

High-resolution Radar Data and Products over the Continental United States

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Abstract

The Warning Decision Support System – Integrated Information (WDSS-II) is capable of ingesting WSR-88D data in real-time from all of the available Continental United States (CONUS) radars and combining the information with data from the RUC2 model, lightning detection network, and GOES satellite imagery to create severe weather diagnostic products. These products include parameters such as the probability of severe hail (POSH), reflectivity composite, echo tops, vertical integrated liquid (VIL), storm cell tracking, rotation tracks, lightning density and short-term forecast fields. Since these products are computed from data from multiple radars and other sensors, they are of better quality than their single-radar counterparts. Also, these products are available as latitude-longitude grids covering large spatial areas. Consequently, they are also much easier for researchers and end-users to work with.

In the CONUS-wide real-time system that we describe here, the radar products are rapidly updated every 2 minutes from elevation scans as they arrive from any radar in the country. The resulting products are at a resolution of approximately 1km x 1km x 1km. These products can be disseminated as GeoTiff, NetCDF and/or Grib2 files for easy incorporation into other decision-support and visualization systems.

1. Introduction

The Weather Surveillance Radar 1988 Doppler (WSR-88D) network now covers most of the continental United States, and full-resolution base data from nearly all the WSR-88D radars are compressed using block encoding (Burrows and Wheeler 1994) and transmitted in real-time to interested users (Droegemeier et al. 2002). This makes it possible for clients of this data stream to consider combining the information from multiple radars to alleviate problems arising from radar geometry (cone of silence, beam spreading, beam

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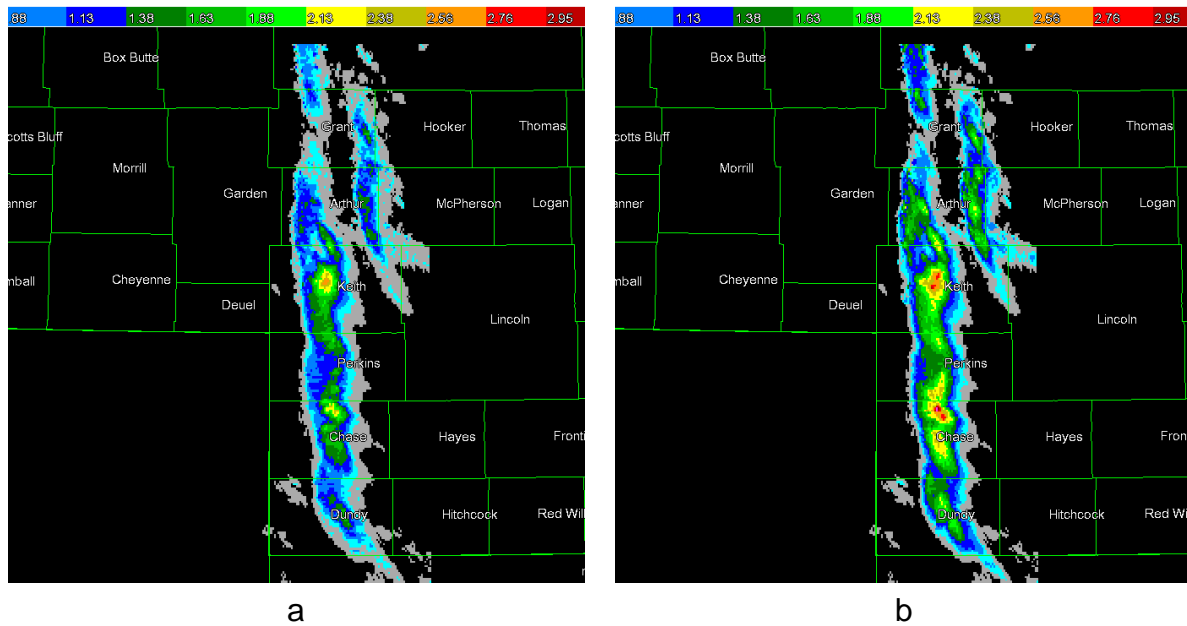


Figure 1: Maximum expected size of hail in inches, calculated from reflectivity at various temperature levels. The temperature levels were obtained from the Rapid Update Cycle (RUC) analysis grid. The radar reflectivity was estimated from KFDR, KAMA, KLBB and KFWS on 03 May 2003. (a) Without advection correction. (b) With advection correction. When advection correction is applied, the cores of the storms sensed by the different radars line up and the resulting merged products are less diffuse.

height, beam blockage, etc.) and radar outages. Greater accuracy in radar measurements can be achieved by oversampling weather signatures using more than one radar.

