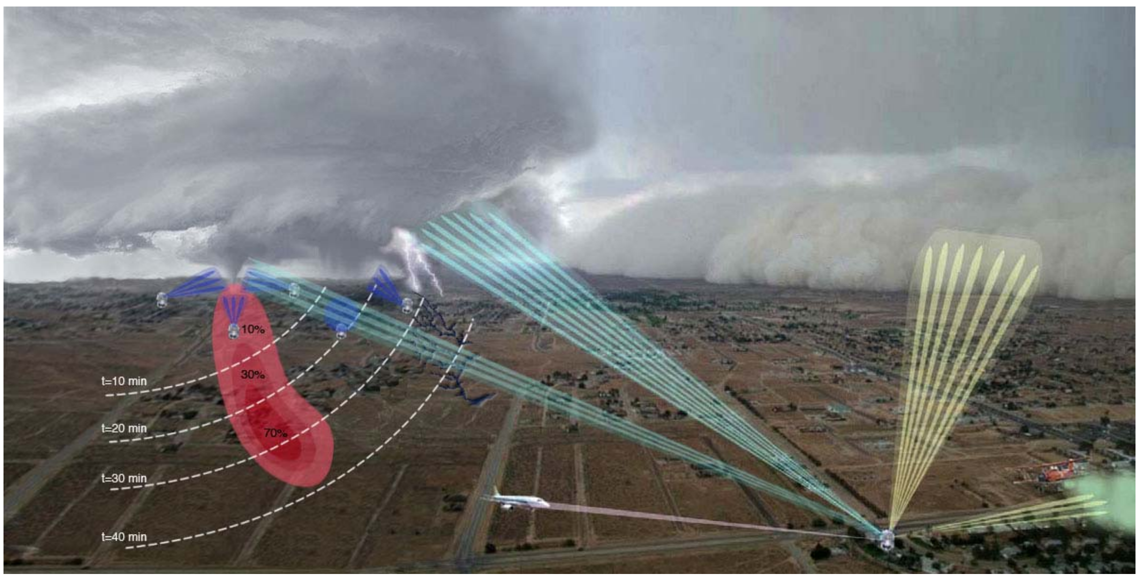
NOAA 2008 Weather Radar 20-Year Vision Planning

Significantly increasing severe weather service performance through high-resolution advanced weather radar, cloud-scale modeling and adaptive data integration.



NOAA Joint Radar Planning Team (JRPT)

August 2008

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Executive Summary:

The Joint Radar Planning Team (JRPT) was created in 2006 at the request of OAR and NWS management to provide guidance into NOAA's Planning, Programming, Budgeting and Execution System (PPBES) and to help articulate the potential benefits of emerging new radar technologies. Since significant breakthroughs in weather surveillance radar technology typically require more than 20 years of research, development, and technology transfer time before becoming operational, the JRPT was asked to develop a 20 year vision for NOAA's weather surveillance program.

This document represents a weather radar vision for NOAA that integrates research and operations. Both the vision and general budget recommendations are included in the document, to be revised annually. The scope of this initial version of the plan is restricted to ground-based weather radar; this in no way should not be regarded as prejudicial to airborne or space-based weather radar technologies. The scope is a function of the initial charge to the group and a consequence of the expertise of the members selected to meet that charge.

The overarching vision is to significantly improve severe weather warnings based upon improved radar observations coupled with numerical model forecasts (Warn-on-Forecast) and not solely on event detection (Warn-on-Detection), as is done today. Research indicates this goal is achievable through new *adaptive data integration* technology comprised of "intelligent" algorithms, advanced radars, storm-scale models, and advanced computational resources.

The JRPT recommends six specific actions to achieve this vision. First, fund the deployment of dual-polarization and super-resolution. These technologies are funded through the NEXRAD Product Improvement (NPI) program's technology infusion activity that insures a robust, world class NEXRAD radar network. Second, in coordination with other governmental agencies, continue research and development on the Multi-function Phased Array Radar in order to assess its potential value as a multi-function system that includes a long-range weather surveillance component and aircraft tracking component. Third, continue collaborative research with government and non-government groups on short-wavelength radars in order to determine their benefit to severe weather operations and ability to enhance precipitation estimation. Assess the potential value of these short range radars to fill gaps between larger surveillance radars to improve observations within the boundary layer in support of the NWS warning operations and high resolution modeling of hazardous weather. Fourth, research and develop a coordinated set of algorithms, adaptive scanning techniques, advanced matched resolution data assimilation, and cloud-scale numerical weather modeling in order to investigate performance of adaptive radar data integration leading toward the Warn-On-Forecast vision. Fifth, explore the use of non-NOAA radar data sources (e.g., FAA, commercial TV, Canadian, Mexican, Caribbean, etc.) into operational warnings and forecasts. The sixth and final recommendation is to utilize NOAA's existing testbeds to

facilitate the evaluation of new weather radar technologies and associated products. Adoption of any new technology will require development of a compelling business case.

1. Introduction

The National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS) relies primarily on weather surveillance radar to accomplish its warning and a significant part of its forecast mission. The current operational weather radar used by the NWS is the Weather Surveillance Radar – 1988 Doppler (WSR-88D). NWS has established the NEXRAD Product Improvement (NPI) Program to ensure a continuous infusion of technology into the WSR-88D and to plan and manage other NOAA/NWS weather radar improvement projects. Technical advice is provided to the NPI Program through the Technical Advisory Committee (TAC) http://www.roc.noaa.gov/app/TAC/reference/TAC_charter.asp and management oversight is provided by the Program Management Committee (PMC). The success of the NPI program is often cited as a model within NOAA for other programs to follow due to its effectiveness as a vehicle for successful infusion of research into operations.

NOAA's NWS is committed to improving mission performance across a wide range of weather services. This commitment is reflected in the NOAA 2006-2011 Strategic Plan as NOAA Goals and as Weather and Water (W&W) Mission Goals. The W&W Goals include:

- Reduced loss of life, injury and economic damage,
- Better, quicker, and more trusted weather and water information to support informed decisions,
- Increased satisfaction with quality of weather and water information and services.

Many of the services improvement goals involve identification and forecasting of high impact events such as severe weather, landfalling hurricanes, heavy rainfall and heavy snowfall, and the associated warnings for tornadoes, etc. NOAA/NWS relies primarily on weather surveillance radar to provide observational information on such storms to support warnings. Such "detection based" warnings improved dramatically with the introduction of the capabilities of the WSR-88D, but their ultimate effectiveness is limited by the short time and spatial scale of tornadoes and other storm-based phenomena. Recent advances in storm scale numerical modeling have led NOAA/NWS to explore the concept of 'Warn-on-Forecast' to extend warning performance (increased lead times and probability of detection, reduced false alarms).

Improved storm scale observational capabilities are required to enhance 'Warn-on-Detection' performance as well as to provide the necessary information for storm scale model initialization to support reliable forecasts of tornadoes in the one to two hour time frame. These necessary observational improvements include temporal and spatial resolution, broader geographic coverage, especially in the boundary layer, and data quality advances.

Significant advances in weather surveillance radar technology typically require lengthy periods for research, operational prototype development, and acquisition programs to transfer the technology into operations. From inception to transfer to operations, the WSR-88D took about 23 years, while the addition of Dual Polarization to the WSR-88D will culminate nearly 30 years of effort. Recognizing the cost in time and dollars for such radar improvements, NOAA established the Joint Radar Planning Team (JRPT), comprised of NWS and NOAA Office Oceanic and Atmospheric Research (OAR) personnel, to develop a 20-year vision with respect to weather radar that would integrate research radar planning, and the long term NOAA weather services improvement goals.

The plan provides specific recommendations on long term research into fundamental breakthroughs in weather radar technology (e.g., National Severe Storms Laboratory (NSSL) work on Phased Array Radar, short range Boundary Layer radars), short and near term improvements to the WSR-88D (e.g., Super Resolution, Dual Polarization, science algorithms), incorporation of non-NOAA radar assets to supplement the WSR-88D and utilization of radar data within storm scale numerical model development. Through this document, and through various working groups, the JRPT is providing radar planning guidance for the NOAA Planning, Programming, Budgeting and Execution System (PPBES). Several guiding principles of the document are:

- NOAA/NWS mission performance can be significantly improved,
- Weather radar data will continue to be crucial to forecast and warning operations,
- Weather radar data can be significantly improved,
- Long term research into advanced technologies and short term improvements to current capabilities are both critical to service improvements,
- Weather radar data from non-NOAA organizations, including other countries, should be evaluated for, and integrated into, NOAA operational use as appropriate,
- Organizational infrastructure (e.g., plans and program management) must be maintained to assess observational data gaps, evaluate relevant applied research results, and accomplish the transfer of new science and technology to operations.

The plan is consistent with key elements of the National Research Council (NRC) recommendations from the 2002 report, "Weather Radar Technology *beyond* NEXRAD", the 2008 NRC report, "Evaluation of the Multifunction Phased Array Radar Planning Process", and the Office of the Federal Coordinator for Meteorology (OFCM) 2006 Report, "Federal Research and Development Needs and Priorities for Phased Array Radar." In addition, the plan addresses recommendations contained in the NRC 2005 report on weather radar in complex terrain ("Flash Flood Forecasting Over Complex Terrain: With An Assessment of the Sulphur Mountain NEXRAD in Southern California". The recommendations from the OFCM study and the 2008 NRC report may be found in Appendix 3: "Blue Ribbon" Recommendations.

2. Existing Capabilities and Motivation

Despite nearly twenty years of operational use and continual improvement to the WSR-88D, there remains a need for improved forecasting and warning services as identified by unmet Government Performance and Results Act (GPRA) goals and by verification statistics compiled by the NWS. For instance, only about half of all tornadoes are warned for with positive lead time and about 75% of tornado warnings are false alarms. Current radar-based quantitative precipitation estimates suffer from large biases and significant geographic coverage under sampling. Operational sensors miss many high-impact weather precursors such as those related to thunderstorm evolution and precipitation phase and intensity. This has broad impact, affecting aviation, marine, fire weather and other societal activity.

To support observational data gap analyses, and to help establish goals and requirements for new observing capabilities, NOAA established the NOAA Observing System Architecture (NOSA). NOSA has developed the NOAA Consolidated Observation Requirements List (CORL), which comprises detailed spatial, temporal, coverage domain, etc., requirements for all observation elements deemed important for the various NOAA mission services. The JRPT has collaborated with the NWS Office of Climate, Water and Weather Services (OCWWS) to define storm scale observation requirements to support severe weather warnings and other storm related forecast services. It is important to note that the CORL includes two levels of requirements: 1) threshold – the minimum, or currently achievable, necessary for effective services, and 2) optimal – data that would significantly enhance meeting the NOAA missions. This Plan focuses on achieving the optimal data observing requirements for storm scale events (Appendix 6).

Radar impacts many NWS services and associated phenomena such as non-severe thunderstorms, severe convective weather (e.g., tornadoes, strong thunderstorms, and large hail), floods, flash floods, landfalling hurricanes, wild fires, winter weather, aviation weather, marine weather, drought, and water management information. Radar is, and will remain, the principal sensor specifying hydrometeorological observables at high temporal and spatial resolution for the foreseeable future (see Hydro Tech Note–4 (1984): "NEXRAD Technical Requirements for Precipitation Estimation and Accompanying Economic Benefits"). No other technology is known to provide similar or better spatial and temporal resolution with broad coverage and at comparable cost. Since other sensors are not likely alternatives, continuous improvements to operational radar remain necessary. Continuous technological and scientific enhancements are made to the WSR-88D weather radar through the NPI program.

Radar has also improved upon severe weather warnings and associated threats (e.g., flash floods), especially since the implementation of the WSR-88D operational Doppler weather radar. However, the rate of improvements made to severe weather warnings has slowed significantly in recent years (Figure 2.1). Scientists believe the best opportunity for improving warning times and predicting storm-scale phenomena and their evolution will result from the assimilation of radar data into high-resolution models capable of matching and exceeding today's operational radar resolution in time and space. The term Warn-on-Forecast (WoF) has been coined to describe a future state of severe weather warning capability based upon assimilation of high resolution data (e.g., radar data) into high resolution weather forecast models such that warnings are not based solely upon event detection, as they are today, but also upon a forecast of an event that exists either in a weather model or, at most, in the form of identifiable observed precursors somewhere.

