

# System Requirements for Phased Array Weather Radar

Dusan S. Zrníc and Richard J. Doviak  
National Severe Storms Laboratory, Norman OK

## Table of Contents

<b>Preamble</b> .....	1
<b>1. INTRODUCTION</b> .....	1
<b>2. WEATHER RADAR SPECIFICATIONS</b> .....	2
<b>2.1 Surveillance</b> .....	3
2.1.1 <i>Range</i> .....	3
2.1.2 <i>Time</i> .....	3
2.1.3 <i>Volumetric coverage</i> .....	4
<b>2.2 Signal to Noise Ratio (SNR)</b> .....	5
<b>2.3 Wavelength</b> .....	6
<b>2.4 Angular resolution</b> .....	6
<b>2.5 Range resolution</b> .....	7
<b>2.6 Accuracy of measurements</b> .....	7
<b>2.7 The WSR-88D specifications</b> .....	8
2.7.1 <i>Transmitted power</i> .....	8
2.7.2 <i>Transmitted pulse widths</i> .....	9
2.7.3 <i>Transmitter phase noise</i> .....	9
2.7.5 <i>Dynamic range</i> .....	10
2.7.7 <i>Ground clutter canceling</i> .....	11
2.7.9 <i>Estimation errors</i> .....	16
<b>3. REFLECTIVITY FACTOR FOR VARIOUS SCATTERING MEDIA</b> .....	16
<b>3.1 Non precipitating clouds</b> .....	16
<b>3.2 Precipitation</b> .....	17
<b>3.3 Cloudless skies</b> .....	18
<b>4. POLARIMETRIC REQUIREMENTS</b> .....	19
<b>4.1 Match of H and V patterns</b> .....	21
<b>5. REFERENCES</b> .....	22

# **System Requirements for Phased Array Weather Radar**

## **Preamble**

This is the final report to Lockheed Martin on the requirements for a phased array weather radar. Discussed herein are those meteorological requirements that need to be met by weather radars having either reflector type antennas or active phased array elements. These requirements impact the design of the antenna, the transmitter-receiver, and signal processor. Justifications for these meteorological requirements (presented in this report) are based, for the most part, upon meteorological considerations, but sometimes practical limitations of the radar dictate what can be done. Because microwaves penetrate cloud and rain, they are in an unchallenged position to remotely survey the atmosphere.

The Doppler radar is the only remote sensing instrument that can detect tracers of wind to reveal a storm's internal structure and the hazardous phenomena harbored therein. The recent inclusion of polarimetric capability to research Doppler weather radars has added a new dimension to radar observations by providing information that can be used to considerably improve the estimation of rainfall, as well as allow for the classification of precipitation type. Thus, included in this report is discussion on the requirements for polarimetric radar. The unique capabilities of the polarimetric Doppler radar make this the instrument of choice to survey weather.

## **1. INTRODUCTION**

Weather observations have been part of radar technology since its very beginning. Although military applications have driven this technology and are often credited with its inception, first radar-like instruments were made in the 1920s to remotely probe the ionosphere. Today a similar technology is used to produce vertical profiles of winds throughout the troposphere (to over 15 km above ground). These wind profiling radars operate in the UHF (e.g., 400 MHz) and VHF (e.g., 50 MHz) bands and serve mainly the research community. Nonetheless, specialized applications exist to monitor conditions at launch or landing of space vehicles, and there is even a small experimental network of profiling radars in the central USA.

Over the decades the weather radars have undergone considerable change, principally because of the advances in solid state technology that allows for real time quantitative analysis of the weather signal, the continuous stream of echoes from scatterers that can be distributed over hundreds of kilometers. These advances in solid state technology, however, have principally impacted the receiver, signal processing, and display components of the radar; the transmitter and antenna have essentially been unchanged, and the transmitted signals to this day are pulsed sinusoids of relatively short duration and high power. The advent of the phased array antenna, and the potential to distribute the transmitted power over an array of elements, as well as provide agility in positioning the beam, offers the potential of improving weather observations and the timeliness of warnings. Thus, this report presents those basic requirements that, for the most part, are met by the present day weather radars, and therefore must be met on modern phased array radars.

Of all weather radars, the most commonly used are airborne surveillance radars. Yet the general public is mainly aware of ground based surveillance radars whose images are displayed on television sets. The prime purpose of ground based radars is to estimate the amount of rain or snow reaching the ground. Equally important for the National Weather Service is to detect severe storms that harbor hazardous winds and damaging hail so that timely warnings can be issued. Three frequency bands are allocated to weather surveillance radars. These are the S (~ 10 cm wavelength), C (~ 5 cm wavelength) and X (~ 3 cm wavelength) bands. The shorter wavelength radars are less expensive and have smaller size but are significantly affected by attenuation, briefly discussed in Section 2.3 of this report. Hence the USA national network of Doppler weather radars (i.e., the WSR-88Ds) operates at about 10 cm wavelengths. Throughout this report, stated requirements are for 10 cm wavelength weather surveillance radars.

## 2. WEATHER RADAR SPECIFICATIONS

We start with the specifications given in Table 2.1 for observing weather with radar. These are obtained from Tables 3.1 and 6.1 in Doviak and Zrnich (1993) which are based upon years of experience with the USA 's national network of non-Doppler radars (i.e., the WSR-57), as well as the experience gained with Doppler radar observations by the research community. It is important to distinguish between the requirements that are based on proven meteorological grounds and those which are consider desirable, but are still in the process of exploratory development.

Table 2.1  
Requirements for weather radar observations

1.1. Surveillance	
1.1.1 Range:	460 km
1.1.2 Time:	< 5 minutes
1.1.3 Volumetric coverage:	hemispherical
1.2. SNR:	> 10 dB, for Z . 15 dBZ at r = 230 km
1.3. Angular resolution:	≤ 1°
1.4. Range sample interval $\Delta r$	
1.4.1 for reflectivity estimates:	$\Delta r < 1$ km; $0 < r < 230$ km $\Delta r < 2$ km; $r < 460$ km
1.4.2 for velocity and spectrum width estimates ( $r < 230$ km):	$\Delta r = 250$ m
1.5. Estimate accuracy:	
1.5.1 reflectivity:	≤ 1 dB
1.5.2 velocity:	≤ 1 m s <sup>-1</sup> ; SNR > 8 dB; $\sigma_v = 4$ m s <sup>-1</sup>
1.5.3 spectrum width:	≤ 1 m s <sup>-1</sup> ; SNR > 10 dB; $\sigma_v = 4$ m s <sup>-1</sup>

The specifications in Table 2.1 have, for the most part, been accepted by the meteorological community. The principal parameters are those that determine the weather radar's SNR required to estimate reflectivity, Doppler velocity, and spectrum width with specified accuracy for scatter from various classes of weather (principally precipitation), and the required spatial resolution. These fundamental requirements of SNR and spatial resolution are met by the WSR-88D radar and thus should serve as a baseline for the phased array radar.

## **2.1 Surveillance**

The surveillance range, time, and volumetric coverage are routed in practical considerations, previous experience with weather radar, and the sizes and lifetimes of some significant meteorological phenomena.

### *2.1.1 Range*

Surveillance range is limited to about 460 km because storms beyond this range are usually below the horizon. Without beam blockage, the horizon is at 12.5 km altitude at 460 km; thus only the tops of strong convective storms can be detected. Although these storms can be detected at ranges between 230 and 460 km, quantitative measurements of precipitation are only required for storms at ranges less than 230 km. Nevertheless, in the region beyond 230 km, storm cells can be identified and their tracks can be established. Even at the range of about 230 km, the lowest altitude that the radar can observe under normal propagation conditions is about 3 km. Extrapolation of rainfall measurements from this height to the ground is subject to large errors, especially if the beam is above the melting layer and is detecting scatter from snow or melting ice particles. In this regard satellite borne radars have an advantage because they can have nearly uniform vertical resolution over large areas. But satellite borne weather radars are, for now, limited to orbiting satellites, and thus they cannot continuously monitor weather phenomena.