A combination of information from multiple radars has typically been attempted in two-dimensions. For example, the National Weather Service creates a 10 km resolution national reflectivity mosaic (Charba and Liang. 2005). In this paper, we describe a real-time method of creating a 3D combined grid because such a 3D grid is more suitable for creating severe weather algorithm products.

We summarize the technique described by Lakshmanan et al. (2005b) here. The input polar data are combined using virtual volumes (Lynn and Lakshmanan 2002), whereby an elevation scan from any radar replaces the data from that radar in an constantly updating grid. This yeilds a merged grid that has a theoretically infinitesimal temporal resolution. In order to be able to perform the 3D combination of data from multiple radars in real-time, the required weights are precomputed. The appropriate set of weights corresponding to a radar and elevation scan is loaded as needed. Since the precomputed weights are in a rectilinear coordinate system, the precomputed weights for a domain can be extracted from a larger domain at the same resolution. We therefore created a CONUS-sized pre-computed cache, taking beam-blockage and radar coverage patterns into account, and extracted the domain's precomputations on demand. Having thus combined radar reflectivity data from multiple radars into a 3D grid of reflectivity, we can apply severe weather algorithms to the 3D grid to create derived 2D products. Data sensed at earlier times are advected to the time of the output grid so as to resolve the storms better, as shown in Figure 1.

Using data from other radars helps mitigate radar geometry problems, achieve a much better vertical resolution, attain much better spatial coverage and obtain data at faster time steps. Figure 2 demonstrates a case where information on vertical structure was unavailable from the closest radar, but where the use of data from adjacent radars filled in that information. Using data from other sensors and numerical models would help provide information about the near storm environment and temperature profiles. Considering all the advantages of using all the available data in conjunction, and considering that technology has evolved to the point where such data can be transmitted and effectively used in real-time, there is little reason to consider products derived from single-radar reflectivity data for diagnosing severe weather potential or the likelihood of hail.

2. Architecture

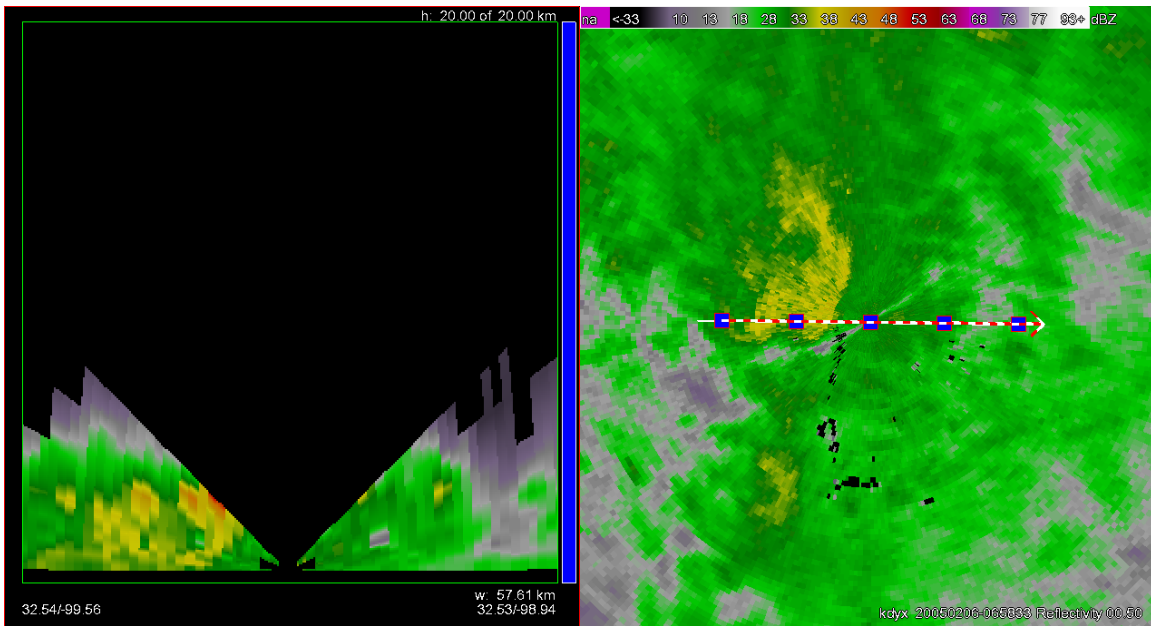
The Warning Decision Support System – Integrated Information (WDSS-II) provides a set of uniform Application Programming Interfaces (APIs) and a networking architecture based on that of the WSR-88D Open Radar Products Generator. The APIs are written using C++ and provide common data ingest, output, transformation and manipulation functionality to the WDSS-II applications (Lakshmanan 2002). The networking architecture is based on a single server applications daemon, called rssid, running on the hosts that make up the deployed application. The rssid daemon provides client processes with event notification and access to remotely hosted data files (Jain et al. 1998). Depending on the final products desired, and the hardware available, we have run the WDSS-II system in different configurations.

