# NOAA/National Weather Service Radar Functional Requirements

Approved by the NOAA Observing Systems Council

September 2015

# Signatures

## Radar Functional Requirements Validation

## NOSC Endorsement

The NOAA Observing Systems Council (NOSC) has received the National Weather Service Radar Functional Requirements with Line Office, Subject Matter Expert and Research Program concurrence, and is satisfied with the Level-of-Validation provided for the threshold and "optimal for 2030" requirements.

8/26/15

VADM Manson Brown
NOSC Chair (Assistant Secretary for Environmental Observations and Prediction)

Date

8/26/15

Steve Volz
NOSC Vice Chair (NESDIS)

Date

9/2/15

Dr. Louis Uccellini
NOSC Vice Chair (NWS)

Date

8/28/15

RADM David Score
NOSC Vice Chair (OMAO)

Date

## NOAA/NWS Radar Functional Requirements Validation

### Line Office Endorsement

The Directors of the National Weather Service (NWS) Office of Science and Technology (OST), Office of Climate, Water and Weather Services (OCWWS), and Office of Operational Systems (OOS) Radar Operations Center (ROC), and the Director of the Office of Oceanic and Atmospheric Research (OAR) National Severe Storms Laboratory (NSSL) have received NOAA/NWS Radar Functional Requirements (RFR) document with Project Lead and Developmental Team concurrence and are satisfied with the level of validation for requirements that extend from present day through 2030, given information known at the date of signing.

18 Sep 14
Date

Mr. John D. Murphy
Director, NWS/OST
NWS Representative, NOSC

9/18/14
Date

Mr. Christopher S. Strager
Director, NWS/OCWWS (Acting)

24 Dec 2014
Date

Mr. Terrance Clark
Director, NWS/OOS/ROC (Acting)

27 Dec. 2014
Date

Dr. Steven E. Koch
Director, OAR/NSSL

## Radar Functional Requirements Lead Validation

The NWS OST Radar Improvement Development Manager, and OCWWS Meteorological Services Division Chief have validated the process and contents of this NOAA/NWS Radar Functional Requirements document.

| | |
|---|---|
| Mr. Michael Istok<br>Radar Improvement Development Manager, NWS/OST | 7/24/2014<br>Date |
| Mr. Andrew D. Stern<br>Chief, Meteorological Services Division (acting), NWS/OCWWS | 7/24/14<br>Date |

## Radar Functional Requirements Integrated Working Team Concurrence

The Radar Functional Requirements Integrated Working Team (IWT) membership concur that the requirements contained herein, comprise NOAA/NWS Radar Functional Requirements from the present day through 2030, given information known at the date of signing.

Mr. Donald W. Burgess, OAR/National Severe Storms Laboratory (Associate)
Mr. Joe N. Chrisman, NWS/OOS, Radar Operations Center
Dr. Jeffrey G. Cunningham, NWS/OOS, Radar Operations Center (Associate)
Mr. John T. Ferree, NWS/OCWWS, Public and Fire Weather Services Division
Mr. Richard L. Ice, NWS/OOS, Radar Operations Center (Associate)
Dr. Daniel Melendez-Alvira, NWS/OST, Program Plans Division
Mr. Dennis A. Miller, NWS/OHD, Hydrologic Science and Modeling Branch
Mr. Robert E. Saffle, NWS/OCWWS (Contractor)
Dr. David J. Stensrud, OAR/National Severe Storms Laboratory
Mr. Christopher C. Wamsley, NWS/OCWWS, Integrated Services Division

### Subject Matter Expert/Consultant Contributors

The following subject matter experts provided information to both support the requirements formulation process, and over the horizon (~2030) requirements linked to strategic research and future modeling programs.

Mr. Louis Cantrell, NESDIS, Technology, Planning and Integration for Observation (TPIO) (Contractor)
Dr. Jacob Carley, NWS/NCEP, Environmental Modeling Center (Contractor)
Mr. Carlos Diaz, NWS/OCWWS, Requirements Division
Dr. David Dowell, OAR/ESRL/GSD, Assimilation and Modeling
Mr. Kurt Hondl, OAR/NSSL, MPAR Program Manager
Mr. Mark B. Miller, NWS/OST, NextGen Weather Program Manager
Mr. Fred Toepfer, NWS/OST, Hurricane Forecast Improvement Program
Dr. Sebastian Torres, OAR/NSSL, Senior Research Scientist (Associate)

## Contents

## 1. Introduction

The mission of the National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS) is to provide weather, water, and climate data, and forecasts and warnings for the protection of life and property and enhancement of the national economy. Weather radars are a critical component of the weather data observing systems that support this mission. This document formalizes NOAA/NWS Radar Functional Requirements (RFR) that are radar-design independent (as much as possible), address current and future (~2030) multiple mission needs, and support agency planning associated with next generation weather radar surveillance within NOAA/NWS.

## 2. Scope

This document considers multiple areas, including the types of weather phenomena for which radar observation is a significant factor; NOAA/NWS current mission performance goals and strategic goals for the future; evolving weather observation needs from activities such as storm scale numerical modeling and anticipated growth in aviation traffic; and support to other Government agency and private sector partners. The functional requirements reflect current needs as well as capabilities anticipated to be needed for agency performance goals extending to approximately 2030.

The focus of this document is on single site radar data acquisition and signal processing functionality, the Radar Data Acquisition (RDA) component of a weather radar system, but discussions are included on the broad range of uses for these observations. The extent and quality of geographic and vertical coverage of individual radars are encompassed in RFRs such as wavelength, beamwidth, minimum/maximum elevation angles and scan strategy flexibility. National geographic coverage is a function of the number of NOAA/NWS radars deployed and the availability of data from non-NOAA radars. The number of NOAA/NWS radars deployed is a programmatic determination involving cost and climatology across the nation, and is beyond the scope of this document.

## 3. Intended Use of Document

This document informs NOAA/NWS management on the substance and rationale for future radar functional requirements. The RFRs provide a basis for ongoing evaluations of the role of NOAA/NWS radar capability improvements in meeting strategic performance goals.

The document also helps to inform potential radar acquisition programs, including NOAA/NWS engagement with the Federal Aviation Administration (FAA) in the FAA Next Generation Surveillance and Weather Radar Capability (NSWRC) program to replace current FAA terminal tracking, aircraft surveillance, and weather radars. These NOAA/NWS RFRs would inform the acquisition program in the development of engineering system specifications for any particular radar acquisition.

It is important to recognize that the RFRs are not, in themselves, sufficient to act as system acquisition requirements. In any system acquisition, the procuring agency must balance cost, technical performance and schedule when developing a system specification and evaluating potential system improvements. Although this RFR document largely represents the functional capabilities achieved with the present WSR-88D system, it does not preclude agency consideration of potential future radar systems that would address the RFRs with different radar designs (e.g., Phased Array Antenna radars; low power, short wavelength radars). Further, agency management may well judge that the overall functional capability of a potential radar design will improve operations even if certain RFRs are not fully met.

This is a “living document” which is meant to be revisited and revised at approximately five year intervals to take advantage of changing technologies and potentially refined requirements.

## 4. Terms and Definitions

It is not practical to discuss weather radar functionality requirements without using technical parameters and terminology. Appendix B, Terms and Definitions, contains explanations of the terminology used in this document. These explanations are not meant to be comprehensive engineering definitions, but rather, guidance to the intended audience for this document, e.g., managers, budget analysts, program planners. More rigorous definitions can be found in sources such as the American Meteorological Society Glossary of Meteorology, Federal Meteorological Handbook No. 11, or the Warning Decision Training Branch’s Distance Learning Operations Course (WDTB DLOC) radar training web site.

## 5. Radar Data Acquisition Functional Requirements

This section provides a concise listing of NOAA/NWS RFRs grouped into three categories: RDA transmit and receive, RDA data signal processing and RDA scan strategy adaptability. A brief example of operational impact of each RFR is included. More comprehensive discussions of the use of various radar capabilities for particular weather scenarios are contained in Section 8.

### 5.1. NOAA/NWS Strategic Performance Goals

These RFRs are directly related to meteorological phenomena observations needed to maintain the current high level of forecast and warning performance, and to meet future performance goals as stated in NOAA and NWS Strategic Plans. These strategic performance goals include the following:

- Increase warning lead times for tornado and other high-impact events (e.g., flash floods, severe thunderstorms)
- Reduce tornado warning false alarm rate without degrading probability of detection
- Promote comprehensive weather situational awareness
- Improve weather decision services and convey uncertainties associated with data and products

### 5.2. Threshold Requirements

NOAA/NWS must maintain the high quality of radar information provided by the operational Weather Surveillance Radar – 1988 Doppler (WSR-88D) with Dual Polarization. Threshold RFRs generally represent the achieved operational capabilities of the WSR-88D. In cases where the achieved WSR-88D capability is greater than the minimum requirements of the WSR-88D System Specification, the achieved capability is cited in the relevant RFR. The WSR-88D capabilities continue to be improved, and these RFRs represent minimum required functionality – not limits to system improvements. Future updates to the RFRs will reflect any approved modifications based on these improvements.

### 5.3. Optimal Requirements

For some areas, more advanced functionality would be needed to better support science and analysis tools necessary to accomplish NOAA/NWS strategic goals for mission performance improvements. These strategic goals include developing a capability to provide large increases in tornado warning lead times through the application of storm scale numerical models to forecast the formation of tornadoes, a capability termed Warn-on-Forecast (WoF). Such RFRs will be identified as 'Optimal for 2030' operations. Certain Optimal RFRs are also related to the general observing requirements for particular weather phenomena contained in the NOAA Consolidated Observation Requirements List (CORL) as described in Chapter 9.

## 5.4. RDA Transmit and Receive

These RFRs comprise the basic functionality of weather radar hardware design.

### 5.4.1. Weather radar variables

The radar must provide observations for the following basic variables of polarimetric Doppler weather radar. Forecasters typically utilize multiple radar variables, along with non-radar information, to analyze weather events and issue forecasts and warnings.

**Threshold: WSR-88D capability**

- **Reflectivity (Z)**
- **Radial Velocity (V)**
- **Spectrum Width (SW)**
- **Differential Reflectivity (ZDR)**
- **Correlation Coefficient (CC)**
- **Differential Phase (PHI)**

Numerical model initial conditions and forecasts are sensitive to the radar-observation errors specified during data assimilation, but the characteristics of these observation errors are currently poorly known. Improved specification of observation errors, both in a mean sense and on an observation-by-observation basis, would be possible if sample variances for the observation estimates were available. Extensive assimilation of radar data for input to storm scale numerical models is critical to achieving the capability for forecasting the development and evolution of tornadic storms, and thus extending tornado warning lead times significantly.

**Optimal for 2030: Within each sample bin**

- **Sample variance for reflectivity**
- **Sample variance for radial velocity**
- **Sample variance for differential reflectivity**
- **Sample variance for correlation coefficient**
- **Sample variance for differential phase**

### 5.4.2. Wavelength

The radar must provide high quality information throughout, and beyond, regions of heavy rainfall to long ranges. The radar must also provide operationally acceptable (e.g., provision of data that significantly enhance forecast and warning operations) values of maximum unambiguous range and maximum unambiguous velocity for any given pulse repetition frequency.

**Threshold: Performance of WSR-88D (S-Band, ~10 cm)**

The WSR-88D wavelength of ~10 cm is the optimal choice as it supports a maximum range of 460 km due to minimized attenuation by heavy rainfall and also provides the best combination of maximum unambiguous range and maximum unambiguous velocity compared to shorter wavelengths. This wavelength ensures that each radar will provide critical coverage within its umbrella.

**5.4.3. Beamwidth**

The radar must provide sufficient spatial resolution (both horizontally and vertically) to detect fine scale features, such as tornadic circulations, to an operationally acceptable (e.g., provision of data that significantly enhance forecast and warning operations) range.

**Threshold: Performance of WSR-88D (1.0 deg Beamwidth in azimuth and elevation)**

Due to antenna rotation and processing of multiple pulses per data radial, the WSR-88D hardware beamwidth (~ 1 deg) provides an effective beamwidth of 1.5 deg in azimuth. A signal processing windowing technique, termed Super Resolution, provides high quality data radials at 0.5 deg increments with an effective beamwidth of 1.1 deg.

**5.4.4. Pulse length**

A short pulse length is necessary to provide the linear resolution required for detection of complex, small scale storm features such as tornadic circulations. An additional, longer pulse length is also necessary to enable greater ability to detect returns from weaker targets such as light snow and clear air.

**Threshold: Performance of WSR-88D (1.57 µs (short pulse) and 4.71 µs (long pulse))**

Future use of complex pulse generation methods such as Pulse Compression could provide increased sensitivity without degrading other requirements such as linear range resolution. Increased sensitivity could extend the range of coverage of weaker targets, thereby enhancing forecast and warning operations.

**5.4.5. Pulse repetition frequencies (PRFs)**

The radar must provide useful information for a wide variety of weather scenarios, including the concurrent presence of multiple storms along the same radial, multiple storms at different ranges in different sectors, and strong radial velocities in the storms. The radar must support multiple PRF values to minimize the effects of range folding on particular storms while preserving the best possible estimations of radial velocity for those storms.

**Threshold: WSR-88D capability**

- **A PRF, or combinations of PRFs, to support a maximum unambiguous velocity of ± 32 m/s**
- **A PRF to support a maximum unambiguous range of 460 km**
- **A range of PRFs between 318 hertz and 1310 hertz**

Radial velocities often exceed 32 m/s in association with tornadic supercells and strong mid-latitude cyclones. Since there is a strong relationship between observed radial velocities, storm intensification, and wind damage of all kinds, increasing maximum unambiguous velocity would lead to improved decision support services and more effective assimilation of these observations into numerical forecast models. Furthermore, an increase in maximum unambiguous velocity in the lower elevation angles would help assure that strong circulations occurring within the planetary boundary layer are routinely well sampled within a radar's coverage area.