Likewise, radar greatly improved upon the NWS flash flood and quantitative precipitation estimation capability. In fact, the greatest relative performance improvement due to NEXRAD was in this area (Fig. 2.2). Weather radar is also prominent in upcoming aviation weather improvements such as the Federal Aviation Administration's NextGen project, which calls for improved detection and forecast of aviation-related phenomena, much of it requiring advanced weather radar technology. Similar advances to those achieved with the implementation of NEXRAD are possible with investments in the weather radar technologies and techniques articulated in this plan.

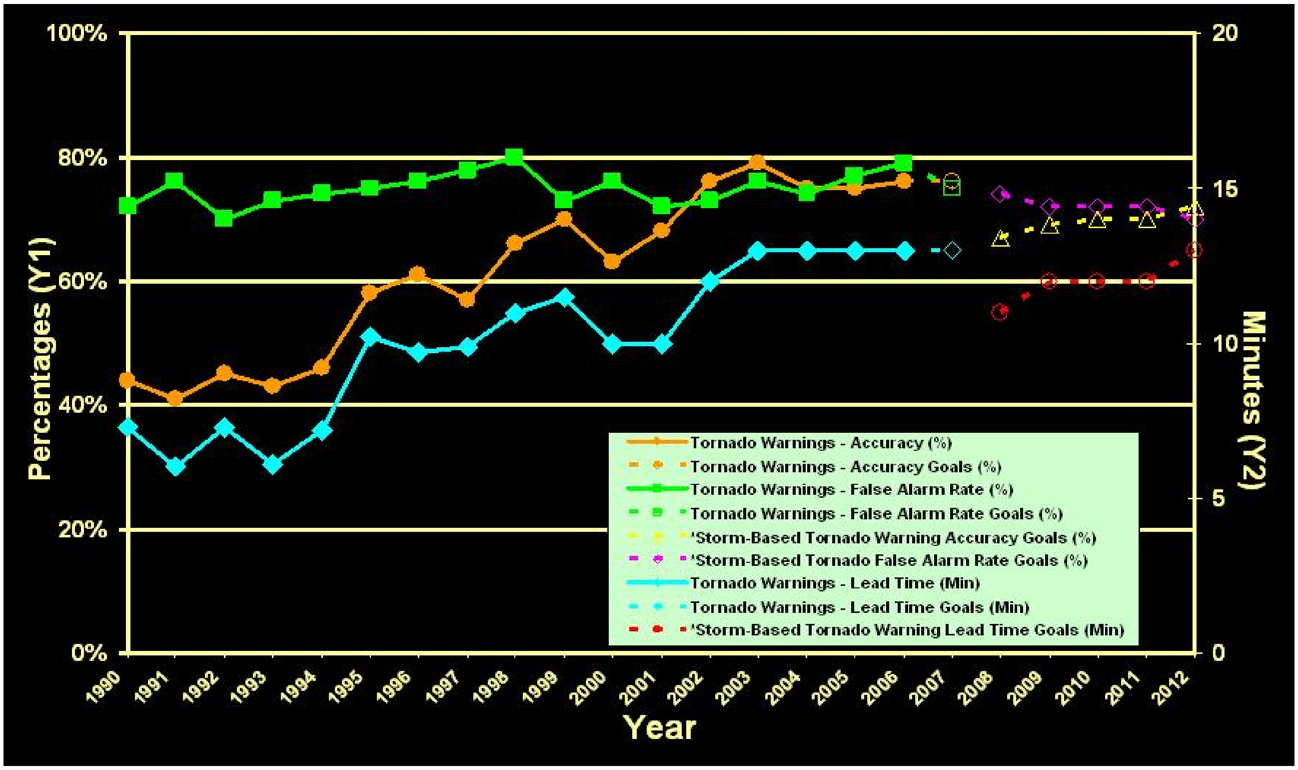

Figure 2.1 Tornado warning performance has leveled off, and is not projected to improve significantly without a paradigm shift such as adoption of warn-on-forecast rather than the current warn-on-detection. The NWS modernization occurred between 1995-1999, accounting for the largest relative increases in performance such as tornado lead time increasing from six to about ten minutes. Also, new performance measures are proposed in the coming years to coincide with the implementation of more precise storm-based warnings.

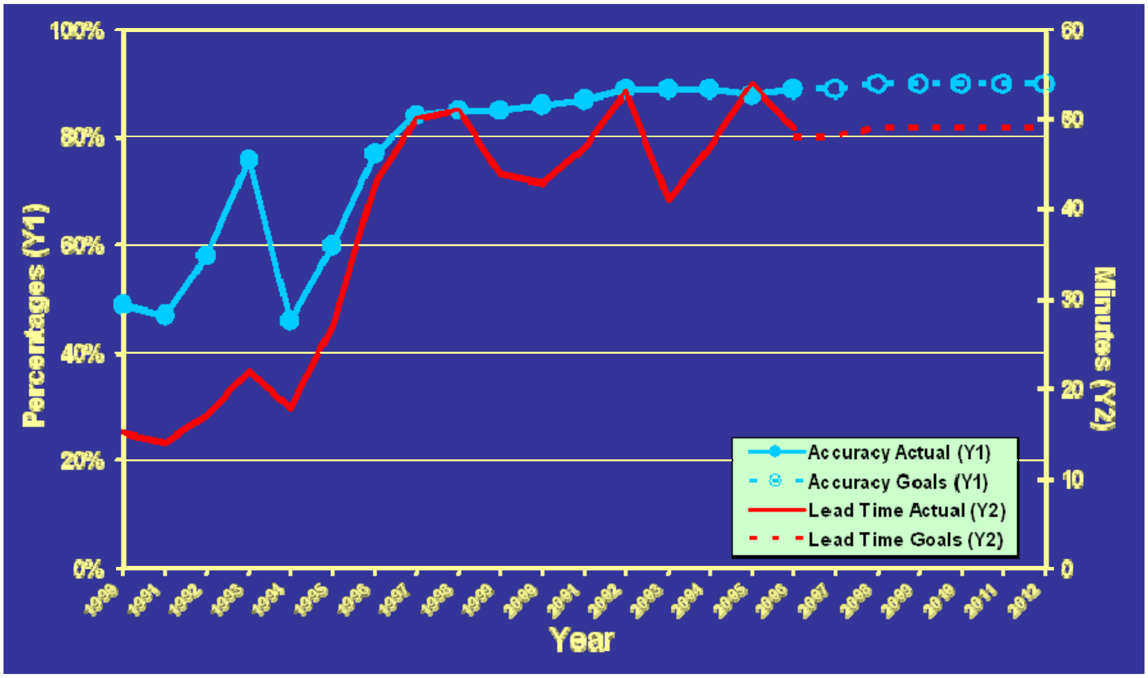

Figure 2.2 Implementation of NEXRAD during 1994-1998 resulted in the largest increase in flash flood performance in the past decades. However, flash flood warning performance has leveled off, and is not projected to improve significantly without significant technological advances such as dual polarized radar.

3. NOAA 20-year Weather Radar Vision for 2025

The JRPT developed this long-term integrated radar vision based upon existing capabilities within NWS operations, current research within the OAR laboratories, NOAA and NWS GPRA goals, existing capabilities within the private sector and academia that NOAA can leverage, and industry predictions for radar technology evolution. The vision is aggressive, but deemed achievable with sustained investments in research and development by NOAA and, where possible, partners in other agencies such as the FAA. The vision is expected to evolve in time as technologies evolve and mission goals evolve.

The current 20 year NOAA weather radar-based vision may be summarized as follows:

- A multi-function surveillance radar capable of simultaneously collecting NWS data to support severe weather warnings, near terminal weather data to support FAA and DoD Air Force aviation operations, and aircraft tracking data to support FAA and Department of Homeland Security (DHS) requirements for both cooperative and uncooperative targets (Figure 3.1) is needed. Data from such a system must be used in combination with short-wavelength networked radars (government owned and non-government owned systems) strategically located to sample the boundary layer.
- A paradigm shift from warnings issued based on detected phenomena using primarily radar data (Warn-on-Detection) to warnings based upon high resolution numerical forecast models assimilating high resolution radar from multiple radar systems along with other data sources (Warn-on-Forecast; Figure 3.2)
- The expected outcomes of such a paradigm shift can result in tornado warning lead times on the order an hour or more rather than minutes
- Enhanced air traffic safety and capacity resulting from joint FAA and NOAA development of new tools, technologies, and procedures under the NextGen 4D Data Cube concept
- Neighborhood-scale warnings of high impact weather events, including tornadoes and landfalling tropical cyclones with detailed inundation information
- At least three hour flash flood warning lead times
- Improved rainfall and snowfall accumulation and forecast information in support of drought and water resource management including a four-fold increase in accuracy of precipitation intensity estimates with increased spatial resolution and geographical coverage
- Highly accurate, multi-hour forecasts of convective storm intensity and location in support of aviation services, marine services, and general improvements in public safety from threats such as lightning.

The success of this vision depends upon executing focused field programs such as VORTEX-II that will increase knowledge of storm scale phenomena and cloud microphysics; improving understanding of mesoscale weather processes; assessing the value of experimental technologies and products in a quasi-operational testbed environment (e.g., the National Weather Radar Testbed (NWRT), the Hydrometeorological Testbed (HMT), Hazardous Weather Testbed (HWT), and Joint Hurricane Testbed (JHT)); developing advanced technologies like phased array radar, dual polarized radar, and gap filling (e.g., Collaborative Adaptive Sensing of the Atmosphere or CASA-like) radars enabling significant improvements in observation resolution and boundary layer coverage; and developing high resolution storm-scale models that embody this understanding. Success in significantly extending lead times is dependent upon advances in radar data assimilation and the development of adaptive data integration technology. ADI technology is the automated "brain" behind the observational and predictive technology in the plan. ADI is the core controlling system adding user-defined value to the combined observational inputs and integrating these with high-resolution numerical weather models, advanced or "intelligent" algorithms operating under the ADI itself, and high-resolution data assimilation to produce an unprecedented Warn-On-Forecast capability. Intelligent algorithms are in a class of non-linear computational code operating dynamically and recursively on a broad array of data as well as other subservient codes through self-learning, pattern recognition, and optimization protocols. Ensemble Kalman filters may be regarded as an early prototype of such algorithms. In this particular context, the ADI algorithms would control beam formation and surveillance modes to maximize weather information, fill-in missing observational features by drawing from data mining and models, and optimizing model output to match and enhance observations in real time.

Focused testing and evaluation is pre-requisite to the selection and procurement of any of these substantial technology options.

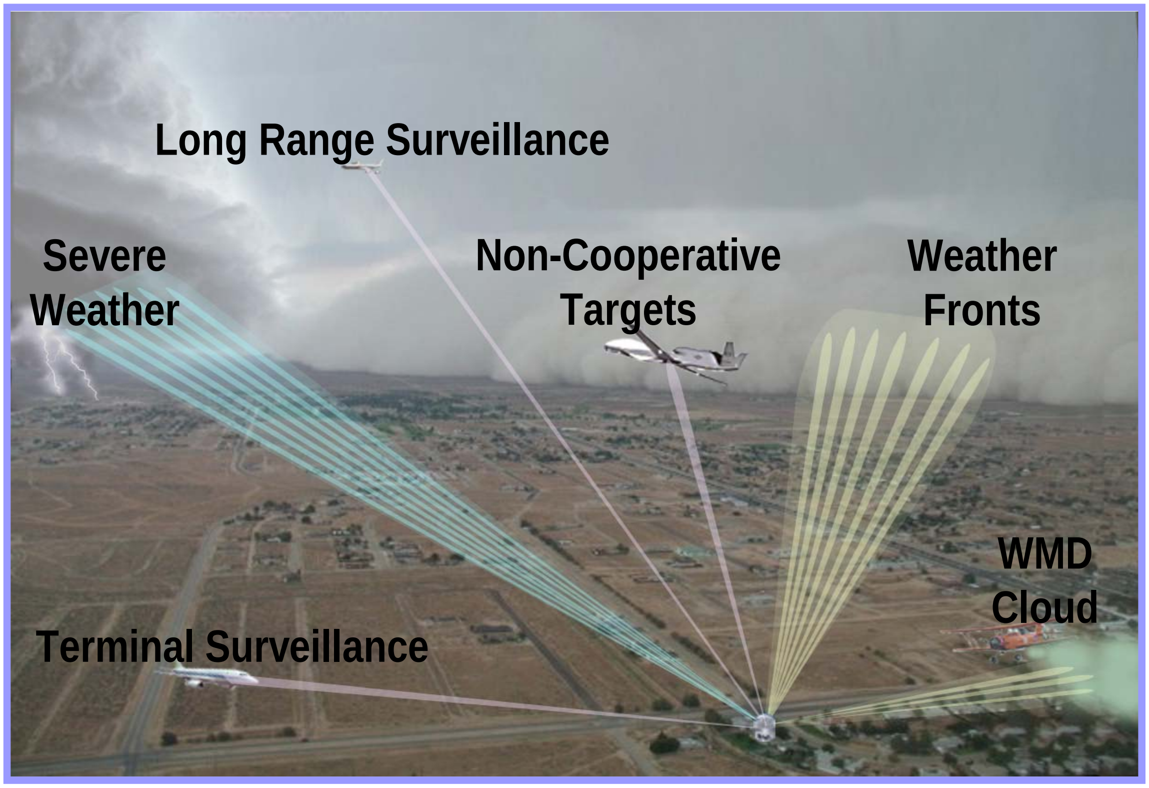

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Figure 3.1 -- Conceptual depiction of the capability of a multifunction phased array radar (MPAR) being developed at the National Weather Radar Testbed (NWRT) in Norman, Oklahoma. Illustrated are aircraft surveillance at long range and over the terminal area, detection of non-cooperative targets, detection of severe weather, observation and tracking of weather fronts, and particulate cloud such as the type associated with weapons of mass destruction (WMD).