2a. CONUS 2D Products

The flowchart of the 2D CONUS system is shown in Figure 3. Data from the individual radars, RUC model and satellite are ingested and converted into the data formats used by the WDSS-II applications (netCDF and XML). The radar reflectivity data are quality-controlled using QCNN, the Quality Control Neural Network (Lakshmanan et al. 2005a), which is given additional environmental information in the form of surface temperature. QCNN also provides a composite field at the end of every elevation scan, computing the composites on a virtual volume basis. The single-radar composite products (ReflectivityQComposite) are fed into the merger (Lakshmanan et al. 2005b) which produces a 2D distance-weighted composite based on the latest radar data every 2 minutes. This composite field is subjected to a second level of quality control using information from a cloud cover field, computed from satellite data and surface observations (Lakshmanan and Valente 2004).

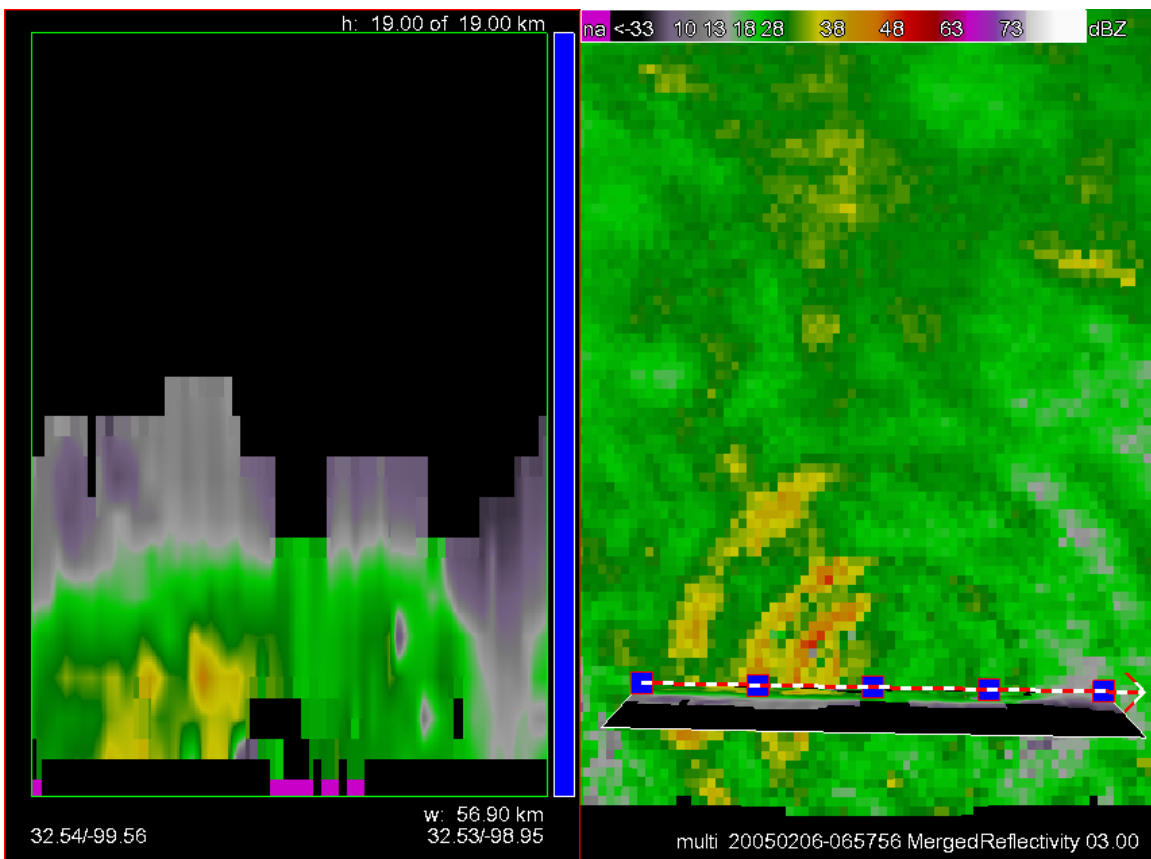
The 2D CONUS architecture provides the most basic algorithms to yield a national CONUS radar mosaic if no other severe weather products are desired. Other single-radar products (VIL, Hail diagnosis, echo tops, etc.) can be merged over a CONUS domain in a similar manner, but in this case the more full-fledged 3D architecture is recommended.

