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Hydro-NEXRAD-2: real-time access to customized radar-rainfall for hydrologic applications

Witold F. Krajewski, Anton Kruger, Satpreet Singh, Bong-Chul Seo and James A. Smith

ABSTRACT

Hydro-NEXRAD-2 (HNX2) is a prototype system that allows hydrologic users real-time access to NEXRAD radar data in support of a wide range of research. The system processes basic radar data (Level II) and delivers radar-rainfall products based on the user's custom selection of features such as spatial domain, rainfall product space and time resolution, and rainfall estimation algorithms. HNX2 collects real-time, unprocessed data from multiple NEXRAD radars as they become available, processes them through a user-configurable pipeline of data-processing modules, and publishes the processed data-products at regular intervals. Modules in the data-processing pipeline encapsulate algorithms such as non-meteorological echo detection, radar range correction, radar-reflectivity-rain rate (Z-R) conversion, echo advection correction, mosaicking of products from multiple radars, and grid projections and transformations. This paper describes the challenges involved in HNX2's development and implementation, which include real-time error-handling, time-synchronization of data from multiple asynchronous sources, generation of multiple-radar metadata products, and distribution of products to a user base with diverse needs and constraints. HNX2 publishes products through automation and allows multiple users access to published products. Currently, HNX2 is serving near real-time rain-rate maps for Iowa in the USA using data from seven radars covering the state. Hydrologic models operated by The University of Iowa's Iowa Flood Center use these products.

Key words | Hydro-NEXRAD, NEXRAD, real-time rainfall estimation, super-resolution

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INTRODUCTION

Rainfall quantities are vital information for the monitoring and forecasting of extreme hydrologic events and for planning and managing water resource systems. Accurate rainfall estimation with adequate space and time resolution is an essential prerequisite for the prediction of hydrologic processes (e.g., Habib *et al.* 2008; Collier 2009; Germann *et al.* 2009; Villarini *et al.* 2010). Weather radars offer spatially extended rainfall information with spatial resolutions as high as ~250 m and with time frequencies as short as 5 min (e.g., Istok *et al.* 2009; Seo & Krajewski 2010).

However, availability of such high-resolution radar data for hydrologic research is often limited due to restrictions imposed by the radar system operators, or a lack of database organization. In the USA, all 'raw' data (Level II data) and some very basic products are available post-factum from the National Climatic Data Center (NCDC). In real-time, Level II data are available from the Unidata Program Center of the University Corporation for Atmospheric Research (UCAR).

In this paper, we describe a prototype system called Hydro-NEXRAD-2 (HNX2), which was developed to provide the hydrologic research community convenient access to customized radar-rainfall products in near real time. The system builds on the experience and software

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components developed in Hydro-NEXRAD (Krajewski *et al.* 2011a; Kruger *et al.* 2011; Seo *et al.* 2011). Herein, to distinguish the two systems, we will call the original Hydro-NEXRAD system Hydro-NEXRAD-1 (HNX1). HNX1 is a 'browser-enabled software' that allows users to request radar-rainfall maps with custom selections for data period, spatial domain, estimation algorithms, and product resolution. The system uses NEXRAD Level II (e.g., Fulton *et al.* 1998) data to generate product maps and delivers rainfall maps with resolutions as high as 5 min and 1 km. This is higher than the commonly used map resolution (hourly and a fixed ~4-km grid) provided by the US National Weather Service (NWS). The National Mosaic and Multi-sensor QPE (NMQ) system (Zhang *et al.* 2011) provides radar-rainfall product with 2.5-min and 0.01° (approximately 1-km) resolution. The NMQ system uses some inventive estimation algorithms (e.g., bright band identification and storm type classification using the structure of vertical profile of reflectivity) to improve rainfall product quality. The NMQ product covers the entire US, implying that users must extract data for the domain of their interest, and provides no user-selectable option for the rainfall estimation algorithm and product resolution. On the other hand, HNX1 provides the flexibility afforded by starting with the most basic, i.e., Level II data, while making the task of creating customized rainfall products as easy as just a few clicks. Using the system requires no radar expertise, is highly intuitive, and offers repeatable results, which may not be available for other products.