### *2.1.2 Time*

Surveillance time is determined by the time of growth of hazardous phenomena as well as the need for timely warnings. Five minutes for a repeat time is sufficient for detecting and confirming features with lifetime of about 15 min or more. Typical mesocyclone life time is 90 minutes (Burgess, et al., 1982). Ordinary storms last tens of minutes but microbursts from these storms can produce dangerous shear in but a few minutes.

The principal driver to decrease the surveillance time is the prompt detection of the tornado and the need to have timely warnings of its presence. Presently, the lead time for tornado warnings (i.e., the time that a warning is issued to the time the tornado does damage) is about 12 minutes. Tornadoes can rapidly develop from mesocyclones and it takes about six minutes for the reflector antenna to return to the position of the first radar sighting of the tornado. Because two consecutive radar observations of tornado vortex signatures (TVS) are required before a tornado is confirmed to be observed, a beam agile phased array has a definitive advantage; it can return to location of the first detection of a TVS within the minute. Thus about 5 minutes can be added to the lead time of tornado warnings.

For over ten years meteorologists have been developing schemes to retrieve winds transverse to the radar beam. Recent results at the University of Oklahoma (Fig. 1) indicate that a rapid increase of errors ensues if the update time increases beyond 1 min. Figure 1 suggests that further improvement is possible for even shorter update times.

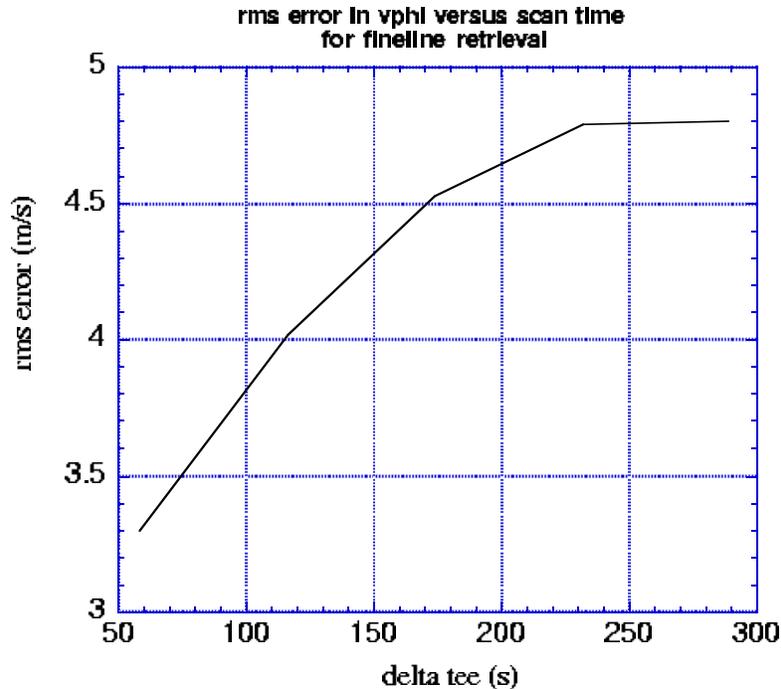


Figure 1. Root mean square error of transverse wind as a function of time between scans. Figure was provided by Alan Shapiro.

### 2.1.3 Volumetric coverage

There is no firm requirement for the highest elevation the radar should cover, and in practice a compromise is made between the highest elevation, the scan time, and the number of tilts in the scan pattern. The volume scan patterns currently available on the WSR-88D have maximum elevations of 20 deg. For example the VCP-11 has 14 elevations and ends at 19.5 deg in about 5 minutes. Brown and Wood (2000) have examined alternative scan patterns. The demanding one (Fig. 2), termed VCP- $\gamma$ , is quite similar to the VCP-11, it has 14 elevations, it ends at 19.5 deg, but it has to be completed in 4.1 min. Meteorologists from the NWS have expressed a desire to extend the coverage to higher elevations to reduce the cone of silence. Therefore, NSSL has proposed and collected data in a pattern that extends to 30 deg, has 14 elevations and can be executed in less than 5 min. Furthermore, there are proposed patterns that update at 5 min and end at 50 deg, but no data have been collected using these. It is fair to state that a maximum elevation of 50 deg will likely remain an upper limit, and the 30 deg might be a practical upper limit for the WSR-88D. Top elevations higher than 20 deg have not been justified by strong meteorological reasons. In NSSL's recently proposed patterns, the data (i.e., spectral

moments) are provided at 0.5 deg in azimuth in order to extend the range for detection of mesocyclones and violent tornadoes (Wood et al. 2001). This improvement in range of detection is at a small expense of velocity accuracy.

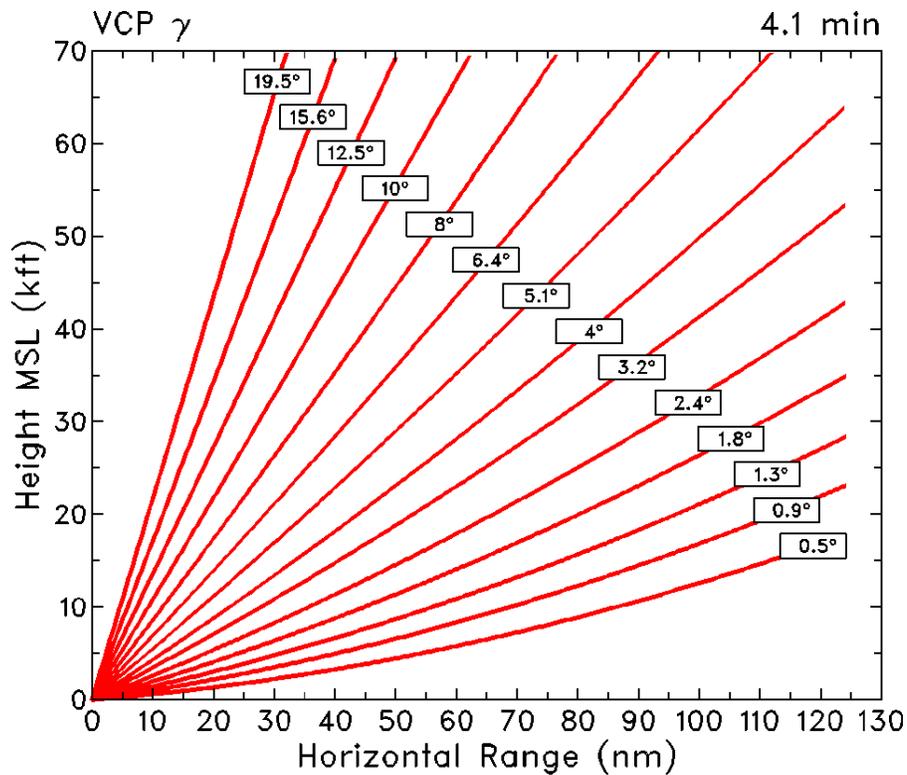


Figure 2. A demanding scanning strategy for the WSR-88D, from Brown and Wood (2000).

## 2.2 Signal to Noise Ratio (SNR)

Using the relations between rainfall rate and equivalent rainfall rate for snowfall given by Doviak and Zrnicek (1993, Section 8.4) for  $Z = 15$  dBZ, the SNR listed in Table 1 provides the specified accuracy of velocity and spectrum width measurements to the range of 230 km for both rain and snowfall at a rate of about 0.3 mm of liquid water depth per hour. The SNR specified in Table 1 is consistent with the SNR = 0 dB for a reflectivity factor  $Z = -8$  dBZ at 50 km specified in the Nexrad Technical Requirements (NTR 1984) document; 10 dB or more is added to insure that Doppler velocity and spectrum width estimates are made with specified accuracy independent of SNR given the surveillance time constraints. Furthermore, at rainfall rates smaller than about  $1 \text{ mm h}^{-1}$ , the differential reflectivity factor is practically unresolvable (Doviak and Zrnicek 1993, Fig.8.21), so that polarimetric measurements would not add any additional information to improve rainfall or to classify precipitation. In conclusion, the SNR specified in Table 1 provides quantitative measurements of precipitation to ranges of about 230 km, and potential, with polarimetric Doppler radar, to improve rainfall measurements for rain rates larger than about  $1 \text{ mm h}^{-1}$  (corresponding to  $Z$  values of about 25 dBZ).