The radar ingest requires a dual 2.4 GHz Xeon processor with 4 GB RAM for every 30 (approximate) radars. In our real-time system, we use the same radar ingest machines for both the 2D products and for the 3D products (described in the next section). Therefore, these hardware specifications also include velocity processing. It is likely that



a

b



c

d

Figure 2: Using data from multiple, nearby radars can mitigate cone-of-silence and other radar geometry issues. (a) Vertical slice through full volume of data from the KDAYX radar on 06 Feb. 2005. Note the cone of silence – this is information unavailable to applications processing only KDAYX data. (b) Lowest elevation scan from KDAYX radar. (c) Equivalent vertical slice through merged data from KDAYX, KFDR, KLBB, KMAF, KSJT. Nearby radars have filled in the cone-of-silence from KDAYX. (d) Horizontal slice at 3 km above mean sea level through merged data.

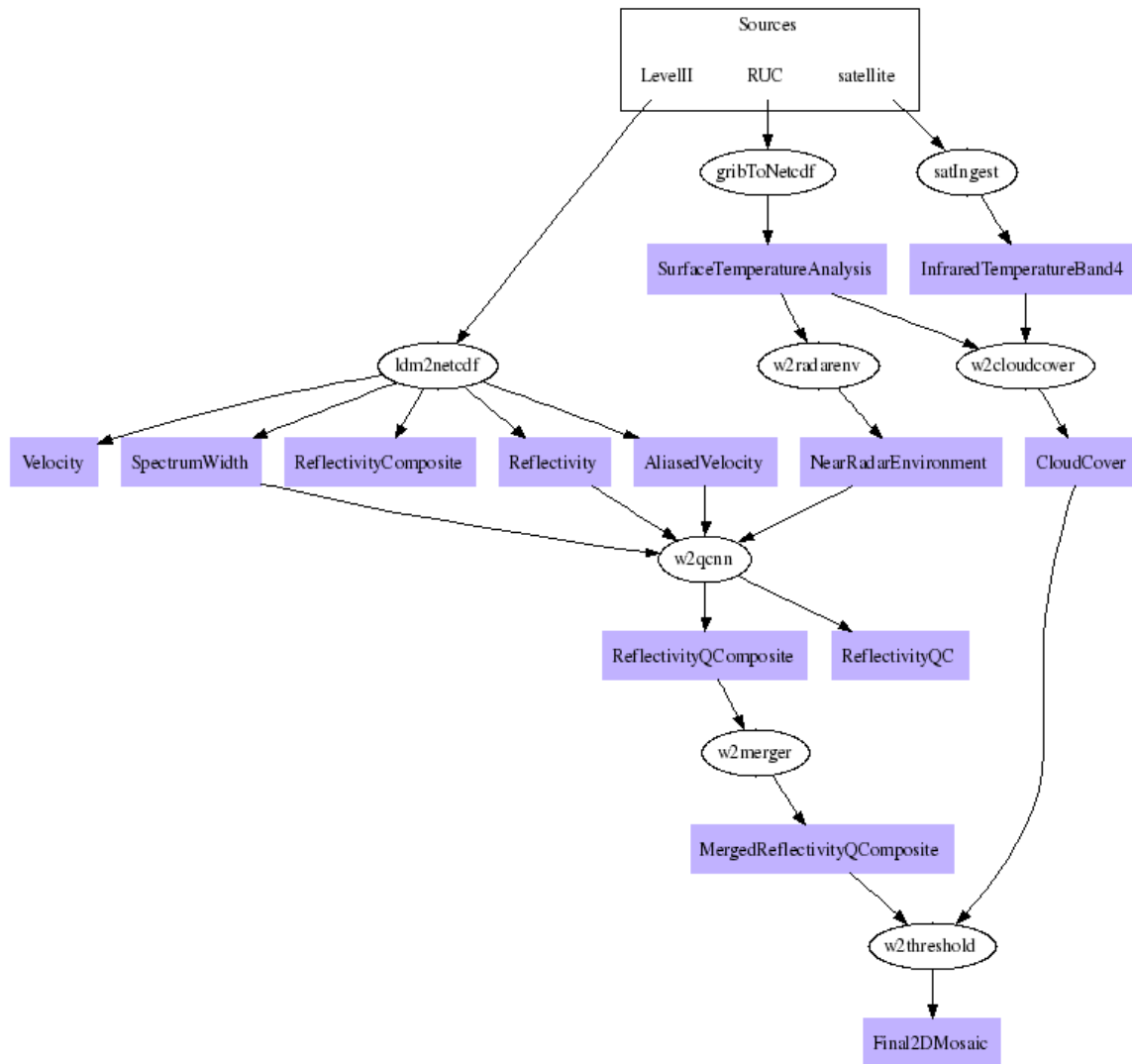


Figure 3: Data flow in a system set up to create 1km x 1km radar reflectivity mosaics over the entire continental United States.

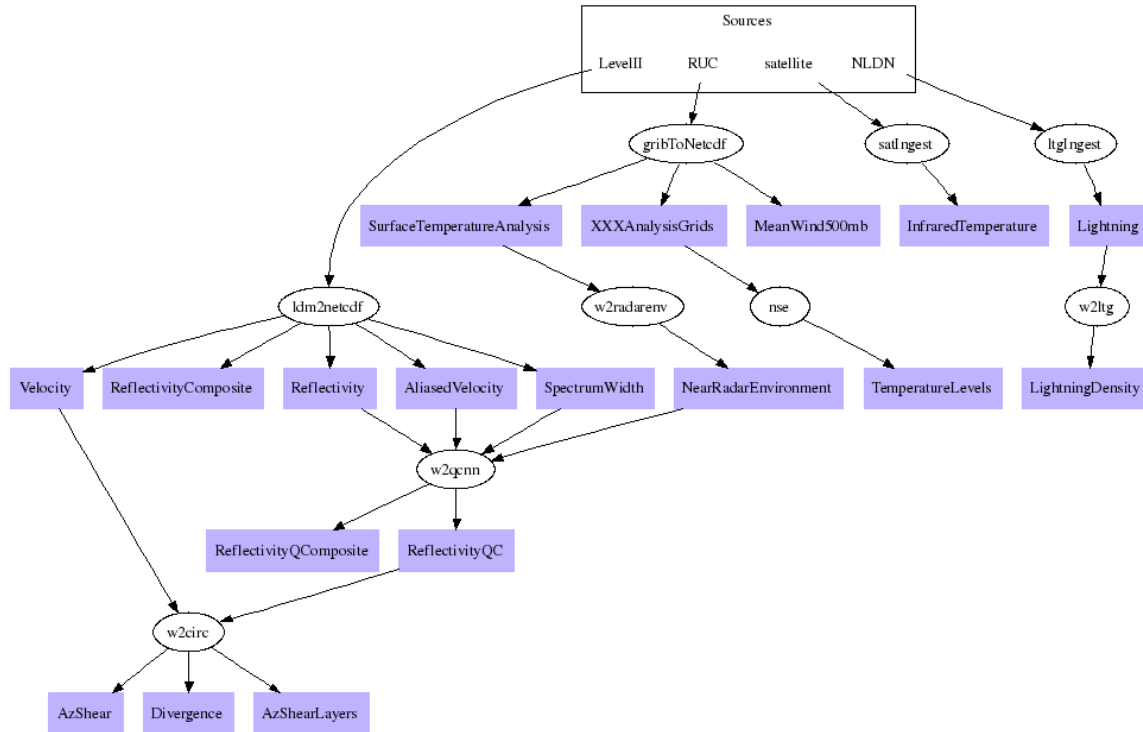


Figure 4: Part 1 of the data flow in a system set up to create 2D and 3D products at a 1km resolution over domains ranging in size from 800 km x 800 km to the entire Continental United States. This diagram shows much of the single-source processing.

for just reflectivity processing, one of these machines could handle data from about 40 radars. All the multi-source algorithms also run on a similar dual Xeon machine. We therefore operate this configuration over the entire CONUS (130 radars) with 5 dual-Xeon machines. The end result is a quality-controlled 2D radar composite field at approximately 1 km resolution every 2 minutes.