Many studies (e.g., Ntelekos *et al.* 2008, 2009; Rosenzweig *et al.* 2008; Mandapaka *et al.* 2010; Villarini & Krajewski 2010; Krajewski *et al.* 2011b; Seo & Krajewski 2011; Smith *et al.* 2012) have benefited from HNX1. However, the NEXRAD Level II data format changed around the middle of 2008 to accommodate new super-resolution data (Istok *et al.* 2009), and this change marked the closing of HNX1's database that is static. Thus, the system works of the database is static in space and time (for details see Krajewski *et al.* 2011a).

HNX2 addresses the super-resolution data format issue, removes the spatial and temporal domain limitations, and also provides new real-time capabilities. A user can set up, via a web browser-based graphical user interface (GUI), a customized feed that will then deliver customized products that the user can input into hydrologic models running in near real time. Providing real-time access to customized radar-rainfall products using enhanced data spatial resolution (up to 250 m) represents a paradigm shift in hydrologic prediction that is particularly significant for urban hydrology. Rainfall variability at the time and space scales provided by the new super-resolution capabilities of the WSR-88D radar system is important for examining urban flood hazards, urban water balance, and biogeochemical cycling in urban environments (see e.g., Javier *et al.* 2007; Smith *et al.* 2007; Ntelekos *et al.* 2008; Rosenzweig *et al.* 2008).

HNX2 can provide high-quality rainfall products in a flexible manner. Users can configure HNX2 to deliver rainfall products specifically tailored for their application. They can specify radar data quality control options (e.g., non-meteorological target identification and removal), desired map projections, the data format, and the accumulation interval. HNX2 provides its products in near real time (we will explain this further), and users can integrate the products into various forecasting models.

This paper is structured as follows. In the section below, we briefly describe the HNX1 system that is the basis for the current enhancements. The next section documents three major improvements/changes in HNX2: real-time capability, the removal of space and time coverage limitation, and adaptation to super-resolution. The following section illustrates the overall architecture of the system and the functionality of all internal components. Then, we present and briefly describe rainfall estimation algorithm options that are used by the main (currently) user of HNX2, i.e., a browser-accessible Iowa Flood Information System (IFIS) to feed rainfall information to the flood forecasting system in real time. The final section summarizes the main features of the system and discusses its limitations and future.

SUMMARY OF HNX1

HNX1 is a prototype research software system that offers hydrologists easy access to NEXRAD radar-rainfall estimates with user-customized algorithms and user-selected space and time resolutions. A key aspect of the system is its use of well-defined and pre-computed metadata (see Kruger *et al.* 2011) managed in a relational database that provides quicker access to the data required for further processing. Another significant aspect, from the hydrologic point of view, is that basin-centric rainfall maps based on the United States Geological Survey (USGS) Hydrologic Unit Code (HUC; Seaber *et al.* 1987) can be generated upon a user's request through a web browser-based GUI and then delivered to users.

The main features of the system are characterized by: (1) the use of an efficient Level II data format (ASCII Run Length Encoding; see Kruger & Krajewski 1997) that significantly reduces data storage and reading time; (2) a relational database that links the user's request with data storage and information (see Kruger *et al.* 2006); (3) radar- and basin-centric metadata, organized in the relational database, that provide Level II data file descriptions and locations as well as some hydrological statistics which assist users in finding important rainfall events for their studies (see Kruger *et al.* 2011); (4) modular rainfall estimation algorithms that allow users to select a customizable or predefined (i.e., Quick Look, Hi-Fi, and Pseudo NWS PPS) algorithm combination (see Seo *et al.* 2011). While the Quick Look is the fastest algorithm with no correction of the negative effects of radar error sources for reflectivity processing, all corrections (i.e., anomalous propagation (AP), advection, range effects) that are available in the HNX2 system are performed in the Hi-Fi algorithm. The Pseudo NWS PPS is the Hydro-NEXRAD implementation of the US NWS Precipitation Processing System algorithm (see Fulton *et al.* 1998); (5) utilities that generate final products with various space and time resolutions for further hydrologic applications; and (6) a web browser-based GUI that interacts with the database and algorithm components. For more specific and detailed information on the structure and components of the HNX1 system, refer to Krajewski *et al.* (2011a), Kruger *et al.* (2011), and Seo *et al.* (2011).

ENHANCEMENTS IN HNX2

Real-time capability

In the USA, real-time weather radar data are available to non-government users through a commercial distribution subscription system or by a real-time radar-rainfall data feeding system such as HNX2. Real-time accessibility of radar Level II data is the most crucial factor to the design and construction of the system. Fast real-time acquisition of these data enables immediate production of radar-rainfall estimates for hydrologic forecasting and applications.