## 2.3 Wavelength

Accurate rainfall estimates depend upon accurate  $Z$  measurements which require corrections for propagation loss. Although, for a given antenna size, angular resolution improves in proportion to the wavelength, and thus shorter wavelengths are favored, a 0.1 m wavelength has been selected for weather radars in the USA because attenuation through rain is relatively negligible compare to that at shorter wavelengths. Correcting for attenuation becomes excessively inaccurate if propagation losses exceed 10 dB (Hitschfeld and Bordan 1954). To have accurate measurements to ranges of 230 km requires that the specific attenuation be less than  $0.02 \text{ dB km}^{-1}$ .

But at wavelengths much shorter than 10 cm (e.g., 5 cm, a weather radar band) specific attenuation is higher than  $0.02 \text{ dB km}^{-1}$  for  $Z > 40 \text{ dBZ}$ . Severe storms along squall lines have  $Z$  values as high as 60 dBZ and specific attenuation up to  $0.6 \text{ dB km}^{-1}$ . Thus 5 cm wavelength radars will not meet the requirements under severe conditions (i.e.,  $Z > 40 \text{ dBZ}$ ). Furthermore, it has been observed that storms aligned along the radial can be significantly obscured by attenuation, and important observations of tornado cyclones can be lost if 5 cm wavelength Doppler radars are used. Nevertheless, countries at higher latitudes, where tornadoes are infrequent, generally have opted for 5 cm wavelength radar because precipitation usually forms in stratiform conditions, reflectivity values are typically less than 40 dBZ, and storms are smaller.

## 2.4 Angular resolution

The cited spatial resolutions are principally determined by the need to resolve meteorological phenomena such as tornados and mesocyclones to ranges of about 230 km, and the practical limitations imposed by antenna size at wavelength of 0.1 m. To achieve angular resolution significantly less than  $1^\circ$  at wavelengths of 10 cm is cost prohibitive due to the size of the reflector. Thus the angular resolution of  $1^\circ$  has been accepted as a practical limit for weather radars operating at wavelengths of 10 cm.

Even though a beamwidth of  $1^\circ$  is considered to provide relatively high resolution (e.g., the WSR-57 weather radar's angular resolution was  $2.2^\circ$ ), the spatial resolution at a range of 230 km is 4 km. This is larger than many mesocyclone diameters, and thus these important weather phenomena, precursors to many tornadoes, can be missed. Tornadoes have even smaller diameters and therefore many of these cannot be resolved at ranges to 230 km.

Because the beam of the WSR-88D weather radar is scanning azimuthally, the effective angular resolution in the azimuthal direction is somewhat larger (Doviak and Zrnicek 1993, Section 7.8). Typically, the effective azimuthal resolution is about 40% larger at the 3 RPM scan rates of the WSR-88D. The advantage of the phase array radar is that the beam can be stationary during the time that echo samples are being processed to estimate the moment (i.e., reflectivity factor  $Z$ , Doppler velocity  $v$ , and spectrum width) fields. Thus, the phase array radar could have an antenna that is 40% smaller in width without compromising the present performance experienced by NWS radar meteorologists. But the vertical size of the array needs to be about same as that of

the WSR-88D radar (i.e., about 8.5 m) in order to maintain the same vertical resolution. On the other hand, for the same size aperture, the phased array radar would provide an azimuthal resolution that is 40% better than presently achieved with the scanning reflector antenna provided the beam is pointed in the bore sight direction.

In conclusion, a phased array radar with beamwidths in  $el < 1$  deg, and  $az < 1.4$  deg should be acceptable. Because the atmosphere is vertically stratified a narrower beam width in elevation is typically needed. For example the melting layer is few hundred meters deep and should be resolved to as large a range as possible so that it does not contaminate rainfall measurements.

## **2.5 Range resolution**

The range resolution is somewhat controlled by the angular resolution; there is practically no gain in having range resolution much finer than the angular one. For example, the angular resolution equals the 250 m range resolution at a range of about 15 km. Thus, improving the range resolution can significantly enhance observations only if the phenomena are closer than 15 km. But, better range resolution can provide additional shear segments and therefore improve detection of vortices at larger distance.

Although angular resolution limits, for the most part, the resolving power of the radar, maintaining a higher resolution in range for most of the range of measurements is useful on two accounts. First of all, detail estimates of tornadic winds and size can be calculated from the Doppler spectrum (e.g, Doviak and Zrníc 1993; Figs 9.29 and 9.31) at appropriate ranges. Another reason for this relatively fine range resolution is to allow accumulation of independent samples in a range interval of 1 km. The average of these samples reduces statistical uncertainty of estimates.

The range resolution for reflectivity is coarser for two reasons: (1) reflectivity is principally used to measure rainfall rates over watersheds and thus spatial resolution as high as that required to resolve mesocyclones is not needed, and (2) reflectivity samples at a resolution of 250 m are averaged in range (Doviak and Zrníc, 1993, Section 6.3.2) to achieve the required accuracy of 1 dB.

## **2.6 Accuracy of measurements**

Using the reflectivity-factor/rainfall-rate relation for stratified rain given by Doviak and Zrníc (1993, Eq.8.22a), the specified 1 dB accuracy of reflectivity measurements provides about a 15% relative error of rainfall rate. This has been accepted by the meteorological community. Nevertheless, errors larger than this are often found because the radars, except polarimetric ones, cannot provide sufficient information about the drop size distribution required to estimate rainfall rate at the ground.

The specified accuracies of velocity and spectrum width estimates are those derived from observations of mesocyclones with research radars which provided the accuracies specified in Table 2.1. The 8 dB SNR is roughly that level at which the accuracy of velocity and spectrum

width estimates do not improve significantly for increases in SNR (Doviak and Zrnic, 1993; Sections 6.4, 6.5). But, it is possible that lower accuracies can be tolerated and benefits can be derived therefrom. For example, it has been proposed (Wood et al. 2001) that velocity estimates be made with less samples (e.g., by a factor of two) in order to improve the azimuthal resolution. Although this decreases the accuracy of the Doppler velocity estimates by the square root of two, the improved angular resolution can increase the range, by about 50% (Brown et al. 2002 and 2005), to which mesocyclones can be detected. With more signal processing power, automated algorithms can search the higher resolution data fields for tornado signatures, while the data field with normal resolution and accuracy can still be available for other algorithms that might require velocity fields with higher accuracy. But even if data at the finer resolution but worse accuracy is only available, the increased accuracy can often be obtained by simply spatially averaging the data under the assumption that in most regions the spatial resolution is finer than the spatial scale of the weather.

## 2.7 The WSR-88D specifications

To achieve the specifications presented in Table 1, the WSR-88D radar has been designed to have the parameters listed in Table 2.2.

Table 2.2  
WSR-88D parameters

2.1 Peak transmitted power:	475 kW
2.2 Transmitted pulse widths:	1.57 and 4.57 $\mu$ s
2.3 Transmitted phase noise:	<0.2°
2.4 System noise power:	-113 dBm
2.5 Dynamic range:	93 dB
2.6 PRFs:	
2.6.1 short pulse (8 selectable):	320 to 1300 Hz
2.6.2 long pulse:	320 to 450 Hz
2.7 Ground clutter canceling:	>50 dB
2.8 Antenna	
2.8.1 Gain:	45.6 dB
2.8.2 Beamwidths (equal in azimuth and elevation):	1°
2.8.3 Sidelobes:	see Fig. 3

The parameters values listed in Tables 2.1 and 2.2 can be used to derive a reasonable set of requirements applicable to phase array radar. We now discuss these parameters.