**Optimal for 2030:**

- **A PRF, or combinations of PRFs, to support a maximum unambiguous velocity of ± 50 m/s**

### 5.4.6. Minimum detectable signal (MDS) and Sensitivity

A low MDS is necessary to provide the sensitivity to detect weak, fine scale targets such as gust fronts and weak circulations, and to obtain valid velocity measurements from targets such as insects and moisture discontinuities. Radar sensitivity is closely related to the MDS. Higher sensitivity corresponds to an ability to detect weak signal strength features to longer ranges. The Threshold RFR is cited for a range of 50 km to provide reference point values of the required MDS.

**Threshold: Performance of WSR-88D**

- **0.0 dB Signal to Noise Ratio (SNR) for a -9.5 dBZe target at 50 km in short pulse and a -18.5 dBZe target at 50 km in long pulse**

### 5.4.7. Dynamic range

The radar must process returns from both weak and strong targets concurrently (e.g., mix of fine lines and strong thunderstorms). The receiver dynamic range must be large enough to accommodate typical weather scenarios.

**Threshold: WSR-88D capability of 93 dB**

A larger dynamic range will support improved processing of strong clutter targets and increased sensitivity for weak returns. The improved data quality will enhance the utility of radar data in the numerical models that are crucial to providing tornado and other severe storm warnings based on forecasts of storms.

**Optimal for 2030: 97 dB**

### 5.4.8. System bias

The radar hardware calibration must determine the measurement uncertainties related to the system hardware components as accurately as possible for all radar variables. Accurate system bias calculation ensures that observations accurately represent the returned signals for those variables.

**Threshold: WSR-88D capability, in the absence of clutter filtering.**

- **Reflectivity: 1 dBZ for target with true spectrum width of 4 m/s and SNR > 10 dB**
- **Velocity: 0.0 m/s for target with true spectrum width of 4 m/s and SNR > 8 dB**
- **Spectrum Width: 0.2 m/s for target with true spectrum width of 4 m/s and SNR > 10 dB**
- **Differential Reflectivity: 0.1 dB for target with true differential reflectivity (ZDR) of less than ±1 dB, true spectrum width of 2 m/s, Correlation Coefficient ≥ 0.99,**

**dwell time of 50 ms and SNR ≥ 20 dB (for ZDR with a magnitude greater than 1 dB, bias should be less than 10% of the ZDR magnitude)**
- **Correlation Coefficient: 0.006 for target with true spectrum width of 2 m/s, Correlation Coefficient ≥ 0.99, dwell time of 50 ms and SNR ≥ 20 dB**
- **Differential Phase: 1 deg for target with true spectrum width of 2 m/s, Correlation Coefficient of ≥ 0.99, dwell time of 50 ms and SNR ≥ 20 dB**

**5.4.9. Minimum elevation angle**

The radar must be able to scan at negative elevation angles to improve low altitude weather detection from high altitude sites (e.g., mountain sites).

**Threshold: WSR-88D capability of -1.0 deg**

**5.4.10. Maximum elevation angle**

The radar must be able to observe the mid-level and upper portions of convective storms close to the radar site. These are the regions of storms where the parent rotation of tornadoes, large hail, and the beginnings of microbursts are often first observed. The radar must also be able to observe high elevations to support calibration procedures based on measurements of the sun and the clear blue sky.

**Threshold: WSR-88D capability of 60.0 deg**

**5.4.11. Beam elevation and azimuth positioning accuracy**

Beam location accuracy is critical to properly locate tornadoes and other severe weather phenomena for accurate specification of warning areas and for assimilation of radar data into numerical models.

**Threshold: WSR-88D capability of 0.15 deg**

Further improvements to Differential Reflectivity calibration of system bias and general data quality will require better beam positioning accuracy and precision. Research radars have positioning accuracy of 0.0055 deg.

**Optimal for 2030: Elevation and azimuth positioning accuracy within 0.0055 deg**

**5.4.12. Side lobes**

The radar observation data must be calculated predominantly from the signal power returned within the main lobe of the beam pattern to ensure the data represent the nominal spatial resolution of each sample volume. Signal power returns from energy transmitted in nearby lobes (side lobes) must be minimized.

**Threshold: WSR-88D capability, two-way side lobes:**
- **First side lobe: ≤ -70 dB relative to the peak of the main lobe**
- **Side lobes beyond ± 2 deg from beam center decrease to ≤ –96 dB at ± 6 deg relative to the peak of the main lobe, decreasing to -110 dB at ± 20 deg relative to the peak of the main lobe.**

## 5.5. RDA Signal Processing

Sophisticated RDA signal processing of target returns is necessary to generate accurate, reliable radar variable estimates, and to utilize flexibility in setting radar transmit and receive parameters.

### 5.5.1. Standard deviation of estimates of radar variables

The radar variable values generated by signal processing of target return signals must be consistent from observation to observation for any given type of spatially homogeneous weather target to ensure reliability and dependability for subjective and objective applications of the data. Accurate estimations of system bias and low standard deviations of estimates of radar variables are critical components of the accuracy and representativeness of the radar variable estimates.

**Threshold: Performance of WSR-88D**

- **Reflectivity: ≤ 1 dB for target with true spectrum width of 4 m/s and SNR ≥ 10 dB**
- **Velocity: ≤ 1 m/s for target with true spectrum width of 4 m/s and SNR > 8 dB**
- **Spectrum Width: ≤ 0.5 m/s for target with true spectrum width of 2 m/s and < 0.95 m/s for true spectrum width of 4 m/s and SNR > 10 dB**
- **Differential Reflectivity: < 0.4 dB for target with true spectrum width of 2 m/s, Correlation Coefficient ≥ 0.99, dwell time of 50 ms and SNR ≥ 20 dB**
- **Correlation Coefficient: < 0.006 for target with true spectrum width of 2 m/s, correlation coefficient ≥ 0.99, dwell time of 50 ms and SNR ≥ 20 dB**
- **Differential Phase: < 2.5 deg for target with true spectrum width of 2 m/s, correlation coefficient of ≥ 0.99, dwell time of 50 ms and SNR ≥ 20 dB**

Optimal standard deviation goals for 2030 are not well established. However, techniques that reduce the standard deviation of estimates should be developed so that data quality can be traded for other things such as faster updates.

### 5.5.2. Quantization of radar variables

Radar variables must be provided to data processing systems with sufficient quantization to support data accuracy determinations and to provide the capability to reveal the small scale, often critical, variations of values within many weather targets (e.g., convective storms). Radar variable quantization is sometimes used interchangeably with precision of the variable estimates (e.g., the WSR-88D System Specification), even though such usage is not technically correct.

**Threshold: Performance of WSR-88D**

- **Reflectivity: 0.5 dB**
- **Velocity: 0.5 m/s**
- **Spectrum Width: 0.5 m/s**
- **Differential Reflectivity: 0.0625 dB**
- **Correlation Coefficient: 0.00333**
- **Differential Phase: 0.35 deg**

WSR-88D's quantization of spectrum width is too coarse, given the standard deviation of estimate requirement and typical range of spectrum widths. Reducing the quantization would provide improved discrimination of turbulence intensity.

**Optimal for 2030: Spectrum Width Quantization of 0.1 m/s**

**5.5.3. Linear (radial) range resolution**

The radar must provide sufficient spatial resolution to detect fine scale features, such as tornadic circulations. Range Resolution is determined by pulse length and the Range Weighting Function (RWF). The RWF is a combination of transmitted pulse characteristics and processing within the receiver and signal processor. The RWF delivers optimum values of SNR and range resolution for the radar variables.

**Threshold: Performance of WSR-88D**

- **250 m for the Short Pulse Length**

**5.5.4. Effective angular resolution**

Signal processing techniques have been developed to use windows of overlapping azimuthal samples to significantly increase the antenna's nominal effective angular resolution at the cost of a slight increase in the standard deviation of radar variable estimates. Combined with 250 m linear range resolution, the resultant data have proven to be highly valuable in identifying tornadic circulation patterns and extending the effective range of such identifications.

**Threshold: Performance of WSR-88D: Effective angular resolution of 1.1 deg**

**5.5.5. Complex waveforms**

The radar must provide useful information for a wide variety of weather scenarios, including the concurrent presence of multiple storms along the same radial, multiple storms at different ranges in different sectors, and strong radial velocities in the storms. To optimize the radar operation, the radar must provide for the use of complex radar waveform transmission and signal processing in order to minimize range-velocity ambiguities.

**Threshold: Performance of WSR-88D**

- **Multi-PRF**
- **Systematic Phase coding**
- **Staggered Pulse-Repetition-Time (PRT)**

**5.5.6. Clutter detection and filtering**

Undesirable signal artifacts such as ground clutter and electromagnetic interference can degrade the meteorological utility of the radar data (e.g., rainfall estimation, tornadic circulation analysis). The radar system must identify and provide a means of removing such artifacts. Artifact removal must minimize any degradation of the desirable meteorological data.

**Threshold: Performance of the WSR-88D**

- **Automated detection of clutter at Clutter to precipitation Signal Ratios (CSRs) down to -13 dB.**
- **Clutter filtering resulting in reduction of CSRs to -13 dB or better.**
- **Minimize the bias and standard deviation induced by the clutter filter process: 1 dB bias and standard deviation for reflectivity and 1 m/s bias and standard deviation in radial velocity and spectrum width estimates.**

#### 5.5.7. Coverage

Radar data should be provided to the maximum range and altitude for which the data provide operationally useful meteorological information.

**Threshold: Performance of WSR-88D**

- **Maximum range: 460 km for reflectivity; 300 km for velocity and polarimetric variables**
- **Maximum altitude: 70,000 ft**

### 5.6. Scan Strategy Adaptability

The forecaster must have the ability to optimize radar operations for weather scenarios ranging from clear air to fast moving tornadic storms. This functionality must include defining preset scanning strategies (also termed Volume Coverage Patterns, or VCPs) to sample specific elevation and azimuth positions (i.e., the spatial sampling grid), with certain RDA parameters such as waveform, PRF, and antenna beam scan speed for each slice. The functionality must also support forecaster and automatic selection of PRF values to dynamically tune the preset scan strategy to minimize range folding and velocity aliasing in the area of significant storms. Through selection of preset scan strategies appropriate for different general weather scenarios, and dynamic tuning of the PRF within the scan strategy in use, forecasters exercise the best possible operational trade-offs concerning sensitivity, standard error of estimates, maximum unambiguous range, maximum unambiguous velocity and volume coverage time.

**Threshold: Performance of WSR-88D**

- **Multiple Clear Air and Precipitation Mode VCPs with adaptable parameters including:**
  - **Number of elevation slices and the elevation angle for each slice**
  - **For each elevation slice:**
    - **Transmit waveform**
    - **PRF**
    - **Antenna scan speed**
    - **Pulse length**
    - **Number of pulses to process for each sample bin**
    - **Edge angles of PRF sectors**
    - **SNR thresholds for each of the 6 radar variables estimated**
    - **Azimuth angular resolution**
    - **Velocity quantization (0.5 m/s and 1 m/s)**
- **Support for PRFs between 318 hertz and 1310 hertz**
- **Manual and automatic selection of different PRFs for three azimuthal sectors for each of two sets of elevation slices**

- **Ability to repeat the lowest elevation angle mid-way through a volume scan and/or to eliminate high elevation angle scans when insufficient weather echo exists.**

The design parameters of the WSR-88D limit the temporal resolution of volume updates to three to five minutes (two to three minutes update of the lowest elevation slice), depending on the locations and heights of storms in a particular weather scenario, while retaining the required sensitivity, spatial resolution and standard deviation of estimates. While this temporal resolution has been sufficient to support dramatic increases in tornado warning lead times since the introduction of the radars, it does not adequately represent the true speed of formation and evolution of tornadoes. Faster scanning capability, with retention of the data quality attributes stated above, would improve the timeliness of tornado detection, thus increasing the average tornado warning lead time. Further, data update times on the same scale as tornado evolution would better support the development of storm scale numerical models intended to forecast tornado development, leading to greater increases in tornado warning lead times with the Warn-on-Forecast approach.

Currently, the lowest elevation angle scanned by the WSR-88D is 0.5 deg (0.17 deg at one site, Langley Hill, WA) even though the physical lower limit of the radar is -1.0 deg. Phased array technology could provide adaptability of acquisition parameters (e.g., PRT or PRT sequence, number of pulse samples) for every point in the spatial sampling grid. On top of this, the spatial sampling grid could be adaptable as well (e.g., super-resolution vs. legacy resolution, different elevation spacing).

**Optimal for 2030:**

- **One minute or less volume coverage time with no degradation of the sensitivity, spatial resolution or standard deviation of measurement for radar variable estimates.**
- **Capability to define scan strategies with elevation angles as low as the operational siting and radar design allow**

## 6. Radar Functionality Constraints and Tradeoffs

Coverage, spatial resolution, sensitivity, maximum unambiguous velocity and range parameters vary in an inter-related manner with the radar's transmitted power, wavelength of the transmitted signal, beamwidth, and radar waveform including pulse length and PRF. For rotating dish antenna radars, the transmitted power, wavelength and beamwidth are generally constant for a given design. For phased array antenna radars, the wavelength may change with sub-array partitioning, and the transmitted power and beamwidth are adaptable. The pulse length and PRF are adaptable for both types of radars. In operations, a given scanning strategy takes advantage of the available adaptable parameters to best sample the existing weather scenario, with phased array antenna radars having more such adaptability. Often, a particular scanning strategy may degrade one parameter in order to enhance another with more value to operations for the given weather.

The following bullets summarize the effects of differing radar operating parameters on radar functionality.

- Effective radar coverage increases with:
    - Greater sensitivity, broader scan angles, lower elevation angles (extending the spatial sampling grid), increased pulse samples and/or signal processing techniques to lower variance of estimates and permit use of data at lower signal to noise ratios.
- Spatial resolution increases with:
    - Narrower effective beamwidth, shorter wavelength, shorter pulse length, and sharper range weighting function
- Temporal resolution increases with:
    - Faster effective beam scanning speed, smaller spatial sampling grid, and shorter dwell times.
- Sensitivity increases with:
    - Shorter wavelength, higher transmit power, longer pulse length, narrower beamwidth (for a given transmit power), lower receiver noise power
- Attenuation decreases with:
    - Longer wavelength
- Maximum unambiguous velocity increases with:
    - Longer wavelength, shorter PRT, multiple PRTs and signal processing methods
- Maximum unambiguous range increases with:
    - Longer PRT

## 7. Accuracy

The accuracy of radar estimates of reflectivity and other radar variables is a complex issue involving radar hardware design and calibration, appropriateness of selected values for scanning strategy adaptable parameters, and the complexity and strength of weather and other targets. The following sub-sections briefly discuss these major factors affecting accuracy. These discussions do not include specific requirements, but are intended to inform the readers of this document and to highlight the inter-related nature of the RFRs listed in section 5.

