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Hydro-NEXRAD Radar-Rainfall Estimation Algorithm Development, Testing and Evaluation

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Abstract

The Hydro-NEXRAD radar-rainfall estimation algorithms involve three main components: 1) preprocessing, 2) rain rate, and 3) rainfall accumulation. The preprocessing algorithm performs the quality control of reflectivity volume data and generates a *hybrid scan*. That is, reflectivity values for each azimuth and range bin are assigned from the several lowest elevation angles. It optionally estimates an azimuth-dependent vertical reflectivity profile and performs a correction for range effects. The rain rate algorithm converts the corrected reflectivity to rainfall intensity. The user can specify any power-law type empirical relationship between reflectivity and rainfall intensity. The last step of rainfall estimation is to integrate consecutive rate scans for specific time duration ranging from 15 minutes to daily. The algorithm mimics real-time calculations and involves advection correction.

Introduction

The main advantage of radar observations is that the measurement can be assembled over large area with fairly high temporal and spatial resolution. Quantitative estimation of radar rainfall is needed for various hydrologic applications such as flood forecasting models, hydrosystem operation and control, and design of hydraulic structures. Different applications may require different space and time resolution and accuracy of the rainfall input. Although the operational WSR-88D rainfall estimation algorithm, called the *Precipitation Processing System* or *PPS*, provides rainfall products for the purpose of the National Weather Service's warning and forecast missions, such products are not always best suited for other applications.

As part of the Hydro-NEXRAD (Krajewski et al. 2007, this volume), a prototype software system that enables increased use of NEXRAD data in hydrologic research and applications, we are developing a number of customized modular algorithms related to radar-rainfall estimation. The algorithms include *Quick Look* (default), *Hi-Res*, *Pseudo NWS PPS*, and *Custom* options. We briefly describe which algorithms are used to estimate radar-rainfall from reflectivity volume data in each option. The PPS is an option implemented in Hydro-NEXRAD. This allows comparison of effects of different options used by users with respect to the NWS products. We describe example test results of the PPS option as well as the sensitivity of other modules. For the tests, we used use large samples of Level II radar-reflectivity data from several locations in the U.S.

Structure of the Algorithms

The radar-rainfall estimation algorithm of the Hydro-NEXRAD involves three components relevant to quantitative rainfall estimation and a functional component as shown in Figure 1. Preprocessing, rain rate, and rainfall accumulation are the main algorithms of radar-rainfall estimation, and grid conversion is a function to support follow-on hydrologic research and applications.

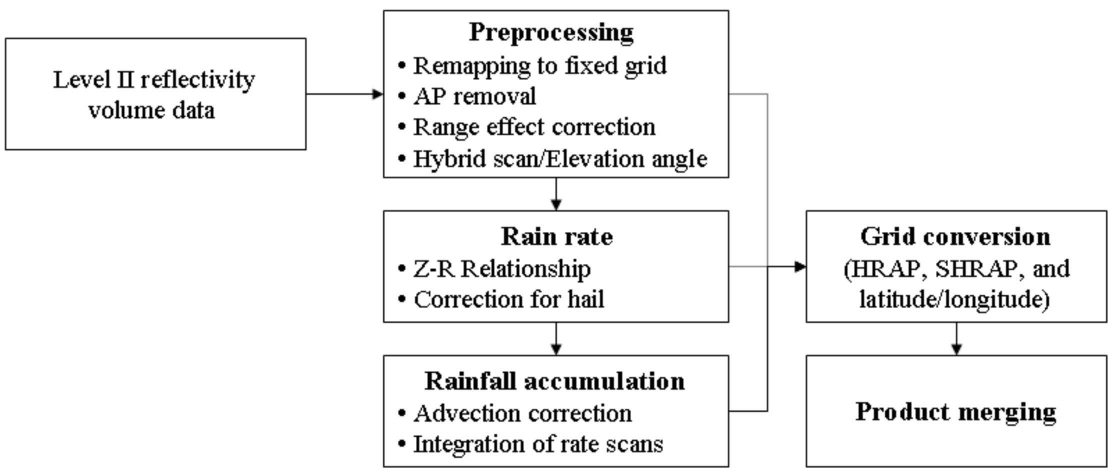

Figure 1. Overview of the Hydro-NEXRAD rainfall estimation algorithm.