### 2.7.1 Transmitted power

The peak transmitted power level is chosen to provide the required SNR specified in Table 2.1; pulsed sinusoids are transmitted and their length (also listed in Table 2.1) determines the range resolution. Probably of greater importance than the peak power is the average

transmitted power. The duty factor of the WSR-88D radar is 0.002, and thus the transmitter needs to supply an average power as high as 1 kW. Lower peak powers can be tolerated if larger pulse widths are transmitted to maintain the average power and SNR requirements, under the condition that pulse compression techniques are used to preserve range resolution, and range sidelobes are smaller than 50 dB.

### *2.7.2 Transmitted pulse widths*

The transmitted pulse width of the WSR-88D is simply that required to meet the range resolution listed in Table 2.1. As noted in the previous section, longer pulse widths can be tolerated if pulse compression techniques are implemented. Note that the radar has a non storm observation mode whereby a long pulse (4.57  $\mu\text{s}$ ) is transmitted. Again this can be increased to longer pulse widths and, contrary to the need for pulse compression to maintain range resolution for storm observations, these techniques are not required for fair weather observations because there is no specified range resolution in this mode; further most non storm weather phenomena do not require the range resolution needed to observe hazards in storms.

Although this mode of operation is not the principal driver of the specifications of the WSR-88D radar, it has been observed that this radar can detect returns from refractive index irregularities in the convective boundary layer, and it has been suggested that weather radar could as well monitor the wind throughout the troposphere (Doviak and Zrnic, 1993, Section 11.8.1.2). The principal motivation for making observations in clear air is to obtain wind profiles to complement those obtained from rawinsonds and wind profilers. Thus the pulse width in this mode will only be limited by the need to obtain a height resolution of about 300 m for soundings below 7 km and of the order of 1 km for higher altitudes; these are the specifications for wind profilers (Doviak and Zrnic, 1993, Fig.11.26). Thus, for radar beam elevation angles of about 30°, range resolution could be as large as 600 m for wind measurements to 7 km altitude, and 2,000 m for measurements at higher altitudes. To detect clear air refractive index irregularities, the radar must operate in its most sensitive mode (i.e., longest pulse widths and smallest bandwidths, and largest average power).

### *2.7.3 Transmitter phase noise*

The performance of range velocity mitigation techniques proposed by the NSSL (Sachidanada et al., Parts 1-4, 1997-2000), depend strongly upon the phase noise of the radar. For example, if there were no phase noise in the system, the proposed systematic phase coding schemes could retrieve velocity (with accuracies better than 2 m s<sup>-1</sup>) of signals 60 dB below the signal power of a stronger overlaid out-of-trip echo (i.e., the logarithm of power ratio,  $10\log(p_s/p_w) = 60$  dB, assuming that spectrum width of each signal is 4 m s<sup>-1</sup> or less, and the unambiguous velocity is at least 32 m s<sup>-1</sup>). However, if the phase noise is about 0.2°, the weaker signal has to be within 40 dB of the stronger signal (i.e.,  $10\log(p_s/p_w) < 40$  dB). The phase error of the WSR-88D has been measured to be less than 0.2°.

### *2.7.4 System noise power*

The system noise power listed herein is the one that meets the SNR requirements (Table 2.1) for the given transmitted power. Lower system noise power is possible if a lower noise

amplifier (LNA) is used, and transmission line losses are minimized. But very low noise LNAs are typically expensive and difficult to maintain, and reducing line losses entails significant modification to the microwave hardware. Furthermore, the improvement in receiver noise power is not expected to be significant because the weather radar has to operate at elevation angles near the horizon, and thus sky radiation and thermal emissions from the ground ultimately limit the noise power improvement (Doviak and Zrníc, 1993; Section 3.5.1).

#### 2.7.5 *Dynamic range*

It is the very nature of weather signals that imposes limitations and tradeoffs. Weather signals easily span a dynamic range of about 90 dB along the beam. More than 40 dB of dynamic power change is simply due to the  $r^2$  dependence (e.g., to observe weather from about 2 to 400 km) of weather signals, and about 45 dB is associated with the variation of the reflectivity factor of rainfall (from 15 to 60 dBZ). There are two aspects to the dynamic range: 1) the range of input powers for which the radar is calibrated, and 2) the ratio of the weather spectral density peak to spectral noise density.

A calibrated dynamic range of about 90 dB is required to insure that rainfall rate is correctly estimated over the range (i.e., from about 2 to 230 km) of quantitative measurements for the stipulated range of rainfall rates. This dynamic range imposes severe demands on digital to analog converters (ADCs) which must accommodate it. Hence Automatic Gain Control (AGC) circuits are used, although the requirements on the ADCs can be reduced if a range dependent attenuation is imposed on the weather signals. Unfortunately this will compromise the observations of the non stormy regions which might harbor dangerous winds associated with the outflows of thunderstorms. Thus the dynamic range of 93 dB of the WSR-88D radar allows for unmitigated simultaneous observations of storms as well as non stormy regions.

A large spectral dynamic range is required if range velocity mitigation techniques recommended by researchers at NSSL and NCAR are implemented. The 75 dB measured spectral dynamic range of the WSR-88D (Frush 1999, Section 3.2) would not compromise the performance of the phase coding techniques used to estimate the Doppler velocity of the weak signal buried in the of out-of-trip signals that are 40 dB stronger.

#### 2.7.6 *PRFs*

In order to have reflectivity fields that are clear of overlaid echoes the strategy on the WSR-88D is as follows (Doviak and Zrníc 1993, Table 7.1). For the two lowest elevations (0.5 and 1.5 deg) two pulse repetition times (PRT) are used; a long PRT scan with an unambiguous range larger than 460 km is followed by a scan that has a four times shorter PRT. Data obtained at a long PRT have no ambiguity in range because the beam height beyond 460 km exceeds the height of the storms. But the unambiguous velocity at such long PRTs is smaller than about  $8 \text{ m s}^{-1}$  and dealising of the velocity field would often be impossible. Hence a short PRT is used to measure the velocities. Detection of overlaid echoes is made by comparing signal powers at locations within the long PRT (where these echoes could be present). If one of the overlaid echoes is stronger than the other one by a prescribed amount it would be accepted at the expense of the other. Otherwise both would be censored. At intermediate elevations the long and short

PRTs are interleaved in a dwell time for one radial and at the highest elevations a uniform PRT is used. Inclusion of variable PRFs is principally motivated by the need to minimize the effects of overlaid echoes

### *2.7.7 Ground clutter canceling*

Ground clutter echoes are formed if a significant portion of the antenna pattern illuminates the ground. Typically the reflectivity of objects on the ground (including ground itself) is stronger than the reflectivity of atmospheric scatterers. Thus the ground clutter signal can overwhelm the weather signal. Echoes that come from the antenna's main lobe are strongest but the ones due to sidelobes can also be significant. Ground clutter is typically confined to ranges close to the radar (i.e., ranges less than a few tens of kilometers); but under anomalous propagation conditions, or the presence of distant mountains, ground clutter can appear to ranges of a hundred kilometers or more.

The NTR requirements for ground clutter elimination consider two clutter models. One is Gaussian random process with a Gaussian spectrum shape centered at zero mean velocity. The clutter rms spectrum width is the root sum square of  $0.1 \text{ m s}^{-1}$  plus the rms spectrum width resulting from the antenna rotation rate (i.e.,  $.20^\circ\text{s}^{-1}$ ) at the two lowest elevation angles; the  $0.1 \text{ m s}^{-1}$  comes from measurements made in central Oklahoma by Zrnich and Hamidi (1981). The other model is a point scatterer that produces a return signal as the antenna is scanning by it. Although the first model is not necessarily applicable to other locations, it could be adapted to local conditions (e.g., to better account for motion and moisture content of vegetation under strong winds) and to the phased array radar. But the second model is not at all applicable because there is no beam motion during the dwell time (i.e., the time during which samples are collected from a resolution volume).

A possible clutter model for the phased array radar could be a superposition of a discrete strong echo from fixed point scatterers, and a Gaussian spectrum with a width about  $0.1 \text{ m s}^{-1}$ . Therefore, a notch filter with total removal of the DC component could be quite appropriate. Measurements with stationary beams are needed to determine representative value of ground reflectivity that can affect the agile beam radar.