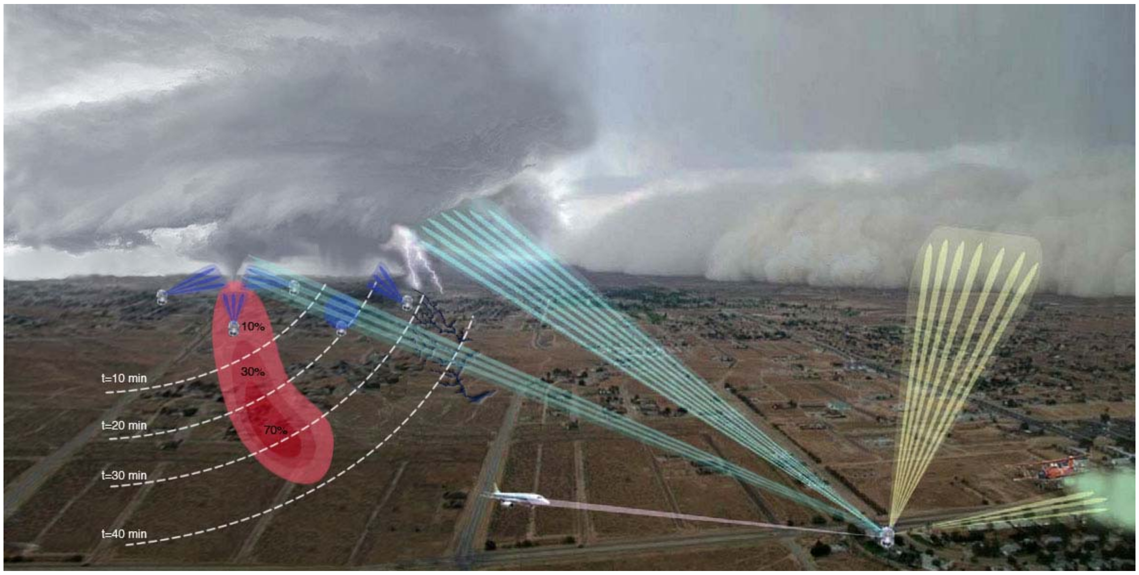

Figure 3.2 Tornado forecast expressed as a probability (out to 40 minutes in this example) created by assimilating high-resolution MPAR and gap filling (e.g., CASA) radar data into cloud-scale models (Warn-on-Forecast)

4. Existing Capabilities

The NWS operates 121 WSR-88D S-Band NEXRAD radars. The NWS shares WSR-88D data with the DoD and DOT NEXRAD tri-agency partners and receives data from the 34 WSR-88Ds the DOD and DOT operate in the U.S., Guam, and Puerto Rico (Figure 4.1). FAA TDWR weather radars located at major airports are being connected to the nearest NWS Forecast Office in support of operations (Istok et al., 2008). These 45 C-Band radars (Figure 4.2) provide localized higher resolution radar data to the local Forecast Offices, but are not currently networked outside the local NWS Forecast Office. The FAA also operates Air Surveillance Radars that may be of value to the NWS in the future (i.e., the ARSR-4, ASR-9, ASR-11 radars; coverage maps shown in Appendix 5). Researchers at NSSL have obtained access to 31 Canadian C-Band weather radars that are providing near real time data along the northern U.S. boarder (Figure 4.3). The NWS has initiated a project to provide the Canadian radar data to WFOs in the WSR-88D product formats. NSSL researchers have also begun work with a commercial TV station to assess the value of making its C-Band Doppler weather radar data available to the nearest Forecast Office. In this particular case in California, the TV station radar provides coverage in an area that the NWS NEXRAD radar is partially blocked by mountainous terrain. The WSR-88Ds continuously scan their environment at preselected elevation angles between 0.5° and 19.5°.

The NWS collects and makes real-time and archived WSR-88D radar products (Termed Level III data) and base data (termed Level II data) available to users (Kelleher et al., 2007). These products and the Level II data are used by NWS national centers, researchers, private companies, and the public. At least two DOC and NOAA mission goals are supported by distributing WSR-88D products and data in real time. The DOC mission goal supported promotes the Nation’s economic development by increasing the amount of environmental data private industry can use to provide customers value-added products. Provision of such data to the private sector makes their customers more productive and enables them to take actions to safeguard resources and people. The NOAA Strategic Goal supported is under Weather & Water and reads “Serve society’s needs for weather and water information”. Additional information about the WSR-88Ds can be found in the Federal Meteorological Handbook No. 11 – Doppler Radar Meteorological Observations (WSR-88D) (http://www.ofcm.gov/homepage/text/pubs.htm).

Through the years the WSR-88D operational capability has improved as advances in radar science and technology have been incorporated in the WSR-88D. This has been done through the NEXRAD Product Improvement program (NPI), which has funded various radar projects such as the Open Systems Radar Product Generator (ORPG), Open Systems Radar Data Acquisition (ORDA), TDWR data access and integration, and currently manages Dual Polarization. The NPI program, through the TAC and PMC, also provides planning and management structure for adding new science capability to the WSR-88D and TDWR product generation systems.

In order to test quantitative precipitation estimation and forecasting technology, NOAA has funded a Hydrometeorological Testbed-West (HMT-West) in California to address cool season QPE issues. This capability allows for targeted radar QPE research and development. HMT-West serves Science Technology Infusion (STI) NOAA mission goals. Testing plans include portable short-wavelength radar technology. Details about HMT can be found in http://hmt.noaa.gov/figs/stip.html. Larger scale surveillance radars are being tested at the National Weather Radar Testbed (NWRT; see http://www.nssl.noaa.gov/projects/pardemo). In general, testbeds are a desirable means to evaluate candidate technologies and performance questions and are seen as an important capacity to the goals of this plan.

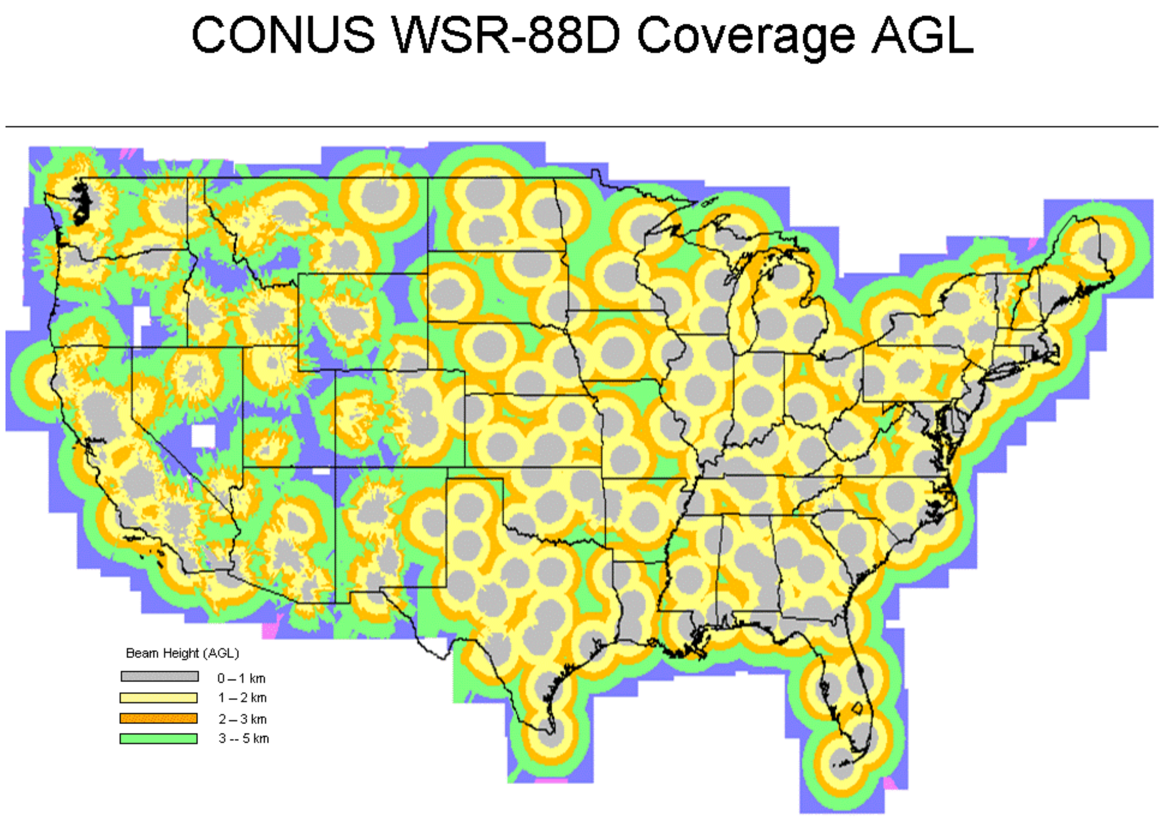

Figure 4.1. Depiction of the coverage of the WSR-88D network (above ground level). Most coverage gaps are found in the intermountain west. OCONUS sites are not shown.

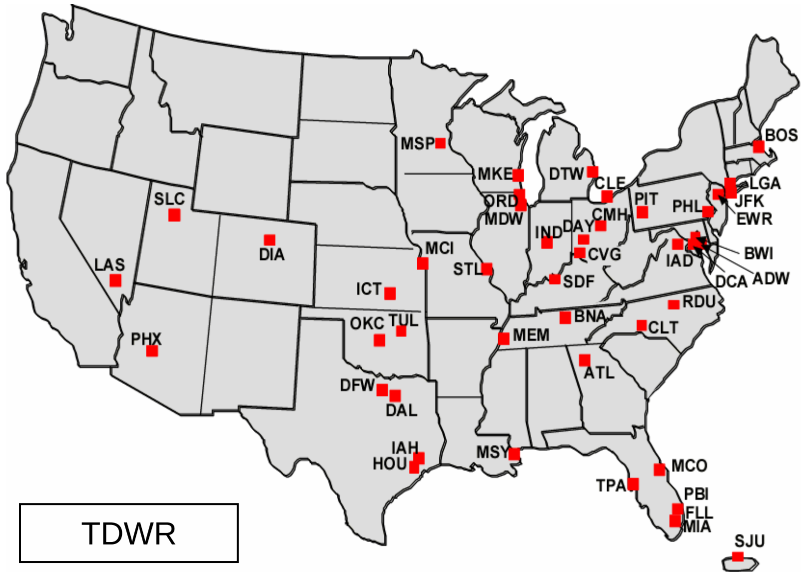

Figure 4.2. Locations of the FAA Terminal Doppler Weather Radars (TDWR) at selected airports. Data from these radars augment the coverage and resolution of the current NWS WSR-88D network