1. Preprocessing.

Radar data may be contaminated by well-known error sources (e.g. Zawadzki 1982; Smith et al. 1996). Many quantitative applications in hydrometeorology and hydrology require that one identify and account for these error sources. The preprocessing algorithm in Figure 1 performs volume scan data quality control, and generates either a single elevation (for user specified antenna angle) or a *hybrid scan*. Specifically, the algorithm assigns reflectivity values for each azimuth and range bin in the hybrid scan, from the corresponding values of several of the lowest elevation angles. The algorithm optionally carries out a correction of range- and azimuth-dependent vertical profile of reflectivity (Vignal and Krajewski 2001). Below we briefly discuss the main aspects of the steps involved.

1. Fixed grid and reflectivity product. Once the Level II reflectivity volume scan data are read from RLE files (Krajewski et al. 2007, this volume) into memory, the algorithm remaps reflectivity measurements from every elevation angle onto a corresponding fixed polar grid with resolution of 1° in azimuth by 1 km in range. The preprocessing algorithm can take one of the elevation angles as a reflectivity product if the user specifies a hybrid scan. The algorithm uses CAPPI (Constant Altitude Plan Position Indicator) to assign reflectivity values from the several lowest elevation angles to each azimuth and range bin. The CAPPI product is smoothed by a Gaussian kernel function defined by the CAPPI height to reduce the discontinuity of the reflectivity values between different elevation angles. Another option that the user can specify it to use the hybrid scan defined in Fulton et al. (1998).

2. Anomalous propagation. Anomalous propagation (AP) from ground echoes, when interpreted as rainfall, may cause a significant overestimation of rainfall amount. In Hydro-NEXRAD we applied an automated procedure (Steiner and Smith 2002) to mitigate ground clutter contamination of radar data. The algorithm considers the likelihood of atmospheric conditions for anomalous propagation by evaluating decision factors such as the vertical extent of radar echoes, their spatial variability, and vertical gradient of intensity. Other algorithms (e.g., Grecu and Krajewski 2000) can be easily added as a user-specified option.

3. Range effect correction. Range-dependent bias coming from the non-homogeneous vertical structure of radar reflectivity is a significant error source in rainfall estimation. The error source can be corrected by the vertical profile of reflectivity (VPR) determined from reflectivity data measured at multiple elevation angles. Azimuth-dependent VPR based on the aggregation of every 1 hour volume data for an operational application is estimated using the algorithm described by Vignal and Krajewski (2001) to correct range effect. This approach is more advantageous than the mean VPR (Joss and Lee 1995) as it allows the spatial variability of VPR to be considered. In the future we plan to add a simple scaling paradigm (Chumchean et al. 2004) as another option for the correction of range effect.

2. Rain rate

The rain rate algorithm converts the quality-controlled reflectivity to rainfall intensity. The user can specify any power-law type *Z-R* relationship.

***Z-R* relationship.** The reflectivity, Z (mm^6/mm^3), is measured by the power of electromagnetic waves backscattered from raindrops. Estimation of radar rainfall, R (mm/h or mm), from the reflectivity measurements is determined by an empirical reflectivity-rainfall, or *Z-R* relationship, which one can model adequately with a power law ($Z=aR^b$) relationship. (Krajewski and Smith 2002). In Hydro-NEXRAD, the use can select from three common Z-R relationships:

- NEXRAD: $Z = 300\ R^{1.4}$
- Tropical: $Z = 250\ R^{1.2}$
- Marshall-Palmer: $Z = 200\ R^{1.6}$

A user can also specify custom values for a and b coefficients.

Correction for hail. Occasionally, the hail cores of thunderstorms may lead to unreasonable rainfall intensity by the empirical *Z-R* power law conversion. The *hail cap* threshold in the algorithm defines the maximum instantaneous rainfall intensity. The typical threshold value of the NEXRAD was defined as 104 mm/h corresponding to 53 dBZ (Fulton et al. 1998). In Hydro-NEXRAD these are the default parameter but the user can specify other values.