### 7.1. Radar hardware design and calibration

The system acquisition choices of radar design aspects such as wavelength, beamwidth and transmit power determine fundamental limits of the applicability of the radar for different weather scenarios. For example, long range surveillance of weather scenarios that include both light returns (e.g., gust fronts) and heavy rainfall requires a radar with little attenuation in heavy rain (e.g., longer wavelength) and high sensitivity.

Regardless of the inherent capabilities of a radar’s design, there will be some signal degradation due to the combination of hardware components and their inter-connections. The sum of the signal degradations due to these sources is termed system bias. Radar engineering calibration estimates the signal bias, and must be very accurate to support valid estimates of radar variables. Typically, however, engineering calibration techniques cannot be absolutely accurate, and more stringent techniques can be very expensive to implement operationally. The calibration techniques chosen for a given radar represent a compromise between system bias estimation accuracy and cost.

### 7.2. Operational settings for scan strategy adaptable parameters

Operational weather radar functionality typically offers control over certain scan strategy parameters such as PRF, antenna beam scanning speed, and elevations and azimuths processed. These choices are used to create preset scan strategies (also termed Volume Coverage Patterns) to achieve reasonable tradeoffs among volume update time, maximum unambiguous velocity, maximum unambiguous range, coverage, spatial resolution and clutter mitigation for different weather scenarios. Dynamic tuning of parameters for specific scanning sectors, such as modifying the PRF to mitigate range folding, is used to further enhance performance in the vicinity of significant storms. Selection of the proper scanning strategy and dynamic tuning of adaptable parameters are critical to achieving accurate estimates of radar variables.

### 7.3. Complexity and strength of weather and other targets

Even with high quality radar hardware design and calibration, and with appropriate selection of scan strategy parameters, real world weather returns present significant challenges to accurate estimations of radar variables. Weather, insects, birds, anomalous propagation and ground targets contribute to a complex radar return signal in many different weather scenarios. The distribution, intensities and velocities of precipitation areas may exceed the sampling and signal processing capabilities for mitigating range and velocity ambiguities. The strength and velocity of a storm may vary significantly within a single sample volume, especially for the larger sample volumes at longer ranges. Precipitation areas may fall partially, or wholly, below the lowest beam of a scanning strategy, or may be obstructed by terrain or man-made objects. For certain radar variable estimates, such as Differential Reflectivity, the radar estimate may be accurate but the scientific association with a type of precipitation (e.g., snow) may be problematical due to the variability of the weather target compared to other meteorological data (e.g., temperature).

Given a well-designed and calibrated radar, operations with appropriate scanning parameters and signal processing techniques, and an understanding of the complexities of weather radar estimations of radar variables, the final test of a radar's accuracy is the usefulness of its data for support to operational forecasts and warnings.

## 8. Radar Observations for Meteorological Phenomena and Scenarios

Weather radar provides valuable information on a broad range of meteorological phenomena and weather scenarios. The following sections describe several scenarios and note the radar variables most important to their analysis.

### 8.1. Clear air

This category includes all non-precipitation targets, including insects, birds, bats, smoke and volcanic ash plumes, chaff, Bragg scatter, and fine lines (e.g., frontal boundary, gust front, dryline).

Velocity estimates from insect targets are particularly useful for wind information, including wind shift boundaries. The resultant wind information is useful for real-time activities (e.g., airport runway switching) and as input to numerical model initialization.

Radar signals from clear air targets are often weak, and degrade rapidly with range. The relative absence of insects in cold weather (e.g., winter) reduces the quality and coverage of velocity estimates. Special clear air scanning strategies have been developed to maximize the radar coverage by employing a longer pulse length, and by collecting more samples per estimate.

**8.2. Stratiform rain**

Stratiform rain typically forms in the lowest few kilometers of altitude, and extends over relatively large areas with weak horizontal gradients of intensity and limited vertical extent. In some scenarios, stratiform rain may be associated with other weather phenomena such as mesoscale convective systems and tropical or extra-tropical cyclones.

Reflectivity and the polarimetric variables are used to analyze the intensity and areal extent of stratiform rain, and to estimate rainfall accumulations. Velocity data are used to calculate vertical wind profiles and as a general indication of wind direction and speed. Polarimetric variables are also used, in combination with other types of observations, to analyze rain/snow transition zones and to assess the likelihood of freezing rain and aircraft icing areas.

Radar-derived quantitative stratiform precipitation estimates can be degraded by several factors, including: overshooting precipitation areas with the lowest beam, anomalously enhanced reflectivity values for precipitation in the melting layer, and beam blockage. These factors limit the range to which such quantitative estimates are valid.

**8.3. Winter weather**

Winter weather includes a variety of precipitation types: freezing rain, ice pellets (sleet), snow, snow pellets, and graupel. Some or all of these precipitation types may occur concurrently within the radar umbrella. Winter weather precipitation has stratiform characteristics similar to those of stratiform rain. One of the most important uses of radar for winter weather is the identification of transition zones between the different types of precipitation (e.g., the rain-snow line). However, much winter precipitation occurs at low altitudes – presenting a challenge for single radar coverage at longer ranges. In areas where the winter precipitation is detected on the lowest radar beam at longer ranges, other effects (e.g., melting, refreezing, sublimation, drifting of snow) add to the uncertainty of radar estimates of precipitation types, amounts and surface locations.

Reflectivity and the polarimetric variables are used to analyze the intensity, type and areal extent of precipitation, and to estimate snowfall accumulations. Velocity data are used to calculate vertical wind profiles and as a general indication of wind direction and speed. Polarimetric variables are also used, in combination with other types of observations, to analyze precipitation type at the ground and aloft important to surface and air transportation.

Clear air scanning strategies with longer sampling times are often used to detect the weaker reflectivity. Higher scan angles are typically not required since the precipitation areas do not have a great vertical extent. Coverage limitations are similar to those of stratiform rain.

**8.4. Heavy rainfall**

Heavy rainfall can be showery (intense rainfall rates for tens of minutes) or stratiform (moderate rainfall rates for hours) in nature. Heavy rainfall from convective storms may have larger raindrops resulting from melting hail or graupel, and its intensity typically varies greatly both spatially and temporally. Heavy rainfall can also occur with densely packed small raindrops formed from 'warm process' coalescence growth of raindrops in temperatures warmer than 0 deg C. Warm process rainfall tends to be stratiform (i.e., lower spatial and temporal variation in intensity), and can occur with tropical or non-tropical systems.

Radar estimates of heavy precipitation amounts have much greater spatial and temporal resolution than those from rain gage networks. Reflectivity, Differential Reflectivity and Differential Phase (as converted to Specific Differential Phase in downstream processing) are the main radar variables used in precipitation estimation algorithms. Combined with rain gage data, the radar rainfall estimates have led to dramatic advances in flash flood warning performance. The introduction of dual polarization capability to the WSR-88D has improved precipitation estimates versus using reflectivity only, with the promise of further improvements as the polarimetric precipitation estimation algorithms are refined.

There are significant inherent limitations in capabilities of a single radar for precipitation estimation. Precipitation estimates typically degrade with range due to several factors, e.g., overshooting of low altitude precipitation, overestimation in bright band areas, uncertainties of estimating surface rainfall rates from observations in snow above the bright band, and evaporation below lowest sampling beam. However, single radar data are also used in downstream data fusion and data assimilation systems that integrate networks of radar and other operational datasets into advanced precipitation estimation models.

### 8.5. Convective storms

This category includes convective rain showers, general and severe thunderstorms (i.e. those that produce NWS-defined severe wind gusts or severe-sized hail), and tornadic storms. Convective precipitation forms in cumulus or cumulonimbus clouds and occurs where updraft velocity is large relative to the fall speed of precipitation particles. Convective precipitation often has strong horizontal reflectivity gradients and can extend several kilometers vertically. Convective storms typically have rapid evolution (on the order of 1 min or less) in strength and size and given the right ingredients in the near-storm environment, can develop severe weather features such as tornadoes. Tornadic circulations are very small scale and can vary significantly across distances of just a few hundred meters. Convective storm scenarios, including tornadic storms, range from isolated storms in limited areas of the radar umbrella, to widespread storms throughout the umbrella, to squall lines oriented along the full diameter of the umbrella.

Convective storms, especially severe/tornadic ones, present the largest challenge for weather radars, and their surveillance drives the most stringent values of the various radar functionality requirements. These storms have precipitation and up/downdraft cores where the key processes determining rainfall rate/type, updraft and downdraft strengths are contained. Specification of the structure (i.e., vertical extent) and contents of these cores is critical to warning operations. All of the standard and polarimetric radar variables are used extensively in the analysis of convective storms and are critical observation data used to issue severe thunderstorm, tornado, or flash flood warnings.

### 8.6. Tropical cyclones

Tropical cyclones are large scale warm-core storms with organized convection that exhibit cyclonic rotation around a low pressure center. These storms contain spiral rain bands and can contain very high gradient winds. The rain bands often generate very high rainfall rates. In addition, tropical cyclones can contain tornadic storms, which are often weak with very rapid development and short life times.

Timely detection of tropical cyclone tornadic potential requires fast scanning strategies with good low altitude coverage. Ground-based radar provides the main source of position fixes and other diagnostic information for near land and land-falling tropical cyclones. Such observations are also foundational to short-term forecasts as tropical cyclone conditions persist near and over land. NWS has developed guidance for operating WSR-88D units during tropical cyclone conditions. The application of dual polarization parameters to tropical cyclones is rather new but these parameters are already being used to identify strong updraft cores and to improve rainfall estimates.

Heavy rainfall and tornadoes associated with tropical cyclones often occur at low altitudes, and their detection is degraded at longer ranges as the radar beam overshoots the precipitation and rotational signatures.

## 9. System-independent Observation Requirements for Weather Phenomena

NOAA has developed the Consolidated Observation Requirements List (CORL), part of the NOAA Program Observation Requirements Document (PORD). Together, the CORL and PORD constitute an extensive database that summarizes specific NOAA program requirements. The Local Forecast and Warnings (LFW) CORL identifies 31 environmental observation requirements covering physical properties of the atmosphere and oceans. These observation requirements are further specified by spatial, temporal, accuracy and other attributes. The CORL requirements are based on the physical attributes of weather phenomena, e.g., size, gradients of storm features, rapidity of evolution, vertical extent, etc. They are purposely not observation system dependent, but provide guidance to NOAA/NWS efforts to improve observing capabilities and for comparing observing system interdependencies.

Weather radar provides information on 11 of the 31 CORL requirements, and is critical for convective storm scale observations. It is important to note, however, that CORL values are not meant to be used directly as NOAA/NWS radar functional requirements, nor as system specification requirements for any hardware acquisition. Instead, they should be used as input to the development of such requirements and this RFR document used them as guidance where applicable. CORL values denote the observation attributes that would describe a particular weather phenomenon in enough detail to completely inform current and anticipated analysis and scientific techniques for detection and forecasting of that phenomenon. For example, although the CORL states 100 m spatial resolution for storm area precipitation rates, a single radar can only achieve this capability within a short range of the radar. Any specific radar acquisition program would need to balance affordability, performance and schedule to address CORL requirements.

The CORL requirements most relevant to single radar functionality are listed in the following table.

| Phenomenon | Vertical Resolution | Horizontal Resolution | Accuracy | Sampling Interval |
|---|---|---|---|---|
| Precipitation Rate Profile: Storm Area | 100 m | 100 m | 1 mm/hr | 30 sec |

| | | | | |
|---|---|---|---|---|
| Precipitation Type: Storm Area | 100 m | 100 m | Not Applicable | 30 sec |
| Wind Direction Profile: Storm Area | 100 m | 100 m | 1 deg | 30 sec |
| Wind Speed Profile: Storm Area | 100 m | 100 m | 0.5 m/s | 30 sec |

## 10. Individual Radars and Network Considerations

This document's focus is on functional requirements for individual radar data acquisition. The following sections present additional discussions to help place these requirements within the context of overall radar information use by NOAA/NWS and other users.

### 10.1. Geographic coverage

NOAA/NWS forecast and warning operations use combined data from the network of radars present in a given region. The over-lapping radar umbrellas will often mitigate the coverage limitations of the individual radars concerning spatial resolution, overshooting of low altitude precipitation, and ability to detect weak targets. Individual radar coverage functionality remains critical, however, for areas where multiple radar coverage is not present, and for operations when one or more of the overlapping radars is down for maintenance.

Low altitude (below ~1500' AGL) coverage will become increasingly important for initiation of storm scale numerical models as the complexity of these models' underlying physics is improved. Quality information on the pre-storm environment is critical to the effectiveness of severe storm forecasts from these models, and to achieving the performance goals that depend on Warn-on-Forecast techniques. The requirements developed in this document should be used to inform the development of radar network coverage requirements for NOAA/NWS.

To supplement its own network data, NOAA/NWS explores opportunities to use data from non-NOAA radars in particular locations. Currently, NOAA/NWS acquires data from the 45 Terminal Doppler Weather Radar (TDWR) units operated by the Federal Aviation Administration (FAA). In the future, such supplemental data acquisition efforts may include other FAA radars as well as local radars operated by television stations or local governments or any other public or private entities willing to share radar data. While NOAA/NWS will not control the functional characteristics of any non-NOAA radars, these data can be very valuable to WFO operations as well as some national centers.

### 10.2. Individual radar products

The primary user of particular NOAA/NWS radar is the local WFO. Radar products generated using only that radar's data are the primary guidance for a forecaster's issuance of tornado and other severe weather warnings. The Federal Meteorological Handbook, Number 11, contains descriptions of all of these radar products. Radar products from neighboring network radar sites are also routinely used by a WFO's forecasters, as well as products generated from data acquired from nearby TDWR units. Most of the locally generated radar products, as well as the base data, are disseminated in near real-time for the benefit of other NOAA users, other Government agencies and the private meteorology sector.