Although NEXRAD data are accessible from the NCDC archive, Level II data files in the archive are only available after a 24-h delay from the point of data creation. This delay effectively excludes it from being considered as a viable source for our application. Therefore, we used the Unidata Program Center of the UCAR to obtain Level II data. The Unidata distributes geoscience data using the Local Data Manager (LDM) software in near real-time over the Internet Data Distribution (IDD; http://www.unidata.ucar.edu/software/idd/overview/idd.html).

The challenge of adding real-time capability lies in combining the user-friendliness of HNX1 with the proven efficiency of the Unidata LDM/IDD data delivery system. To address this challenge, we developed a simplified version of the HNX1 GUI using a web browser that allows users to place their (standing) order for specific real-time rainfall products. Simplification in the GUI results from users not having to interface with the metadata displays that are used to select period of interest. The interface defines a job configuration that will: (1) reconfigure the LDM system in Iowa to receive Level II data from the radar of the user's choice; (2) invoke appropriate algorithms to compute user-specified products at the required grid and time resolution and for the required location (basin, radar umbrella, or an arbitrary lat/lon box) while merging data from multiple radars, if necessary; and (3) deliver the products through an assigned URL.

Removal of space and time coverage limitation

A straightforward method to remove the spatial and temporal coverage limitation of HNX1 (40 radar sites and 5 years) would be to add all Level II data, for all radars, to the database. While possible, this is an expensive solution. It would also duplicate the NCDC national archives. A logical alternative is to bring the HNX1 capabilities to NCDC, though this is also difficult. First, metadata for all radars and basins would have to be calculated at NCDC. Second, NCDC would have to maintain the set of algorithms used in HNX1 to create customized products. It is simply not in their mission to do that.

In HNX2, the system connects to the Unidata LDM/IDD system and attains required Level II data once a user selects basin or radar locations that are covered by the US NEXRAD network. When the data are available in the local LDM, the data are converted to products according to a user's specification, and the products are delivered to users. The main loss of functionality is an inability to browse the metadata. Corrupted Level II data files that cannot be used are discarded or restored in the harvesting procedure (we will elaborate on this in the section dealing with system architecture). Since the HNX2 system provides only near real-time products, and not historic data-products, temporal coverage is not a matter of concern as it is in HNX1.

Adaptation to super-resolution

Radar Level II data are organized as a three-dimensional volume structure using a conical plane (spherical polar coordinate system) represented by the azimuth, range (distance from the radar), and elevation angle. Each Level II data file contains radar reflectivity and Doppler information (radial velocity and spectrum width). The number of elevations/scans in a volume scan data and the temporal span of volume production are subject to the Volume Coverage Pattern (VCP), which depends on the local weather conditions (see e.g., Crum & Alberty 1993; Fulton *et al.* 1998). In the super-resolution Level II data, the lowest three elevation angle data, generally called 'split cuts', are collected with a radar sampling resolution of 0.5° in azimuth and 250 m in range. The legacy-resolution format (1° by 1 km) was still used for higher elevation angle data, called 'above cuts', until October 2010. However, the sampling resolution for the above cuts has changed with the ongoing dual polarization upgrade and is currently 1° by 250 m (see details at http://www.roc.noaa.gov/WSR88d/DualPol/DPLevelII.aspx).

The documentation on new data and their format exists in the form of a source code called CODE, which is an algorithm development environment for the NEXRAD system. As such, its use is cumbersome and, unfortunately, no stand-alone version of the data reading code exists (e-mail correspondence with Mike Istok, NOAA, CODE manager). To incorporate all resolution-related changes that have been made after the super-resolution upgrade into the HNX2 environment, we developed a piece of code to read the new data format and to transfer the volume data structure into the rainfall estimation modules using the National Aeronautics and Space Administration (NASA) Radar Software Library (RSL; http://trmm-fc.gsfc.nasa.gov/trmm_gv/software/rsl/). We also modified the rainfall estimation algorithms and all other codes, as appropriate, to use the new super-resolution data. For some radar locations where the dual polarization upgrade has been completed, our modules are also compatible with the Level II data that contain information on the dual polarization variables. As the availability of new super-resolution data presents an important opportunity for the hydrologic community to investigate the high variability of rainfall–runoff generation processes (e.g., Dabberdt *et al.* 2000; Smith *et al.* 2007), the product resolution of HNX2 is provided in as high of a grid spacing as $0.5 \times 0.5\ \mathrm{km}^2$.