3. Rainfall accumulation

The last step of rainfall estimation is the integration of consecutive rain rate scans for specific time durations ranging from 15 minutes to daily in order to obtain rainfall accumulation. The rainfall accumulation computations in Hydro-NEXRAD mimic real-time calculations of the PPS, and involve (optionally) advection correction.

Advection correction. The procedure applied in Hydro-NEXRAD is based on the basic approach first proposed by Fabry et al. (1994). For every two consecutive volume scans converted to Cartesian domain a velocity vector is calculated using a cross-correlation method. The assumptions used (constant velocity of precipitation fields, and linear intensity change) are reasonable considering short (6-10 minutes) time interval between the scans. If certain criteria are met (non-zero velocity vector, existence of precipitation fields) velocity vectors can be used to generate interpolated intermediate volume scans. The default configuration allows generating precipitation fields with one minute interval. Such high temporal resolution provides significant improvement of the accumulation maps.

Integration of rate scans. A linear average between consecutive rate scans is applied to integrate rainfall amount based on 1° by 1 or 2 km polar grid. The integration for specific duration such as 15 minutes or 1 hour is summed after the period integration between two consecutive rate scans over 5~10 min. If the missing time exceeds 10% of the used-specified integration interval no accumulation product is generated.

4. Grid conversion and product merging

The NWS rainfall products are given on the HRAP grid with the spatial resolution of about 4 km. Since many applications require higher resolution, Hydro-NEXRAD provides several options for other grids. The requested products are specified for a latitude/longitude bounding box centered on the basin of interest, or for a specified radar umbrella, or for a user-specified arbitrary domain. The latitude/longitude bounding box defines a polar bounding box for each radar looking over the domain of interest. Only Level II data from the polar bounding box are processed in the generation of the rainfall products. Below we briefly discuss the grids and the related issue of merging data from multiple radars.

1. Grid conversion. Hydro-NEXRAD computes rainfall estimates based on a polar grid centered on the radar. The rainfall accumulation product should be remapped from the radar-centered grid to a projected grid for follow-on hydrologic applications. Using a projected grid can enable rainfall estimates to be mosaic-ed onto a common grid across the U.S. The NWS have developed a polar stereographic projection called the HRAP (Hydrologic Rainfall Analysis Project) grid. The HRAP is a quasi-rectangular grid and has a nominal grid spacing of 4 km × 4 km (Fulton 1998). The Hydro-NEXRAD provides the L-DAS, HRAP, and SHRAP (so-called Super HRAP) we have developed based on the HRAP algorithm (Reed and Maidment 1999) as a finer HRAP grid with nominal resolution of 1 km × 1 km.

2. Product merging. In many cases, multiple radars cover or partially cover a hydrologic unit represented by a watershed or basin. From a basin-centered point of view one needs to combine radar products of multiple radars. We are exploring reflectivity-based merging as well as accumulation-based merging.

5. Rainfall estimation options

As shown in Figure 2, Hydro-NEXRAD has four user-selectable options: *Quick Look*, *Hi-Res*, *Pseudo NWS PPS*, and *Custom*. The default *Quick Look* option has no AP and range correction for the quality control of reflectivity volume data, and no advection as well. Therefore, the run time of the *Quick Look* option is the shortest of all options. Conversely, all corrections are performed in the *Hi-Res* and it has the longest running time. The *Pseudo NWS PPS* enables expert users to select options they consider the best for a specific application.

Hydro-NEXRAD allows the hydrology user to think in terms of rainfall requirements, and not be burdened by radar-rainfall issues. Proper addressing of many of these issues requires considerable expertise and experience in the physics of radar observational process, radar hardware issues, radar data processing, and estimation (i.e., uncertainty) issues. Expecting all hydrologic users to have such expertise is not reasonable. Hydro-NEXRAD aims to shield users whose focus is on hydrologic processes from the details of radar-rain-fall estimation. At the same time, expert users may specify many of the parameters according to their experience and expectation. Still, there are many choices algorithm designers and programmers made both in the PPS and the Hydro-NEXRAD algorithms that while scientifically not fundamental might affect the outcomes. Discussing all those situations is beyond the scope of this paper.