2b. 3D Products

Instead of computing just a 2D composite over the CONUS, it is possible to create a 3D grid in real-time and compute derived information for severe weather diagnosis from those grids in real-time. Such a 3D processing over the entire CONUS takes 5 dual-Xeons as before for the single-radar processing, but also requires 2 other dual 64-bit Opterons with 16 GB of RAM to perform all the multi-radar processing.

The typical data flow for a 3D WDSS-II domain is shown in three parts. The data ingest (See Figure 4) is similar to the basic 2D CONUS diagram, except for the addition of velocity processing and a few other sources of data. Shear is estimated from the radar velocity data using a linear least squares derivative technique (Smith et al. 2004) and stamping out only those regions with valid reflectivity echo.

The reflectivity processing over the domain is shown in Figure 5. The QC'ed reflectivity data from the single-radar processing is now input into a 3D merger process where motion estimates from a K-Means segmentation and Kalman estimator (Lakshmanan et al. 2003) are used to provide time-and-space correction. These 3D grids are further quality-

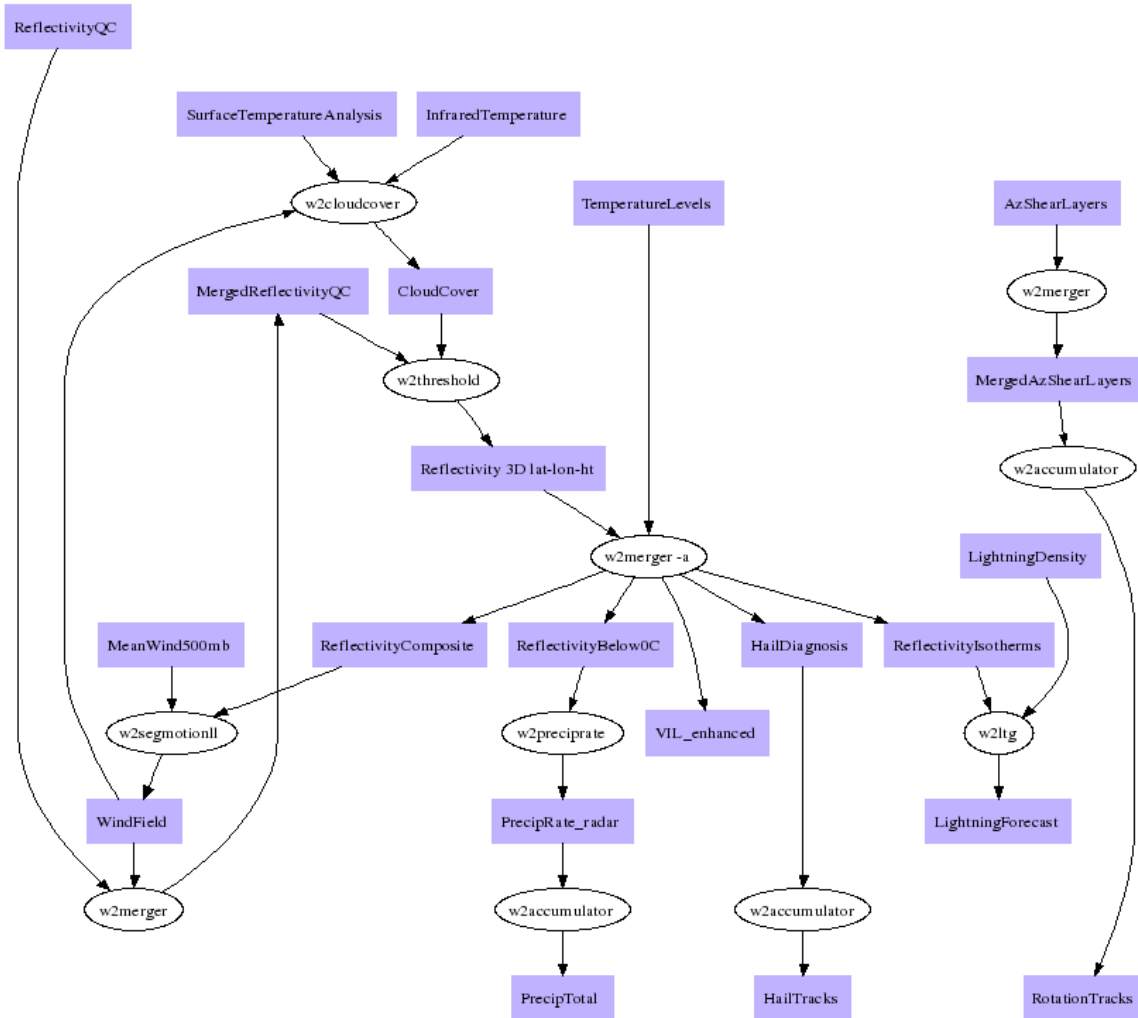


Figure 5: Part 2 of the data flow (See Figure 4). This diagram shows the creation of 3D and derived 2D products that cover the entire spatial domain.

