to radar underestimation of rainfall.

A critical need exists for research on the joint use of volumetric reflectivity data, environmental data available from observations and/or the Numerical Weather Prediction (NWP) model output, and topographic data 1) to identify conditions for which radar rainfall estimates are subject to multiple sources of error and 2) to develop real-time correction procedures.

Radar Hardware Calibration

A number of cases exist where differences in radar rainfall estimates between two overlapping radar umbrellas have been traced to one of the radars being either 'hot' or 'cold.' A need exists for an algorithm that monitors in real time, either in dBZ or in rainfall units, potential calibration differences among adjacent radars. The mean field bias estimation algorithm (Seo et al. 1997) can serve this purpose, but only at relatively gage-rich sites.

Anomalous Propagation (AP)

Reflectivity data only-based techniques for automatic detection and removal of ground returns from AP have been found to be inadequate for situations where ground returns from AP are embedded in precipitation echos. Further research is needed on the joint utilization of reflectivity and Doppler data (Smith et al. 1997).

3.2 *Stage II*

The current radar-gage rainfall analysis algorithm assumes that the mean field bias-adjusted HDP field is also locally unbiased. Due primarily to range-dependent biases and nonuniform Z-R parameters, the assumption is not met in general. Ongoing efforts to acquire as many rain gage data as possible in the real-time rainfall estimation stream has resulted in a number of WSR-88D umbrellas under which real-time local bias adjustment is now considered possible. Given that bias adjustment has by far the greatest impact on quantitative estimation of rainfall among all Stage II/III operations, much research is needed to develop a local bias estimation algorithm which is applicable to a wide range of gage network densities.

Rain gage data come in various time scales of aggregation, ranging from 15 minutes to 24 hours. Currently, only hourly gage data are used in bias estimation: further research is needed to develop an algorithm that objectively utilizes rain gage data of all durations.

Because the number of rain gage data available for real-time bias adjustment is usually very small, it is very important that each gage report is of high quality. Much research is needed on both statistical (Pan 1997) and physically-based approaches to rain gage data QC.

Methodologies for objective merging of satellite-derived rainfall estimates with rain gage and radar rainfall data must be developed to provide spatially continuous estimates of rainfall over areas of beam blockage and outside of the effective range of radars as identified by the sampling geometry vs. reflectivity morphology.

3.3 *Stage III*

Currently, Stage III mosaics Stage II products over the entire RFC service area via either arithmetic averaging or taking the maximum among the overlapped. This practice does not objectively take into account range- and 0°C isotherm-dependence of radar rainfall estimates. Further research Is needed on objective mosaicking of overlapping radar rainfall data from multiple sites based on sampling geometry vs. reflectivity morphology.

4. IMPLEMENTATION ENVIRONMENT

One of the difficulties in implementing algorithmic changes/additions to Stage I has been that the current RPG is greatly constrained by limitations on CPU, disk space, and operating systems. The Open RPG (ORPG) environment, which the current WSR-88D engineering is migrating to, is expected to greatly accelerate the pace of operational implementation of algorithmic improvements in PPS and to substantially expand the scope of functionalities implementable in new algorithms.

Likewise, the Stage II/III environment is in a transition to the Advanced Weather Interactive Processing System (AWIPS), which, with a ready access to a spectrum of data sources and substantially increased computing power, presents new opportunities to improve the accuracy of real-time rainfall products for operational hydrologic forecasting in NWS.

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