A Review of NEXRAD Level II: Data, Distribution, and Applications

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ABSTRACT
For the first time, the full national feed of Weather Surveillance Radar's (WSR-88D) Level II data is available in real time from the National Weather Service via a collaborative distribution partnership with universities. Radar reflectivity, Doppler radial velocity, and spectrum width are provided at extraordinarily fine temporal and spatial resolution, which are critical for understanding, monitoring and predicting severe weather and flooding events. The Level II radar data stream also presents an exciting opportunity for universities and the broader community—including commercial enterprises—for use in severe storm research and prediction, hydrological cycles research, precipitation estimation and measurement, transportation logistics, combination and co-location with complementary *in situ* and remote sensing networks, 3D visualization, model-data assimilation, emergency response, homeland security assessments, and education enterprises at all levels. By enabling free, unrestricted, and real-time access to Level II data, the stage is set for a major evolution in our ability to probe and understand atmospheric and hydrologic processes and phenomena.

(1) INTRODUCTION

The Weather Surveillance Radar-1988 Doppler (WSR-88D), also known as "NEXRAD," is a pulsed Doppler weather radar deployed throughout the United States to detect and indirectly measure meteorological and hydrological phenomena. There are nearly 150 essentially identical radars deployed throughout the continental United States and in selected regions around the world. The NEXRAD network is complemented by other critical data sources including the FAA's Terminal Doppler Weather Radar, Air Force surveillance radars, wind profilers (Rich, 1992), and private sector radar systems, as well as by the national network of weather stations and rain gauge stations. Each WSR-88D continuously scans the precipitating or the "clear-air" atmosphere within a few hundred kilometers of the radar site, and produces discrete fields of: radar reflectivity factor, mean Doppler radial velocity, and a measure of the width of the Doppler velocity spectrum. These parameters are measured for all volume scans and at the highest temporal and spatial resolution, and constitute the fully three-dimensional, Level II data stream. The primary mission of the NEXRAD network is to provide real-time measurements of winds and precipitation to dramatically improve the ability to monitor and forecast weather, especially severe weather events such as tornadoes (e.g., Trapp et al., 1999) and flash floods. Data from this distributed network are collected to directly support the missions of the National Weather Service (NWS), the Federal Aviation Administration (FAA), and the Department of Defense (DOD). The National Climatic Data Center (NCDC) currently houses over 1 petabyte of Level II data and provides a central clearinghouse of archived Level II data as a resource to the research, teaching, and technology development communities.

In this review we briefly cover some technical details of the NEXRAD system (Section 2), sketch the new means by which Level II data are being distributed (Section 3), and we conclude in Section 4 with a description of challenges and opportunities in the use of Level II data. The near future evolution of NEXRAD is discussed in Section 5.

(2) NEXRAD BACKGROUND

The transmitter, receiver, and antenna are contained within the radar data acquisition (RDA) component of the system. A complete description of the technical details of these subsystems can be found in NOAA (1991) and further introduction can be found in NRC (1995). Briefly, a master oscillator power amplifier-type transmitter operates in a frequency range of 2700-3000 MHz, and hence with a nominal wavelength of 10.71 cm; the peak power is 750 kW. Microwave pulses of horizontal polarization are transmitted over a few microsecond duration, yielding along-beam or radial resolution gates of $\geq$ 250 m. The repetition frequency of successive pulses ranges from 320 to 1300 Hz, depending on the application; in typical "precipitation mode" applications, the resultant maximum unambiguous range (velocity) is ~ 150 km (~25 m/s).

Because the returned power from weather targets is relatively weak, the receiver has a dynamic range of 93 dB. The weak RF signal is mixed in the receiver subsystem to produce an intermediate frequency signal that is further amplified and processed. The antenna subsystem has a circular parabolic reflector of 8.54 m diameter, which provides beams with a half-power width of 0.95° in the horizontal and vertical; the first sidelobe is approximately 26 dB down from this main lobe. The antenna is mechanically positioned by an aluminum and cast iron pedestal. It continuously rotates the antenna over 360° in azimuth at a maximum rate of 30° s^{-1}, and incrementally changes the antenna in elevation at a rate of one step (from 1° to ~ 3°) per complete revolution in azimuth.