controlled, as in the 2D case, using cloudcover information. The resulting 3D grids are used to compute severe weather algorithms such as hail diagnosis and VIL (Stumpf et al. 2004). These instantaneous grids are accumulated in time to provide hail tracks or precipitation totals. Lightning forecasts are made from the current lightning density and reflectivity isotherms (Lakshmanan and Stumpf 2005). Such reflectivity processing for the entire CONUS is possible on a dual Opteron machine with 16 GB of RAM.

The velocity data processing over the domain is also shown in Figure 5. The QC'ed reflectivity data are dilated and used to determine where the velocity data ought to be used. The results of the single-radar LLSD algorithm are combined in space (Lakshmanan et al. 2005b) to yield layer averages of shear and accumulated in time to provide rotation tracks. Initial benchmarks suggest that such velocity, lightning and segmation processing for the entire CONUS is possible on a dual Opteron machine with 16 GB of RAM.

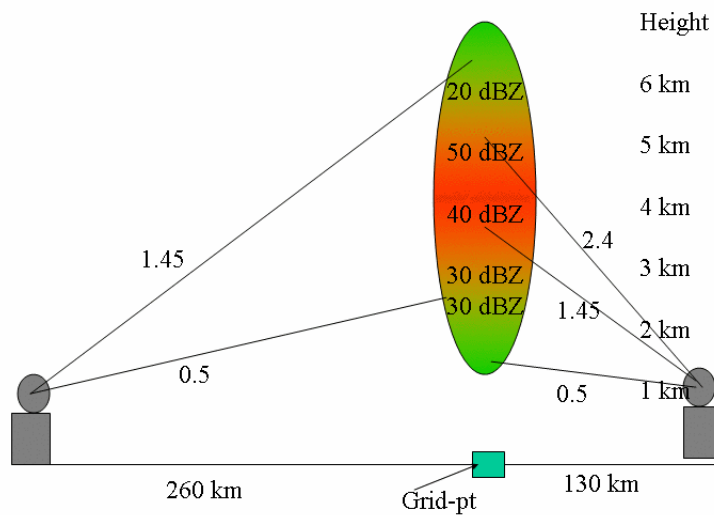


Figure 6: Estimating the vertical maximum of the reflectivity at the point marked “Grid-pt”. Estimating by combining single-radar 2D composites will lead to an underestimate. Estimating using the 3D architecture will provide a truer representation of the storm.

2c. 2D vs 3D

Where possible, we recommend that users utilize the 3D products and 2D products derived from the 3D grids. The 2D architecture, above, is more cost-effective as it requires fewer and less powerful machines. However, 2D CONUS products created from a combination of single-radar 2D products will be underestimates of the true field, while 2D CONUS products derived from 3D CONUS grids formed from the radar elevation scans will provide a truer representation.

Figure 6 demonstrates why the 2D architecture yields underestimates. Consider a convective cell 260 km from one radar and 130 km from another. For simplicity, let us assume that both radars are at VCP 11 (the lowest three elevation angles of which are at 0.5, 1.45 and 2.4 degrees) and have no calibration differences or differences in time synchronization. Let us also disregard effects of beam curvature or attenuation. The first radar senses the storm at heights of 2.2 km, 6.8 km and 10.8 km while the second radar senses it at heights of 1.1 km, 3.4 km and 5.4 km.

If the storm core is around a height of 5 km, then only the second radar senses that maximum value. The composite from the first radar has radar reflectivity from a height of 2.2 km (say 30 dBZ). The composite from the second radar has radar reflectivity from a height of 5.4 km (say 50 dBZ). The 2D product will blend these two to yield a value in between the two numbers, but closer to the 50 dBZ sensed by the closer radar (say 45 dBZ). Blending by taking the maximum of any radar’s estimate will result in over-estimates and visually unappealing rings around radars, especially in accumulation products.