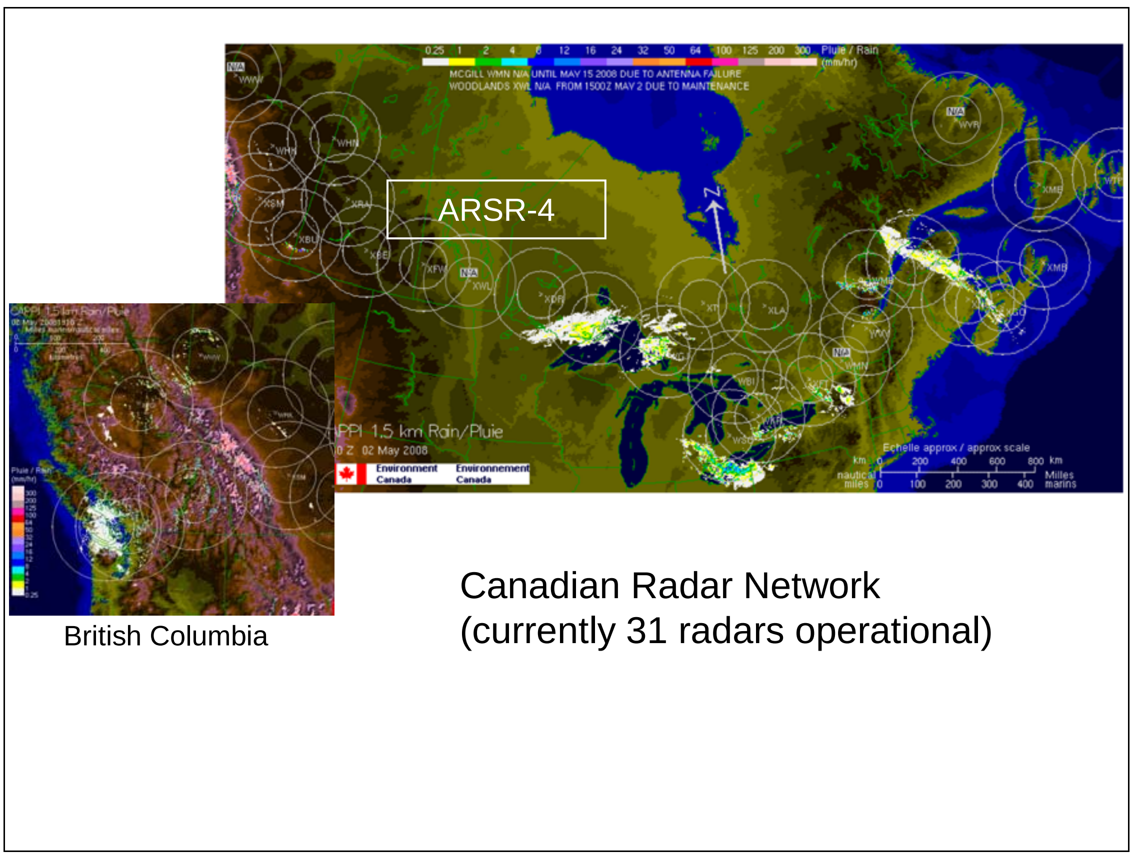

Figure 4.3 Location and coverage of the Canadian Radar Network. NOAA's National Severe Storms Laboratory is receiving the data from these radars in near real time (~15min latency) and using it in its national radar mosaic product.

5. Performance/Vision Gaps

There are significant gaps in the areas of severe weather, quantitative precipitation estimation and tropical cyclones as revealed by an analysis of NOAA *optimal* requirements for services currently supported by radar data (Appendix A.6). Various NRC reports (listed in Section 9) on weather radar planning and performance identify observational gaps in the current weather radar network. In addition, there are phenomenological gaps reflecting intrinsic sampling limitations of the current weather radar network, which affect the certainty and accuracy of all related products. Performance gaps are related to unmet service goals. Data gaps account for the inherent observational limitations. Research and Development (R&D) gaps account for shortfalls in the needed research supportive of the service needs and goals. Research to operations gaps focus on what is needed to adopt research products into operations, which is comprised of considerable evaluation activity. Radar technology gaps address needs associated with developing and testing new radar technologies and techniques. A depiction of the various hydrometeor spatio-temporal characteristics can be found in Figure 5.1, and illustrates the observational resolution that lead to gaps and limitations in weather detection. The gaps can be summarized as follows:

Performance Gaps

- 50% of tornadoes are not warned for with positive (non-zero) lead time
- 75% tornado False Alarm Ratio
- Geographical overwarning: many tornado, severe thunderstorm and flash flood watches and warnings lack sufficient spatial resolution (goal is “neighborhood scale” warnings)
- Large biases in quantitative precipitation estimates (QPE) and limited coverage

Data Gaps

- Tornadic storm development and significant storm evolution can occur in a minute or less, however, low altitude WSR-88D observations of such storms are only updated every 4-6 min.
- At longer ranges beam height - and clutter in complex terrain - degrade the detection of shallow precipitation as well as the precursors of convective initiation such as dry lines and convergent wind boundaries.
- As much as 72% of the atmosphere below one km is not sampled by the WSR-88D network with the current sampling protocol.
- Complex terrain found in the intermountain west and some OCONUS sites, for example, often blocks low-level NEXRAD coverage in key areas around population centers and river basins.

Research and Development Gaps

- Current NOAA budget profiles do not fund the research and development necessary for informed programmatic decisions on whether to pursue phased array radar, multi-function PAR, CASA-like gap-filling radar, or some integrated combination of these systems.
- Current storm-scale numerical data assimilation techniques, quality control techniques, data observations (temporal and spatial), and state-of-the-art modeling do not support “Warn-on-Forecast” operations as they lack the needed observational and numerical resolutions.

RTO (Research-To-Operations) Gaps

The JRPT has developed a roadmap to improve the contribution of weather radar to the mission of NOAA and its partners (see Figure 5.2). This roadmap requires investment to develop the knowledge base to support informed evaluation at key decision points. This strategy not only addresses infusion of advanced technologies over the next 20 years, but also addresses maintaining and, where appropriate, improving the current level of NEXRAD performance. Since NEXRAD is the primary tool upon which warnings are based, continuous maintenance and improvements will be needed until it is replaced.

Key projected activities include:

- Development of improved tornado identification techniques utilizing Super Resolution, polarimetric radar, multi-function phased array radar (MPAR) and data from gap-filling radars
- Determination of the alternatives for “gap-filling” radar technologies
- Research and evaluation of gap-filling (X-band) radar and polarimetric X-band radar by FY12 in anticipation of NWS go/no go deployment decision in limited geographical areas
- Research and evaluation of MPAR radar within the NWRT as a viable alternative technology to eventually replace NEXRAD and FAA radars by FY17 in anticipation of NWS go/no go deployment decision
- Development of storm scale numerical data assimilation techniques for high spatial/temporal resolution and Dual Polarization data
- Dissemination of FAA TDWR radar data beyond local forecast offices
- Expansion of activities to ingest weather radar data from existing, non-NWS weather radars (e.g., FAA, Canadian, Mexican, Caribbean, private sector)
- Development and deployment of infrastructure upgrades to maintain NEXRAD system reliability
- Development of testing and evaluation criteria to assess the value of the various alternatives in the 2025 JRPT roadmap (cf. Fig. 5.2)
- Advocating the inclusion in NOAA budget profiles of funding for the NPI program beyond the completion of Dual Polarization, and for critical organization infrastructure sustaining near- and longer-term RTO activities.

JRPT Vision Gaps

The JRPT vision is service-centered, calling for dramatic increases in tornado (from ~15 min to an hour or more) and flash flood (from ~ 1 hr to 3 hr) warning lead time, a four-fold improvement in QPE accuracy, multi-hour forecasts of convective systems, and high-resolution data among others by 2025. The vision is build upon development and implementation of key enabling technology lines (Fig. 5.2) comprised of a strategic mix of the following: long-range surveillance radars (such as NEXRAD and MPAR); adaptive data integration, consisting of highly intelligent adaptive radar and meteorological algorithms: diverse boundary layer short-wavelength sensors (SWR), consisting of “gap-filling” radars capable of sampling the boundary layer at very high resolution; and, partnerships with non-NOAA radar data sources such as FAA, TV stations, and border-country radars. These enabling technologies should be developed under a coordinated and integrative testing and evaluation framework to better understand how each technology enhances the various service goals and the overall vision. A coordinated framework is needed to maximize value. For instance, a given sensor technology may be unnecessary if another sensor is fully capable of providing equivalent information. Moreover, some technologies may be capable of satisfying the requirements of several governmental agencies simultaneously, thus providing opportunities for agencies to share in the investment and reducing the overall cost to the taxpayer.

Next are listed the specific perceived gaps grouped in terms of the enabling technologies discussed above:

Radar Technology Gaps

Long-range Surveillance Radar Gaps

- Dual polarization
- MPAR Prototype costs
- MPAR Pre-acquisition testing and development
- Go/No-Go MPAR testing decision jointly with FAA
- Determination of viability of multi-function radar capability
- NEXRAD Product Improvement continuance for stand-alone WSR-88D as sole alternative in case of No-Go for MPAR or similar technology
- Identification of any alternative technologies to MPAR

Adaptive Data Integration Radar Gaps

- Concept and system definition
- Prototype code development
- Hardware requirements
- Advanced data assimilation definition
- Adaptive multi-sensor algorithms

- Integrative cloud-scale numerical model
- Testing of Warn-On-Forecast

Diverse Boundary Layer Sensor Radar Gaps

- Prototype cost
- Acquisition strategy (pre- or post-prototype)
- Operations concept
- Dual polarization
- Data assimilation system

Partnership Sensor Radar Gaps

- Ingest of FAA radars (TDWR, ARSR-4, ASR-11)
- Ingest of radar data from international partners (Canada, Mexico, Caribbean)
- Identification of suitable commercial-TV radars
- Multi-sensor data integration and calibration
- Data archiving protocol
- Data assimilation plans for NWP
- NEXRAD Product Improvement continuance as critical organizational infrastructure for planning and managing current and future NOAA/NWS weather radar improvement projects

Key Decision Points

A number of key decisions are mapped in the plan (Fig. 5.2), driven by milestones and deadlines internal and external to NOAA. The decision points also arise from developmental considerations. For instance, adaptive data integration must first develop Warn-on-Forecast before adopting more advanced algorithms integrating cloud-scale and data mining techniques. Some key decision points are set by plans from other agencies (e.g., FAA) to replace given radar systems. FAA, in particular, is expected to rely on ADS-B technology to separate traffic though radar surveillance will continue albeit not as a primary capability. Each decision point may change due to agency requirements, budgets or other factors so they should be regarded as approximate. Detailed explanations of MPAR planning can be found in the OFCM reports listed in Section 9. The following summarizes the known decisions points with approximate dates corresponding to the various enabling technologies:

Surveillance Radar (NEXRAD/MPAR)

A1: FY08 - Super-res Go/No Go decision.

A2: FY09 - Dual-pol Go/No Go decision.

A3: FY09 - Begin enhanced NWP data assimilation?

A4: FY11 –Projected NPI Zero Funding.

A5: FY17 - Evaluate future WSR-88D network operation in light of MPAR.

MPAR

B1: FY12 - Implement dual-pol capability; begin demonstration for go/no go decision in FY17

B2: FY10 – NOAA R+D Go/No Go decision

B3: FY17 – Go/No Go decision for FAA partners (drives Cost Benefit analysis). Begin prototype acquisition process? Has the technology proven itself?

B4: FY19 - Begin full production design program?

