TRAINING PAPER NWS TC-1

DOPPLER WEATHER RADAR PRINCIPLES

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OBJECTIVES

Material in this guide should enable you to:

1. Distinguish between doppler weather radar and conventional weather radar in terms of basic design theory and major operational components.
2. Describe major operating advantages and limitations of existing doppler weather radars as compared to conventional NWS network radars.
3. Cite basic characteristics of doppler velocity spectra and the properties of radar and target which affect spectrum shape.

INTRODUCTION

Technology continually increases the amount and detail of information available to us in operational meteorology. This availability, however, does not necessarily simplify our job of weather analysis, but often instead increases the sophistication with which we must screen and apply observations and other data. Optimum real-time application of any new operational data source thus requires knowledge of its theoretical basis and capabilities, as well as its design limitations.

The availability of real-time doppler weather radar data will increase drastically in the years to come, in both the public and private sectors, as commercial sources continue to produce and refine economically feasible sets and the public sector proceeds with development and installation of the NEXRAD network. This will require us, as NWS employees, to properly interpret and apply information which shows us atmospheric mechanisms as we have not been able to observe them before. The number and types of radar data displays will increase dramatically, and selection/application of those we need for a given decision will demand an increase in both (1) understanding of the radar and (2) understanding of the atmosphere. This guide, it is hoped, will provide the first of these. Research, experience, and further training will continue to expand the second.

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October, 1982

RADAR COHERENCY

Conventional network and local warning radars are pulsed NONCOHERENT systems. These radars are designed to provide information on the location of, and amount of power returned from, a given target. Existing doppler weather radars, by comparison, are pulsed COHERENT radars. In addition to information about target location and amount of returned power, doppler radars can provide information on atmospheric motions in or near a target.

DOPPLER SHIFT

When electromagnetic energy is reflected from a target moving toward the transmitting/receiving site, it returns at a higher frequency than the transmitted frequency. Conversely, when the reflection of energy is from a target moving away from the site, energy returns at a lower frequency than the transmitted frequency. The change in frequency (or wavelength) due to motion of the reflecting target in this case is called the DOPPLER SHIFT. It is the doppler shift which, through sophisticated circuitry and statistical techniques, allows a doppler radar to determine the motion of targets either toward or away from the transmitter.

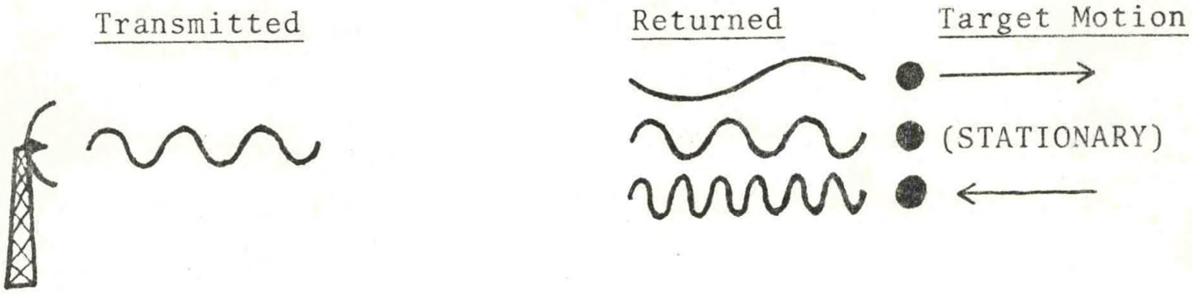

Figure 1. Doppler frequency shift due to target motion.

BASIC DOPPLER COMPONENTS

To determine the frequency change between transmitted and received energy, the doppler radar compares the PHASE (location of crest, trough, or other specific point in a cycle) of the returning signal to the phase of the transmitted signal. This is done with some unique electronic circuitry.

The stable local oscillator (STALO) generates a stable reference signal with which the transmitted signal is mixed in the locking mixer before being stored in the COHERENT OSCILLATOR (COHO). The COHO allows the radar to "remember" the phase of the transmitted signal. Returning energy is mixed with the STALO output and amplified before being compared to the transmitted signal in the PHASE DETECTOR where the phase shift between the two is determined. Output of the phase detector is then available for further processing and display.