### 10.3. Multi-radar and multi-parameter products

The base data and products disseminated from individual radar units are used to generate many multi-radar and multi-parameter products at regional and national geographic scales. Examples of such products are simple mosaics of a particular product (e.g., reflectivity) from a regional set of radars, and precipitation estimates determined from radar, satellite and rain gage data. For many uses, these regional and national products significantly mitigate the coverage and other limitations of data from an individual radar.

### 10.4. Local and downstream users

The NOAA/NWS radar data and products support the national economy through the operations of many users, including:

- NWS WFO forecasters and River Forecast Center hydrologists
    - Tornado and severe thunderstorm warnings, flash flood warnings, winter weather advisories, general forecasting, river stage forecasts, general flooding, flash flood guidance calculations, wind speed/direction profiles
- NWS National Centers (e.g., Storm Prediction, Hurricane, Aviation Weather, Environmental Modeling)
    - Severe thunderstorm and tornado watches, tropical cyclone strength and movement advisories, aircraft icing potential, general thunderstorm avoidance, data assimilation for model forecasts, climate studies, long term data archival, forecast model verification, use of precipitation analyses, etc.
- Other NOAA Line and Staff Offices
    - Office of Oceanic and Atmospheric Research: Input to research models, storm scale research, radar improvements
    - National Ocean Service: Input for storm surge modeling
    - Office of Marine and Aviation Operations: Safety information for both marine and aviation assets
    - National Environmental Satellite, Data and Information Service: Data for nation's hydrometeorological archives
- Other Government agencies (Not comprehensive)
    - Department of Defense (DOD): Resource/installation protection, airspace protection, presidential support, space launch/landings)
    - Federal Aviation Administration: Terminal and en route weather guidance
    - Department of Homeland Security: Customs/Border protection

    - Federal Emergency Management Agency: Planning, response and recovery information for any event
    - National Transportation Safety Board (NTSB): Accident investigations.
    - U.S. Geological Survey: Precipitation estimates for stream flow
    - U.S. Army Corps of Engineers: Precipitation information for runoff into main stem rivers and dams
    - Department of the Interior: Convective information for firefighting and aircraft navigation
    - State and local governments: Emergency management, road weather management
- Private meteorological sector (e.g., commercial weather companies, television stations, energy generators, drought monitoring, fire risk, water resource management, etc.)
    - Tailored forecasts for specific customers

These users have developed an extensive infrastructure to acquire and process the NOAA/NWS radar data. It is critical that future plans for additions to, or modifications of, NOAA/NWS radar functionality consider these users' investments, minimize disruptions to their operations, and minimize the need for costly modifications of infrastructure.

**Appendix A: References**

American Meteorological Society, 2013: Glossary of Meteorology, http://glossary.ametsoc.org/wiki/Main_Page

Federal Meteorological Handbook No. 11, http://www.ofcm.gov/fmh11/fmh11.htm

IEEE Standard Radar Definitions, IEEE STD686-2008, 21 May 2008, by the Radar Systems Panel, IEEE Aerospace and Electronic Systems Society.

National Institute of Standards and Technology, International System of Units (SI), http://physics.nist.gov/cuu/Units/units.html

National Oceanic and Atmospheric Administration (NOAA), 2013: Consolidated Observations Requirements List (CORL), Technology, Planning and Integration for Observation (TPIO) website, https://www.nosc.noaa.gov/tpio/main/aboutrap.html

National Oceanic and Atmospheric Administration (NOAA), 2012: NOAA Strategic Plan, http://www.ppi.noaa.gov/ngsp/

National Oceanic and Atmospheric Administration (NOAA), 2011: National Weather Service Strategic Plan, http://www.nws.noaa.gov/sp/

Warning Decision Training Branch's Distance Learning Operations Course (WDTB DLOC ) radar training, http://www.wdtb.noaa.gov/courses/dloc/outline.php

**Appendix B: Terms and Definitions**

The following terms and definitions cover basic weather radar engineering, radar operating parameters and data types. The discussions present information to enable operations, programmatic and management personnel to better understand which radar parameters, and how they are used, affect the data provided to operational users. More rigorous definitions may be found in standard reference publications such as the American Meteorological Society Glossary of Meteorology, Federal Meteorological Handbook No. 11, or the WDTB DLOC radar training web site.

**Antenna Gain**: Antenna gain is a measure of the directivity of the radiation pattern established by the antenna design. It is a measure of how well focused the energy is in the desired direction. Antenna gain is a critical element in establishing system sensitivity.

**Attenuation:** Attenuation refers to the amount of a radar beam's transmitted energy that is absorbed by targets (e.g., rainfall) in that beam. Shorter wavelength energy is absorbed more than that of longer wavelengths. X-Band and C-Band radar detection of storms at longer ranges from the radar can be significantly degraded by intervening heavy rainfall along the same radial. S-Band radars have relatively low rates of attenuation even in heavy rainfall and hail.

**Azimuth Sample Interval (ASI):** Azimuth sample interval is the angular spacing of the reported radials of data.

**Beamwidth:** The antenna beamwidth is the angle subtended by the pattern over which the transmitter power is greater than an established portion of the peak seen at the centerline, or bore sight of the antenna. Typically the boundaries of the angular extent are defined by the points at which the radiated power is one half of the peak.

The antenna beamwidth on planar phased array technology is not a constant, but varies as the beam position bore sight moves away from normal to the plane of the array. For example, every look angle is associated with a different antenna pattern, and the gain, beamwidth, and side lobe characteristics change. For cylindrical type arrays, the azimuth plane can be constant, but variations exist as the beam scans in elevation.

Antenna motion (usually azimuthal rotation as in the WSR-88D) combined with the processing of many pulses per radial creates an *effective* broadened beamwidth. Azimuthal weighting functions can be employed to reduce the effective beamwidth.

**Correlation Coefficient (CC):** This is a measure of the correlation between the horizontal and vertical back-scattered returns (for all pulses used to observe a radar sample volume) from the scatterers within a given volume. If the entire volume is full of similarly sized rain drops, and small compared to the wavelength of the radar, the correlation will be very high, from 0.95 to 0.99. When there is a mixture of particles, the correlation drops. If there is hail or snow mixed with rain, or a wide distribution of orientation of the hydrometeors, or tumbling wet snow aggregates and hail, the correlation will be much less than one, with values sometimes below 0.90. A good indicator of large hail is to have reduced correlation within areas of high reflectivity. The correlation coefficient is thus a measure of the diversity of homogeneity of scatterers detected and thus of the mixture of precipitation type.

**Coverage:** Coverage, also known as the radar umbrella, is simply the three dimensional space for which a radar provides observations. This functionality is generally stated in terms of maximum range (the farthest distance from the radar for which observations are provided) and minimum/maximum height (the height above the ground of the lowest/highest observations for a given range). The minimum height at a given range is determined by the elevation angle of the lowest radar beam and the effects of earth curvature. The maximum height at a given range is determined by the elevation angle of the highest radar beam. Within the nominal radar umbrella, coverage may be degraded by beam blockage from terrain or man-made structures and by gaps between elevation scans driven by temporal resolution and data accuracy considerations.

**Differential Phase (PHI):** Differential Phase is simply the difference in phase between the horizontally- and vertically-polarized returns at a given range along the two-way propagation path. To understand Differential Phase, consider two simultaneous, or consecutive, radar pulses that travel the same propagation path. The first pulse is horizontally-polarized, and the second is vertically-polarized. Along the propagation path is a uniform field of falling raindrops. Falling raindrops are oblate, so the electric field will encounter more water content in the horizontal direction than in the vertical. The horizontally polarized pulse will, therefore, be affected by more water than the vertically polarized pulse. Since electromagnetic waves travel more slowly through water than through air, the horizontally-polarized wave will travel more slowly through the field of raindrops than will the vertically-polarized pulse. This is a two-way process: the horizontally-polarized backscattered radiation will travel more slowly back to the radar than the vertically-polarized backscatter.

**Differential Reflectivity (ZDR):** This is a measure of the ratio of the back-scattered linear horizontal power to the back-scattered linear vertical power, which in dB of reflectivity is horizontal reflectivity minus vertical reflectivity. Hail stones tumble as they fall, yielding similar values for horizontal and vertical reflectivity; hence the ZDR for hail will be close to zero. Heavy rain drops have oblate spheroid shapes, yielding higher horizontal than vertical reflectivity and a ZDR in the range from 1 to 5. Thus, ZDR is a useful measure to separate hail from rain. Using similar reasoning, ZDR can be used to infer the presence of frozen precipitation, super-cooled water drops in updrafts, and the onset of melting snow/hail in the bright band region or near the ground.

**Elevation Slice:** Constant elevation angle sampled as part of a Volume Coverage Pattern (VCP).

**Fine Line:** A narrow radar echo indicating a boundary (such as a frontal boundary, gust front, or dryline) across which a density or moisture discontinuity exists. The reflectivity is apparently explained by scattering from the refractive index gradients across the discontinuity and from insects and insect-eating birds that are concentrated along the line.

**Maximum Unambiguous range:** The Maximum Unambiguous range is the maximum distance from the radar that the outgoing pulse can travel in order for the return signal to arrive back at the radar before the next pulse is transmitted. This is the range within which returns from separate targets along the same radial can be accurately assigned to the proper targets.

**Maximum Unambiguous velocity:** The Maximum Unambiguous Velocity is the maximum actual radial velocity that the ensemble of targets can exhibit before the apparent frequency change due to the Doppler shift exceeds the Nyquist velocity The maximum unambiguous velocity is established by the radar wavelength and the PRF.

**Minimum Detectable Signal (MDS):** The minimum detectable or minimum discernible signal is the smallest signal power, relative to the system's noise level that can provide useful information. MDS, in the context of a weather radar, is the lowest value of the signal to noise ratio that allows meteorological variable estimation that meets specified quality standards. This is analogous to MDS for standard point target radar that allows for a specified probability of detection. MDS is closely related to sensitivity.

**Nyquist Interval:** The Nyquist Velocity (aka Maximum Unambiguous Velocity) is the maximum velocity that can be unambiguously determined for a given pulse repetition frequency (PRF), or combination of PRF's (e.g., Staggered PRT). The Nyquist Interval is the set of velocity values from zero up to and including the Nyquist Velocity. For example, if the Nyquist Velocity is 35m/s then the Nyquist Interval is 0-35m/s.

**Pulse length:** Pulse length refers to the length of time the transmitter fires for a given pulse. It is defined by the points where its magnitude is 6db lower than its peak value. Shorter pulse lengths generate shorter physical lengths of the pulses and therefore increase the linear range resolution of data volumes. However, such pulse lengths decrease the ability to see weaker targets in that data volume due to less energy per pulse.

In the phased array domain, the lower power potential of the solid state Transmit/Receive (TR) modules may drive toward use of pulse compression. So the requirements analysis may entail a review of the applicability of pulse compression to weather and a subsequent understanding of how much isolation between the adjacent resolution volumes can be accepted. This is analogous to the isolation desired between adjacent volumes in the azimuthal direction that drives antenna pattern specifications.

**Pulse Repetition Frequency (PRF)** and **Pulse Repetition Time (PRT):** Weather radars that are employed to provide high spatial resolution, both horizontally and vertically, for a wide spectrum of targets (e.g., strong, weak, short range, long range) generally transmit individual pulses of energy. The PRF is simply the number of pulses transmitted per second. An analogous, commonly used term, is Pulse Repetition Time (PRT), the time between pulses. Operationally, the users or algorithms can generally choose from among several PRF values for a given scan, or portion of a scan. The PRF value chosen has dramatic impact on the radar data. At constant scan rate, higher PRF values generate more pulse samples per radial, lowering estimate variance which allows for processing at lower signal to noise ratios, which increases the ability to observe weaker targets. This also increases the maximum wind speeds that can be directly estimated (see Maximum Unambiguous Velocity definition). However, higher PRF values reduce the maximum range for which returns from targets that are positioned along the same radial can be directly assigned to the proper range location (see Maximum Unambiguous Range definition). The flexibility to choose from a range of PRF values gives users and algorithms the ability to adapt the radar to a given weather scenario.

**Radial Velocity (V):** Radial Velocity is the power weighted average of the radial velocities of all the scatterers in the radar resolution volume toward or away from the radar along a given radial (the complete term is mean radial velocity).

**Range Resolution:** Range resolution is a function of the pulse length and the range weighting function. It denotes the linear extent of a sample volume along a given radial, and is typically defined as the distance in range between the points in the range weighting function that are 6 dB below the maximum value of the function.

**Range Sample Interval (RSI):** The range sample interval is the time between the discrete samples obtained and produced by the receiver and signal processor from the continuous return signal. Typically, the range sample interval is selected to be compatible with the range resolution.

**Range Weighting Function (RWF):** The RWF defines the radial extent of the radar resolution volume. The RWF is the combination of transmitted pulse characteristics and the processing done within the receiver and signal processor that shapes the response of the system in the range dimension. The RWF determines how the individual scatterers are weighted within the radar variable estimation process. It defines the range dimension of the radar resolution volume in the same way the antenna beam shape defines the azimuth and elevation dimensions of the radar resolution volume. Well implemented range weighting functions can deliver optimum values of the signal to noise ratio and range resolution in the return signals available for meteorological variable estimation.

**Reflectivity (Z):** Reflectivity is the backscattering cross section per unit volume, derived from the returns in the horizontal channel. More precisely, it is the equivalent reflectivity factor of liquid rain drops assuming scattering in the Rayleigh regime (drop size diameters small with respect to wavelength). If the return from the beam with vertical polarization is meant, the term reflectivity-vertical will be used. Reflectivity is, perhaps, the most widely used radar parameter, and provides a wide range of information, including rain and snowfall rates, storm strength and evolution, storm location and movement, and storm outflow and other wind boundaries. Patterns of reflectivity within a storm are also used to assess the storm's likelihood to produce a tornado. The aviation community uses high reflectivity values in a storm as an indication of likely turbulence in the vicinity of the storm.