Zrnich and Hamidi (1981) give values of ground reflectivity (i.e., the scatter cross section per unit area) as a function of distance from the radar (Table 2.3). Their average values are composites from elevations of 0.0, 0.4 and 0.8 deg, and are about 10 dB lower than values reported by Nathanson (1969). They also present histograms of the equivalent reflectivity factor of ground clutter.

Table 2.3  
Average clutter cross section

Range interval (km)	8 to 12	13 to 17	18 to 22	23 to 26
Cross section (dB below $1\text{m}^2/\text{m}^2$ )	40	52	40	68

Suppose that the weather signal at 50 km is at the limit specified by the NTR (i.e., 2 dBZ producing a 10 dB SNR) to generate accurate moment estimates, and that the equivalent reflectivity factor of the clutter is 50 dBZ. Then it would take  $(48 + 10) = 58$  dB of clutter suppression to estimate the spectral moments of the weak weather signal. This stringent requirement assumes that a pulse pair algorithm estimates the mean velocity; hence the residual of the suppressed clutter needs to be about 10 dB below the weather signal power. A more sophisticated spectral method for moment estimation could relax this suppression by about 10 dB.

Currently there is no requirement for the value of clutter power to be eliminated; the 50 dBZ might be a logical choice. It is based on histograms of clutter reflectivity factors observed by Zrníc and Hamidi (1981) in Central Oklahoma from which the values listed in Table 2.4 are extracted (the percentage in Table 2.4 is with respect to areas that have clutter  $Z > -10$  dBZ):

Table 2.4

Percentage of occurrence of clutter reflectivities larger than 50 dBZ

Elevation	0 deg	0.4 deg	0.8 deg
Percentage	5 %	2 %	0.5 %

Clearly, if up to 50 dBZ of clutter power is eliminated the remaining areas contaminated by clutter would be very small.

On the other hand, clutter suppression level should be an adaptable parameter that varies in accordance with measurements of the clutter power in various range locations. Having an adaptable clutter suppression level would lessen the suppression of weather that has zero Doppler shift. For example, if clutter reflectivity is 10 dBZ, there is no need to have any more than 8 dB of clutter suppression because the moment estimates of rain having a reflectivity factor of 20 dBZ will not be significantly biased by ground clutter residual. A ground clutter filter

without adaptable levels would only attenuate unnecessarily those weather signals that have near zero Doppler shift.

An advantage of the phased array antenna is that ground clutter spectra would be significantly narrower than those observed with scanning reflector type antennas, and hence narrower clutter filters could be employed. This would lessen the amount of weather signal that is attenuated because weather spectra would be much broader than the ground clutter filter width.

### *2.7.8 Antenna*

Probably the principal limitation of weather radar is the antenna. Angular resolution is limited by the size of the antenna whether it is a phased array or reflector type, and by the requirement of using 10 cm wavelengths in order to avoid large attenuation when the microwaves propagate through severe storms and squall lines. Thus the 1° beamwidth is a practical limit on angular resolution for weather radars operating at wavelengths of about 10 cm, and therefore it has been chosen for the WSR-88D.

As already stated the typical mesocyclone diameter is between 3 and 10 km. Often violent tornadoes have a diameter of about 1 km and are merged into the mesocyclone. To detect these, new scanning strategies have been proposed (Brown and Wood 2000; Wood et al. 2001). These involve over sampling in azimuth (at 0.5 deg) and a special sequence of elevations one of which is plotted in Fig. 2.

Reflectivity factors can vary from near 60 dBZ in hail regions of severe storms to values near 0 to -10 dBZ in clouds (Section 3 of this report) surrounding the storm, and because important meteorological phenomena (e.g., tornado cyclones) can form in the cloud regions of a storm, it is quite important to have low sidelobes. Note that sidelobes can intersect large volumes of high reflectivity regions of the storm, and thus the sidelobe power is the integral of power received through many sidelobes. The highest sidelobe levels are caused by the feed supports, but these occupy a small fraction of the total volume of sidelobes. In this regard the sidelobe performance of the phased array antenna should be somewhat better because there are no feed supports and thus the sidelobes are only those produced by the diffraction pattern of the tapered illumination of the reflector.

The radiation pattern of NSSL's Research and Development WSR-88D is presented in Fig. 3 and is the radiation pattern with radome (Doviak and Zrnic 1998). This pattern is along the line (i.e., the horizontal cut) in which there is a diffraction pattern due to the vertical feed support. Included in this figure are the specifications of the radiation pattern and it is seen that these specifications are met by the WSR-88D antenna. This is the only pattern available for a WSR-88D at its installation site, and the only one made with a fully installed radome. Nevertheless, this radiation pattern should be representative of all the WSR-88Ds in the network of radars operated by the National Weather Service (NWS). The first few sidelobes are those due to the diffraction pattern of the main reflector, whereas the sidelobes two deg beyond beam axis

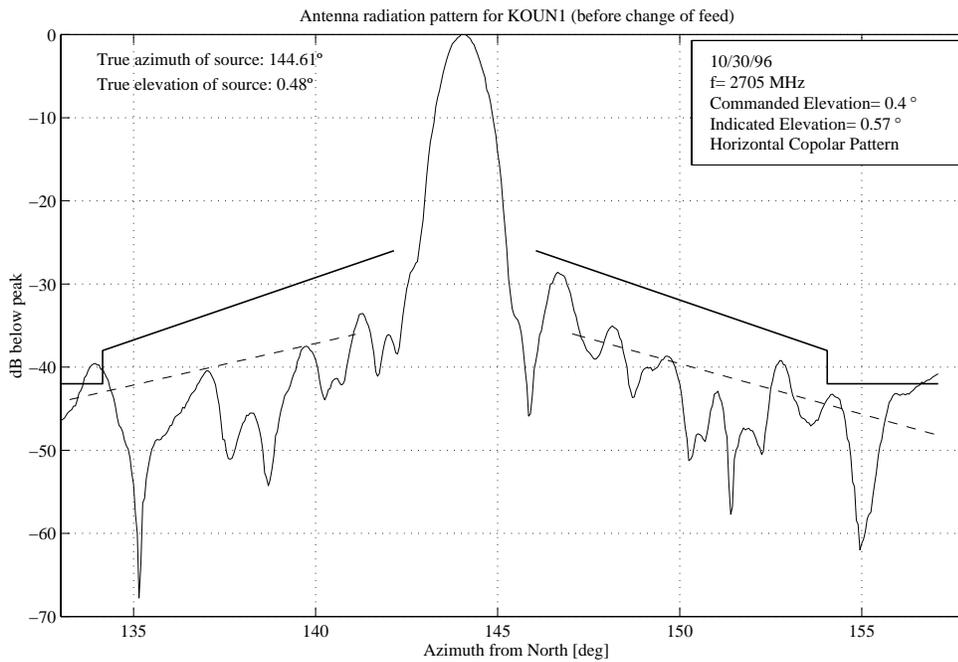
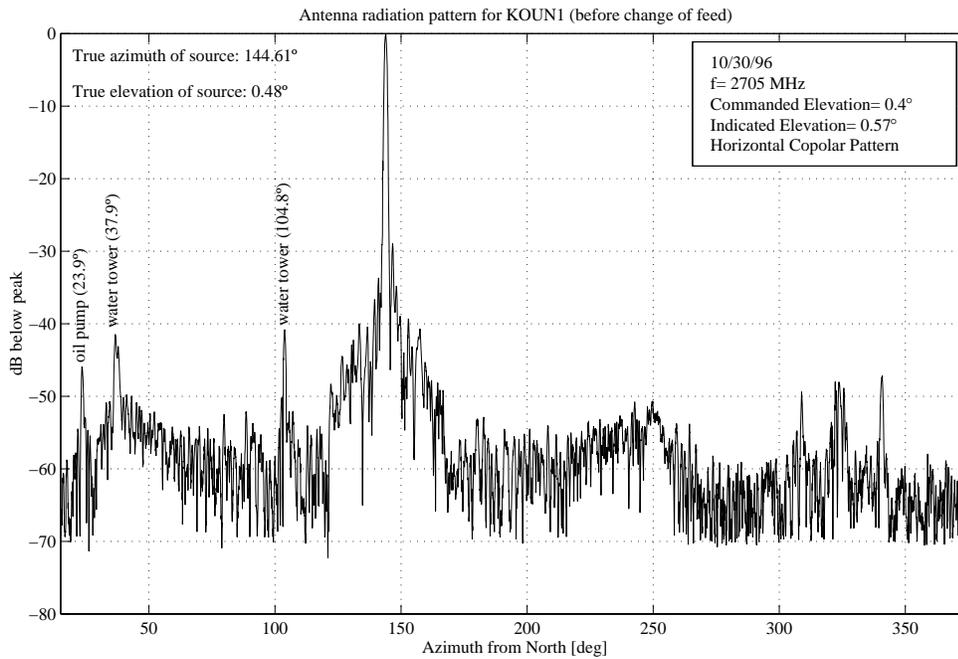