Adaptive Data Integration:

C1: FY13 – Go/No Go on Adaptive Scanning

C2: FY15 – Develop Warn-on-Forecast

C3: FY?? – Develop adaptive “closed loop” intelligent data integration

Short-Wavelength Radar:

D1: FY09 – NOAA R&D Support Go/No Go decision

D2: FY09 – CASA & SWR QPE/F Testbed Go/No Go (branches off to non-SWR options if decision is no-go)

D3: FY11 – NOAA SWR Prototype Assessment complete

Targets of Opportunity/Non-NOAA Partnerships:

E1: FY06 - FAA Radars

E2: FY09 - Canadian Radars

E3: FY09 - Private-sector Radars

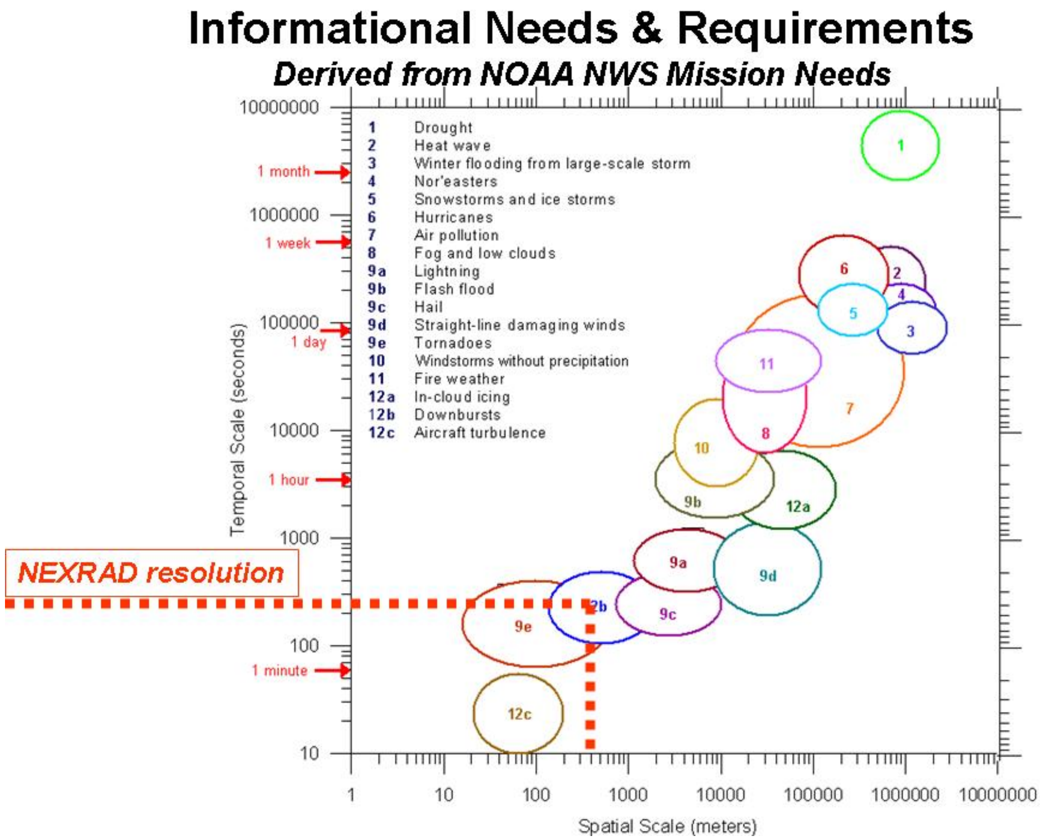

Figure 5.1 Informational Needs and requirements shown in terms of temporal and spatial scales as well as depicting the current level of NEXRAD resolution available (dashed red lines). Scales below the current level of NEXRAD resolution (lower left portion of graph bounded by dashed red line) are not sampled as well as various other uncharted phenomenology arising from the various features.

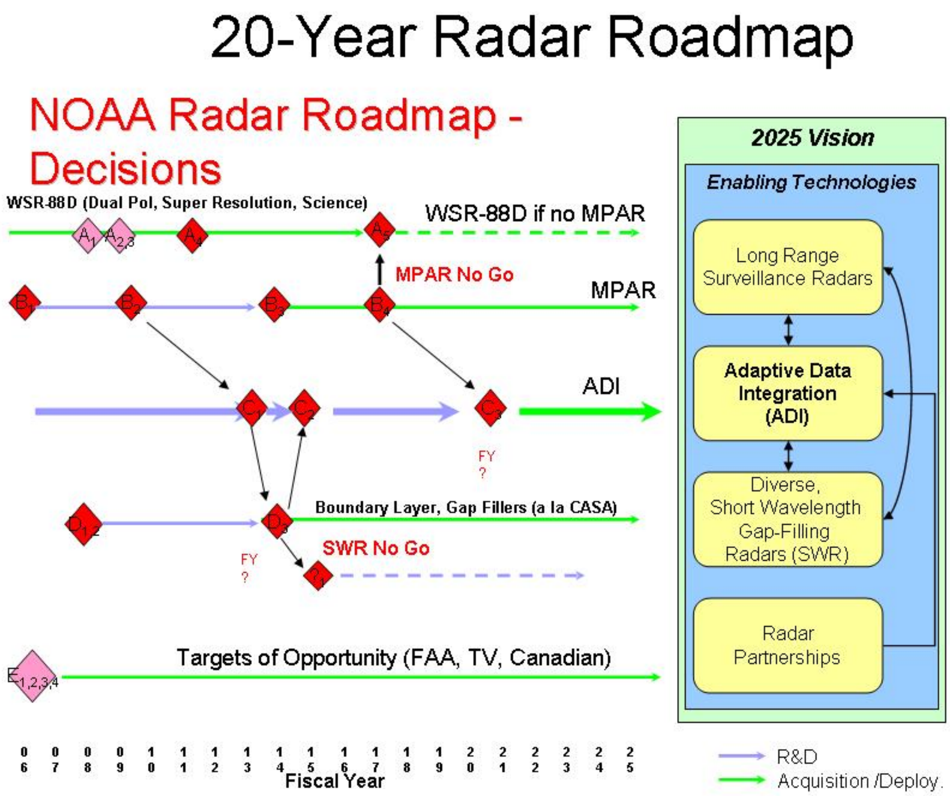

Figure 5.2 NOAA 20-Year Roadmap for Weather Radar. The 20-year vision guides the roadmap from which four enabling technologies are identified: long-range surveillance, adaptive data integration (ADI), short-wavelength radars (SWR), and radar partnerships with non-NOAA radar data sources. ADI is the master "controlling" technology integrating all the others to provide Warn-On-Forecast and intelligent algorithm capabilities needed to achieve the vision. The diamonds denote various decision points as a function of fiscal year. Various go/no-go critical decision points are shown as well as the associated branching to other options. See text for further discussion.

6. Proposed Capability Enhancements

The proposed strategy calls for infusion of new technology as well as upgrades to the current technology in order to achieve the short-term and long-term improvements needed to sustain current and future service. The enhancements listed below are consistent with two NRC 2002 report and the OFCM 2006 study on MPAR (see References).

a) Resolution

Enhance temporal/spatial resolution and low level coverage with existing radars:

- **NEXRAD WSR-88D**
    - Add dual polarization capability
    - Develop and implement signal processing techniques to reduce volume scanning times and increase data accuracy
    - Develop and implement algorithms to utilize Dual Polarization data and the increased spatial detail of Super Resolution data
    - Include Super Resolution and Dual Polarization in Level II distribution

- **FAA, Canadian, Mexican, Caribbean, and private sector data**
    - Implement data connections to all such radars that could provide significant supplemental geographic coverage to the WSR-88D network or valuable backup capability during WSR-88D outages
    - Develop and implement post-processing algorithms to utilize non-NEXRAD radar data similar to that in NEXRAD
    - Distribute non-proprietary base data and products to NWS, private sector and other users in standard WSR-88D Level II and III formats

b) Research-to-Operations (RTO)

Ensure a funding profile to continue the effective NEXRAD Product Improvement program for:

- Managing WSR-88D technology implementations such as Dual Polarization
- Expanding the incorporation of non-NWS radar data
- Prioritizing and implementing new scientific algorithms and working with the ROC for their integration into operations
- Assistance to NOAA/NWS planning for the potential incorporation of MPAR and CASA-like radar capabilities

c) New Technology

- **Cost Benefit – Surveillance radars**

Conduct the science and engineering research and development necessary to evaluate the cost-benefit of an MPAR acquisition to replace the WSR-88D.

- The WSR-88D and the FAA's TDWR are aging systems, with no replacement technology yet identified.
- PAR technology offers the promise of a significant improvement in weather detection, with sub-minute volume update rates, co-sampling of the entire vertical structure of a storm, storm-focused detailed scanning concurrent with umbrella surveillance, and rectilinear wind field measurements as opposed to only the radial component measured by NEXRAD and single-beam systems.
- The FAA is partnering with NOAA on a research and development program to develop a PAR prototype capability for aircraft tracking and terminal airspace weather surveillance to explore replacements of its TDWR surveillance radars. The FAA is looking to NOAA to conduct scientific research and development with PAR to ensure that weather detection requirements are addressed.
- FAA, NOAA, DHS, and possibly DoD participation in a multi-agency, multi-function PAR research and development program is crucial to deriving a realistic cost-benefit ratio for meeting the requirements of the participating agencies.
- Without PAR or other potential replacement technology, NOAA is committing to an indefinite service life extension for the WSR-88D.

- A joint FAA/NOAA MPAR implementation would result (see OFCM 2006 report listed in Section 9) in the following:
  - 35% reduction in weather and aircraft tracking radar units versus current total
  - Estimated savings of up to $1.8B in acquisition costs if replacing all existing FAA and NOAA radars with similar technology
  - Estimated savings of up to $3B in life cycle costs over 30 years due to 35% fewer radars
  - Reduction in number of short range radar units needed to cover gaps in low altitude coverage as compared to current coverage gaps
    - Supplement WSR-88D coverage with high quality weather data from all FAA units
    - Gaps would still persist below lowest beam at the longer MPAR ranges, and in complex terrain

- **Cost Benefit – Boundary layer/"Gap filling" radars**

  Conduct the science and engineering research and development necessary to evaluate the cost-benefit of an acquisition to complement the NOAA surveillance radar network (WSR-88D now, potentially MPAR in the future) with low cost, short range, short-wavelength, gap filling radars for boundary layer and complex terrain coverage.

- The WSR-88D network coverage is excellent for detecting mature thunderstorms and precipitation with significant vertical development.
- At longer ranges and in complex terrain, the WSR-88D can miss shallow yet potentially significant precipitation as well as precursors of convective initiation.
- The CASA project, led by the University of Massachusetts, has been funded by NSF as an Engineering Research Center to develop low cost radars to provide for the testing of reliable detection of low altitude severe weather, rain/snow, and the pre-storm environment. Prototypes have been deployed and provided highly promising results.
- CASA offers the promise of affordable radar deployment with improved storm detection similar to MPAR, but with low altitude coverage.
- Opportunities to investigate NOAA operational cost-benefit ratios for CASA technology:
    - The CASA operated Severe Weather Test Bed in Oklahoma
    - The NOAA Hazardous Weather Test Bed in Oklahoma
    - The NOAA Hydrometeorological Test Bed in the American River Basin in California (HMT-W).

7. Evaluation Framework

The alternatives in the plan (Fig. 5.2) will need to be tested and evaluated in terms of their potential value and contribution to the NOAA mission and the services needs and goals. All alternatives will be subject to the NOAA Operations and Services Improvement Process (OSIP), which provides the enterprise-wide structure for evaluation. Funding and program plans are also reviewed and approved by the tri-agency NEXRAD Program Management Committee.

A baseline for radar evaluation is the NEXRAD level of performance (e.g., Figures 2.1 and 2.2), at the time of evaluation since no degradation of services or inherent radar capability is a cornerstone requirement endorsed by this vision document. Testing and evaluation criteria should include all of the service metrics related to radar observations such as impact on lead times, probabilities of detection, false alarm rates and information content for tornadoes, severe weather, flash flood, quantitative precipitation estimation, wind profile retrieval, hydrometeor classification, turbulence, Doppler spectral accuracy, resolution, and geographical coverage amongst others. As many of the wanted acquisition criteria should be incorporated in the testing and evaluation of new radar techniques and technologies as possible.

The impact of enabling technology alternatives to numerical weather prediction should also be considered. Numerical models are increasingly capable of assimilating radar data at progressively higher resolution. The correlation of model performance to observational data assimilated varies considerably depending on the particulars of the model. The JRPT plan envisions operational cloud-scale modeling of the atmosphere fed by radar and other data as an optimal strategy to significantly raise performance levels. Likewise, enabling technologies may provide new observables such as moisture, ocean wave spectra or three-dimensional wind information beneficial to non-tradition weather goals. Ultimately, alternative technologies must have a service link.

Adaptive Data Integration should be tested in a fashion similar to that of the radar alternatives, in addition to traditional software criteria such as hardware requirements, size, etc. However, ADI is not an end by itself, but a new class of high-level algorithms controlling sensors and models in order to maximize efficiency in the selection, processing, and assimilation of real time observations in critical areas of the storm and storm environment.

NOAA recently issued a Transition Policy that governs all RTO activity. In general, one of the RTO steps is the testing of the candidate technology. This includes measurable exit criteria from the testing to be used prior to a transition decision. Measurable exit criteria are quantitative results with which to judge the testing against prescribed requirements. NOAA is also developing a policy for obtaining environmental data from external sources that is expected to govern the use and acquisition of the partnership radar data, thereby supporting portions of this vision.

The critical success exit criteria for testing each candidate technology includes the following:

Technical Criteria

- Performance improvement compared to NEXRAD at the time of evaluation
- Quantitative results in terms of applicable NOAA performance measures

Business Case Criteria

- Costs of acquisition, deployment, operation and maintenance
- Cost-benefit in regard to environmental data of high economic value (e.g., floods, hurricanes)
- Ability to leverage resources from other federal government agencies to reduce cost to NOAA and maximize the benefit

These overarching criteria will be further detailed into specific measures along with procedural recommendations. A Working Group consisting of research, operational and academic experts should be formed to make recommendations. The overall objective is to assess how benefits outweigh costs through the testing and evaluation process.