SYSTEM ARCHITECTURE

HNX2 is a system that collects real-time radar Level II data from single or multiple NEXRAD radar sources, processes them through a series of data-processing modules (which are configured on the basis of the user's selections), and then publishes the processed products so that they are accessible to the user. In many ways, HNX2 is similar to the HNX1 system, with the major differences being that user-requested rainfall products are generated continuously in near real-time and that no metadata search is possible (because no archival radar data are stored in the system). The presented system architecture is divided into three sections: frontend, backend, and database. Figure 1 shows a simplified view of the HNX2 architecture.

Frontend

The term 'frontend' refers to the interface with which users set up new feeds or stop existing feeds as well as the

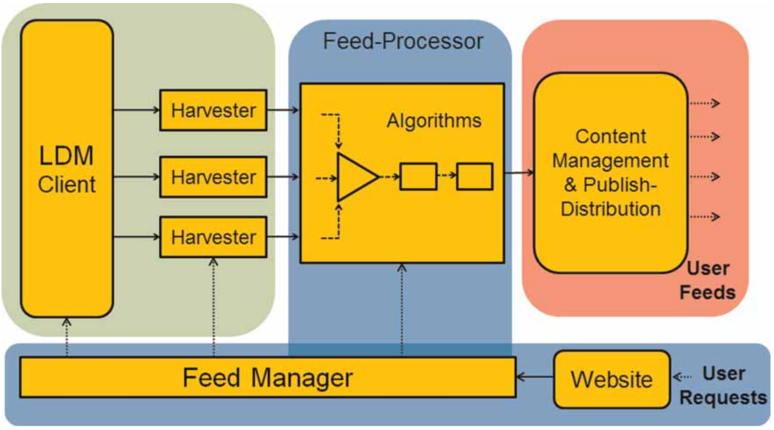

Figure 1 | The internal structure of HNX2: Users use the web browser-based GUI to select spatial constraints (basin/radar-coverage area) and parameters (algorithms, grid, and output format) to set up a feed. The GUI passes this request on to the feed manager which configures the rest of the system to produce the new feed. The feed processor is invoked at regular intervals and is responsible for the generation of new products. Upon each invocation, it looks for new radar files that are made available to it through the LDM/harvesters setup and then passes these files through a pipeline of processing modules. Generated products are put on a web-accessible product delivery interface for the user to collect.

interface used to access data from the feeds that were already set up.

For HNX2, we developed a new GUI that is very similar to the one in the HNX1 system but without the metadata browsing component. The GUI is accessible over the Internet and allows users to log in and configure customized real-time rainfall product feeds for their location of interest. The GUI enables users to choose between radar-centric and basin-centric rainfall product feeds. Additionally, users can select a spatial domain using a map-based interface (Figure 2), time and space resolution of the rainfall products, product type (e.g., reflectivity, rain rate, or accumulation maps), rainfall estimation algorithm (predefined or custom), merging scheme (product-based or data-based) if necessary, and the output file format. For detailed information on rainfall estimation algorithms and merging

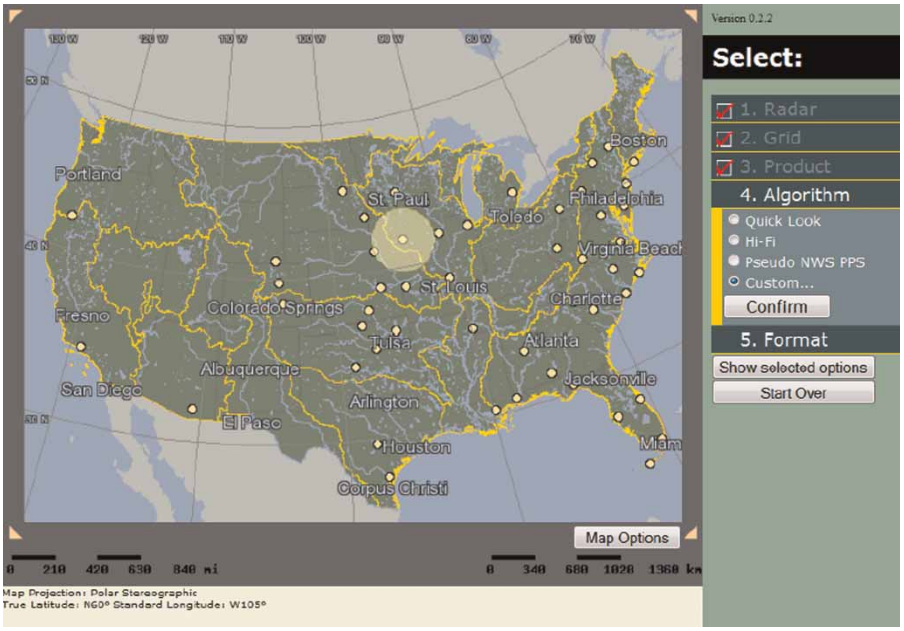

Figure 2 | Snapshot of the HNX2 GUI showing the feed setup interface.