The units of the operational Z are dBZ. This is a logarithmic measure used for convenience due to the large potential range of values for the reflectivity factor.

**Sample variance:** Sample variance is very nearly just the average squared difference between the data points and their sample mean. However, the mean and sample variance calculations are more complicated for weather radars, because only one measurement is available and we need to infer, or estimate, the variance of this measurement using knowledge of weather signal characteristics and the methods used to produce the radar observations. The radar observation sample variances depend upon the pulse repetition time, sample size, signal to noise ratio, radar system parameters and the true properties of the hydrometeors, or scatterers, in the radar volume.

**Sensitivity:** Sensitivity is a measure of the weakest signal the radar can reliably detect and process at a given range. Sensitivity is closely related to the radar's minimum detectable signal. Sensitivity increases with higher transmit power, shorter wavelengths, and lower receiver noise power. High sensitivity corresponds to an ability to detect weak signal strength meteorological features (e.g., light snow, gust fronts, outflow boundaries, weak circulations) to longer ranges.

**Side lobes:** The characteristic of an antenna pattern that diverts radiated power from the main beam (or lobe) and allows undesirable signal return that contaminates the signal.

**Signal to Noise Ratio (SNR):** The ratio of a given signal power level to the system noise power level.

**Spatial resolution:** The nominal spatial resolution for a given data sample volume is determined by the angular width of the radar beam, the range of the data sample, pulse length, and the range weighting function. Radar data signal processing is often used to provide data to the user with spatial resolution somewhat different from the intrinsic resolution supported by the antenna beam pattern and the range weighting function. Since the arc of the radar beam increases with distance, the spatial resolution will decrease. Signal processing and data manipulation can reduce the effective dimensions of the resolution volume. For rotating dish antennas, the angular width of the radar beam is constant, but for planar phased array antennas the beamwidth can vary based on the beam pointing angle with respect to the antenna orientation.

**Spatial Sampling Grid:** The spatial sampling grid is the three dimensional structure defining the spatial locations of the radar variables for a particular scan strategy. The spatial sampling grid is typically established in polar coordinates with dimensions of range, azimuth angle, and elevation angle.

**Specific Differential Phase (KDP):** Since the Differential Phase (PHI) will increase with range from the radar, its range derivative is taken to determine the change in PHI within individual range bins. This derivative is called the Specific Differential Phase. KDP is valuable for estimating rainfall rates, is not affected by non-liquid targets, and is independent of a target's reflectivity.

**Spectrum Width (SW):** Spectrum width is the estimation of the spread about the mean radial velocity of targets toward or away from the radar along a given radial. SW is used to identify areas of wind shear and turbulence.

**Storm Area:** As defined in the CORL, "Storm Area" does not encompass a fixed time/space region. Storm Area is: "A relocatable, three dimensional region of sufficient size to observe the pre-convective, convective and near-storm environments encompassing convective storm phenomena, from MCS-scale down to tornado scale, for times 6-12 hours prior to anticipated convective initiation through dissipation of convective phenomena."

**Super Resolution Processing:** A technique whereby returns from overlapping azimuthal samples are used to produce 0.5°azimuthal estimates. Sample weighting functions are employed to reduce the effective azimuthal beamwidth. Azimuth weighting functions are primarily useful for radars using fixed beam rotating antennas.

**System bias:** System bias is the estimation, obtained through engineering calibration measurements, of the combined contributions to degradation of data accuracy of all the hardware components of the system. The estimated system bias is compensated for in signal processing of the radar returns. Therefore, an accurate estimation of system bias is critical to obtaining accurate estimations of radar variables.

**Temporal resolution:** Temporal resolution is the length of time between successive observations of a given data sample volume within the radar umbrella. For rotating dish antenna radars, the temporal resolution is constrained by a particular scanning strategy (the set of elevation angle scans that comprise the radar umbrella and scan sequence). For phased array antenna radars, the temporal resolution is highly adaptable to the types and locations of weather phenomena within the radar umbrella.

**Volume Coverage Pattern (VCP):** Automatic radar scanning sequence that specifies the scanning parameters required to sample a specific spatial sampling grid surrounding a radar. For each elevation angle within the VCP definition, particular parameters (e.g., azimuthal scanning rate, active waveform, pulse repetition frequency, etc.,) are defined to increase the likelihood of effectively sampling a particular meteorological phenomena type.

**Waveform:** A term used to describe the sequence of PRFs (or time intervals between transmitted pulses) used in data collection for each radial of particular elevation scan. Waveforms are selected to exercise different tradeoffs between maximum unambiguous range and maximum unambiguous velocity (also known as the Doppler Dilemma). The WSR-88D employs the following waveforms:

- **Surveillance Waveform:** A low PRF is employed for each radial for the entire 360° scan to determine proper target location and returned power. This PRF provides a maximum unambiguous range that extends to the maximum range of coverage. Generally used as part of a split cut consisting of a surveillance waveform followed immediately by a range-ambiguous Doppler waveform scan.

- **Doppler Waveform:** A high PRF is employed for each radial for the entire 360° sweep. Generally used at low elevation angles where high velocity winds are expected and accurate estimates are required. When used on low elevation angles range ambiguity resolution is required. Also used at high elevation angles where range ambiguity is not a problem.

- **Batch Waveform:** The Batch Waveform uses a combination of low and high PRF sequences for each radial within the elevation scan. For each radial, the radar transmits a few pulses using a low PRF to obtain reflectivity data with unambiguous range information. Then, for the remainder of the 1° radial, the transmitter switches to a high PRF to obtain Doppler information. This series of a few (generally 3-8) low PRF pulses and several (25 or more) high PRF pulses per radial results is two complete Doppler power spectra data sets for each radial. The high PRF data are used to calculate the three base data moment (reflectivity, velocity and spectrum width) estimates and Dual Pol variables. The low PRF data are used to range unfold the high PRF data and to calculate the reflectivity estimates for the range gates where the Doppler (high PRF) reflectivity estimates are not available (overlaid (range folded) gates). Generally used in the middle elevations angles of most VCPs where data from beyond the first Doppler trip are expected, but where ground clutter contamination is generally not a major problem.

- **Systematic Phase Coding Waveform:** Systematic phase coding is used to help mitigate range/velocity ambiguities. With systematic phase coding, the phase for each pulse is set according to a predetermined set of phase ‘codes’. The code sequence repeats every set number of pulses while the sequence of differences between consecutive phases repeats at a different frequency. This scheme provides a method to reliably separate overlaid signals in the spectral domain.

- **Staggered Pulse-Repetition Time (SPRT) Waveform:** SPRT is used to help mitigate range/velocity ambiguities and to reduce the standard deviation of estimates of radar variables. With SPRT, pulses are transmitted using alternating PRTs at a known PRT ratio. SPRT processing calculates a velocity from each PRT using lag-1autocorrelations. Then it uses a velocity difference transfer function to recover velocities beyond the maximum unambiguous velocity for either of the original PRTs. SPRT is currently being implemented on the WSR-88D to replace the Batch waveform for some VCPs.

**Wavelength:** Weather radars transmit and receive beams of electromagnetic energy in the microwave part of the electromagnetic spectrum. Wavelength is the physical length of one complete cycle of the transmitted microwave. Weather radars generally are designed to operate with one of four wavelengths: 3, 5, 10 or 20 cm. The parts of the microwave spectrum used by these wavelengths are termed X-Band, C-Band, S-Band and L-Band, respectively. Shorter wavelengths are more sensitive to smaller targets and have a narrower beamwidth for a given antenna size. Shorter wavelength energy is more quickly absorbed by stronger rainfall, however. A shorter wavelength also reduces the maximum unambiguous velocity for a given Pulse Repetition Time (PRT); reducing the PRT to increase the maximum unambiguous velocity, however, decreases the maximum unambiguous range. Choice of wavelength for a particular radar acquisition is, then, dependent on the types of weather to be observed, the mission performance requirements and costs.

## Appendix C: Requirements Validation

This section summarizes the NOAA/NWS Radar Functional Requirements in tabular format and provides a confidence level and linkage to validation reference materials, if available. The definitions describing "Threshold Requirements" and requirements that are "Optimal for 2030" are included in sections 5.2 and 5.3, respectively.

It is expected that threshold requirements will contain a large percentage of high confidence (green level) requirements as these represent present day or near term NWS capabilities. However, it is natural for the number of green level requirements to lower and yellow level requirements to increase as the requirements focus on over the horizon strategic goals where some technologies may not yet exist. In this case, subject matter expertise will be used to provide justification and validation based upon strategic objectives.

### Confidence Levels for Validation

The requirements validation process uses colors to identify confidence levels as illustrated in the following table.

| Confidence Level | Criteria | Examples |
|---|---|---|
| Green | A document showing that the data are being used in a **current NWS operational environment**, or are included in **research linked to strategic plans**. | Operational user manuals or software documentation, current hardware specifications, research plans directly linked to strategic plans, Federal Meteorological Handbooks, NAS Reports, Interface Control Documents, and test reports. |
| Yellow | In the absence of validation documentation**, subject matter expert statements** are used to justify current or future requirements. | Memos written by one or more subject matter experts to validate a requirement – to include justifications and/or linkages to cost/benefits. |
| Red | No validation documentation is provided or documentation provided does not validate the requirement. | |

**Requirements Validation Table**

The following table summarizes the requirements presented in the NOAA/NWS Radar Functional Requirements document for both near term and over the horizon targets (~2030). The background color of the threshold (T) and optimal (O) requirements cells indicates the level of validation confidence. Validation documents are listed at the end of this table and are denoted here by their document reference number. Any requirement can be validated by more than one reference document. If a SME statement is used for validation, then the documents will be numbered, included in the reference listing and appended to the end of this document.

During the requirements validation audit, it was found that a number of the values within the 2010: WSR-88D System Specification (Document Number 2810000) were incorrect, or were not updated to represent the current state of the system. Those requirements that are validated by the updated/corrected system specification are noted with an asterisk (*).

| Req Num | Category (and Section Number) | Threshold (T) Requirement | Optimal (O) Requirement for 2030 | Validation Reference # |
|---|---|---|---|---|
| | **RDA Transmit & Receive (Section 5.4)** | | | |
| 1 | Weather Radar Variables (Section 5.4.1) | Reflectivity (Z) | | T: 10h<br>O: |
| 2 | | Radial Velocity (V) | | T: 10i<br>O: |
| 3 | | Spectrum Width (SW) | | T: 10i<br>O: |
| 4 | | Differential Reflectivity (ZDR) | | T: 10j<br>O: |
| 5 | | Correlation Coefficient (CC) | | T: 10k<br>O: |
| 6 | | Differential Phase (PHI) | | T: 10l<br>O: |
| 7 | | | Sample variance for Z | T:<br>O:SME Statements 1-2 |
| 8 | | | Sample variance for V | T:<br>O: SME Statements 1-2 |
| 9 | | | Sample variance for SW | T:<br>O: SME Statements 1-2 |
| 10 | | | Sample variance for ZDR | T:<br>O: SME Statements 1-2 |
| 11 | | | Sample variance for CC | T:<br>O: SME Statements 1-2 |

| Req Num | Category (and Section Number) | Threshold (T) Requirement | Optimal (O) Requirement for 2030 | Validation Reference # |
|---|---|---|---|---|
| 12 | | | Sample variance for PHI | T:<br>O: SME Statements1-2 |
| 13 | Wavelength (Section 5.4.2) | 10 cm (S-Band) | | T: 10f, 10v, 10z<br>O: |
| 14 | Beamwidth (Section 5.4.3) | 1.0 deg beamwidth in azimuth and elevation | | T: 10o, 10t, 25<br>O: |
| 15 | Pulse Length (Section 5.4.4) | 1.57 µs (Short Pulse) | | T: 10e, 10aa<br>O: |
| 16 | | 4.71 µs (Long Pulse) | | T: 10d, 10aa<br>O: |
| 17 | PRF (Section 5.4.5) | Support maximum unambiguous velocity of ± 32 m/s* | Support maximum unambiguous velocity of ± 50 m/s | T: 10a, 10e<br>O: SME Statement 3 |
| 18 | | Support a maximum unambiguous range of 460 km | | T: 10h<br>O: |
| 19 | | Support a range of PRFs between 318 Hz and 1310 Hz* | | T: 10b, 10w<br>O: |
| 20 | Minimum Detectable Signal (Section 5.4.6) | 0.0 dB SNR for a -9.5 dBZe target at 50 km in short pulse* | | T: 10s, 23, 24<br>O: |
| 21 | | 0.0 dB SNR for a -18.5 dBZe target at 50 km in long pulse* | | T: 10s, 16, 17<br>O: |
| 22 | Dynamic Range (Section 5.4.7) | 93 dB | 97 dB | T: 10s<br>O: SME Statement 4 |
| 23 | System Bias (in the absence of clutter filtering) (Section 5.4.8) | Reflectivity: 1 dBZ for target with true spectrum width of 4 m/s and SNR > 10 dB | | T: 7, 27<br>O: |
| 24 | | Velocity: 0.0 m/s for target with true spectrum width of 4 m/s and SNR > 8 dB | | T: SME Statement 5<br>O: |
| 25 | | Spectrum Width: 0.2 m/s dBZ for target with true spectrum width of 4 m/s and SNR > 10 dB | | T: 18, 29<br>O: |
| 26 | | Differential Reflectivity: 0.1 dB for target with true differential reflectivity (ZDR) of less than ± 1 dB, true spectrum width of 2 m/s, Correlation Coefficient ≥0.99, dwell time of 50 ms and SNR ≥ 20 dB (for ZDR with a magnitude greater than 1 dB, bias should be less than 10% of the ZDR magnitude ) | | T: 8a<br>O: |