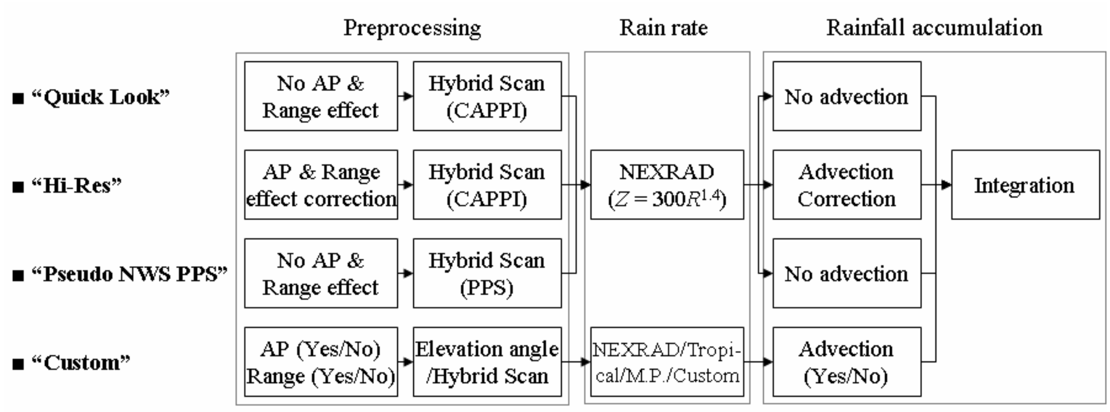

Figure 2. Rainfall estimates options of the Hydro-NEXRAD.

Testing and Evaluation

In this section we briefly discuss the testing and evaluation for the rainfall estimates of Hydro-NEXRAD considering the main algorithm options as shown in Figure 2 and the temporal resolution of the product. We show results related to the 15-minute and 1 hour rainfall accumulation for the *Quick Look* and the *Pseudo NWS PPS* using an event of October (1998) from the Oklahoma City WSR-88D (KTLX). The grid system used in this test is Super-HRAP.

The 15-minute products (Figure 3) and 1-hour product (Figure 4) shows a convective storm event. Both products demonstrate that the removal of ground clutter is necessary at the close range from the radar, even though the hybrid scan is applied to reduce the effect of ground clutter in both products. The maximum difference of the rainfall estimates between the *Quick Look* and the *Pseudo NWS PPS* was about 10 % of its maximum rainfall amount (59.8 mm) for the 1-hour accumulation. In case of the HRAP grid, the difference was about 5 % because of the smoothing effect of the larger size of the grid. The *Pseudo NWS PPS* option allows us to compare NWS product with our quick and simple radar-rainfall estimate products.

A comprehensive testing and comparison of all the different options available in Hydro-NEXRAD is well beyond the scope of this short article. Also, addressing the issue of "which algorithm is the best" is difficult and we refer an interested reader to Ciach and Krajewski (1999) and Krajewski and Smith (2002).

Summary

We did not elaborate or emphasize, due to the limited scope of this publication, a significant scientific and practical challenge the merging of data from multiple radars presents. While there are many ad-hoc methods a scientifically sound approach should have its base in the uncertainty of the merged components. These components could be basic reflectivity data or the commensurate products from different radars. Perhaps the most significant practical obstacle is the fact that the WSR-88D radars are not cross-calibrated. That is adjacent radar exhibit relative biases even for common targets (i.e. storm cells).