schemes, refer to Seo *et al.* (2011). Figure 2 shows a snapshot of the HNX2 GUI for the real-time feed creation and customization. After selecting the required options, users can submit the configuration for the feed processing. Based on this, the GUI implements a new job in a processing machine by making an XML-RPC (e.g., St. Laurent *et al.* 2001) Remote Procedure Call (RPC). If the job submission is successful, users receive a URL where the requested products begin to appear. In the case of any error, an explanatory error message is returned to the user.

Backend

The backend consists of the following components, as shown in Figure 1: (1) the LDM/Harvesting that enables the system to acquire and use NEXRAD Level II data in real time from the Unidata IDD feed; (2) the feed manager that initiates the configuration of the feed processor and stops the feed processing when demanded; and (3) the feed processor that runs the harvested data through the pipeline of data-processing modules to generate user-requested rainfall products.

LDM/Harvesting

Once users define a spatial domain of interest, the LDM/IDD is configured to receive real-time streaming data for the required NEXRAD radars. Harvesting refers to all processing steps after raw radar-data files are received from LDM/IDD. The harvesting procedure provides error-free data files to the next stage in the pipeline, the feed processor. A harvester takes Level II data files from the LDM/IDD, checks and discards unusable files, and converts usable files into a format that is readable by the data-processing and rainfall estimation modules in the feed processor. The harvesting procedure also includes the recovery of partially packed data due to network losses. Depending on whether the feed is configured for single or multiple radars, one or more harvesters deliver the data to the feed processor. Figure 3 illustrates the harvesting process, and we present details of the process below.

Since the file format of LDM-received data is not compatible with the rainfall estimation modules that use the NASA RSL to read and manipulate radar volume scan data, an additional step is required to convert the file format. This step decompresses the packed data received through LDM/IDD into an uncompressed format that is RSL-readable. Some files acquired through the LDM/IDD are incomplete or damaged due to network instability or other random losses. In such cases, this conversion step fails, and a subsequent conversion step is needed to recover the partially packed data. Based on our preliminary observation for the transferred data completion, with the assistance of Unidata, we found that a significant proportion of the error rate (approximately 15%) could be recovered by a partial-file recovery procedure (see Singh 2010).

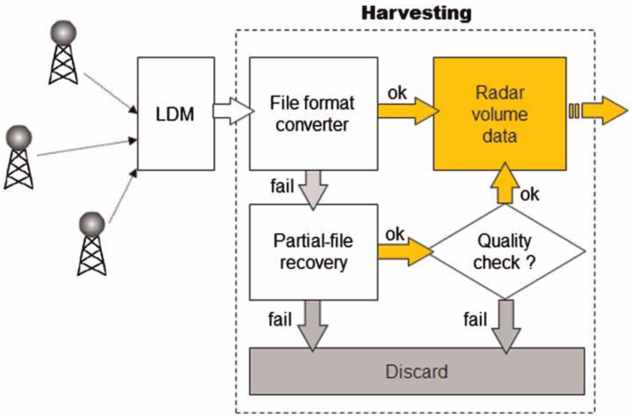

Figure 3 | Harvesting procedures in the HNX2 system.

To evaluate the usability of the recovered data, we considered the structure of the radar volume data. Since our quantitative radar-rainfall estimation does not require the full information of radar volume data, the quality-check step in Figure 3 inspects the completeness of radar reflectivity rays in several of the lowest elevation angle scans. If the minimum number of reflectivity rays required is satisfied, the entire volume file is marked as usable and forwarded to the next stage in the pipeline. As a result of this data quality check, the data availability and the error rate were significantly reduced to approximately 1.5% (see Singh 2010).