The RDA derives three parameters, reflectivity, radial velocity, and Doppler spectrum width. Range resolution of the WSR-88D is 1 km for reflectivity and .25 km for velocity and spectrum width, whereas azimuthal resolution is 1° for reflectivity, velocity and spectrum width. A user-selectable volume coverage pattern (VCP) determines the number and increment of elevation angles per scan sequence. For example, a VCP often used for the detection of severe thunderstorms is comprised of fourteen elevation angles that vary from 0.5° to 19.5°, and is executed in about 5 min. Coverage of the NEXRAD network is limited by the Earth's curvature. In general, the spacing between NEXRAD radars is approximately 230 km, but strong surface intensified flows such as gust fronts may only be adequately observed at about 80 km distance from the NEXRAD station in regions of flat terrain (NRC, 1995). As a consequence of such limitations approximately half of the continental United States does not have high quality coverage of strong surface winds.

Within the radar product generator (RPG) component of the WSR-88D system, numerous products are derived from these moments, for more specific applications ranging from tornado and hail detection to rainfall-rate estimation to more derived applications such as in tracking bird migration or insect flights (e.g. Lang et al., 2004).

A variety of tools exist to analyze and visualize the WSR-88D data. We mention one. The Integrated Data Viewer (IDV), developed by the University Corporation for Atmospheric Research's Unidata Program is a free data visualization and analysis software package which is implemented in Java and supported on several commonly used platforms. This software allows the display of a variety of meteorological data including Level II radar data in both two and three dimensions. IDV also provides the capability to analyze and calculate derived quantities from raw data, thus allowing for example, precipitation estimates to be calculated from Level II data and displayed. The software can be downloaded from my.unidata.ucar.edu/content/software/IDV/.

Examples of Level II data are shown in Figures 1 and 2, produced with the IDV software. Whereas Figure 1 is typical of the kind of two dimensional NEXRAD perspective that many potential users are familiar with, Figure 2 demonstrates the full 3 dimensional perspective that the unexpurgated Level II data stream can provide, and will provide in real time in the new distribution model.

(3) LEVEL II DATA DISTRIBUTION

The NWS has effectively implemented plans, announced in 2003, to replace the previously existing method of Level II data distribution. This had consisted of recording the data onto 8mm tapes and mailing them to NCDC, a method that proved to be difficult and expensive to maintain, as well as creating a bottleneck to widespread distribution and analysis of the data. In practice, only about one half of the total data collected was successfully transferred to and archived at the NCDC. In order to distribute the data in near-real time, decrease maintenance and distribution costs, and increase the availability and reliability of the data distribution to such entities as the National Center for Environmental Prediction (NCEP) and NCDC the decision was made to distribute the data over Internet2 by partnering with universities in a tiered peering arrangement. This distribution model was built on the early success of the CRAFT project (Droegemeier, 2002). The software tool used to deliver this data from the National Weather Service to the university community, in a reliable and rapid way, is the Local Data Manager (LDM) developed by Unidata. This approach has the added benefit of making immediately feasible distribution of Level II data in near-real time to the research and educational communities as well as to the broader pool of stake-holders, including commercial enterprises.

The NWS collects and distributes Level II WSR-88D data in near-real time from 121 NWS NEXRAD sites and 11 DOD sites (see Crum et al, 2003a,b). The data is sent to users via an internal NWS communications network and the Internet2. The topology of this data distribution network is shown in Figure 3. Given that each radar site produces a new data product every 5 minutes or so, and that there are 132 sites, producing such products, 24 hours a day, 365 days per year, the availability of sufficient, and reliable, bandwidth and storage are serious considerations. At each radar site, a workstation compresses (using BZIP2[1]) the data, whereupon it is sent to the NWS weather forecast offices and subsequently to their regional headquarters (in Salt Lake City, UT, Kansas City, KS, Forth Worth, TX, and Bohemia, NY). The critical enabling software technology in this enterprise is Unidata's LDM 6.0 software. Metadata are included in the Level II data stream which assists in the ease of use and application of the data. From these regional headquarters the data are sent through designated Abilene/Internet2 gigapops (see http://abilene.internet2.edu) and then via Internet2, to 4 top-tier sites top level, who each ingest the data, and stream it to 3 downstream peers in turn. These downstream peers, based in universities distribute a subset of this data on to third-tier sites. Because of the high speed connectivity used at all stages of this distribution, there is usually less than a 30 seconds from when the data are recorded at the radar site to when downstream users can access the data. Data continue to be streamed to NCDC for archival purposes. Redistribution of Level II data is unrestricted and non-profit and commercial use of the data is encouraged. Further information on Level II data distribution issues can be found at the NWS web site http://www.roc.noaa.gov/NWS_Level_2.

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[1] This is a freely available and highly used data compressor (see http://www.bzip.org).