Figure 3. The copolar horizontally polarized radiation patterns of the KOUN1 antenna measured at NSSL in October of 1996 before changing the feed. Measurements are made at 2705 MHz. (Top) The pattern over a 360° azimuthal scan. (Bottom) The pattern over a  $\pm 13^\circ$  azimuthal interval about the beam axis. The solid lines are the specified limits of the sidelobe levels; the dashed lines are the estimated sidelobe envelopes for the antenna without radome.

are due to the feed support and irregularities in the phase distribution across the aperture. These irregularities in phase are caused by irregularities in the surface of the reflector.

In Fig. 4 is the radiation pattern taken in the vertical plane which does not contain the diffraction pattern associated with feed supports. The sidelobe levels to about 2 degrees are those associated with the diffraction pattern of the main reflector, whereas the sidelobe levels beyond 2 deg are those due to irregularities in the phase distribution across the aperture caused by irregularities in the surface of the reflector. The designers of the phased array antenna should not exceed the sidelobe levels of the WSR-88D because its antenna delivers acceptable performance to the NWS meteorologists. In this regard, it should be noted, that research weather radars which used reflector type antennas that were thought to have reasonably small sidelobe levels (e.g., Fig.7.26 of Doviak and Zrnich 1993), produce artifacts in the Doppler velocity field as seen in Plate 2 (op cit). The detrimental effects of sidelobes have led researchers, both at Colorado State University researchers and at NCAR, to upgrade their reflector antennas and thus further reduce sidelobes.

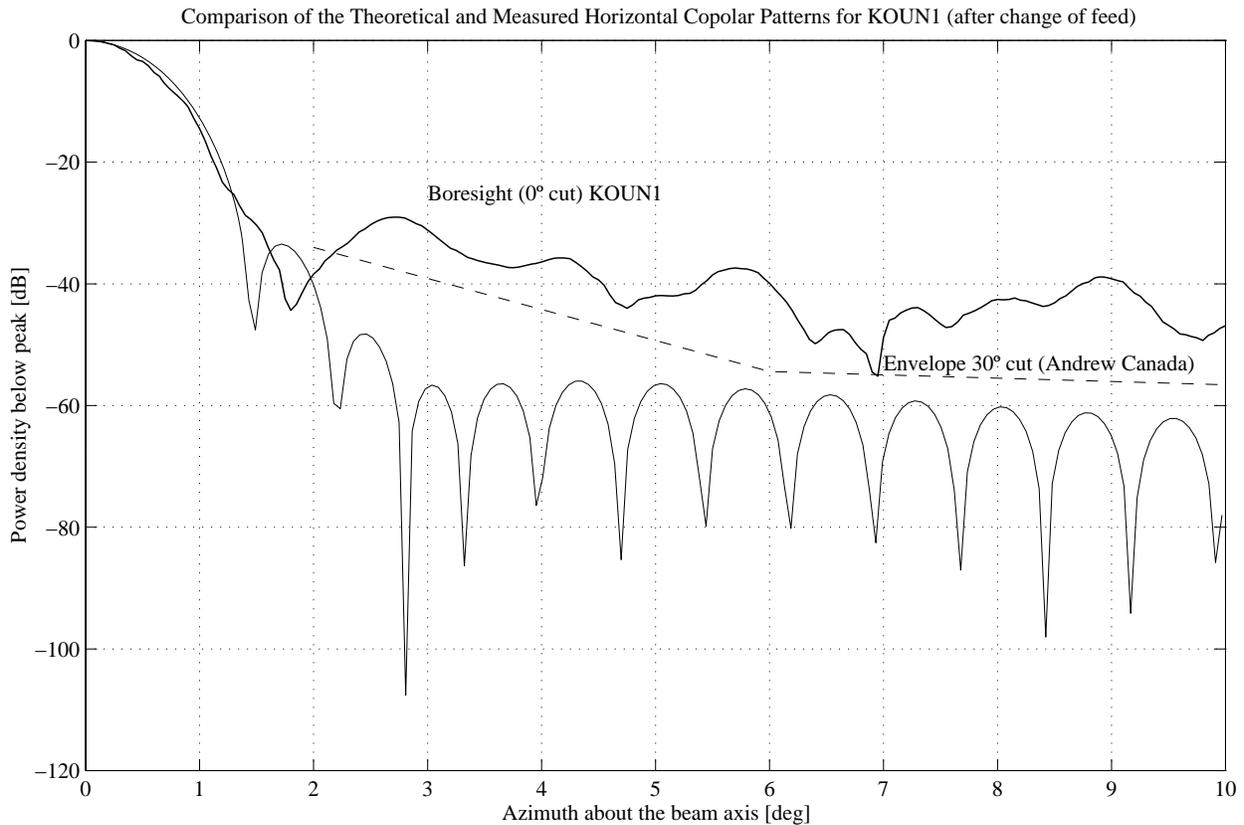


Figure 4. The theoretical radiation pattern (lower solid curve) of the KOUN1 antenna (neglected are blockages and reflector irregularities). Also shown is the copolar pattern (upper solid curve), for reception of horizontally polarized waves, measured (0° cut) with the KOUN1 antenna after the new dual-port feed was installed. The dashed line is the envelope of the sidelobes (30° cut) measured by Andrew Canada for a WSR-88D antenna without radome.

In conclusion, the sidelobe performance of the phased array antenna should not be any worse than the radiation patterns of the WSR-88D along cuts that do not intersect the diffraction sidelobes of the feed supports.

### 2.7.9 Estimation errors

Statistical error of estimates depend on the number of samples (dwell time), spectrum width, SNR, and pulse repetition time. There is also a dependence on the type of estimator. Although the NTR does not specify the type of estimators, the specifications have been obtained by considering autocovariance processing (and dwell times and antenna rotation rates). The requirements are in Table 2.5, for spectrum widths up to  $4 \text{ m s}^{-1}$ .

Table 2.5  
Statistical errors of estimates

Variable	SNR (dB)	Error
Reflectivity	> 10	< 1 dB
Velocity	> 8	$1 \text{ m s}^{-1}$
Spectrum width	> 10	$1 \text{ m s}^{-1}$

The effects of quantization are included in the errors in the Table 2.5.

The range error due to timing instabilities should be smaller than 50 m.

## 3. REFLECTIVITY FACTOR FOR VARIOUS SCATTERING MEDIA

In this section we list the reflectivity factors associated with different scattering media that are present under different weather conditions. This will allow one to estimate the SNR expected for weather signals returned from the different scattering media. The classes of scattering media are: 1) non precipitating clouds, 2) precipitation in the form of rain or snow, and 3) the reflectivity of cloudless skies.

### 3.1 Non precipitating clouds

The reflectivity factor of non precipitating clouds is usually less than 5 dBZ. Typical values for various types of clouds (Zrnic et al. 1986) are listed in Table 3.1.