Feed manager

The feed manager is a multi-threaded Python application with an XML-RPC (see e.g., St. Laurent *et al.* 2001) server running on one independent thread. The XML-RPC server enables requests coming from the GUI and provides procedures that configure new feeds or stop existing feeds. The XML-RPC provides a well-defined interface between the GUI and backend using a well-known protocol.

The feed manager starts a new feed according to the following steps:

- Receives a well-formed XML-RPC request from the GUI.
- Creates a web-visible directory where the feed products will be available.
- Gathers relevant radar-centric and basin-centric metadata (e.g., radar site latitude/longitude and basin bounding-box) from the database.
- Creates a feed configuration file that encapsulates information for a feed processor to process data and generate the product.
- Inserts one or more entries into the local crontab for cron (see e.g., Sobell 2012) to schedule the recurrent execution of the feed processor.
- Inserts a new feed record into the application database.
- Returns the URL corresponding to the web-visible directory where the feed's generated products will be available. If any of the above steps fails, returns an error message.

Stopping an existing feed involves the following steps at the backend:

- Receives a XML-RPC request from the GUI.
- Checks for the presence of a record entered into the database for the existing feed. If it is not available, returns an error message. If available, performs the remaining steps.
- Removes the database record, crontab entry, and files and directories associated with the feed.
- Returns an 'OK' message to the GUI. If any of the above steps fail, returns an error message.

Feed processor

The feed processor is an autonomous component that is repeatedly executed using the UNIX cron mechanism (see e.g., Sobell 2012) to generate user-customized rainfall-data products. Based on the feed configuration created by the feed manager, the feed processor finds the latest files available for the radars specified in the configuration. It feeds these files as inputs to a pipeline of preprocessing modules followed by a series of algorithmic modules to generate the new products. These modules are concerned with time-synchronization of data streams from multiple radars, rainfall estimation, and grid conversion algorithms similar to those used in HNX1 (see Seo *et al.* 2011). Some algorithmic components of the modules used for our main user, the IFIS, are described in the next section. Most modules are written in C, and Python scripts are used to organize, combine, and run the modules. Once the processes defined in the feed configuration are complete, the feed processor deposits and publishes the generated products to a web-accessible location for the user to access and acquire the data.

Database

In HNX2, unlike in HNX1, an extensive database of metadata for basins and radars is not available for browsing prior to placing a data request. The HNX2 database allows the system to connect several components such as GUI, feed manager, and harvesters.

Using the database, the GUI authenticates users into the system, obtains the list of currently active user accounts and feeds, attains the list of processing machines, and inserts new user account information. The feed manager creates new or existing feed data and retrieves basin and radar metadata (e.g., basin bounding box) for the feed configuration. Harvesters acquire the list of processing machines and information on where the harvested data should be deposited from the database. Since HNX2 has been designed to serve for an arbitrarily large number of user feeds, the system is scalable (eligible to add new machines) in both LDM/IDD and feed processing. The system administrator can monitor the load on each machine in the system and make pre-emptive scaling decisions before the system gets overloaded. Consequently, the database has tables for user accounts, feeds, processing machines, and radar and basin metadata.

CUSTOMIZED RAINFALL ESTIMATION ALGORITHM

Since re-elaborating all of the algorithms related to radar-rainfall estimation that were developed in HNX1 is not in the scope of this presented effort (but most algorithmic modules were adapted to use the super-resolution data in

HNX2), we introduce a prototype of the customized rainfall estimation algorithm that has been used in the IFIS system and briefly describe its algorithmic components in Figure 4. Full descriptions on the radar-rainfall algorithms can be found in Seo *et al.* (2011).

Generating real-time rainfall inputs is a fundamental step for hydrologic forecasting. Radar-rainfall map production in the system involves several independent and optional modules that perform radar reflectivity data processing, merge multiple radar data onto pre-defined common spatial and temporal domains, and transform radar-measured reflectivity to rainfall amounts (rain rate/accumulation), as shown in Figure 4. For the IFIS, HNX2 provides real-time radar-rainfall maps (i.e., radar reflectivity, rainfall rate/intensity, and rainfall accumulation) for the State of Iowa in the US. To cover the entire state, the Level II data from seven WSR-88D radars (KDVN in Davenport, Iowa, KDMX in Des Moines, Iowa, KARX in La Crosse, Wisconsin, KMPX in Minneapolis, Minnesota, KOAX in Omaha, Nebraska, KFSD in Sioux Falls, South Dakota, and KEAX in Kansas City, Missouri) are collected and processed.