By the end of 2004, WSR-88D Level II data distribution reached full operational capability (FOC), enabling the community to have ready near-real time access to the highest resolution digital, full volume scan data that is produced by the NEXRAD network. This extremely large digital data set of research quality data from the highly sensitive WSR-88D opens new frontier in discovery, learning, and engagement in observation of winds, water, and tracers.

(4) LEVEL II DATA:APPLICATIONS AND OPPORTUNITIES

Level II data are the highest resolution and most complete observational constraints on winds and precipitation available over the continental U.S. University research and teaching programs throughout the U.S. utilize NEXRAD data in the fields of atmosphere science and climatology, hydrology, agriculture, transportation and logistics, aviation and air traffic safety, economics, air pollution and dispersion modeling, ecology, civil engineering, as well as in many other disciplines. Where dense and complementary sensor networks exist NEXRAD data provide key insights into a wide range of human and industrial activities with significant economic, societal, and security consequences (Morris et al., 2001; Serafin and Wilson, 2000). NEXRAD data is used extensively by the private sector including by emergency responders, recreation centers, economic forecasters, risk mitigation industries, energy providers, commercial transport providers. When assimilated or otherwise integrated with models or other data streams, NEXRAD data can provide a key component of a comprehensive meteorological and hydrological monitoring and prediction framework.

A host of challenges and opportunities for improvement await (Serafin and Wilson, 2000; NRC, 2000) and we describe several of those here.

Improved Calibration

It is well established that Doppler radar estimate precipitation rates are frequently at odds with gage observations, and large uncertainties and systematic biases are common (Anagnostou, et al., 1998; Westrick et al., 1999; Seo et al., 2000). This has led the NRC (1998) to suggest that:

> *There is a need to establish quantitative measures and goals in radar calibration, radar-gage comparisons, and their effect on flood forecast accuracy.*

Clearly, this is an opportunity for the combination of surface *in situ* observations of precipitation and streamflow, weather station profiles of atmospheric states, surface meteorological estimates, and space-based remote sensing estimates of water vapor convergence (i.e. via GOES or GPS), rainfall (e.g. microwave scanners) and surface energy fluxes (e.g. CERES), together with assimilation in weather forecast models, to validate and improve precipitation estimation and our knowledge of overall hydrological balance.

Hydrology

Knowledge of the net water balance of a watershed or region is the main goal of hydrological investigation. As summarized in NRC (1998), measuring the sharply varying and scale-dependent inputs and outputs of water (through precipitation, evaporation, and flow) in this balance is the main challenge facing hydrology. In order to meet immediate needs such as the real time prediction of localized flooding events as well as to making long-term assessments of the adequacy of spillways and stormwater treatment facilities more detailed and accurate observations of the input term (precipitation) are needed (Droegemeier et al., 2000). Level II NEXRAD data provide a key to meeting this challenge by measuring water in its various phases as well as the convergence of water by the wind fields (Sun et al., 1997). Such analyses have been performed by Smith et al. (1996) who showed that with sufficiently high resolution 3-D radar data, supplemented with other information, extensive information can be gleaned about the mass balance and efficiency of severe storms. Such radar-derived improvements in our understanding are especially possible when the Level II data stream is combined remote and *in situ* measurements (e.g. Lakshmanann and Valente, 2004) or with modeling (Andrieu et al., 2003).

Assimilation into Weather Models

Because of the wide area coverage and extremely high temporal and spatial resolution of NEXRAD observations, and the fact the data are available in real time, this observing system is unique in its ability to be used for providing initial conditions and evolution constraints for numerical weather prediction models. NEXRAD provides direction observations of winds and water (in various phases), which are both necessary ingredients to initialize a weather forecast model or process-oriented study. As summarized by Alberoni et al. (2000), Doppler radar data can provide important observational constraints when assimilated into models and analyses. NEXRAD data can be used to estimate rainfall rates or precipitation loading which can be assimilated (e.g. using 3-D or 4-DVAR variational assimilation methods) into models (Xue et al., 2003; Gao et al., 2004; Zhang, 1999; Grecu and Krajewski, 2000, Falkovich et al., 2000), although a thorough characterization of error statistics (Ciach and Krajewski, 1999; Keeler and Ellis, 2000) is a crucial step to make such assimilation useful. In clear air it is possible to accurately measure winds even with a single Doppler radar site (Wilson et al., 1994; Gossard, 1990; Serafin and Wilson, 2000) Inclusion of NEXRAD-data based observational constraints within forecast models will substantially improve predictive skill, whereas an improved knowledge of climate can be an outgrowth of the assimilation of these fields into reanalysis products (such as produced by NCEP).