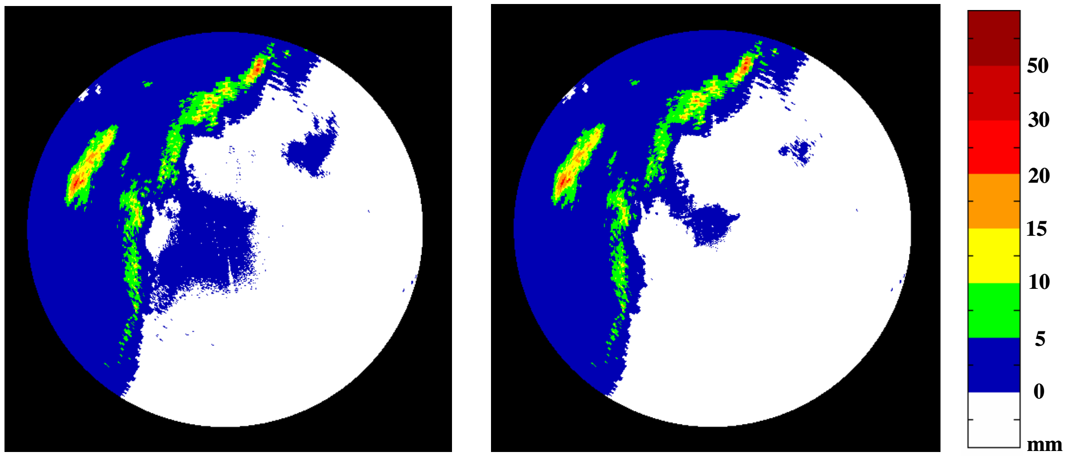

Figure 3. 15-minute products for *Pseudo NWS PPS* (left) and *Quick Look* (right) ending at 0845 UTC 2 Oct. 1998 from the Oklahoma City, OH (KTLX).

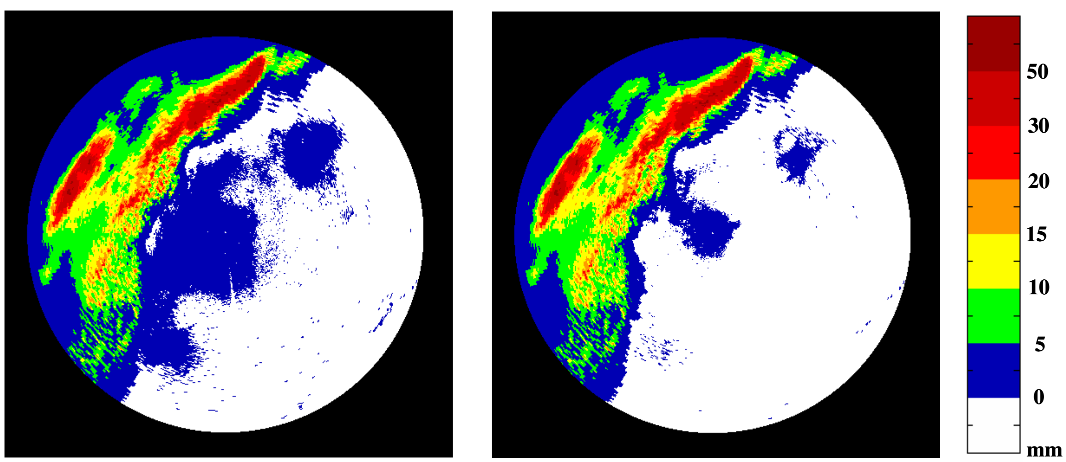

Figure 4. One hour products for *Pseudo NWS PPS* (left) and *Quick Look* (right) ending at 0845 UTC 2 Oct. 1998 from the Oklahoma City, OH (KTLX).

There are many advantages of Hydro-NEXRAD algorithms structure for the hydrologic research and engineering community. Perhaps the most important one is the repeatability of the results. Two users who specify the same options in Hydro-NEXRAD will obtain exactly the same results. This is in contrast to the current practice where it is difficult to exactly reproduce the results published by others. The Hydro-NEXRAD system has a modular design and it is relatively easy to add another option as module to the system. For example, one could add different AP detection, range correction, or advection correction algorithms. Therefore, Hydro-NEXRAD has the potential to represent a community resource for the future development of radar-based rainfall estimation. While there are many issues that are included in Hydro-NEXRAD that we have not discussed herein (e.g., radar observations in complex terrain), we hope that this short communication introduces the hydrologic community to the system designed to serve its multiple needs.

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