8. Summary

Improved storm scale observational capabilities are required to enhance "Warn on Detection" performance as well as to provide the necessary information for storm scale model initialization to support reliable forecasts of tornadoes in the one hour time frame (Warn-on-Forecast). These necessary observational improvements include temporal and spatial resolution, broader geographic coverage, especially in the boundary layer, and data quality advances.

The Joint Radar Plan integrates research activities in support of the NOAA NWS operational service mission. The plan is built upon a vision of hour-long tornado lead times, a three-fold increase in flash flood (from ~ 1 hr to 3 hr) warning lead time, a four-fold improvement in QPE accuracy, multi-hour forecasts of convective systems, and neighborhood scale warnings by 2025. Four enabling technology lines support the vision: (1) long-range, multi-function weather radar surveillance at high temporal resolution; (2) short-wavelength "gap filling" radar networks capable of sampling the boundary layer with unprecedented resolution; (3) advanced modeling and algorithms integrating multi-sensor observations, advanced data mining, and cloud-scale models, collectively known as adaptive data integration; (4) partnerships with non-NOAA radar data sources; and (5) advanced computer technology enabling fast acquisition, quality control, and model completion in near real time.

The plan also calls for short-term improvements, such as dual-polarization of the NEXRAD radar network, through an adequately funded NPI program that facilitates technology transfer into operations on a continuous basis. A key component of the vision, and part of Adaptive Data Integration, is the development of Warn-on-Forecast capability in order to significantly extend lead times of various storm phenomena.

Radar requirements needed to support NOAA's severe weather mission have been provided as part of the CORL database. The database offers guidance for the development and evaluation of candidate observing systems. The plan supports continued testing and evaluation of MPAR as one of the candidate long-range weather surveillance technologies with a multi-mission design purpose. NOAA testbeds allow for evaluation of technologies and techniques to improve weather radar in support of NOAA's hydrometeorological and severe weather mission and are integral to the plan. Testbeds will help to determine operational cost-benefit ratios.

The plan contains budgets for MPAR and NPI supported activities, as well as a testing and evaluation framework, key decision points, and a general research to operations timeline. The testing and evaluation framework considers both technical and business case criteria.

Substantial socio-economic benefit has resulted from improved weather radar technology such as NEXRAD. Targeted research and development, such as investigation of short-wavelength radar networks or improved understanding of cloud microphysics, is of fundamental importance to the success of this plan. The plan recommendations overlap significantly with those articulated in the NRC report “Beyond NEXRAD” (2002), the OFCM report on Phased Array Radar as a candidate weather radar technology (2006), the NRC hydrometeorological report on complex terrain and radar observations (2005), and the NRC report on MPAR planning (2008).

9. References

Federal Meteorological Handbook No. 11 – Doppler Radar Meteorological Observations (WSR-88D), Office of the Federal Coordinator for Meteorology (OFCM), (http://www.ofcm.gov/homepage/text/pubs.htm)

Federal Research and Development Needs and Priorities for Phased Array Radar, Office of the Federal Coordinator for Meteorology (OFCM) Report R25-2006, Joint Action Group for Phased Array Radar, June 2006.

Istok, M.J., A.D. Stern, R.E. Saffle, B. Bumgarner, B.R. Klein, N. Shen, Y. Song, Z. Wang, and W.M. Blanchard, 2008: Terminal Doppler Weather Radar for NWS Operations: Phase 3 Update, 24th Conf on Interactive Information and Processing Systems, Amer. Meteor. Soc., New Orleans, LA, Paper 6B.10.

Kelleher, K. E., K. K. Droegemeier, J. J. Levit, C. S. Sinclair, D. E. Jahn, S. D. Hill, L. Mueller, G. Qualley, T. D. Crum, S. D. Smith, S. A. Del Greco, S. Lakshmivarahan, L. Miller, M. Ramamurthy, B. Domenico, D. W. Fulker, 2007: Project CRAFT: A Real-Time Delivery System for NEXRAD Level II Data Via the Internet. Bulletin of the American Meteorological Society, 88, doi:10.1175/BAMS-88-7-1045.

National Research Council (NRC) 2002 report, "Weather Radar Technology *beyond* NEXRAD", http://books.nap.edu/openbook.php?isbn=0309084660

National Research Council (NRC) Report 2005, "Flash Flood Forecasting Over Complex Terrain: With An Assessment of the Sulphur Mountain NEXRAD in Southern California", http://www.nap.edu/catalog/11128.html

National Research Council (NRC) Report 2008, "Evaluation of the Multifunction Phased Array Radar Planning Process", Committee on the Evaluation of the Multifunction Phased Array Radar Planning Process; NRC Board on Atmospheric Sciences and Climate. ISBN: 0-309-12430-1, 90pp. http://www.nap.edu/catalog/12438.html

NOAA Transition Policy, effective 7/31/08.

Sutter, D., and Simmons, K., 2005: WSR-88D radar, tornado warnings, and tornado casualties. *Weather and Forecasting*, **20(3)**, 301-310.

APPENDICES

A.1 Mandates

- U.S. Code Title 15 Chapter 9 for warning and forecast services directing NWS to forecast the weather, issue storm warnings, etc.
- Public Law 107-253 for inland flood forecasts and warnings, authorizing NOAA to improve forecast and warning capabilities.
- DHS National Response Plan (Dec 04) calls for an all-hazards approach to incident management. DOC/NOAA is tasked with acquiring, disseminating weather data, forecasts, and emergency information.
- BLM Interagency Agreement identifies NWS as the official source of meteorological information.
- National Hurricane Operations Plan, 2007

A.2 Linkages to NOAA 2006-2011 Strategic Plan

- NOAA Goals:
    - Serve society's needs for weather and water information
    - Support the Nation's commerce with information for safe, efficient and environmentally sound transportation.
- W&W Mission Goals:
    - Reduced loss of life, injury and economic damage
    - Better, quicker, and more trusted weather and water information to support informed decisions.
    - Increased satisfaction with quality of weather and water information and services.

A.3 "Blue Ribbon" Recommendations

- **(2002) National Research Council Report: Weather Radar Technology Beyond NEXRAD**
    - The potential value and technology to incorporate data from complementary radar systems to provide a more comprehensive description of the atmosphere should be investigated
    - Adaptive waveform selection, which may even be applied to present systems, and agile beam scanning strategies, which require an electronically scanned phased array system, should be explored to optimize performance in diverse weather.

  - The technical characteristics, design, and costs of phased array systems that would provide the needed rapid scanning, while preserving important capabilities such as polarization diversity, should be established.
  - The potential for a network of short-range radar systems to provide enhanced near-surface coverage and supplement (or perhaps replace) a NEXRAD-like network of primary radar installations should be evaluated thoroughly.
- **(2002) NWS Tornado Warning Improvement Team**
  - Integration of FAA radar data; increased spatial and temporal data density; Improved data assimilation/analysis
  - Evolution of existing radar systems
  - Phased array radar
  - Focus on numerical data assimilation and local/regional storm-scale models
- **(2004) National Research Council Report: Flash Flood Forecasting Over Complex Terrain**
  - To extend radar coverage, all available regional real-time weather radar data should be made accessible to the NWS WFOs, including FAA and DOD NEXRAD radars; FAA TDWR radars and other surveillance radar equipped to provide weather echo data; local television station Doppler radars; and operational radars from other organizations.
  - The NWS should consider augmenting the NEXRAD network with additional short-range radars to improve observations of low-level meteorological phenomena.
- **(2006) OFCM Report: Federal Research and Development Needs and Priorities for Phased Array Radar**
  - **Finding 1:** Multiple federal agencies currently rely on radar networks to provide essential services to the nation. The principal current uses are for weather surveillance and other atmospheric observations and for aircraft surveillance.
  - **Finding 2:** A single MPAR network with the capabilities described in this report could perform all of the existing civilian radar functions. In addition, other existing and emerging needs not being adequately met by existing systems could be met with this same MPAR network.
  - **Finding 3:** The timing is right to conduct a thorough evaluation now of MPAR as an alternative to conventional radar for the full range of current and emerging applications described in this report. The aging of our existing domestic radar networks for weather and aircraft surveillance will require substantial commitments of federal resources to either maintain or replace them.
  - **Finding 4:** A preliminary cost evaluation shows that one MPAR network designed to meet multiple national needs can be developed, implemented, and maintained at a lower cost, on a life-cycle basis, than would be

required to sustain the existing conventional radar networks through required maintenance and incremental upgrades.

- **Finding 5:** The JAG/PARP proposes a risk-reduction and development (R&D) plan that, for a modest investment, will provide a sound technical and cost basis for a national decision between MPAR implementation versus continued maintenance and upgrade of the aging, existing radar systems. The estimated total cost for this risk reduction plan is $215 million.
- **Recommendation 1:** The FCMSSR should endorse the concept of an MPAR risk-reduction R&D program that substantially incorporates the objectives and the three components of the plan outlined in chapter 6 of this report.
- **Recommendation 2:** The FCMSSR should consider organizational options to foster collaborative and joint R&D on the MPAR risk reduction activities by establishing a joint entity, such as a Joint National Center for advanced Radar Research and Development, to manage agencies' contributions to the risk reduction program outlined in this report.
- **Recommendation 3:** For the period prior to standup of a joint management entity, the FCMSSR should direct OFCM to form an interagency MPAR Working Group (WG/MPAR) within the OFCM infrastructure to coordinate and report on the R&D activities of participating agencies in implementing an MPAR risk reduction program. Activities of the WG/MPAR should include, but not be limited to:
  - Identification of agency contributions to the first phase of risk-reduction activities in each component prong of the program.
  - Establish a cost basis for near-term agency contributions, sufficient to allow incorporation into agency budget submissions.
  - Explore options to foster interagency cooperation and collaboration on MPAR risk-reduction activities.
  - Develop a set of specific program progress metrics against which annual progress toward risk reduction goals and objectives can be assessed.
  - Prepare and publish an annual statement of the next-year objectives and activities for the risk reduction program. This annual statement should include a review of progress in the current year and connections to out-year activities and objectives, to show how each year's activities contribute toward achieving the overall risk-reduction goals. As guidance to the participating agencies, the report should include an estimate of budget resources needed for the next-year activities and a summary of prior-year funding by agency. Progress toward goals and objectives, using the program metrics, should be reported each year, with an analysis of areas of shortfall and substantial progress.

    - Identify opportunities for review of program plans and progress by appropriate boards or study committees of the National Academies' National Research Council.
    - Prepare and publish an MPAR Education and Outreach Plan to build understanding of and garner support for a national surveillance radar strategy decision within all the potentially affected federal agencies, Congress, state and local governmental entities, the private sector, and the public. This plan should involve the academic community and the media and include dissemination of results from the NRC studies suggested above. A series of workshops, coordinated through the National Center for Atmospheric Research (NCAR), should be considered for engaging the academic research community.
  - **Recommendation 4:** The FCMSSR should direct that, in conjunction with the MPAR risk-reduction program, a cost-benefit analysis be undertaken to establish the cost-effectiveness of the MPAR option and competing domestic radar strategies. The basis for MPAR acquisition and life-cycle costs should include results from the technology development and test activities and the MPAR network refinement, as appropriate.

- **(2008) National Research Council Report: Evaluation of the Multifunction Phased Array Radar Planning Process**

COMMITTEE RECOMMENDATIONS - Overarching Recommendation

- The committee recommends that the MPAR Research and Development (R&D) program be continued with the objective of evaluating the degree to which a deployable MPAR system can satisfy the national weather and air surveillance needs cost effectively. This program should incorporate the following features:
  - Full evaluation of the unresolved technical issues
  - An evaluation of the full operational requirements of all participating agencies and the ability of MPAR to meet these requirements
  - Development of the basis for reliable and realistic estimates of acquisition and lifecycle costs of a nationally deployed MPAR System
  - Independent assessment of the cost effectiveness of the R&D program itself, especially prior to commitment of major funding for the full-scale prototype.

Specific Recommendations for the R&D Plan

- ***Recommendation:*** The R&D Plan outlined in Appendix D in the JAG/PARP Report should be expanded to provide detailed descriptions of the tasks to be undertaken, their priorities, the associated costs, and key decision points.