Homeland Defense and Emergency Response

To meet the U.S. security and emergency response needs associated with the accidental or intentional release of nuclear, biological, or chemical agents into the atmosphere, the existing NEXRAD network—with its extensive, high resolution coverage and "always on" capabilities—could be combined with a high-resolution mesoscale model (e.g. the Weather Research and Forecasting model; Skamarock et al. 2005) with tracer transport, dispersal, and deposition components via real-time data assimilation. Supplemented with mobile radar units such as used in field campaigns and other observation platforms that capture details of the release, transport, and deposition of harmful agents, evacuation, mitigation, and treatment options could be developed in rapid response mode.

(5) **NEAR FUTURE OF NEXRAD**

Combination of the Level II data stream with models and other observational platforms will catalyze, and in turn by enhanced by, a more complete observation-based understanding of severe weather and the hydrological cycle. A path for the further evolution of NEXRAD, including enhanced data resolution, is enabled through the WSR-88D Open Radar Data Acquisition, the deployment of which began in 2005. Further down the road, dual polarization technology may be implemented in the NEXRAD network, which should greatly increase the ability of their ability to provide better rainfall estimates, higher quality data, and better discrimination of water versus frozen hydrometeors. These improvements will also dramatically increase the size of the data stream, which will present challenges in maintaining the speed and reliability of the distribution model.

FIGURE CAPTIONS

Figure 1. Reflectivity (units are dBZ) measured by the Indianapolis NEXRAD radar installation (KIND) in October of 2004. This is a 2D view of only the lowest scan of the radar. Such observations are typically used to estimate rainfall rates.

Figure 2. Reflectivity as above, but all scans of the KIND radar are depicted. Individual scan volumes are easily identifiable. Also included are isosurfaces of the 30 dBZ reflectivity level to indicate means by which important structures, e.g. precipitation, may be clearly identified from such observations. Both of these figures were created from the real-time Level II stream provided by Purdue University using the freely available IDV software package.

Figure 3. The current operational topology for Level II data distribution, from NWS to university peers and then to the broader community of users.

REFERENCES

Alberoni, P.P., Mezzasalma, P., Costa, S., Paccagnella T., Patruno P. and Cesari, D., 2000: Doppler Radar Wind Data Assimilation in Mesoscale Analysis. Phys. Chem. Earth (B), 25, No. 10-12, 1263-1266.

Anagnostou, E.N., W.F.Krajewski, D.J.Seo, and E.R.Johnson. 1998. Mean-field radar rainfall bias studies for WSR-88D. ASCE Journal of Engineering Hydrology 3(3):149–159.

Andrieu, H., M.N. French, W.F. Krajewski and K.P. Georgakakos, 2003. Stochastic-dynamical rainfall simulation based on weather radar volume scan data, *Advances in Water Resources*, 26(5), 681-693.

Ciach, J.G. and W.F.Krajewski. 1999. On the estimation of radar rainfall error variance. Advances in Water Resources 22(6):585–595.

Crum, T.D., and R.L.Alberty. 1993. The WSR-88D and the WSR-88D operational support facility. B. Am. Meteorol. Soc. 74:1669–1687.

Crum, T.D., R.L.Alberty and D.W.Burgess. 1993. Recording, archiving, and using WSR-88D data. B. Am. Meteorol. Soc. 74:645–653.

Crum, T. D., K. Kelleher, P. Cragg, J. Barna, F. Toepfer, W. Blanchard, T Sandman, K. Droegemeier, G. Almes, and L. Miller, 2003a, Progress in implementing near real time collection, distribution, and archive of WSR-88D Level II data. Preprints, 31st *Int. Conf. on Radar Meteorology, Oceanography, and Hydrology., 9-13 February, Amer. Meteor. Soc., Seattle, Washington, Paper 12.B3.*

Crum, T. D., D. Evancho, C. Horvat, M. Istok, and W. Blanchard, 2003b, An update on NEXRAD program plans for collecting and distributing WSR-88D base data in near real time. Preprints, *19th Int. Conf. on Interactive Information Processing Systems (IIPS) for Meteorology, Oceanography, and Hydrology., 9-13 February, Amer. Meteor. Soc., Long Beach, California, Paper 14.2*.

Droegemeier, K.K., K.Kelleher, T.Crum, J.J.Levit, S.A.Del Greco, L.Miller, C.Sinclair, M. Benner, D.W.Fulker, and H.Edmon. 2002. Project CRAFT: A test bed for demonstrating the real time acquisition and archival of WSR-88D Level II data. Preprints, 18th International Conference on Interactive Information Processing Systems (IIPS) for Meteorology, Oceanography, and Hydrology, 13–17 January, AMS, Orlando, Fla. 136–139.