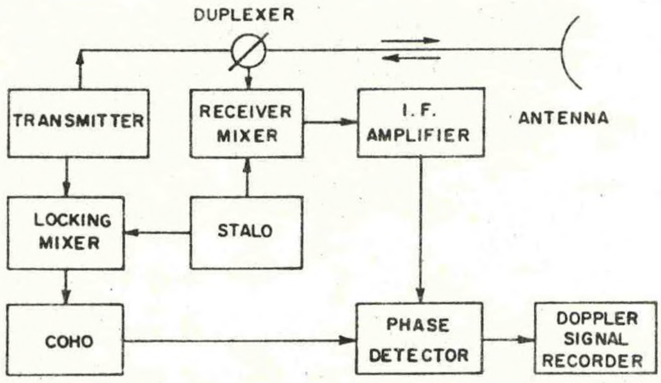

Figure 2. Schematic block diagram of pulsed doppler weather radar (after Battan).

RANGE AND VELOCITY DESIGN LIMITATIONS

Phase comparison allows pulsed doppler weather radar to unambiguously measure velocities toward and away from the radar (RADIAL VELOCITIES) within a range of values which depends on the pulse repetition frequency (PRF) and wavelength of the radar. This range of velocity measurement is limited by the velocity at which a target moves one half wavelength between pulses and is called the UNAMBIGUOUS VELOCITY RANGE. It is determined for a given radar by the equation,

$$(1) \qquad V_{max} = \frac{(\lambda)\ (PRF)}{4} ,$$

where "λ" (Greek letter lambda) stands for wavelength.

Substituting appropriate values of PRF and wavelength for conventional radars into Equation 1 results in values of V_{max} as follows:

Radar	Unambiguous Velocity (Toward or Away)
WSR-57 (long pulse, 164 pps)	9.4 mph
WSR-57 (short pulse, 545 pps)	31.4 mph
WSR-74C (259 pps, 5.4 cm.)	7.8 mph

Studies of an Oklahoma tornado in May, 1981 by the National Severe Storms Laboratory (NSSL) indicated maximum wind speeds near 196 mph. To bring velocities of this magnitude within the unambiguous velocity range, assuming optimum weather detection wavelength of 10 cm., would require a pulsed doppler radar with a PRF of approximately 4,000 pps!

Recall, however, that the maximum unambiguous range of a pulsed weather radar also depends upon the PRF, as determined by the equation,

$$(2) \qquad R_{max} = \frac{c}{2\,(PRF)} ,$$

where "c" is the speed of light. Substitution into this equation of the 4,000 pps PRF discussed earlier results in an unambiguous operational range of 20.2 nautical miles!

Thus, a pulsed doppler radar of maximum utility for atmospheric detection requires a compromise between unambiguous range and unambiguous velocity in the choice of an operating PRF. Potential operating combinations of these parameters are shown in Figure 3 as a function of wavelengths commonly used by surface-based weather radars.

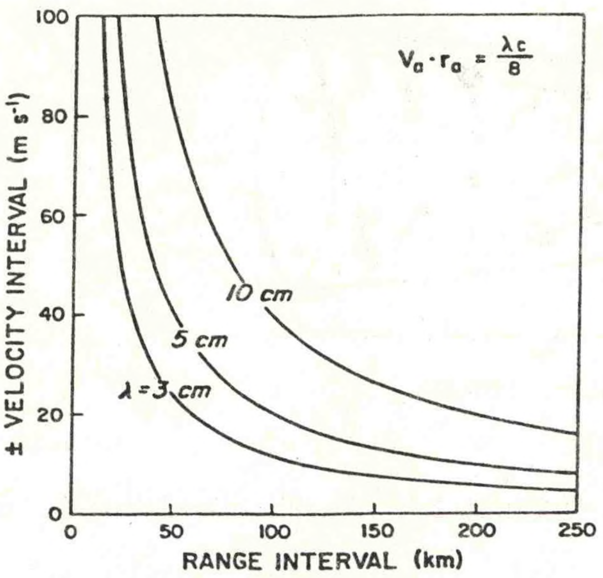

Figure 3. Combinations of unambiguous range and unambiguous velocity for pulsed doppler radars of 3, 5, and 10 cm. wavelengths.