Table 3.1  
Reflectivity factor of various cloud types

Cloud Type	Reflectivity Factor (dBZ)
Fair Weather Cumulus	-32
Cumulus Congestus	-1 to -19
Stratocumulus	-16
Alto cumulus	5
Altostratus	-11
Cirrus	2

Measurements of Doppler velocity in clouds could augment the wind data that are only obtained routinely twice a day from rawinsondes; or those winds obtained more frequently from profilers. For example at a range of 23 km, clouds with reflectivity factors of about -15 dBZ would produce a SNR = 0 dB. Even at this low SNR, and at even lower SNR with sufficient averaging, Doppler velocity measurements are still useful. For example, the rms error for velocity in each resolution volume, for SNR = 0 dB, would increase by a factor less than 2 over that specified in Table 2.1. Thus there are many cloud types that could provide sufficient SNR to make Doppler velocity measurements useful for estimating the horizontal wind, and thus supplement the wind data obtained from rawinsondes or wind profilers.

### 3.2 Precipitation

Here the reflectivity factor of rain and snow are given. A representative, not always correct but nevertheless useful, relation between the stratiform rain rate  $R$  and the reflectivity factor  $Z$  given by Doviak and Zrnice (1993, Eq.(8.22a) is:

$$Z_e \text{ (dBZ)} = 23 + 16 \log_{10}[R(\text{mm h}^{-1})] , \quad (1)$$

where,  $Z_e$  is the equivalent reflectivity factor obtained from application of the radar equation (i.e., Eq.4.35 in Doviak and Zrnice 1993); for stratiform rain,  $Z$ , the sum of drop diameters raised to the sixth power per unit volume, is usually well approximated by  $Z_e$ . Other relations for convective showers are available (Doviak and Zrnice, op cit).

An accepted equation for snow is the Srivastava-Sekhona relation, adjusted for the increase of volume due to the expansion of ice (Doviak and Zrnice, 1993, Eqs.8.24 and 8.25b)

$$Z_e \text{ (dBZ)} = 26 + 22.1 \log_{10}[R(\text{mm h}^{-1})], \quad (2)$$

where  $R$  is snow rate in equivalent liquid water amount ( $\text{mm h}^{-1}$ ). A simple conversion of equivalent water accumulation to snow depth is obtained by multiplying  $R$ , obtained from (2), with 10. One can quickly see that a rain rate of  $0.32 \text{ mm h}^{-1}$  produces the same reflectivity factor of 15 dBZ for both snow and rain. At higher equivalent rainfall rates,  $R$ , the reflectivity factor of snow is larger.

### 3.3 Cloudless skies

No strict requirements exist for detecting scatterers in optically clear air. Nonetheless there are potential uses for obtaining velocities in clear air. Scatterers in clear air are either sparse objects (like insects, birds, and other particles including hydrometeors invisible to the unaided eye), or fluctuation in refractive index. Typical values of reflectivity factor in clear air from insects are between -5 and 10 dBZ; in convergence lines the values are 5 to 15 dB higher, and the maximum values are in the range of 20 to 35 dBZ (Wilson et al. 1984).

Fluctuations of refractive index with spatial wavelength of 5 cm can be detected with 10 cm wavelength radar. Hence there is motivation to explore utility of this wavelength for mapping vertical profiles of horizontal winds above the radar. Two techniques have been tested for profiling of winds. One capitalizes on the assumption that the wind is linear in cylindrical volumes above the radar; then from the measurements of mean radial velocity at a high elevation angle and several azimuths it is possible to retrieve the horizontal component (Doviak and Zrnica 1993, p 487). An alternate technique determines the correlation of electric fields returned to three spaced receiver at the ground (Latatis and Doviak 1995). Either approach can be applied to agile beam phased array radar.

By using the equation (i.e., Eq.4.31 of Doviak and Zrnica 1993) that relates reflectivity  $\eta$  to the equivalent reflectivity factor  $Z_e$  and equating this to the reflectivity associated with the structure parameter  $C_n^2$  of clear air (i.e., Eq.11.104, op cit), the following relation

$$\log_{10}(C_n^2) = -11.5 + 0.1Z_e \quad (3)$$

is obtained, where  $Z_e$  is expressed in dBZ units and  $C_n^2$  has units of  $\text{m}^{-2/3}$ . Median value  $C_n^2$  as a function of height  $h$  (km) is (Doviak and Zrnica 1993, Fig 11.17)

$$\log_{10}(C_n^2) = -14.4 - 0.22 h \text{ (km)}. \quad (4)$$

From these two equations the median equivalent reflectivity factor  $Z_e$  due to refractive index fluctuations is

$$Z_e \text{ (dBZ)} = -29 - 2.2 h \text{ (km)}. \quad (5)$$

This is indeed a very weak reflectivity factor, but could be detected at near ranges if ground clutter can be canceled, and if the Doppler spectrum is free of artifacts. For example, if the long pulse listed in Table 2.2 is transmitted, and a pulse repetition time of  $3.75 \times 10^{-3}$  s and a dwell time of 100 s are used, velocity estimates can be made with an accuracy of  $1 \text{ m s}^{-1}$  with SNR as low as -19 dB for spectra having widths of  $1.5 \text{ m s}^{-1}$  (Doviak and Zrnic 1993, Eq.11.154). Thus at near ranges of about 5 km, it can be shown that velocity can be estimated with an accuracy of  $1 \text{ m s}^{-1}$  even if the reflectivity factor of the clear air is as low as -59 dBZ.

#### **4. POLARIMETRIC REQUIREMENTS**

Unlike Doppler radars which have been adopted by meteorological services in several countries, polarimetric weather radars have not yet become part of operational networks. Nonetheless, there is sufficient scientific evidence about their utility to improve quantitative precipitation measurement and classify precipitation (Zrnic and Ryzhkov 1999) that the NWS is committed to install dual polarization capability on the WSR-88Ds. Current plans are to transmit simultaneously two linear polarizations so that the composite is an arbitrary elliptical polarization, and on reception to decompose the returned electric fields into linear (horizontal and vertical) components. Another option, well tested by researchers, is the switched (on-transmit) linear polarization whereby a horizontal H and vertical V polarizations are transmitted sequentially and one (copolar component) or both (copolar and cross-polar component) of these are received and processed.

The requirements concerning dual polarization are therefore drawn from our own experience and are partly based on known capabilities of the classical hardware (that is the parabolic dish reflector). NSSL is transforming its R&D WSR-88D radar into a polarimetric one. Thus far measurements have been made of the antenna patterns at both polarizations and a cross pattern in one cut has been made (Doviak and Zrnic 1998). Soon we will determine the overall polarization isolation (or leakage) of the system and we will know much more about balancing and calibrating the H and V receivers. We will include these results in a subsequent report as they become available.

Considerations that motivated us to suggest simultaneous transmission and reception of H and V signals are:

1. The high power ferrite switch needed for alternate transmission is expensive; it is an uncommon hardware that would add to maintenance cost. It has substantial losses (about 4 dB two-way).
2. The alternate transmission would create problems if ground clutter filters are used. That is, because separate filters are needed for the H and V channels, the Nyquist interval would be correspondingly reduced creating twice as many notches as there are currently. Moreover, the first notches would be at relatively low velocities (20 to 30 m s<sup>-1</sup> and -20 to 0 30 m s<sup>-1</sup>). These would degrade data which otherwise on the current WSR-88D, would not be affected.
3. None of the algorithms developed so far for the WSR-88D would be altered if simultaneous transmission is the choice.

But with simultaneous transmissions of H and V, it is not possible to obtain all the elements of the covariance matrix and the variables derived from these. Lacking are the depolarization ratio and the correlation coefficients between the strong copolar and weak cross-polar components. On the NSSL 's R&D WSR-88D, these can be obtained in separate volume scans. Preliminary indications are that the linear depolarization ratio can discriminate well snow and rain; the two correlation coefficients do not have such strong discriminatory capabilities. Further study is required to determine if collectively the rest of the polarimetric variable can compensate for the lack of the depolarization ratio.

The preceding paragraph has the following bearing on the polarization of the phased array radar.