Droegemeier, K.K., J Smith, S.Businger, C.Doswell III, J.Doyle, C.Duffy, E.Foufoula-Georgiou, T.Graziano, L.D.James, V.Krajewski, M.LeMone, D.Lettenmaier, C.Mass, R.Pielke, Sr., P.Ray, S.Rutledge, J.Schaake, and E.Zipser. 2000. Hydrological aspects of weather prediction and flood warnings: Report of the ninth prospectus development team of the USWRP. B. Am. Meterol. Soc. 81, 2665–268

Falkovich, A., E.Kalnay, S.Lord, M.B.Mathur. 2000. A new method of observed rainfall assimilation in forecast models. J. Appl. Meteorol. 39:1282–1298.

Gao, J.-D., M. Xue, K. Brewster, and K. K. Droegemeier, 2004: A three-dimensional variational data analysis method with recursive filter for Doppler radars. J. Atmos. Ocean. Tech., 21, 457-469.

Gossard,EE 1990. Radar research on the atmospheric boundary layer. Pp. 477-527 in Radar in Meteorology (D Atlas, ed.). American Meteorological Society: Boston. 806 pp. AN01697.

Grecu, M. and W.F. Krajewski, 2000. Effect of model uncertainty in variational assimilation of radar data on rainfall forecasting, *Journal of Hydrology*, 239(1-4), 85-96.

Xue, M., D.-H. Wang, J.-D. Gao, K. Brewster, and K. K. Droegemeier, 2003. The Advanced Regional Prediction System (ARPS), storm-scale numerical weather prediction and data assimilation. Meteor. Atmos. Physics, 82, 139-170.

Keeler, R. J., and S. M. Ellis. 2000. Observational error covariance matrices for radar data assimilation. Phys. Chem. Earth 25:10-12, 1277-1280.

Lakshmanan, V. and M. Valente: 2004, Quality control of radar reflectivity data using satellite data and surface observations. *20th Int'l Conference on Information Processing Systems*, Seattle, WA., AMS.

Lang, T. J., and S. A. Rutledge, and J. L. Stith, 2004, Observations of quasi-symmetric echo patterns in clear air with the CSU-CHILL polarimetric radar, *J. Atmos. Oc. Tech.* 21, 1182-1190.

Morris, D.A., K.C.Crawford, K.A.Kloesel, and J.M.Wolfinbarger. 2001. OK-FIRST: A meteorological information system for public safety. B. Am. Meteorol. Soc. 82:1911–1923.

NOAA, U.S. Department of Commerce, 1991: Federal Meteorological Handbook No. 11, Doppler radar meteorological observations. Washington, D.C.

National Research Council. 1995. Assessment of NEXRAD Coverage and Associated Weather Services. Washington, DC: National Academy Press.

National Research Council, Hydrologic Sciences: Taking stock and looking ahead. Washington, DC: National Academy Press.

National Research Council. 1999. A Vision for the National Weather Service Roadmap for the Future. Washington, DC: National Academy Press.

National Research Council. 2000.Weather Radar Technology: Beyond NEXRAD. Washington, DC: National Academy Press.

Rich, S.T. 1992. Integrating wind profiler data into forecast and warning operations at NWS field offices. NOAA Tech. Memo. NWS SR-141, 34. Boulder, Colo.: NOAA Forecast Systems Lab.

Seo, D.J., J.P.Breidenbach, R.Fulton, D.Miller and T.O'Banon. 2000. Real time adjustment of range dependent biases in WSR-88D rainfall estimates due to nonuniform vertical profile of reflectivity. J. Hydrometeorol. 1:222–240.

Serafin, R.J. and J.W.Wilson. 2000. Operational weather radar in the United States: Progress and opportunity. B. Am Meteorol. Soc. 81:501–518.

Skamarock, W. C., J. B. Klemp, J. Dudhia, D. O. Gill, D. M. Barker, W. Wang, and J. G. Powers, 2005: A description of the advanced research WRF version 2. NCAR Tech. Note NCAR/TN-468+STR. [Available from the National Center for Atmospheric Research. P.O. Box 3000, Boulder, CO]

Smith, J.A., D.J.Seo, M.L.Baeck, and M.D.Hudlow. 1996. An intercomparison study of NEXRAD precipitation estimates. Water Resour. Res. 32:2035–2045.