DOPPLER SPECTRA

A pulsed radar at any instant during the receiving period is analyzing return from an ECHOING VOLUME which is one beamwidth in cross-section and one half pulse length long. Within this volume may be contained, if the target is precipitation, many particles of varying size, shape, and water/ice composition. Thus, the pulsed doppler weather radar does not instantaneously sense a single motion, but rather a combination of the motions of many individual precipitation particles as shown in Figure 4.

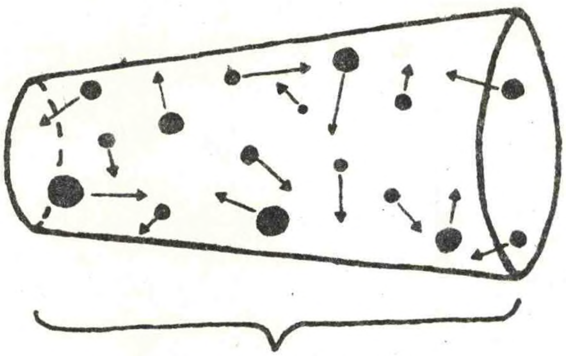

Figure 4. Target motion within an echoing volume.

Since it receives information on the motion of many precipitation (or other) targets simultaneously, the doppler radar processing equipment combines (integrates) the information and interprets it in terms of a DOPPLER SPECTRUM. The doppler spectrum is the distribution of power received by the radar at each frequency. Doppler spectra are typically plotted and analyzed in the format of Figure 5 for research and study purposes. However, similar analysis is done electronically by the doppler radar processing equipment in real time, commonly using applied mathematical techniques called "Fast Fourier Transforms."

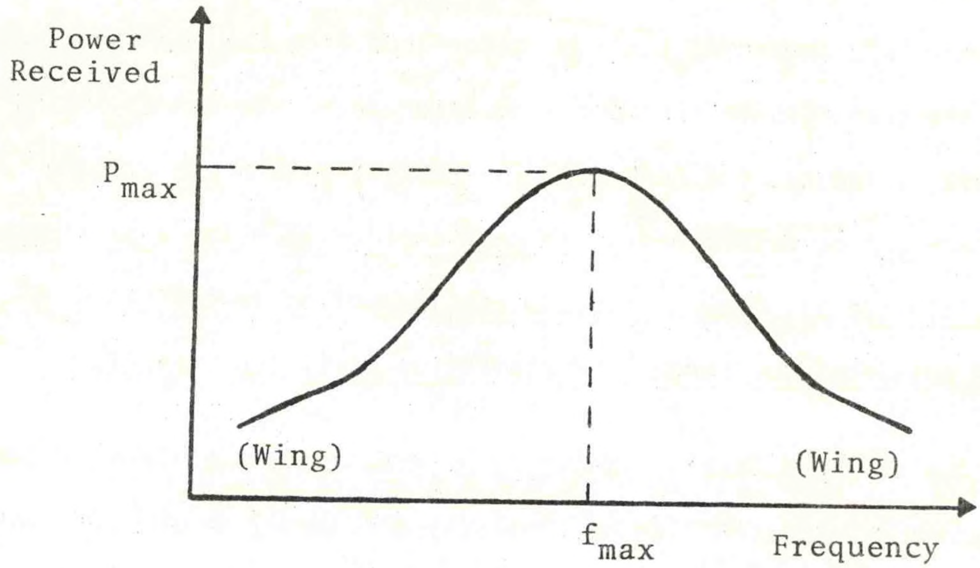

Figure 5. Idealized doppler spectrum of a precipitation target.