The 3D product, however, takes the heights of the elevations into account. Therefore, the 3D product will have values at each height blended according to distance from the radar. With an assumption of no differences in radar calibration and no attenuation, these values will be identical. Thus, the 3D product will have values (say) 10 dBZ, 30 dBZ, 30

dBZ, 40 dBZ, 50 dBZ and 50 dBZ at 1 km height increments. A composite computed from this 3D grid will yield 50 dBZ.

Because the height information is lost in 2D radar composites, using them to create 2D spatial composites will yield poor results – the height information of the radar elevation scans should be preserved as long as possible.

2d. Regional Grids

So, far we have described a networked architecture, where the WDSS-II system operates on data from the entire CONUS. However, the system is set up to operate on any domain of interest. In fact, if the domain is small enough (approximately 800 km x 800 km for the dual 2.4 GHz and 4 GB RAM Xeon), the entire system – from data ingest to 3D product creation – can be hosted on a single machine.

Although the regional domain has to be small in order to be hosted on a single machine, its boundaries need not be static. It is possible for end users to change, in real-time, their domain of interest and start receiving data and products corresponding to that domain in a matter of minutes. Dynamically changing the domain causes the ingested data to come from different radars – such a dynamic change takes about 10 minutes from the time of request to when products computed on data from those radars start to stream in (Levit et al. 2004).

The regional architecture (with user-changing domains) was tested at the Storm Prediction Center (SPC) during spring and fall 2004. The national architecture will be tested at the SPC in fall 2005. With a fixed domain, the regional architecture has been used to supply grids to the AWIPS of selected National Weather Service Weather Forecast Offices (NWS WFOs) starting spring 2005 and to forecast offices using the WDSS-II display since Fall 2002.

3. Data Distribution

The filled rectangles in the data flow diagrams represent products (some of which are single-radar and others based on data from multiple radars). We do not distribute the single-radar products anywhere but the multi-radar products are distributed through three main mechanisms: to AWIPS, on the World Wide Web and to N-AWIPS.

3a. AWIPS

We run a special regional domain that covers the County Warning Areas of three forecast offices – Tulsa, Norman and Fort Worth. On this domain, we create both reflectivity-based and velocity-based multi-radar, multi-sensor products (See Figure 5). These products are converted into a D2D-compatible netCDF format in cylindrical (equal latitude-longitude spacing) projection. These files are then compressed and shipped via LDM to Southern Region Headquarters from where they are shipped on the AWIPS network to the three forecast offices. A forecaster using D2D accesses these products using the volume browser.

We can create subsets of the CONUS products for the various regions, convert them into the AWIPS netcdf format and make them available in a similar manner (via the various

regional headquarters) for interested forecast offices in interested regions.

3b. N-AWIPS

One of our purposes in building these national composites of severe weather products is to demonstrate the utility of high-resolution, complete coverage to the NWS' National Centers for Environmental Prediction (NCEP). The primary display system at the Storm Prediction Center (SPC) is N-AWIPS, which reads gridded files in GEMPAK format. Since N-AWIPS does support the conversion of GRIB2 formatted files to GEMPAK, we distribute the products in the more common GRIB2 format to NCEP. N-AWIPS, however, imposes severe restrictions on the size of grids (750,000 grid points). Our 1km products are approximately 4000 x 3000 i.e. 12,000,0000 points or nearly 16 times the maximum size acceptable by N-AWIPS. We have successfully subsected the CONUS-wide grids into smaller grids at the full resolution and displayed them with N-AWIPS. We envision that a forecaster will choose the sub-grids currently of interest and load only those grids in real-time.

3c. World Wide Web

We distribute the multi-radar, multi-sensor products on the Internet in two ways: as static images and as GeoTiff images. The static images are created by the WDSS-II display which creates offscreen snapshots of the images, with the appropriate map backgrounds. We then automatically mirror these images onto the NSSL public webserver.

We also convert our netCDF products into geo-referenced images (GeoTiff). These GeoTiff images can be easily incorporated into most GIS systems (Smith and Lakshmanan 2006). GoogleEarth is a publicly available GIS system. We provide on our website XML metadata that enables Google Earth to dynamically request updated weather data and overlay the weather data on top of satellite land imagery or other GIS information.

Both the static images and the Google Earth imagery can be accessed from

<http://www.wdssii.org/>

4. Conclusions

We have demonstrated the ability to create high-resolution (1km x 1km x 1km) radar-based products over areas ranging in size from 800 km x 800 km to the entire Continental United States. The domains can either be static or be moved interactively by the user. All of this can be accomplished using relatively inexpensive hardware running the Linux operating system.

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