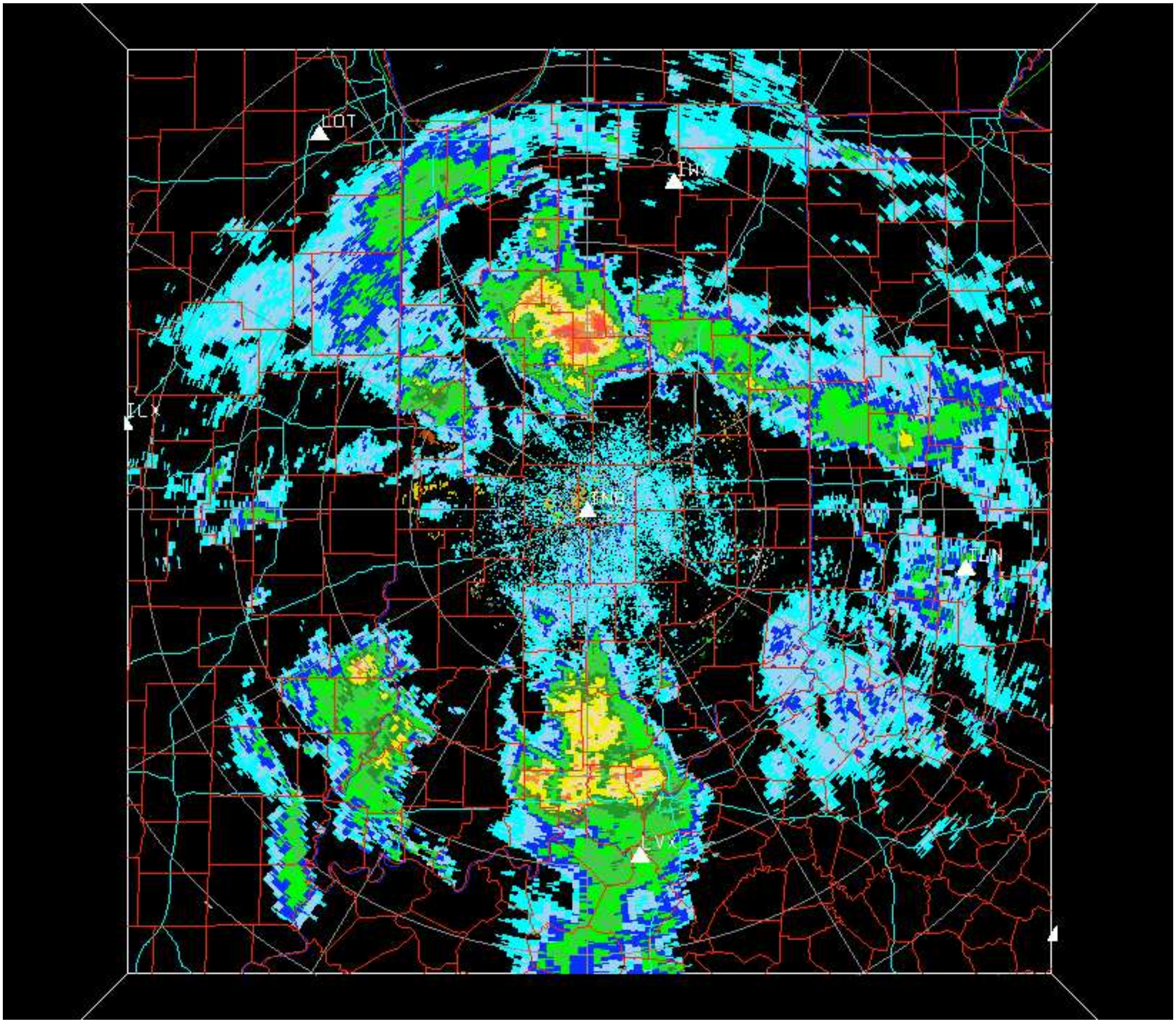
Sun, J. and N.A.Crook. 1997. Dynamical and microphysical retrieval from Doppler radar observations using a cloud model and its adjoint. Part I: Model development and simulated data experiments. J. Atmos. Sci. 54:1642–1661.

Trapp, R.J., E.D.Mitchell, G.A.Tipton, D.W.Effertz, A.I.Watson, D.L.Andra, and M.A. Magsig. 1999. Descending and nondescending tornadic vortex signatures detected by WSR-88Ds. Weather Forecast. 14:625–639.

Westrick, K.J., C.F.Mass and B.A.Colle. 1999. The limitations of the WSR-88D radar network for quantitative precipitation measurement over the coastal western United States. B. Am. Meterol. Soc. 80:2289–2298.

Wilson, J. W., T. M. Weckwerth, J. Vivekanandan, R. M. Wakimoto, and R. W. Russell, 1994: Boundary-layer clear-air radar echoes: Origin of echoes and accuracy of derived winds. J. Atmos. Oceanic Technol., 11, 1184–1206.