- ***Recommendation:*** The FCMSSR should seek a reasonable and continuous funding stream to support the R&D Program**.**
- ***Recommendation:*** The WG-MPAR planning process for the MPAR R&D program should implement frequent updating and improvement of the MPAR program plan to ensure planning robustness and relevance in the face of changing external conditions.
- ***Recommendation:*** Probability estimates of the likelihood of success/failure of achieving objectives at critical decision points in the R&D program should be developed.
- ***Recommendation:*** The committee endorses Recommendation 2 of the JAG/PARP report and would like to see it implemented early in the program**.**
- ***Recommendation:*** The MPAR R&D program should include the staged development of a prototype MPAR, proceeding through a Line Replaceable Unit (LRU), followed by a single antenna face, two faces, or a full four-faced prototype. Cost effectiveness studies should be carried out to determine how many faces would be required to assess the MPAR concept.
- ***Recommendation:*** The MPAR R&D Program, instead of developing new X- and C-band radars, should develop linkages with appropriate organizations within the radar community as a way to avoid duplication of effort and take full advantage of ongoing work related to short-wavelength radar technologies**.**

Specific Recommendations on the Definition of Requirements

- ***Recommendation:*** The MPAR R&D program should produce a fully vetted set of technical performance requirements for an operational MPAR and radar network.
- ***Recommendation:*** MPAR system design studies and analysis of alternatives should consider the MPAR system as a candidate member of a family of systems, carefully considering design and mission tradeoffs with existing and new surveillance capabilities under development.
- ***Recommendation:*** The Airport Terminal Area or T-MPAR concept needs to be developed in sufficient detail to demonstrate that mission requirements for terminal weather and aircraft surveillance can be met. In addition, the ability of a full MPAR to meet Terminal Doppler Weather Radar (TDWR) requirements must also be assessed due to the fact that the beamwidth would be approximately 1 deg (instead of ½ deg) and the frequency choice is S-band (instead of C-band).

Specific Recommendations on Technical Issues

- ***Recommendation****:* The MPAR R&D program should produce a procedure for calibrating the reflectivity and polarimetric measurements at all scan angles
- ***Recommendation:*** Given the high demand for bandwidth at the proposed S-band frequency, the MPAR R&D program must determine the total

required bandwidth as early as possible in the research program to ensure the feasibility of the design.

Specific Recommendations on the Costs and Cost-Benefit Considerations

- ***Recommendation:*** A thorough and complete cost analysis of the total MPAR program should be performed and compared with historical life-cycle costs for the more recently and currently deployed systems such as ARSR-4 and ASR-11 that are roughly equal in performance to MPAR for air-traffic surveillance, and for NEXRAD and TDWR radars that provide a performance baseline versus MPAR for weather surveillance. A detailed baseline operations and maintenance (O&M) cost estimate should be determined for all legacy radar types to identify and quantify those highest cost radar types that are the prime candidates for life extension, upgrade or replacement. Independent cost risk analyses for the acquisition of MPAR and T-MPAR by recognized methods should be performed and frequently re-visited and updated.
- ***Recommendation:*** An alternative weather-only phased array weather radar design trade study and detailed cost analysis should be performed and compared with historical life cycle costs and performance for NEXRAD and TDWR radars.

A.4 Societal Impacts

- NOAA 2006-2011 Strategic Plan

    - Floods, droughts, hurricanes, tornadoes, tsunamis, and other severe weather events cause $11 billion in damages each year in the U.S. Weather is directly linked to public health and safety. Nearly one-third of the U.S. economy (ca. $3 trillion) is sensitive to weather and climate.
    - At least $4 billion is lost annually due to economic inefficiencies resulting from weather-related air traffic delays.
    - Improved surface weather forecasts and specific user warnings would reduce the 7,000 weather-related fatalities and 800,000 injuries that occur annually from crashes on roads and highways (with an annual average related cost of $42 billion).

- Anticipated impacts of NOAA/NWS mission performance improvements:
    - Lives saved and property damage reduced through improved warnings
    - Aviation efficiency and safety
        - Improved terminal and en-route observations and forecasts
        - Improved hail, turbulence, freezing rain and in-flight icing information

    - Surface transportation efficiency and safety
        - Improved winter weather and heavy rain observations and forecasts
    - Weather-impacted commercial activity efficiency and safety
    - Improved data and forecasts leveraged by commercial weather services
    - General public quality of life and planning for daily activities
- Results of Sutter and Simmons (2005) paper indicate that installation of NEXRAD has led to
    - a 40 - 45% reduction in deaths and personal injuries
    - a 25% increase in tornados detected
    - Greater than 4 minutes increase in tornado warning lead time

A.5 Additional Existing Capabilities

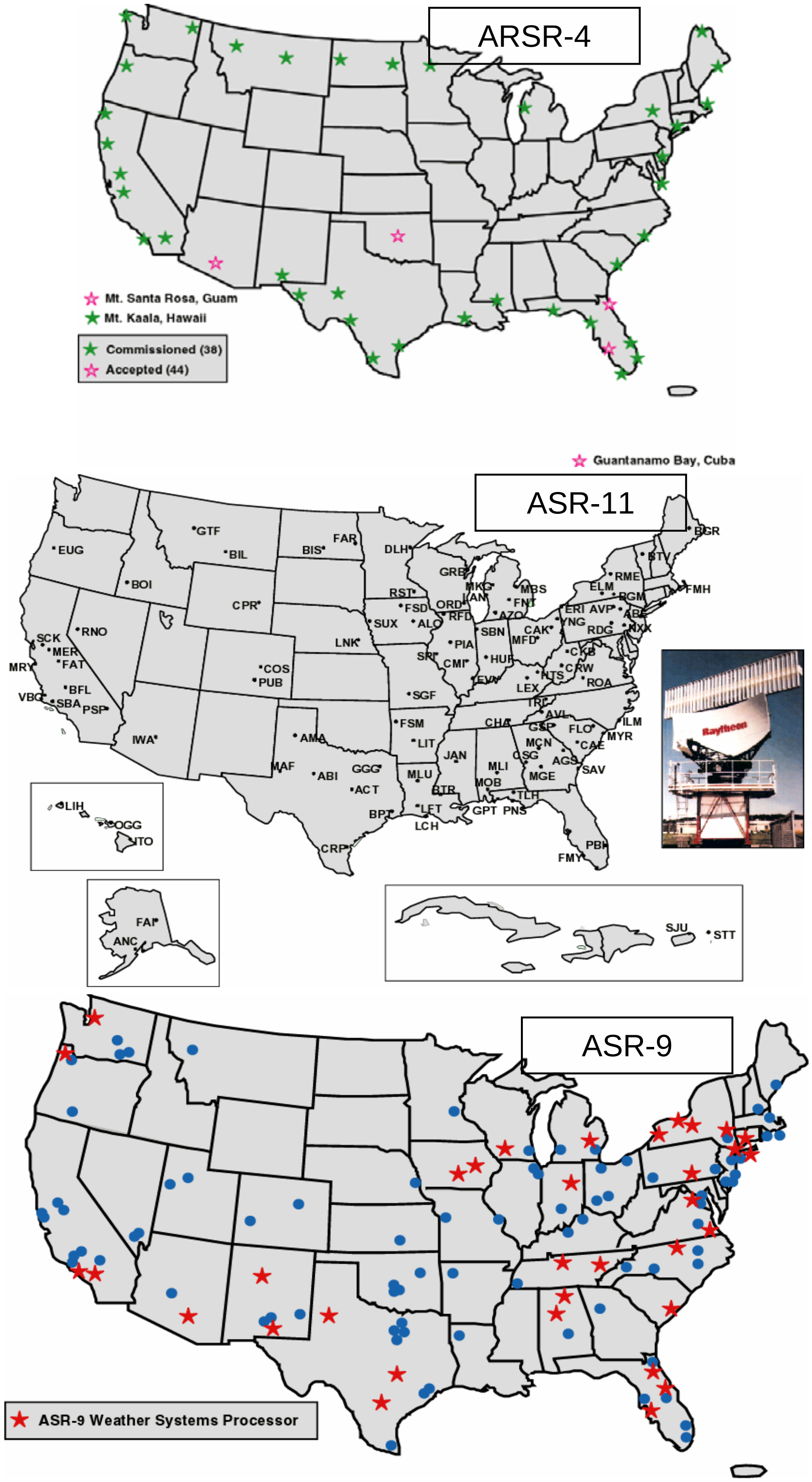

Figure A5.1-3. The geographical coverage of the FAA Air Traffic radars (ARSR-4, ASR-9, ASR-11).

A.6 Requirements

This section synthesizes the most stringent (optimal) requirements applicable to weather radar as derived from NOAA's Consolidated Operational Requirements List (CORL).

Observation Requirement	Priority	Vertical Range (km)	Vertical Resolution (m)	Horizontal Resolution (m)	Measurement Range	Measurement Range Units	Measurement Accuracy	Measurement Accuracy Units	Sampling Interval (sec)	Data Latency (sec)
Winds: Vertical-Horizontal Distribution, Storm Area	1	sfc - 20	100	100	0-100	m/sec	1	m/sec	30	10
Precipitation Rate: Vertical-Horizontal Distribution, Storm Area	1	sfc - 20	100	100	0-200	mm/hr	1	mm/hr	30	10
Precip Type: Vertical-Horizontal Distribution, Storm Area	1	sfc - 20	100	100	na	Category: Rain, Snow, Hail	90	%	30	10
Air Temperature: Boundary Layer, Storm Area	1	sfc - 20	100	250	150-350	Kelvin	1	Kelvin	30	10
Dew Point Temperature: Boundary Layer, Storm Area	1	sfc - 20	100	250	193-328	Kelvin	1	Kelvin	30	10
Winds: Vertical-Horizontal Distribution, Storm Area	1	sfc - 20	250	250	0-150	m/sec	1	m/sec	300	300
Precip Rate: Vertical-Horizontal Distribution, Storm Area	1	sfc - 20	250	250	0-100	mm/hr	1	mm/hr	300	300
Precipitation Rate, Storm Area	1	sfc - 3	100	100	0-300	mm/hr	1	mm/hr	60	300
Precipitation Type: Hail, Storm Area	1	sfc - 20	100	100	na	Category: Rain, Snow, Hail	90	%	60	10

In addition to the threshold requirements specified in the above chart, the requirement exists that no system can perform at a level lower than the existing NEXRAD system.

A.7 Budget Details

FY11 – FY17 Joint Radar Plan Budget

Note: MPAR budget costs are in a separate table below.

JRPT Solutions

100% Requirement

As of 22-Oct-07

Acquisition/Deployment

R&D

Research to Operations

$K

CAPACITY	ACTIVITY	FY07	FY08	FY09	FY10	FY11	FY12	FY13	FY14	FY15	FY16	FY17+
2: WxR	**R&D for Dual Polarization Scientific Applications** ***(Research development of polarimetric scientific applications: QPE, QPF, tornado detection, rain/snow/hail/birds/insects discrimination)***	600	600	600	600	1000	1000	1000	1000	1000	1000	1000
2: WxR	**R&D for Weather Radar Science Applications in General** ***(Optimizing NEXRAD - Research development of non-polarimetric scientific applications: data quality enhancements, super resolution data for tornado detection & QPE, faster scanning strategies)***	100	100	100	100	200	200	200	200	200	200	200
2: WxR	**R&D for CASA-like Short Wavelength, Boundary Layer Radar Applications, and for Drought & Water Resource Services (HMT $2600 per year)** ***(Research development of scientific applications for short wavelength radar: QPE, QPF, tornado detection, adaptive scanning strategies, NWP data assimilation)***	250	250	250	250	3110	3110	3110	1500	1000	1000	500
	2:WxR Sub-total	950	950	950	950	4310	4310	4310	1700	2200	2200	1700
	2:WxR Gap	0	0	0	0	3360	3360	3360	2260	2000	2000	1500