| Req Num | Category (and Section Number) | Threshold (T) Requirement | Optimal (O) Requirement for 2030 | Validation Reference # |
|---|---|---|---|---|
| 27 | | Correlation Coefficient: 0.006 for target with true spectrum width of 2 m/s, correlation coefficient of ≥ 0.99, dwell time of 50 ms and SNR ≥ 20 dB | | T: 8d<br>O: |
| 28 | | Differential Phase: 1 deg for target with true spectrum width of 2 m/s, correlation coefficient of ≥ 0.99, dwell time of 50 ms and SNR ≥ 20 dB | | T: 8c<br>O: |
| 29 | Minimum Elevation Angle (Section 5.4.9) | -1.0 deg | | T: 10m, 10u, 20, 21, 22<br>O: |
| 30 | Maximum Elevation Angle (Section 5.4.10) | 60.0 deg | | T: 10m, 10u<br>O: |
| 31 | Beam Elevation and Azimuth Positioning Accuracy (Section 5.4.11) | 0.15 deg | 0.0055 deg | T: 10u<br>O: SME Statement 6 |
| 32 | Side Lobes: two-way side lobes (Section 5.4.12) | First side lobe: ≤ -70 dB relative to the peak of the main lobe* | | T: SME Statement 7<br>O: |
| 33 | | Side lobes beyond ± 2 deg from the beam center: ≤ -96 dB at ±6 deg relative to the peak of the main lobe, decreasing to -110 dB at ±20 deg relative to the peak of the main lobe* | | T: SME Statement 7<br>O: |
| | **RDA Signal Processing (Section 5.5)** | | | |
| 34 | Standard deviation of estimates of radar variables (Section 5.5.1) | Reflectivity: ≤ 1 dB for target with true SW of 4 m/s and SNR ≥ 10 dB | | T: 10q, 9<br>O: |
| 35 | | Velocity: ≤ 1 m/s for target with true SW of 4 m/s and SNR > 8 dB | | T: 10p, 9<br>O: |
| 36 | | Spectrum Width: ≤ 0.5 m/s for target with true SW of 2 m/s and SNR > 10 dB* | | T: 10p, 9<br>O: |
| 37 | | Differential Reflectivity: < 0.4 dB for target with true SW of 2 m/s, CC of ≥ 0.99, dwell time of 50 ms and SNR ≥ 20 dB* | | T: 10q, 8b<br>O: |

| Req Num | Category (and Section Number) | Threshold (T) Requirement | Optimal (O) Requirement for 2030 | Validation Reference # |
|---|---|---|---|---|
| 38 | | Correlation Coefficient: < 0.006 for target with true SW of 2 m/s, CC of ≥ 0.99, dwell time of 50 ms and SNR ≥ 20 dB | | T: 10r<br>O: |
| 39 | | Differential Phase: < 2.5 deg for target with true SW of 2 m/s, CC of ≥ 0.99, dwell time of 50 ms and SNR ≥ 20 dB | | T: 10r<br>O: |
| 40 | Quantization estimates of radar variables (Section 5.5.2) | Reflectivity: 0.5 dB* | | T: 10q<br>O: |
| 41 | | Velocity: 0.5 m/s | | T: 10p<br>O: |
| 42 | | Spectrum Width: 0.5 m/s | 0.1 m/s | T: 10p<br>O: SME Statement 8 |
| 43 | | Differential Reflectivity: 0.0625 dB* | | T: 10q<br>O: |
| 44 | | Correlation Coefficient: 0.00333* | | T: 10r<br>O: |
| 45 | | Differential Phase: 0.35 deg | | T: 10r<br>O: |
| 46 | Linear (radial) Range Resolution (Section 5.5.3) | 250 m (short pulse length) | | T: 10n, 26<br>O: |
| 47 | Effective Angular Resolution (Section 5.5.4) | 1.1 deg | | T: 10o<br>O: |
| 48 | Complex Waveforms (Section 5.5.5) | Multi-PRF* | | T: 11, 12<br>O: |
| 49 | | Systematic Phase coding* | | T: 11, 12<br>O: |
| 50 | | Staggered Pulse Repetition Time (PRT)* | | T: 11, 12, 13<br>O: |
| 51 | Clutter Detection and Filtering (Section 5.5.6) | Automated detection and removal of clutter at Clutter to precipitation Signal Ratios (CSRs) down to -13 dB | | T: SME Statement 9<br>O: |
| 52 | | Clutter filtering results in a reduction of CSRs to -13 dB or better | | T: SME Statement 9<br>O: |

| Req Num | Category (and Section Number) | Threshold (T) Requirement | Optimal (O) Requirement for 2030 | Validation Reference # |
|---|---|---|---|---|
| 53 | | Minimize the bias and standard deviation induced by the clutter filter process: 1 dB bias and standard deviation for reflectivity and 1 m/s bias and standard deviation in radial velocity and spectrum width estimates | | T: 10x<br>O: |
| 54 | Coverage (Section 5.5.7) | Maximum Range: 460 km for Z | | T: 10h<br>O: |
| 55 | | Maximum Range: 300 km for V and polarimetric variables | | T: 10bb, 10g, 10i, 10j, 10k, 10l<br>O: |
| 56 | | Maximum altitude: 70,000 ft | | T: 10m<br>O: |
| 57 | Scan Strategy Adaptability (Section 5.6) | Multiple clear air and precipitation mode VCPs with adaptable parameters including:<br>• Number of elevation slices and the elevation angle for each slice | One minute or less volume coverage time with no degradation of the sensitivity, spatial resolution or standard deviation of measurement for radar variable estimates | T: 15, 10m, 10y, 10c, 10a, 10b, 10d, 10e<br>O: 2, 3, 4, 5 |
| 58 | | • For each elevation slice<br>○ Transmit waveform<br>○ PRF<br>○ Antenna scan speed<br>○ Pulse length<br>○ Number of pulses to process for each sample bin<br>○ Edge angles of PRF sectors<br>○ SNR thresholds for each of the 6 radar variables estimated<br>○ Azimuth angular resolution<br>○ Velocity quantization (0.5 m/s and 1 m/s) | | T: 15a, 15b, 10f, 10cc |
| 59 | | Support for PRFs between 318 Hz and 1310 Hz* | | T: 10b, 10w |
| 60 | | Manual and automatic selection of different PRFs for three azimuth sectors for each of two sets of elevation slices | | T: 10dd |
| 61 | | Ability to repeat the lowest angle mid-way through a volume scan and/or to eliminate high elevation scans when insufficient weather echo exists* | | T: 10y |

## Validation Reference Number List

The numbers in the rightmost column of the above table link to the numbered documents in the following validation reference list.


1. Maybeck, P. S., 1979: Stochastic Models, Estimation and Control. Volume 1. Academic Press, 423 pp. (Section 1.5) – Referenced in SME statement 1
2. Yussouf, N., and D. J. Stensrud, 2010: Impact of phased-array radar observations over a short assimilation period: Observing system simulation experiments using an ensemble Kalman filter. Mon. Wea. Rev., 138, 517-538.
3. Xue, M., M. Tong, and K. K. Droegemeier, 2006: An OSSE framework based on the ensemble square root Kalman filter for evaluating the impact of data from radar networks on thunderstorm analysis and forecasting. J. Atmos. Oceanic Technol., 23, 46–66. [Section 3a]
4. Lei, T., M. Xue, T. Y. Yu, and M. Teshiba, 2007: Study on the optimal scanning strategies of phase-array radar through ensemble Kalman filter assimilation of simulated data. Preprints, 33rd Int. Conf. on Radar Meteorology, Cairns, Australia, Amer. Meteor. Soc., P7.1. [Available online at http://ams.confex.com/ ams/pdfpapers/124022.pdf.]
5. Heinselman, P. L., D. S. LaDue, H. Lazrus, 2012: Exploring Impacts of Rapid-Scan Radar Data on NWS Warning Decisions. Weather and Forecasting, 27, 1031–1044, doi:http://dx.doi.org/10.1175/WAF-D-11-00145.1
6. Xu, Q. , K. Nai, L. Wei, P. Zhang, S. Liu, D. Parrish, 2011: A VAD-based dealiasing method for radar velocity data quality control. Journal of Atmospheric and Oceanic Technology, 28, 50–62. – Referenced in SME statement 3
7. Hudlow, M.D., R. K. Farnsworth and P. R. Ahnert, 1984: NEXRAD Technical Requirements for Precipitation Estimation and Accompanying Economic Benefits, Hudlow et al, NWS Office of Hydrology, December 1984, Section: 2.2.1.4, Note 4 – NWS Office of Hydrology
8. V.M. Melnikov and D. Zrnic, 2004: "Simultaneous Transmission Mode for the Polarimetric WSR-88D, Statistical Biases and Standard Deviations of Polarimetric Variables" by Valery M. Melnikov (with contributions by Dusan Zrnic), Cooperative Institute for Mesoscale Meteorological Studies, University of Oklahoma, June 2004,
    a. Section: 2.1
    b. Section: 2.2 [Note: the value, correctly interpreted from Fig. 2.6, should be 0.4 dB]
    c. Section: 3.1 [Introduction states a desired bias of 1 degree, however, Section 3.1 shows that the phase estimate is unbiased. 1 degree is a good choice because a value of 0 would be difficult to verify.]
    d. Section: 4.1
9. Laird, B. G. and J. E. Evans, 1982: FAA Weather Surveillance Requirements in the Context on NEXRAD, Project Report ATC-112. MIT Lincoln Laboratory, Table 2.4
10. WSR-88D Radar Operations Center, 2010: WSR-88D SYSTEM SPECIFICATION (Document Number 2810000)
    a. Section: 3.7.1.1.2 Velocity Dealiasing
    b. Section: 3.7.1.2 Pulse Repetition Frequency Selection
    c. Section: 3.7.1.6.4.17 Volume Coverage Pattern Control
    d. Section: 3.7.2.1.3 Long Pulse
    e. Section: 3.7.2.1.4 Short Pulse
    f. Section: 3.7.2.2 Performance Characteristics
    g. Section: 3.7.2.2.1 Coverage

h. Section: 3.7.2.2.1.1.1 Base Reflectivity
i. Section: 3.7.2.2.1.1.2 Base Velocity and Spectrum Width
j. Section: 3.7.2.2.1.1.3 Differential Reflectivity
k. Section: 3.7.2.2.1.1.4 Correlation Coefficient
l. Section: 3.7.2.2.1.1.5 Differential Phase
m. Section: 3.7.2.2.1.2 Volume Coverage
n. Section: 3.7.2.2.2.2 Range Sample Interval
o. Section: 3.7.2.2.2.3 Effective Beam Width
p. Section: 3.7.2.2.3.1 Mean Radial Velocity and Spectrum Width
q. Section: 3.7.2.2.3.2 Reflectivity (Z), Differential Reflectivity
r. Section: 3.7.2.2.3.3 Correlation Coefficient, Differential Phase
s. Section: 3.7.2.2.4 Minimum Detection Capability and Dynamic Range
t. Section: 3.7.2.3.2 Antenna Performance
u. Section: 3.7.2.3.5.1 Pedestal Requirements
v. Section: 3.7.2.4 Transmitter
w. Section: 3.7.2.4.4 Pulse Repetition Frequency
x. Section: 3.7.2.7.2 Clutter-related Estimate Errors
y. Section: 3.7.3.4.15 Volume Coverage Pattern (VCP) Control
z. Section: 3.7.5.3.3 Electromagnetic Environment
aa. APPENDIX I - OPERATIONAL MODES AND SCANNING STRATEGIES
bb. Section: 3.7.1.1.1. Range Unfolding
cc. Table 3-14 (page 3-58)

11. Appendix E-1, 3rd paragraphNEXRAD Technical Advisory Committee, 2002: NEXRAD Technical Advisory Committee Report on meeting December 2001
12. Evans, J., 2001: Report on Workshop on Range-Velocity (R-V) Dealiasing. Report to NEXRAD TAC, December 4, 2001
13. Sirmans, D., D. Burgess and D. Zrnic, 1983: Considerations for Doppler Conversions of NWS Radars. National Severe Storms Laboratory
14. K. Friedrich, U. Germann and P. Tabary, 2009: Influence of Ground Clutter Contamination on Polarimetric Radar Parameters. J. Atmos. Oceanic Technol., 26, 251 – 269 [Recommendation for -13 dB CSR] – Referenced in SME statement 9
15. Radar Operations Center, 2013: INTERFACE CONTROL DOCUMENT FOR THE RDA/RPG (Document Number 2620002N), Table: Table XI Volume Coverage Pattern Data (Message Types 5 & 7)
    a. Fig C,-1 thru C-8
    b. Table Xi (page 3-47)
16. Office of the Federal Coordinator for Meteorology, 2005: FMH-11 Part B, Doppler Radar Theory and Meteorology, Figure 2.1
17. Ice, R. L. and D. Warde, 2010: Sensitivity Analysis Comparing the WSR-88D Baseline and L3 Baron Dual Polarization Modification. WSR-88D Radar Operations Center, Engineering Branch [concluded the loss of sensitivity due to the modification would be no worse than 4.0 dB. The observed performance of the polarimetric WSR-88D reported in April 2013 is consistent with this finding.]
18. Zrnic, D. S., V. M. Melnikov and R. J. Doviak, 2013: Issues and challenges for polarimetric measurement of weather with agile beam phased array radar", NOAA/NSSL Report, May 2, 2013 [shows the need for greater values than what is shown within the system spec document]
19. Baron Services Inc., 2009: Report, Antenna Component Test BS-2000-200-600 [result of testing for dual polarization contract] – Referenced in SME statement 7.