Zhang, J., 1999: Moisture and Diabatic Initialization Based on Radar and Satellite Observation, Dissertation, School of Meteorology, University of Oklahoma, 194.



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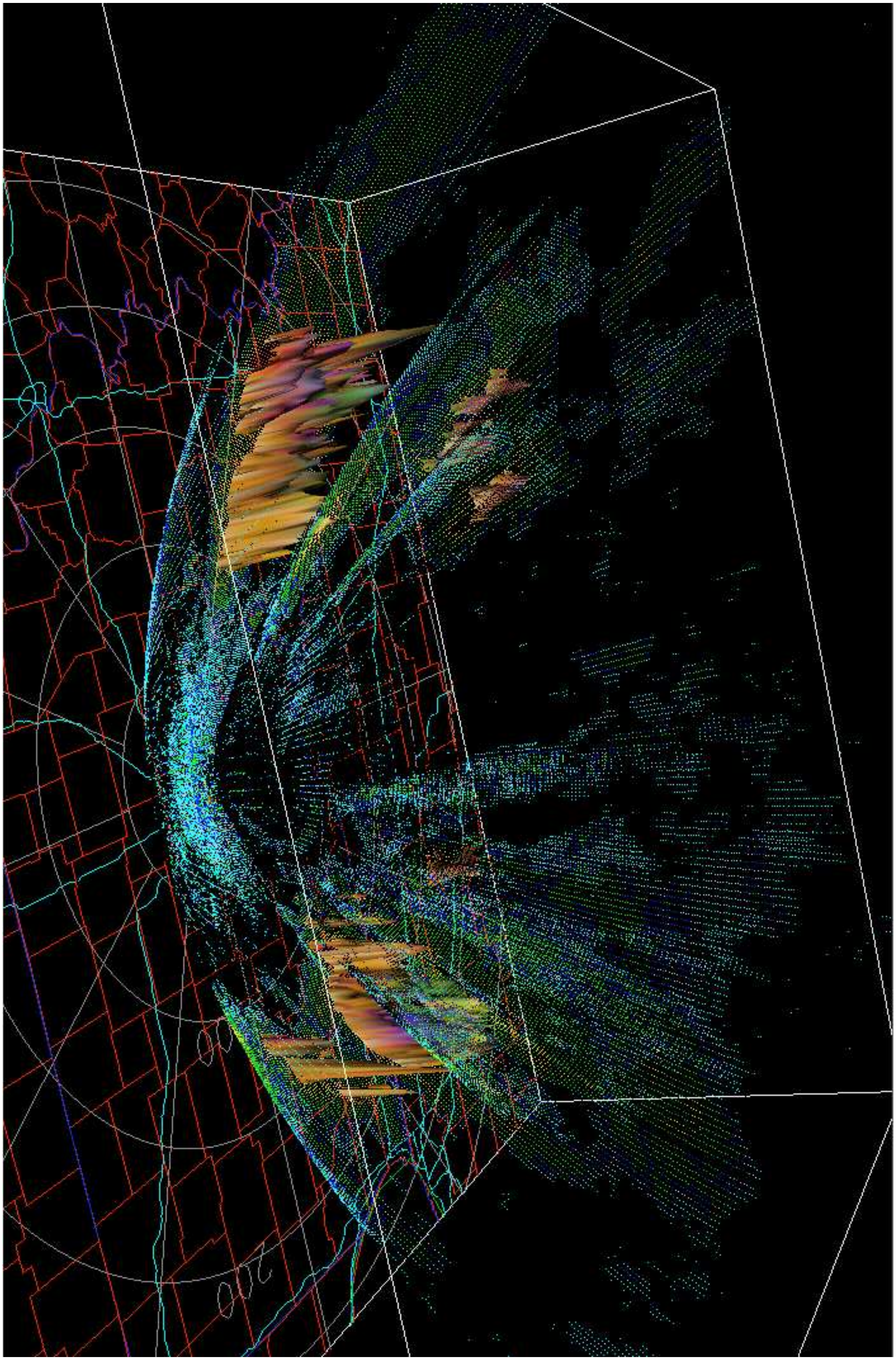