- a) If the cross-polar components are not important, then the elements should only have provision to transmit simultaneous H and V and receive both in a volume scan; thus the same polarization will be used in all volume scans.
- b) If the cross-polar components are important it should be possible to transmit one polarization (say H) and receive both copolar and cross-polar components. Thus one volume scan will be with simultaneous transmissions of H, V, and in alternate volume scans only the H polarized signal will be transmitted. Thus two volume scans will be needed to obtain full polarimetric data. This is the scenario that will be implemented on NSSL 's R&D WSR-88D.

It should be understood that the mode of simultaneous transmission/reception has not been sufficiently tested. Some data were collected by Colorado State University in this mode and in the alternate H,V mode (which is well understood); the preliminary assessments suggest that polarimetric data obtained from two modes are quite comparable, but a thorough quantitative analysis has not been made. We have also inferred, from the full polarimetric data collected by NCAR in Brazil, that the simultaneous H,V scheme will not produced significant biases in the polarimetric variables.

Thus far, the polarimetric discussion implicitly refers to weather surveillance radars. In that mode (i.e., at low elevation angles <30 deg) it might be possible to detect icing conditions. This is a long term goal and a requirement for aviation that may not be achievable in the surveillance mode. It is definitely possible to infer some hydrometeor types that exclude icing. By such exclusion the set of uncertain possibilities would narrow and with ancillary information it might be possible to detect icing.

There is a proven method using elliptical polarization to detect icing in regions close to the radar (Matrosov et al. 2001). It has been demonstrated by scientists at the NOAA Environmental Technology Laboratory. The scheme requires transmission of an elliptical polarization and measurement of both copolar and cross-polar components. The dependence of depolarization on the elevation angle can reveal the type of hydrometeors in the vicinity of the radar. The measurements have to be made to very high elevation angles (~ 70 deg). The scheme has been tested and verified with an 8 mm wavelength radar for which the hydrometeors are still Rayleigh scatterers. Thus there is no fundamental reason to preclude similar results with a 10 cm wavelength radar.

#### 4.1 Match of H and V patterns

Within the main lobe regions, defined by a 20 dB contour below the peak of the H and V patterns, the gain should not differ by more than 1 dB. The antenna side lobes should be as good as or better than the ones on the WSR-88 D, but need to be matched only in the region where the diffraction side lobes are dominant.

The overall isolation of the system should be such to produce acceptable bias in the smallest desired linear depolarization ratio,  $L_{DR}$ . Denote with  $b$  (dB) the upper limit of bias in  $L_{DR}$ , and let the smallest  $L_{DR}$  be

$$L_{DR} = 10 \log_{10}(P_{vh}/P_{hh}) \quad (6)$$

where the  $P_{vh}$  is the cross polar power; that is, the power received in the vertical channel if the horizontally polarized signal is transmitted. Furthermore, it is assumed that  $P_{hv}$  is solely due to the scatterers (the radar system does not depolarize). Now consider a realistic radar and perfect spherical scatterers, so that the cross polar power due to the radar is  $P_{ch}$ . Then the measured linear depolarization  $L_{DRm}$  is

$$L_{DRm} = 10 \log_{10}[(P_{vh} + P_{ch})/(P_{hh} - P_{ch})] \quad (7)$$

The requirement to keep the bias smaller than  $b$  is then expressed as

$$L_{DRm} - L_{DR} < b. \quad (8)$$

The depolarization due to rain is smaller than - 28 dB. Hence we can take - 29 dB as the smallest that is required to be measured. Suppose that the allowed bias is 1 dB, then one finds

$$P_{ch}/P_{vh} < 1/4 \quad (9)$$

and the total linear depolarization by the system should be  $< -35$  dB. This would be a very stringent requirement as it involves every component including the antenna and it is a sum of all contributions. But there is no accepted value for the bias  $b$ . Moreover, the bias is always positive and the linear depolarization ratio is not used for quantitative precipitation measurement.

The system depolarization on current research radars is slightly below  $-30$  dB and a similar value should be achieved with a phased array system. This means that the individual components should have isolation lower than about  $-34$  dB.

## 5. REFERENCES

- Brown, A.R., and V.T. Wood, 2000: Presentation of new volume coverage patterns to the WSR-88D Technical Advisory Committee in August 2000. Final Report prepared for the WSR-88D Operational Support Facility.
- Brown, R. A., V. T. Wood, and D. Sirmans, 2002: Improved tornado detection using simulated and actual WSR-88D data with enhanced resolution. *J. Atmos. Oceanic Technol.*, **19**, 1759-1771.
- Brown, R. A., B. A. Flickinger, E. Forren, D. M. Schultz, D. Sirmans, P. L. Spencer, V. T. Wood, and C. L. Ziegler, 2005: Improved detection of severe storms using experimental fine-resolution WSR-88D measurements. *Weather and Forecasting*, **20**, 3-14.
- Burgess, D. W., V. T. Wood, and R. A. Brown, 1982: Mesocyclone evolution statistics, Severe Storm Conf. Proc., AMS, Boston, MA., 422-424.
- Doviak, R.J., and D.S Zrnic, 1998: NOAA/NSSL=s WSR-88D Radar for Research and Enhancement of Operations: Polarimetric upgrades to improve rainfall measurements. National Severe Storms Laboratory Report.
- Doviak, R. J., and D.S. Zrnic, 1993: "Doppler radar and weather observations." Academic Press, San Diego, CA, p. 562.
- Frush, C., 1999: NEXRAD Range-Velocity: Exploring selected mitigation techniques, 2<sup>nd</sup> year report, May, 1999, National Center for Atmospheric Research, Boulder CO, 88 pp.
- Hitschfeld, W. and J. Bordan, 1954: Errors inherent in the radar measurement of rainfall at attenuating wavelengths, *J. Meteor.*, **11**, 58-67.

Lataitis R. J., and R.J. Doviak, 1995: Precision of spaced-antenna wind estimates, Preprints 27<sup>th</sup> Conference on Radar Meteorology, Vail CO, American Meteorological Society, 717-719.

Matrosov, S.Y., R.F. Reinking, R.A. Kropfli, B.E., Martner, and B.W., Bartram, 2001: On the use of radar depolarization ratios for estimating shapes of ice hydrometeors in winter clouds. *J. Appl. Meteor.*, **40**, 479-490.

Nexrad Technical Requirements (NTR), 1984: Report R400A - SP203.

Nathanson, F. E., 1969: "Radar Design Principles." McGraw-Hill, New York.

Sachidananda, M., 1997-2000: Signal design and processing techniques for WSR-88D ambiguity resolution, National Severe Storms Laboratory reports, Parts 1-4, Norman, OK.

Smith, P.L., 1984: Equivalent radar reflectivity factors for snow and ice particles. *Jour. of Climate and Applied Meteorology*, **23**, 1258-1260.

Wilson, J. W., T.M. Weckwerth, J. Vivekanandan, R.M. Wakimoto, and R.W., Russel, 1984: Boundary layer clear-air radar echoes: origin of echoes and accuracy of derived winds. *Jour. Atmos. Oceanic Technol.* **11**, 1184-1206.

Wood, V.T, R. A. Brown, and D. Sirmans, 2001: Technique for improving detection of WSR-88D mesocyclone signatures by increasing angular sampling. *Weather and Forecasting.* **16**, 177-184.

Zrnic, D.S. , and A.V. Ryzhkov, 1999: Polarimetry for weather surveillance radars. *Bull. Amer. Meteor. Soc.*, **80**, 389-406.

Zrnic, D.S., S.D. Smith, A. Witt, R.M. Rabin, and M. Sachidananda, 1986: Wind profiling of stormy and quiescent atmospheres with microwave radars. NOAA Technical Memorandum ERL NSSL-98.

Zrnic, D. S., and Hamidi, S. (1981). Considerations for the design of ground clutter cancellers for weather radar. Interim Rep., Systems Research and Development Service, Rep. No. DOT/FAA/RD-81/72, 77 pp. [Available from NTIS, Springfield, VA 22151.]