4: NPI	**NEXRAD Dual Polarization Acquisition** ***(Deploy DP capability at all NEXRAD sites: QPE, QPF, NWP Data Assimilation, Severe Thunderstorm/Flash Flood warnings)***			**8850**	**3490**	**7850**	**7830**	**6980**	**0**	**0**	**0**	**0**
	(Provide products from 10 sites/year to WFOs: QPE, QPF, Tornado/Severe Thunderstorm/Flash Flood warnings)											
4: NPI	**NEXRAD Technology Capacity Increase** ***(Enable implementation of future science improvements)***			**0**	**0**				**1000**	**5000**	**5000**	**730**
4: NPI	**Radar Scientific Applications Transition (SEC, OHD, NCEP, NSSL, +)** ***(Research-to-Operations of science improvements for NEXRAD: QPE, QPF, Tornado/Severe Thunderstorm/Flash Flood warnings)***			**4510**	**4890**	**5290**	**5310**	**6160**	**6345**	**6535**	**6731**	**6933**
	(Research-to-Operations of science applications: HMT, Q2: QPE, QPF, NWP, Tornado/Severe Thunderstorm/Flash Flood algorithms)											
4: NPI	**CASA-like Short Wave Length Boundary Layer Radars - Acquisition for High Impact Regions** ***(Operational deployment of 5-10 radars per year at high impact areas: QPE, QPF, Tornado/Severe Thunderstorm/Flash Flood warnings)***			**0**	**0**				**1000**	**2000**	**2000**	**2000**
	4:NPI Sub-total	**0**	**0**	**13360**	**8380**	**13130**	**13130**	**13130**	**8345**	**13535**	**13731**	**9663**
	4:NPI Gap			**0**	**0**	**4750**	**4750**	**4750**	**35**	**5155**	**5351**	**1283**
5: MPAR	**MPAR research and development, pre-acquisition decision**				**0**	**6000**	**5000**	**4000**	**3000**	**5000**	**5000**	**0**

	evaluation costs											
	Current program	**2972**	**2972**	**2972**	**2972**	**2972**	**2972**	**2972**	**2972**	**2972**	**2972**	**2972**
	FY10 PPBES Outcome				**1000**	**1000**	**2000**	**3000**	**4000**	**4000**	**4000**	**1000**
	MPAR to Go/No Go decision in FY17. Beyond FY17, ongoing research will require no new funds (beyond a total of $4.0M expected to be available beginning in FY10 assuming a “Go” decision is made).											
	5:MPAR Sub-Total				**4972**	**9972**	**9972**	**9972**	**9972**	**11972**	**11972**	**3972**
	5:MPAR Gap					**6000**	**5000**	**4000**	**3000**	**5000**	**5000**	**0**

FY10 MPAR Research and Development Plan (with $1M increase in FY10 for a $4M total program):

Multi-Function Phased Array Radar (MPAR) action plan for FY2010	
Task / Positions	**Notes**
Activities toward improving warnings	Begin to verify that a faster refresh rate, longer dwell times on storm areas of interest, and new knowledge gained on storm morphology can lead to improved tornado warnings
Activities toward service improvements	Begin to evaluate potential service improvements, particularly to meet NOAA's public safety mission and improve severe weather warning lead times in accordance with the NOAA's Strategic Plan, the 5- and 20-year research plans, and GPRA goals.
NWRT MPAR data evaluation	Continue to evaluate how the phased array radar data compare with the existing NEXRAD and FAA systems in terms of lead time and accuracy for severe weather warnings and forecasts.
Pre-prototype design	Begin design of a pre-prototype MPAR system with the latest technology from industry to prove feasibility of low cost components (w/FAA, other partners)
Dual Polarization feasibility study	Begin to determine the feasibility and affordability of adding dual polarization to the MPAR
Operations and maintenance	Utility costs, hardware technician salary, maintenance of hardware/computers/communications, computer scientist salaries for data processing and quality control to make data available to outside users, data archiving for post-event analysis, and spare parts

MPAR Performance / Deliverables:

	FY10	FY11	FY12	FY13	FY14
PAR volume scan shown to be at least four times faster than 88D (% task completed)	50	100			
% MPAR Concept of Operations developed and tested	10	25	35	45	50
% of PAR dual polarized sub-array antenna design completed	50	100			
% completion of comparison of MPAR data with NEXRAD WSR-88D data and FAA radar data	20	40	60	80	100
% of information needed to make PAR Go/No Go Decision	10	25	50	50	75

STI RDW: Research & Development for Drought & Water Resource Services (HMT)

A.8 The Role of NOAA Testbeds

NOAA has established and is engaged testbeds that will play a significant role in realizing the NOAA 20-Year Weather Radar Services Vision. Testbeds create an environment that bring both the research and operations communities in the R&D process, and permit the rapid implementation and evaluation of new insights, models, observations and tools in an operational setting. The end result is to accelerate the transition of new research and technology into operations.

Some candidate areas in which testbeds can contribute are:

- Evaluation and/or calibration-validation of new radar technologies (such as MPAR)
- The objective evaluation of new radar network concepts, such as short wavelength gap-filling radars (e.g. the Collaborative Adaptive Sensing of the Atmosphere (CASA) Radar Program
- Science, technology and infusion activities supporting:
    - Algorithm development for both existing, developing and new radar systems (e.g. dual polarized radars)
    - Dual Polarization Radar products and infusion into operations for QPE and QPF analysis
    - adaptive data integration (ADI)
    - Probabilistic flash flood and river flood warnings
    - Better 1st guess analyses of QPE
    - Convective environments
    - Stratiform environments
    - Tropical environments
    - Bright banding problems
    - Winter weather specific problems
    - Enhanced short term QPF analysis and inputs to improve flash flood and quick-responding river flooding warning operations
    - Multi-sensor QPE efforts such as Q2 and MPE (this could be relatively easily done in FY08 as this is a fairly mature project)
- Leverage existing High-Resolution Numerical Modeling (i.e. WRF) and model ensemble research to quantify value to hydrologic forecasting applications and identify information gaps
- A sensitivity study to compare the legacy QPE products to the Q2 enhance products
- Study complex-terrain specific QPE/QPF problems (perhaps more appropriate for FY09 and beyond as Mountain Mapper capabilities are incorporated into MPE.)
- Identify how lightning and RUC Data can be more effectively used in real-time operations to enhance Situational Awareness and for QPE analysis
- Through their collaborative nature, testbeds also function as important environments to introduce and train the operational community on new technologies

Two testbeds are already engaged in activities that support the NOAA 20-Year Weather Radar Services Vision: the NOAA Hazardous Weather Testbed (HWT) and the NOAA Hydrometeorological Testbed (HMT). In the future, at least two other testbeds could potentially be brought to bear in the execution of this vision, the NOAA Joint Hurricane

Testbed (JHT) and the multi-agency Developmental Testbed Center (DTC). Input and support from these and other testbeds is solicited. A brief synopsis of each follows.

The DTC: http://www.dtcenter.org/

The DTC is a distributed facility where the numerical weather prediction (NWP) community can test and evaluate new models and techniques for use in research and operations. To serve as a bridge between research and operations to facilitate the activities of both halves of the NWP community, research and operations, use a common modeling platform known as the Weather Research & Forecasting Model (WRF).

The NOAA HWT: http://www.nssl.noaa.gov/hwt/

The Hazardous Weather Testbed provides the framework for the development and implementation of new technologies in different areas, particularly those focusing on shorter-timescale forecasting challenges. The HWT's efforts provide unique and valuable contributions to our understanding and prediction of hazardous convective weather events, leading to improved severe-thunderstorm and tornado watches and warnings for the public. Through its collaborative environment, the HWT seeks to conduct operationally relevant research and the rapid infusion of research results into operations.

While the HWT activities have ranged from daily map of imminent severe weather to research projects involving 2-3 collaborators, the cornerstone of the testbed is the SPC/NSSL "Spring Program." The Spring Program is a series of annual experiments that seek to provide forecasters with a first-hand look at the latest research concepts and products, while immersing research scientists in the challenges, needs, and constraints of front-line forecasters. In practice, this program gives forecasters direct access to the latest research developments while imparting scientists with the knowledge to formulate research strategies that will have practical benefits. The end result is not only better severe-weather forecasts, but important peer-reviewed science as well.

The NOAA HMT: http://hmt.noaa.gov/

The Hydrometeorology Testbed is a concept aimed at accelerating the infusion of new technologies, models, and scientific results from the hydrometeorological research community into daily forecasting operations of the National Weather Service and its National and River Forecast Centers (RFCs). Consistent with NOAA's Regional Collaboration plan, HMT is a national strategy that is being implemented regionally. HMT is a collaborative effort across a number of OAR and NWS labs and offices and engages local, state and federal stakeholders.

The major activity areas at HMT are aimed at QPE, QPF, snow information, hydrologic applications and verification and decision support tools. Building on extensive research on the West Coast, the first regional testbed, HMT-West, was established in the complex terrain of northern California. In FY10 HMT-Southeast will be stood up, and in FY11

HMT-West will transition into a legacy mode of operations, facilitating the infusion of new hydromet R&D into the western region.

The NOAA JHT: http://www.nhc.noaa.gov/jht/

The mission of the Joint Hurricane Test Bed is to transfer more rapidly and smoothly new technology, research results, and observational advances of the United States Weather Research Program (USWRP), its sponsoring agencies, the academic community and other groups into improved tropical cyclone analysis and prediction at operational centers. As focus of research involves rapid changes in intensity and high-resolution studies, work at JHT is expected to increasingly overlap with aspects of this plan.

The NWRT: http://www.nssl.noaa.gov/projects/pardemo/

The National Weather Radar Test bed (NWRT) is operational in Norman, Oklahoma. This project was developed as a result of a partnership between the National Oceanic and Atmospheric Administration's National Severe Storms Laboratory, the United States Navy's Office of Naval Research, Lockheed Martin Corporation, the University of Oklahoma's Electrical and Computing Engineering Department and School of Meteorology, the Oklahoma State Regents for Higher Education, the Tri-Agencies' (Department of Commerce, Defense and Transportation) Radar Operations Center, the Federal Aviation Administration's Technical Center and Basic Commerce and Industries, Inc.. Using a Navy SPY-1A phased array antenna system, the NWRT provides the first phased array radar available on a full-time basis to the meteorological research community. The NWRT became operational in September 2003, and first data were collected in May 2004.

Acronyms

ADI – Adaptive Data Integration
ASR – Air Surveillance Radars
ARSR – Air Route Surveillance Radar
CASA – Collaborative Adaptive Sensing of the Atmosphere
CONUS - Continental (or Contiguous) U.S.
CORL – Consolidated Observation Requirements List
DHS – Department of Homeland Security
D&WR – Drought and Water Resource
DOD – Department of Defense
DOT – Department of Transportation
DTC – Developmental Testbed Center
ESRL – Earth Systems Research Laboratory
FCMSSR – Federal Committee for Meteorological Services and Supporting Research
GPRA – Government Performance and Results Act
JAG – Joint Action Group
JHT – Joint Hurricane Testbed
JRPT – Joint Radar Planning Team
HMT - NOAA's Hydrometeorological Testbed
HQ – NOAA Headquarters in Silver Spring, MD
HWT – Hazardous Weather Testbed
HWT-E – Hazardous Weather Testbed East
HWT-W – Hazardous Weather Testbed West
ROC – Radar Operations Center
PMC – Program Management Committee (for NEXRAD)
PSD – Physical Sciences Division
MDL – Meteorological Development Laboratory
MPAR – Multi-function Phased Array Radar
MPE – Multisensor Precipitation Estimator
NCAR – National Center for Atmospheric Research
NCEP – National Centers for Environmental Prediction
NextGen – Next Generation (FAA aviation operations plan)
NOAA - National Oceanic and Atmospheric Administration
NOSA – NOAA Observing System Architecture
NHOP – NOAA National Hurricane Operations Plan
NPI – NEXRAD Product Improvement
NRC – National Research Council
NSF – National Science Foundation
NSSL - National Severe Storms Laboratory
NWP – Numerical Weather Prediction
NWRT – National Weather Radar Testbed
NWS – National Weather Service
OAR – Oceanic and Atmospheric Research Laboratories
OCONUS – Outside Continental (or Contiguous) U.S.
OCWWS – Office of Climate, Water and Weather Services
OFCM – Office of the Federal Coordinator for Meteorology

OHD – Office of Hydrologic Development
O&M – Operations and Maintenance
ORPG – Open Systems Radar Product Generator
ORDA – Open Systems Radar Data Acquisition
PAR – Phased Array Radar
PPBES – Planning, Programming, Budget, and Execution System
QPE – Quantitative Precipitation Estimation
QPF – Quantitative Precipitation Forecast
R&D – Research and Development
RTO – Research To Operations
SPC – Storm Prediction Center
STI – Science Technology Infusion
SWR – Short Wavelength Radar
TAC – Technical Advisory Committee (for NEXRAD)
TDWR – Terminal Doppler Weather Radar
T-PAR – Terminal Phased Array Radar
USAF – United States Air Force
USWRP – United States Weather Research Program
WFO – Weather Forecast Office
WMD – Weapons of Mass Destruction
WRF – Weather Research Forecast model
WSR-88D – Weather Surveillance Radar – 1988 Doppler
WoF – Warn-on-Forecast
W&W – Weather and Water