20. Brown, A. R., V. T. Wood, and T. W. Barker, 2002: Improved Detection Using Negative Elevation Angles for Mountaintop WSR-88Ds: Simulation of KMSX near Missoula, Montana. *Weather and Forecasting,* 17, 223-237 [page 232, references -0.8 deg elev angle]
21. Brown, A. R., T. A. Niziol, N. R. Donaldson, P. I. Joe, and V. T. Wood, 2007: Improved Detection Using Negative Elevation Angles for Mountaintop WSR-88Ds. Part III: Simulations of Shallow Convective Activity over and around Lake Ontario. *Weather and Forecasting,* 22, 839-852 [page 851, references -0.4 deg elev angle]
22. Wood, V. T., R. A. Brown, and S. V. Vasiloff, 2003: Improved Detection Using Negative Elevation Angles for Mountaintop WSR-88Ds. Part II: Simulations of the Three Radars Covering Utah. W*eather and Forecasting,* 18, 393-403 [page 393, references -0.8 deg elev angle]
23. Carley, J. R., 2012: Hybrid ensemble-3DVar radar data assimilation for the short-term prediction of convective storms. Ph.D. dissertation, Purdue University, 206 pp. [Section 2.5.2] – Referenced in SME statement 3.
24. Zhang, F., C. Snyder, and J. Sun, 2004: Impacts of initial estimate and observation availability on convective-scale data assimilation with an ensemble Kalman filter. *Mon. Wea. Rev.*, **132**, 1238–1253. [Section 5] – Referenced in SME statement 3
25. Wood, V. T., R. A. Brown, and D. Sirmans, 2001: Technique for improving detection of WSR-88D mesocyclone signatures by increasing angular sampling. Wea. Forecasting, 16, 177-184.
26. Wood, V. T., R. A. Brown, and D. C. Dowell, 2009: Simulated WSR-88D velocity and reflectivity signatures of numerically modeled tornadoes. J. Atmos. Oceanic Technol., 26, 876-893.
27. Dowell, D. C., L. J. Wicker, and C. Snyder, 2011: Ensemble Kalman filter assimilation of radar observations of the 8 May 2003 Oklahoma City supercell: Influences of reflectivity observations on storm-scale analyses. Mon. Wea. Rev., 139, 272-294. [Sections 4a, 4b, 4d and 5] – Referenced in SME Statement
28. Dowell, D. C., F. Zhang, L. J. Wicker, C. Snyder, and N. A. Crook, 2004: Wind and temperature retrievals in the 17 May 1981 Arcadia, Oklahoma, Supercell: Ensemble Kalman filter experiments. Mon. Wea. Rev., 132, 1982-2005. [Section 3b] – Referenced in SME Statement 1
29. FAA case file TO-T-NXRAD-014 dated 09/04/2007. This case file formed the basis of the requirement to implement the Hybrid Spectrum Width Estimator.
30. Doviak, R.J., and D. S. Zrnic, 2006: Doppler Radar and Weather Observations. Second Edition, Dover Publications, 562 pp. – Referenced in SME statement 2.
31. Sirmans, D. and B. Bumgarner, 1975: Numerical Performance of Five Mean Frequency Estimators, Journal of Applied Meteorology, 14, September 1975, 991-1003. – Referenced in SME statement 5.
32. Doviak, R. J., and D. S. Zrnic, 1993: Doppler Radar and Weather Observations, 2nd Ed., Academic Press, Section 6.4. – Referenced in SME statement 5.
33. M. Dixon email "S-Pol vs. WSR-88D antenna pedestal performance", August 20, 2013. – Referenced in SME statement 6.
34. Doviak, R. J., D. S. Zrnic, J. Carter, A. Ryzhkov, S. Torres, and A. Zahrai, 1998: Polarimetric Upgrades to Improve Rainfall Measurements, April 1998 with Errata and Supplements – Referenced in SME statement 7.
35. Williams, J. K., L. B. Cornman, J. Yee, S. G. Carson, G. Blackburn and J. Craig, 2006: "NEXRAD detection of hazardous turbulence," 44th AIAA aerospace sciences meeting and exhibit, 44, paper AIAA 2006-2076. – Referenced in SME statement 8.
36. Hubbert, J. C., M. Dixon, S. M. Ellis and G. Meymaris, 2009: Weather and Ground Clutter, Part 2: Real-time identification and filtering, J. Atmos. Oceanic Technol., 26, 1181-1197. – Referenced in SME statement 9.

37. Meischner, P. (Ed.), “Weather Radar, Principles and Advanced Applications.” Springer, 2004. Referenced in SME statement 9.

**Appendix D: Subject Matter Expert Validation Statements**
SME Letter #1 - for Requirements 7 – 12, inclusive, Optimal for 2030

**Earth System Research Laboratory**
SCIENCE, SERVICE & STEWARDSHIP

MEMORANDUM FOR: The Record

FROM: Dr. David C. Dowell David C. Dowell
Meteorologist
NOAA/OAR/Earth System Research Laboratory
325 Broadway, Boulder, CO 80305-3328

SUBJECT: Requirement for Sample Variances from Radar Observations

This memorandum provides additional information to clarify the "optimal for 2030" requirement to provide sample variance estimates for all dual-polarization radar observations. This requirement is stated in the 2014 NOAA/National Weather Service Radar Functional Requirements document. As outlined in Section 5.4.1 the optimal for 2030 requirement is to have sample variance estimates for radar reflectivity, radial velocity, differential reflectivity, correlation coefficient and differential phase within each sample bin:

> Radar and other observation data are best assimilated for input to numerical models when a measure of the data's quality is available. Extensive assimilation of radar data for input to storm scale numerical models is critical to achieving the capability for forecasting the development and evolution of tornadic storms, and thus extending tornado warning lead times significantly.
>
> **Optimal for 2030: Within each sample bin**
> - **Sample variance for reflectivity**
> - **Sample variance for radial velocity**
> - **Sample variance for differential reflectivity**
> - **Sample variance for correlation coefficient**
> - **Sample variance for differential phase**

Assimilation of radar observations is essential for initializing very-high-resolution numerical weather prediction models, such as those envisioned for Warn-on-Forecast. Having sample variances available for these radar observations could significantly improve the quality of the radar-data assimilation in at least two ways.

First, sample variances could improve radar-data quality control, that is, deciding which observations are accurate enough for assimilation and which ones are potentially spurious and are better discarded. A very high sample variance could indicate a potentially spurious observation.

Second, sample variances could be related to the estimated errors of the assimilated observations. As shown by optimal control theory, one should weight observations based upon their estimated error variance (Eqn. **1-3** in Maybeck 1979). Numerical model analyses produced through radar-data assimilation are indeed sensitive to the assumed observation errors (Section 3b in Dowell et al. 2004), but estimating these errors is currently very difficult. Estimating the observation errors could be more straightforward if sample variances were available.

Maybeck, P. S., 1979: Stochastic Models, Estimation and Control. Volume 1. Academic Press, 423 pp.

Dowell, D. C., and Co-Authors, 2004: Wind and temperature retrievals in the 17 May 1981 Arcadia, Oklahoma, Supercell: Ensemble Kalman filter experiments. Mon. Wea. Rev., 132, 1982-2005.

SME Letter #2 - for Requirements 7 – 12, inclusive, Optimal for 2030 (Supplemental Letter)

UNITED STATES DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
OFFICE OF OCEANIC AND ATMOSPHERIC RESEARCH
National Severe Storms Laboratory
120 David L. Boren Blvd.
Norman, OK 73072

MEMORANDUM FOR: The Record

FROM: Dr. Qin Xu Qin Xu 3/6/2014
Research Meteorologist
OAR/National Severe Storms Laboratory

SUBJECT: Requirement for Sample Variances from Radar Observations

The purpose of this memorandum is to provide additional information to clarify the "optimal for 2030" requirement to provide sample variance estimates for all dual-polarization radar observations. This requirement is stated in the 2014 NOAA/National Weather Service Radar Functional Requirements document. As outlined in Section 5.4.1 the optimal for 2030 requirement is to have sample variance estimates for radar reflectivity, radial velocity, differential reflectivity, correlation coefficient and differential phase within each sample bin:

> Radar and other observation data are best assimilated for input to numerical models when a measure of the data's quality is available. Extensive assimilation of radar data for input to storm scale numerical models is critical to achieving the capability for forecasting the development and evolution of tornadic storms, and thus extending tornado warning lead times significantly.

Sample variance estimates the second moment of the probability distribution of the sampled variable, and it measures how far a set of sampled numbers is spread out with respect to the sample mean, while the sample mean estimates the first moment – the statistic mean of the variable. A large (or small) variance indicates that the sampled values are spread far (or not far) away from the mean.

Reliable sample variance estimates should provide useful information for radar data quality control and radar data assimilation for very high-resolution numerical weather prediction models, such as those envisioned for Warn-on-Forecast, with horizontal grid spacing approaching the radar range gate spacing (250 m). Sample variances can be calculated for each radar variable at each sample bin from 88D level-II data (see section 6.4 of Doviak and Zrnic 2006), but the calculated variances may not be reliable due to the relatively poor data quality in spectrum width – a key variable for variance calculations, and the assumptions used in the formulations that the calculations are based on. Thus, the required inclusion of sample variance estimates cannot be justified if sample variances are calculated using the existing formulations, but the required inclusion can be justified if sample variances can be more reliably estimated from 88D level-I data with improved formulations discovered in future research and these better estimated sample variances can indeed be used, not only effectively but also more effectively than those calculated using the existing formulations, to improve radar data quality control and/or radar data assimilation.

Doviak, R. J., and D. S. Zrnic, 2006: *Doppler Radar and Weather Observations.* Second Edition. Dover Publications, 562 pp.

SME Letter #3 - for Requirement 17, Optimal for 2030

National Oceanic and Atmospheric Administration
NOAA Center for Weather and Climate Prediction
National Centers for Environmental Prediction
Environmental Modeling Center
5830 University Research Court
College Park, MD 20740

March 06, 2014

MEMORANDUM FOR: The Record

FROM: Dr. Jacob R. Carley

Support Scientist
I.M. Systems Group
NOAA/NCEP/Environmental Modeling Center (EMC)

SUBJECT: Optimal 2030 requirement for a pulse repetition frequency to support an increase in unambiguous velocity

PURPOSE

The purpose of this memorandum is to provide additional information to clarify the optimal 2030 requirement of a pulse repetition frequency to support an unambiguous velocity of ± 50 m/s at radar scan elevation angles ≤ 5°.

SUMMARY

To meet the goals of warn-on-forecast and produce accurate short-term forecasts of hazardous convective storms it is necessary to assimilate Doppler radial velocities into numerical weather prediction models. Oftentimes WSR-88D radial velocity observations of storms that exhibit pronounced rotation and/or shear feature strong aliasing, e.g. observations from supercells. These aliased observations are generally rejected by conventional, operational radial velocity quality control algorithms (e.g. Xu et al. 2011). Furthermore, previous storm-scale data assimilation work using data with unambiguous velocities of ~± 30 m/s has shown that aliased radial velocities in mesocyclonic storm regions are often rejected by operational quality control steps, resulting in a large decrease in wind observations where they may be most important for data assimilation (e.g. Carley 2012). An increase in the unambiguous velocity to ± 50 m/s would beneficially reduce the occurrence of aliasing, thus leading to the retention of more data to be used for data assimilation. It is desired that this increase in unambiguous velocity be made standard at radar scan elevation angles ≤ 5°, as previous research has shown that low-level sampling of radial winds is important for accurate storm-scale analyses (e.g. Zhang et al. 2004).

REFERENCES

Carley, J. R., 2012: Hybrid ensemble-3DVar radar data assimilation for the short-term prediction of convective storms. Ph.D. dissertation, Purdue University, 206 pp. [Section 2.5.2]

Xu, Q., K. Nai, L. Wei, P. Zhang, S. Liu, and D. Parrish, 2011: A VAD-based dealiasing method for radar velocity data quality control. J. Atmos. Oceanic Technol., 28, 50–62.

Zhang, F., C. Snyder, and J. Sun, 2004: Impacts of initial estimate and observation availability on convective-scale data assimilation with an ensemble Kalman filter. Mon. Wea. Rev., 132, 1238–1253. [Section 5]

SME Letter #4 - for Requirement 22, Optimal for 2030

**U.S. DEPARTMENT OF COMMERCE**
**National Oceanic and Atmospheric Administration**
NATIONAL WEATHER SERVICE

*Radar Operations Center*
*1313 Halley Circle*
*Norman, OK 73069*

*(405) 573-3382*
*Richard.L.Ice@noaa.gov*

March 17, 2014

MEMORANDUM FOR: The Record

FROM: Richard L. Ice
GS855-13, Electronics Engineer

SUBJECT: Requirement for Receiver Dynamic Range

This memorandum provides additional information to clarify the "optimal for 2030" requirement for a receiver dynamic range of 97 dB. This requirement is stated in the 2014 NOAA/National Weather Service Radar Functional Requirements Document, Section 5.4.7 Dynamic Range.

The current requirement in the WSR-88D System Specification is 93 dB. This requirement is met in the existing baseline using the Vaisala/Sigmet RVP8 IF Digital Receiver and signal processor. The primary factor in determining a digital receiver's dynamic range is the number of bits in the Analog to Digital Converter (A/D). The digital receiver function in the RVP8 employs a 14 bit A/D along with signal processing linearization algorithm to meet the 93 dB requirement. The use of linearization processing is necessary, but not optimal.

Current A/D technology operating at the requisite 100 MHz rate is based on a minimum of 16 bits. This is likely to be the minimum available capability in the near term replacement for the RVP8, and by 2030, A/D converter technology will likely exceed this benchmark.

By the commonly accepted rule for estimating dynamic range of an A/D converter, a 16 bit design will be capable of delivering a dynamic range of greater than 97 dB, without relying on software linearization. Because of the wide span of weather and clutter signals possible within a modern meteorological radar, the largest possible dynamic range is desirable.

The value of 97 dB for dynamic range is recommended as it is both feasible, cost effective, and operationally useful.

SME Letter #5 - for Requirement 24, Threshold (page 1 of 2)

**U.S. DEPARTMENT OF COMMERCE**
**National Oceanic and Atmospheric Administration**
NATIONAL WEATHER SERVICE

*Radar Operations Center*
*1313 Halley Circle*
*Norman, OK 73069*

*(405) 573-3382*
*Richard.L.Ice@noaa.gov*

April 9, 2014

MEMORANDUM FOR: The Record

FROM: Richard L. Ice
GS855-13, Electronics Engineer

SUBJECT: Requirement for Velocity Estimate Bias

This memorandum provides additional information to clarify the thresold requirement for velocity estimate bias of 0 m/s. This requirement is stated in the 2014 NOAA/National Weather Service Radar Functional Requirements Document, Section 5.4.8 System Bias.