Removal of non-meteorological target

The three-dimensional structure of radar volume data allows the detection of non-precipitation echoes (e.g., ground clutters) by estimating the likelihood of AP conditions. The procedure proposed by Steiner & Smith (2002) is used to construct a two-dimensional AP map. The binary mask map is created using the horizontal and vertical radar echo structure that is assessed for the computation of AP occurrence. After applying this AP procedure of radar data quality control, a two-dimensional radar reflectivity map is generated using the kernel weighting proposed in Seo *et al.* (2011).

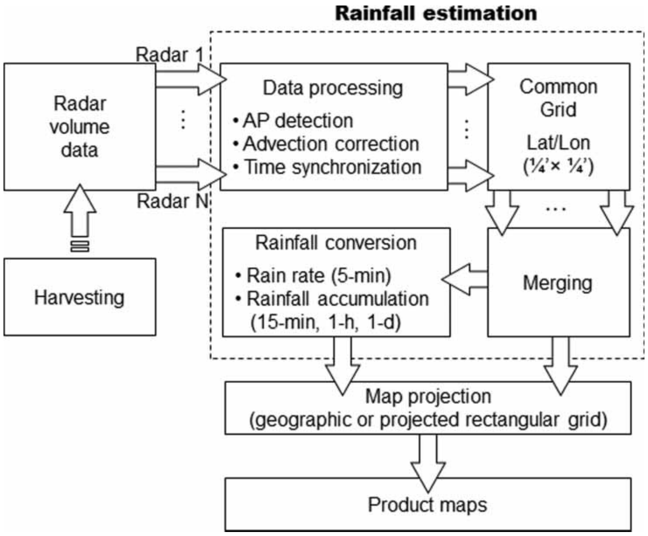

Figure 4 | Structure and flow of the rainfall estimation algorithm in the Iowa Flood Information System.

Time synchronization

Radars in the NEXRAD network operate independently and are not synchronized in time. To merge data from multiple radars, it is necessary that data be available for the same common time-stamp from all radars in consideration. In HNX2, such files are generated by interpolating two adjacent (in time) radar data files (see Seo *et al.* 2011). The interpolation can be done by using an advection procedure (see section Advection correction below) or exponential weighting function that describes time separation of two radar data files from 5-min common time-stamps. Once interpolated files from all radars are available for the common time-stamp, a module generates a merged file which can then be passed on to the later steps of the processing pipeline. For the production of 5-min rainfall maps, interpolated files that are generated for all radars are aligned with a 5-min time-boundary. For example, if radar data files for time-stamps 10:03 and 10:07 are available, then an interpolated product will be produced for time-stamp 10:05 (see Figure 5). Figure 5 illustrates the interpolation and merging processes for multiple radars operating in either scanning mode.

Advection correction

The intermittent sampling span of radar observation, which is dependent on the VCP that typically ranges from 4 to 10 min, could cause a significant radar-rainfall accumulation error. The approach proposed by Fabry *et al.* (1994) is applied to generate radar reflectivity fields at a nominal time stamp (i.e., every 1 min) using computed velocity vectors from two (prior) consecutive reflectivity maps. Another benefit of using this module is that advection

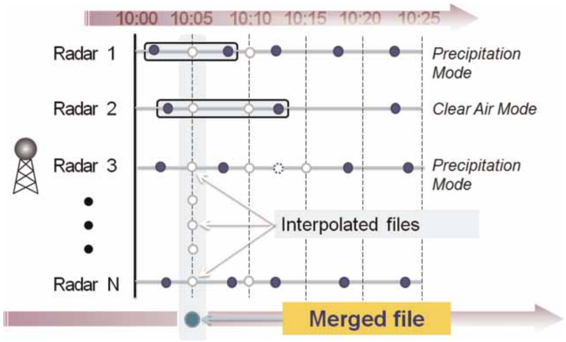

Figure 5 | Synchronization of multiple radar data for generation of merged products: Horizontal lines have markers representing the times at which the radar data are received from individual radars. Merging files are generated at nominal times (:00, :05, :10,…) by interpolating radar-data files that are adjacent in time. Nominal-time files can be merged to create a single merged file.

enables time-synchronization of radar data among the seven radars producing volume scan data at different time-stamps. If the advection module is inactive due to its considerable processing time, the weighting function described in the section above (Time synchronization) is used for the time-synchronization of radar data.