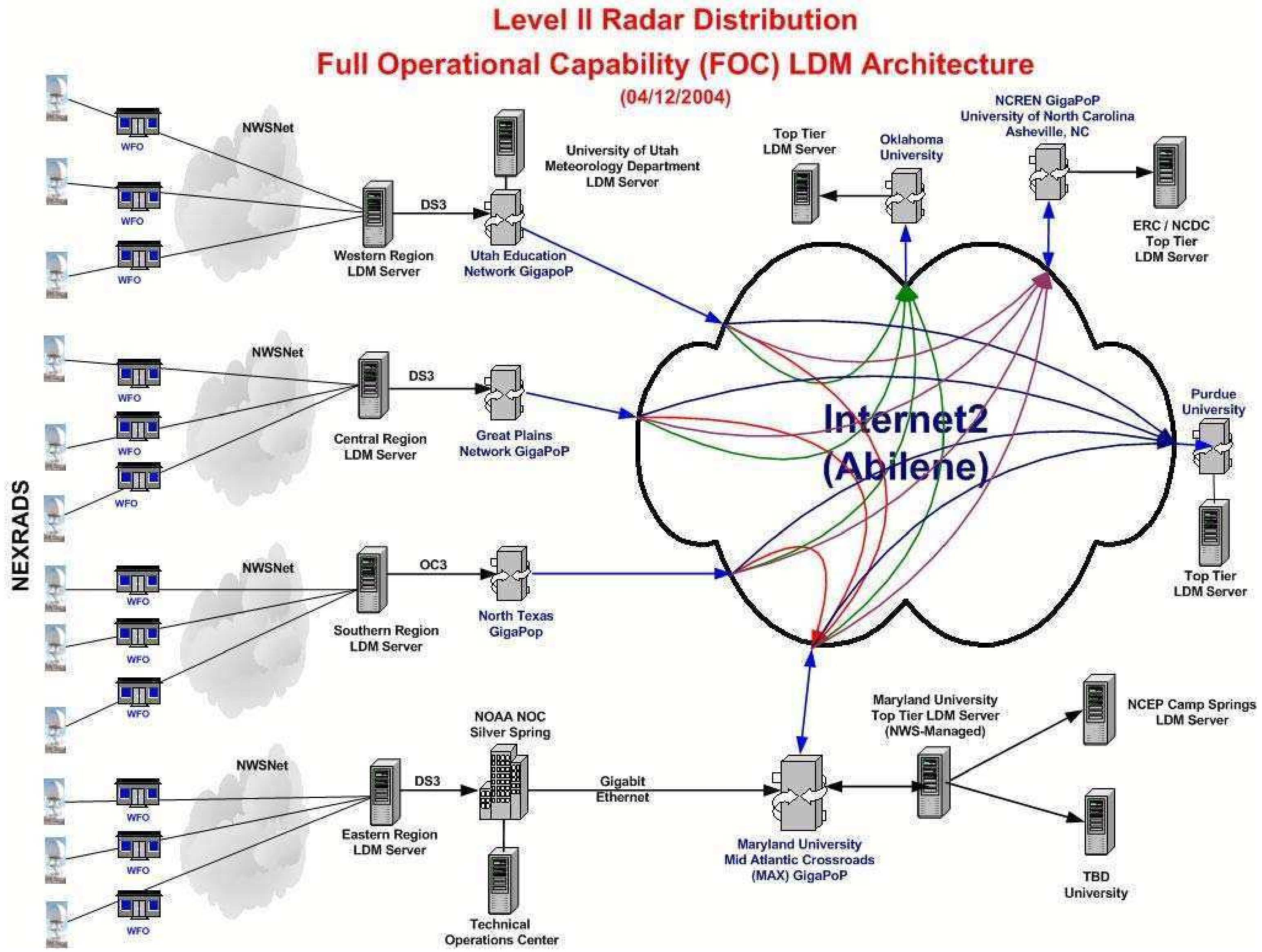
Level II Radar Distribution
Full Operational Capability (FOC) LDM Architecture
(04/12/2004)
NEXRADS
WFO
NWSNet
DS3
OC3
Western Region
LDM Server
Utah Education
Network GigapoP
University of Utah
Meteorology Department
LDM Server
Central Region
LDM Server
Great Plains
Network GigaPoP
Southern Region
LDM Server
North Texas
GigaPop
Eastern Region
LDM Server
NOAA NOC
Silver Spring
Technical
Operations Center
Gigabit
Ethernet
Maryland University
Mid Atlantic Crossroads
(MAX) GigaPoP
Maryland University
Top Tier LDM Server
(NWS-Managed)
NCEP Camp Springs
LDM Server
TBD
University
Internet2
(Abilene)
Top Tier
LDM Server
Oklahoma
University
NCREN GigaPoP
University of North Carolina
Asheville, NC
ERC / NCDC
Top Tier
LDM Server
Purdue
University
Top Tier
LDM Server