The expectation that velocity estimation in modern meteorological radars can be unbiased is supported by long standing research and analysis. While direct analysis of the signal spectrum via Fourier Transform methods can yield unbiased estimates for general cases, other methods are unbiased for practical conditions. Sirmans and Bumgarner (1975) provided a complete analysis of the theoretical performance of five power weighted mean frequency estimators, and found that the covariance argument, or Pulse Pair Processing (PPP), method yielded unbiased estimates for expected operational conditions. This is the method currently employed in the WSR-88D. Doviak and Zrnic (1993) summarize the performance of this estimator as well.

For the benchmark conditions normally associated with these requirements, (i.e. symmetrical spectrum and low spectrum widths), the covariance argument estimator is unbiased. The issue with a requirement for zero value for velocity estimate bias regards verification. Obtaining experimental proof that a value is exactly zero is problematic. Therefore the requirements validation tests should consider practical considerations such as estimate precision and variance.

References

Sirmans, D. and B. Bumgarner, 1975, Numerical Performance of Five Mean Frequency Estimators, Journal of Applied Meteorology, 14, September 1975, 991 – 1003.

SME Letter #5 - for Requirement 24, Threshold (page 2 of 2)

Doviak, R. J. and D. S. Zrnic, 1993, Doppler Radar and Weather Observations, 2nd Ed., Academic Press, Section 6.4.

SME Letter #6 - for Requirement 31, Optimal for 2030

*Radar Operations Center*
*1313 Halley Circle*
*Norman, OK 73069*

*(405) 573-3382*
*Richard.L.Ice@noaa.gov*

April 7, 2014

MEMORANDUM FOR: The Record

FROM: Richard L. Ice
GS855-13, Electronics Engineer

SUBJECT: Requirement Beam Positioning Accuracy

This memorandum provides additional information to clarify the "optimal for 2030" requirement for beam positioning accuracy of 0.0055 degrees. This requirement is stated in the 2014 NOAA/National Weather Service Radar Functional Requirements Document, Section 5.4.11 Beam elevation and azimuth positioning accuracy.

The baseline WSR-88D requirement of 0.15 degrees has been shown to be inadequate for supporting critical polarimetric calibrations. The use of external targets such as the sun and ground clutter cannot yield acceptable results for differential reflectivity calibration with the baseline antenna pedestal performance. Solar scans are used to determine the antenna portion of the system bias and these require precise antenna positioning. Other calibrations require collection of ground clutter from resolution volumes that can be obtained on multiple scans with great precision as well.

Experience with research radars shows that a precision of 0.0055 degrees can support these requirements (M. Dixon, 2013). This forms the basis for the 2030 requirement.

Reference

M. Dixon email "S-Pol vs. WSR-88D antenna pedestal performance", August 20, 2013.

SME Letter #7 - for Requirements 32-33, Threshold

*Radar Operations Center*
*1313 Halley Circle*
*Norman, OK 73069*

*(405) 573-3382*
*Richard.L.Ice@noaa.gov*

April 7, 2014

MEMORANDUM FOR: The Record

FROM: Richard L. Ice
GS855-13, Electronics Engineer

SUBJECT: Requirements for Antenna Side lobes

This memorandum provides additional information to clarify the threshold capability requirements for the WSR-88D antenna side lobes which need to be maintained in any future radar. This requirement is stated in the 2014 NOAA/National Weather Service Radar Functional Requirements Document, Section 5.4.12 Side lobes.

The first effective sidelobe level should be less than -70 dB, two way. The term "effective" considers combined performance of a future radar, including the antenna hardware, effects of array control, and the applied signal processing, such as digital beam forming.

The remaining (effective two way) sidelobes need to be below the line connecting -70 dB at +/- 2 degrees from beam center down to -100 dB at +/- 10 degrees from beam center. Sidelobes should decrease linearly from -100 dB at +/- 10 degrees to -110 dB at +/- 20 degrees. Beyond that point all sidelobes need to be below -110 dB.

This is the current assessed performance of the WSR-88D parabolic reflector antenna. This conclusion is supported by reports documenting polarimetric WSR-88D antenna testing (Doviak, 1998 and 2013, Baron Services, 2009).

References

Doviak, R. J., D. S. Zrnic, J. Carter, A. Ryzhkov, S. Torres, and A. Zahrai, 1998, Polarimetric Upgrades to Improve Rainfall Measurements, April 1998 with Errata and Supplements.

Baron Services, Inc., 2009, Report: Antenna Component Test, Reference Specification: BS-2000-200-600.

SME Letter #8 - for Requirement 42, Optimal for 2030 (page 1 of 2)

COOPERATIVE INSTITUTE FOR
MESOSCALE METEOROLOGICAL STUDIES

THE UNIVERSITY OF OKLAHOMA
120 DAVID L. BOREN BLVD., SUITE 2100
NORMAN, OK 73072-7304
(405) 325-3041
FAX (405) 325-3098

UNIVERSITY OF OKLAHOMA — NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

April 15, 2014

MEMORANDUM FOR: The Record

FROM: Dr. Sebastián M. Torres
CIMMS, Senior Research Scientist
sebastian.torres@noaa.gov

SUBJECT: Optimal requirement for quantization of spectrum-width data

This memorandum provides additional information to justify the optimal requirement for the quantization of spectrum-width data that must be met by any future radar. This requirement is stated in the 2014 NOAA/National Weather Service Radar Functional Requirements Document, Section 5.5.2, Quantization of Estimates of Radar Variables. The optimal spectrum-width data quantization requirement is established at 0.1 m $s^{-1}$, which is five times smaller than the threshold requirement and current WSR-88D capability of 0.5 m $s^{-1}$.

Theoretically, signals with larger spectrum widths occupy wider frequency bands. An extreme example is white noise, which spans *all* frequencies with constant power spectral density. In practice, the output of the radar receiver is a finite-bandwidth discrete-time (sampled) signal, and a signal that spans the entire Nyquist co-interval with equal-power spectral components has the largest *measurable* spectrum width. The spectrum width of such signal can be derived as the maximum unambiguous velocity divided by the square root of three. In fact, the current spectrum-width estimator in the WSR-88D imposes this maximum value as an upper bound on estimates. Thus, with the pulse-repetition-frequency threshold requirements in Section 5.4.5, the largest spectrum width that the radar can measure is 32 m $s^{-1}/\sqrt{3} \sim 18.5$ m $s^{-1}$. Hence, a quantization of 0.5 m $s^{-1}$ allows for only 38 distinct spectrum-width values to be represented (i.e., 0.0, 0.5, 1.0, …, and 18.5 m $s^{-1}$).

A better representation of the spectrum-width information using a quantization of 0.1 m $s^{-1}$ would result in more precise data (i.e., smaller quantization errors) at the Radar Product Generator (RPG), which would potentially translate into performance improvements for all downstream algorithms that rely on spectrum-width data. For example, the NEXRAD Turbulence Detection Algorithm (NTDA, Williams et al. 2006) uses spectrum-width data to provide direct detection of turbulence. Thus, more precise spectrum-width data would naturally lead to improved discrimination of turbulence intensity and more reliable indication of in–cloud aviation hazards.

SME Letter #8 - for Requirement 42, Optimal for 2030 (page 2 of 2)

As side note, it should be mentioned that the proposed change in quantization does not increase the transmission bandwidth required to disseminate the base data. That is, the current spectrum-width quantization scheme in the WSR-88D leads to an 8-bit representation with values in the range from -63.5 to 63 m $s^{-1}$. However, negative spectrum widths are not meaningful and, as argued above, values in excess of 18.5 m $s^{-1}$ are not possible. Conversely, spectrum widths in the meaningful range from 0 to 25.3 m $s^{-1}$ could still be represented with an 8-bit word if using a quantization of 0.1 m $s^{-1}$. Thus, the optimum requirement for spectrum-width data quantization will provide improved representation of spectrum-width information without requiring more bandwidth for its dissemination.

Reference

Williams, J. K., L. B. Cornman, J. Yee, S. G. Carson, G. Blackburn and J. Craig, "NEXRAD detection of hazardous turbulence," 44th AIAA aerospace sciences meeting and exhibit, 44, paper AIAA 2006-0076 (2006).

SME Letter #9 - for Requirements 51-52, Threshold (page 1 of 2)

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
NATIONAL WEATHER SERVICE

*Radar Operations Center*
*1313 Halley Circle*
*Norman, OK 73069*

*(405) 573-3382*
*Richard.L.Ice@noaa.gov*

March 17, 2014

MEMORANDUM FOR: The Record

FROM: Richard L. Ice
GS855-13, Electronics Engineer

SUBJECT: Requirements for Clutter Identification and Filtering

This memorandum provides additional information to clarify the "optimal for 2030" requirement for automated clutter detection at clutter to signal ratios of -13 dB, and subsequent filtering sufficient to reduce clutter to signal ratios to -13 dB or better. This requirement is stated in the 2014 NOAA/National Weather Service Radar Functional Requirements Document, Section 5.5.6 Clutter detection and filtering.

Surprisingly, there has not been very much research into the effects of clutter contamination on polarimetric variable estimate quality. Nor have there been many investigations into the effects of clutter filtering on the polarimetric variables.

The most complete description of the effects of clutter on polarimetric variables can be found in the results of the Swiss and French meteorological service's investigations (Friedrich, 2009). Data from Friedrich indicates that the most sensitive parameter is the correlation coefficient. Based on their simulations, ground clutter contamination is not critical for the measurement precision when precipitation is greater than the clutter by 13 dB for differential reflectivity, 10 dB for differential phase, and 17 dB for the correlation coefficient. These results can vary widely depending on the type of clutter as seen in their Figure 13, which indicates the maximum and minimum values for the clutter to signal ratios that will yield acceptable quality, as measured against their "precision thresholds" of the polarimetric variable estimates. These thresholds were +/- 0.2 dB for differential reflectivity, 0.02 in correlation coefficient, and 3 degrees in differential phase. Given these benchmarks, Friedrich recommends that precipitation "intensity" needs to be 13.5 dB higher than that of the clutter for obtaining acceptable correlation coefficient estimates.

On the other hand, Illingworth reports that the differential phase estimates are "virtually useless" even though the clutter power is 20 dB lower than that of the precipitation (Meischner,2004).

SME Letter #9 - for Requirements 51-52, Threshold (page 2 of 2)

Given this wide range of recommendations, a truly conservative requirement for clutter detection and removal would be for a clutter to signal ratio of -20 dB. However, this is currently not achievable for detection.

Hubbert has extensively analyzed the performance of the Clutter Mitigation Decision (CMD) algorithm that is currently used in the WSR-88D for automatic clutter detection (Hubbert, 2009). He reports that the polarimetric version of CMD has a 50 % probability of detection at clutter to signal ratios of about -12 dB.

Given the limited research on clutter effects, the wide span of the recommendations, and the observed performance of current technology, it is necessary to pose a reasonable objective for the near future. I am thus recommending the requirement of -13 dB as a reasonable goal that is likely to be achievable by the 2030 time frame with expected improvements in signal processing methods and anticipated hardware performance improvements.

References

Friedrich, Katja, U. Germann and P. Tabary, 2009, Influence of Ground Clutter Contamination on Polarimetric Radar Parameters, *J. Atmos. Oceanic Technol.*, 26, February 2009, 251 – 269.

Hubbert, J. C., M. Dixon, S. M. Ellis and G. Meymaris, 2009, Weather radar ground clutter. Part 2: Real-time identification and filtering,. *J. Atmos. Oceanic Technol.*, **26**, 1181-1197.

Meischner, P. (Ed.), "Weather Radar, Principles and Advanced Applications." Springer, 2004

**Appendix E: Integrated Working Team and Subject Matter Expert Concurrence**

## Radar Functional Requirements Integrated Working Team Concurrence

The Radar Functional Requirements Integrated Working Team (IWT) membership concur that the requirements contained herein, comprise NOAA/NWS Radar Functional Requirements from the present day through 2030, given information known at the date of signing.

Signature — Date: 4/30/14
Mr. Donald W. Burgess, OAR/National Severe Storms Laboratory (Associate)

Signature — Date: 5/22/14
Mr. Joe N. Chrisman, NWS/OOS, Radar Operations Center

Signature — Date: 05/22/2014
Dr. Jeffrey G. Cunningham, NWS/OOS, Radar Operations Center (Associate)

Signature — Date: 5/28/2014
Mr. John T. Ferree, NWS/OCWWS, Public and Fire Weather Services Division

Signature — Date: 5/22/2014
Mr. Richard L. Ice, NWS/OOS, Radar Operations Center (Associate)

Signature — Date: 6/20/2014
Dr. Daniel Melendez-Alvira, NWS/OST, Program Plans Division

Signature | Date: 6/16/14

**Mr. Dennis A. Miller, NWS/OHD, Hydrologic Science and Modeling Branch**

Signature | Date: May 14, 2014

Mr. Robert E. Saffle, NWS/OCWWS (Contractor)

Signature | Date: 4/28/2014

**Dr. David J. Stensrud, OAR/National Severe Storms Laboratory**

Signature | Date: 5/30/14

Mr. Christopher C. Wamsley, NWS/OCWWS, Integrated Services Division

**Subject Matter Expert/Consultant Contributors**

The following subject matter experts provided information to both support the requirements formulation process, and over the horizon (~2030) requirements linked to strategic research and future modeling programs and concur that the requirements contained herein, comprise NOAA/NWS Radar Functional Requirements from the present day through 2030, given information known at the date of signing.

Signature | Date: 05/23/2014

Dr. Jacob Carley, NWS/NCEP, Environmental Modeling Center (Contractor)

Signature | Date: 7-24-2014

**Mr. Carlos Diaz, NWS/OCWWS, Requirements Division**

David Dowell — 6/10/2014

Signature — Date

Dr. David Dowell, OAR/ESRL/GSD, Assimilation and Modeling

Kurt Hondl — 7/24/2014

Signature — Date

Mr. Kurt Hondl, OAR/NSSL, MPAR Program Manager

5/20/2014

Signature — Date

Mr. Mark B. Miller, NWS/OST, NextGen Weather Program Manager

July 29, 2014

Signature — Date

Mr. Fred Toepfer, NWS/OST, Hurricane Forecast Improvement Program

5/16/14

Signature — Date

Dr. Sebastian Torres, OAR/NSSL, Senior Research Scientist (Associate