Common grid transformation

The radar-centered two-dimensional reflectivity fields represented by radial azimuth and range are remapped onto a common lat/lon geographic grid (approximately $0.5 \times 0.5\ \mathrm{km}^2$) before merging individual fields from seven radars into a single field. The transformation module assigns a reflectivity value of the nearest (original) polar pixel to a corresponding lat/lon pixel. Since the resolution of the common geographic gird is somewhat comparable to that of the polar grid ($0.5^\circ \times 0.25$ km), an averaging scheme is not considered for the common grid transformation. Such high resolution of rainfall products is compatible with the spatial scale of the hydrologic model the Iowa Flood Center uses for flood forecasting. The geographic coordinates do not cause distortion arising from map projection, and are easy to transform into any projected coordinate system.

Multiple radar data merging

With a common spatial basis, all available individual reflectivity maps (sometimes, data from some radars are missed due to radar maintenance or network delay/loss) are merged into a single reflectivity field. For Level II data reception and the generation of time-synchronized products, the waiting interval specified in the HNX2 system due to unexpected network delay is 25 min (see Singh 2010). If data from certain radars do not arrive within this time frame, only available time-synchronized reflectivity maps are delivered to the merging module. Each individual field is spatially combined using range-dependent weights that are estimated by the double exponentially decaying function (see Seo *et al.* 2011).

Z-R conversion and rainfall accumulation

To convert a merged radar reflectivity field ($\mathrm{mm}^6/\mathrm{mm}^3$) to rainfall rate (mm/h), we apply a typical power law relationship ($Z = 300R^{1.4}$) used for the WSR-88D radars (e.g., Fulton *et al.* 1998). Since two parameters of the above equation are adaptable, a user can specify other values for those parameters according to precipitation types (see e.g., Marshall & Palmer 1948; Rosenfeld *et al.* 1993). Rain rate maps generated every 5 min are integrated to publish rainfall accumulation maps over specific time durations (15 min, 1 h, and 1 d). The final product map can be generated using a user-specified map projection (for map projection options, see Seo *et al.* 2011) as shown in Figure 4.

SUMMARY AND DISCUSSION

There are three major improvements in HNX2 that differentiate it from HNX1: (1) real-time capability, (2) no space and time limitation, and (3) adaptation to the super-resolution data. The real-time streaming of Level II data is available via the Unidata LDM/IDD system. Real-time rainfall products can be requested through the simplified GUI that connects a user's request with the procedures that configure a required job processing. Configurable algorithmic-processing modules read and process the super-resolution data and generate rainfall products based on user-selected options. The generated products can be accessed in the assigned URL.

HNX2 can significantly impact the cyber infrastructure of the hydrologic community as well as the environmental engineering community since rainfall is a key driver in many processes that are important to these communities. However, researchers currently have essentially two unappealing options: (1) use inadequate existing products (in terms of resolution or processing algorithm) generated by the US national agencies, or (2) generate their own rainfall products from the Level II data. However, Hydro-NEXRAD provides high quality rainfall products to diverse users: non-experts, students, researchers in rainfall estimation, and environmental engineers. Products are available for case studies (e.g., HNX1) or in a real-time manner (e.g., HNX2) for incorporation into hydrologic and environmental forecast models. It is important to recognize that Hydro-NEXRAD builds upon and enhances the existing infrastructure: the NEXRAD archive at NCDC and the UCAR/Unidata real-time NEXRAD feed via the LDM/IDD.

Hydro-NEXRAD allows us to investigate numerous aspects of the problem of radar-rainfall uncertainty estimation. Dependence of estimation errors on rainfall magnitude, distance from radar, spatial and temporal separation, and scale all require a more extensive quantitative description. We will continue research on evaluating Hydro-NEXRAD rainfall products and providing statistical descriptions of radar-rainfall uncertainty and its reduction by improving estimation algorithms. Hydro-NEXRAD is the main vehicle to establish radar-rainfall accuracy limits and validation methodologies and to investigate the effects of rainfall climatology on rainfall estimation uncertainty.

The modules of HNX2 are compatible with the Level II data that contain a recent upgrade of dual polarization, implying that there is no alternation in rainfall estimation algorithms and product quality affected by the upgrade. The modules currently neglect to read and use the new variable blocks (differential reflectivity, correlation coefficient, and differential phase). As use of the new variables offers the potential to improve rainfall product quality, for example hydrometeor classification, detection of bright band and anomalous beam propagation, we will need to investigate, develop, and add modules in order to benefit from the dual polarization data.

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