The bell-shaped curve of the function in Figure 5 is broadly typical of precipitation targets. Note that the maximum amount of returned power (corresponding to value, P_{max}) occurs at some specific frequency or small frequency interval (corresponding to value, f_{max}). If the area under the curve represents total power received, the location of f_{max} is such that half the total area under the curve falls right and left of f_{max}.

Recalling that the radar receives proportionally much more power from large drops than from small ones, it is reasonable to assume that f_{max} is commonly the frequency of power returned from the largest drops in the echoing volume (see Figure 5). These largest drops tend to move most conservatively; i.e., with motion similar to the mean air flow, least affected by turbulent gusts. Thus, by effectively comparing the f_{max} determined from the doppler spectrum to the transmission frequency and determining the corresponding radial velocity, the MEAN DOPPLER VELOCITY within the echoing volume can be determined. The mean doppler velocity approximates the average air flow within the echoing volume as indicated by the motion of the largest precipitation particles present.

Motion of precipitation particles progressively smaller than the maximum size present can be similarly obtained from the portions of the doppler spectrum progressively farther right and left of f_{max}. Information on the most variable short-term gustiness, or turbulence, within the echoing volume is contained in the right and left extemes, or WINGS, of the spectrum (see Figure 5).

SPECTRAL SHAPE

The shape of the doppler spectrum varies with the character of the target being sampled. For precipitation targets with very large particles and large internal wind shears (such as thunderstorms), the spectral function has a comparatively flat appearance, but with substantially more total area under the curve than for other targets. For precipitation targets composed of relatively small precipitaion particles and with relatively weak wind shears, the peak in the function plot is sharper by comparison and total area under the curve is comparatively small. Examples of spectra from targets of different character are shown in Figure 6. In general, a wider spectrum corresponds to a more turbulent atmosphere.

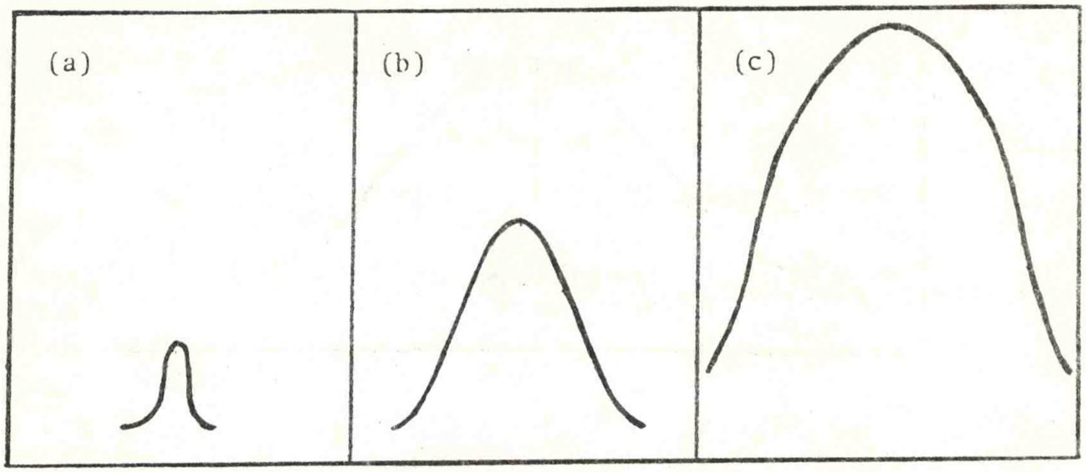

Figure 6. Comparative doppler spectra as a function of precipitation target character.
(a) Light stratiform rain
(b) Rain shower
(c) Thunderstorm

Spectral shape information can be described in terms of the statistical parameter "σ" (Greek letter sigma) which denotes STANDARD DEVIATION of a distribution. If the frequency "f" in Figure 7 corresponds to the mean doppler velocity, then half the total area under the curve falls both right and left of f. The standard deviation is that distance right and left of f within which two thirds of the area under the curve is located. Thus, as the width of the spectrum increases and decreases, standard deviation increases and decreases respectively. The square of the standard deviation (σ^2) is called the VARIANCE and also changes directly as spectrum width.

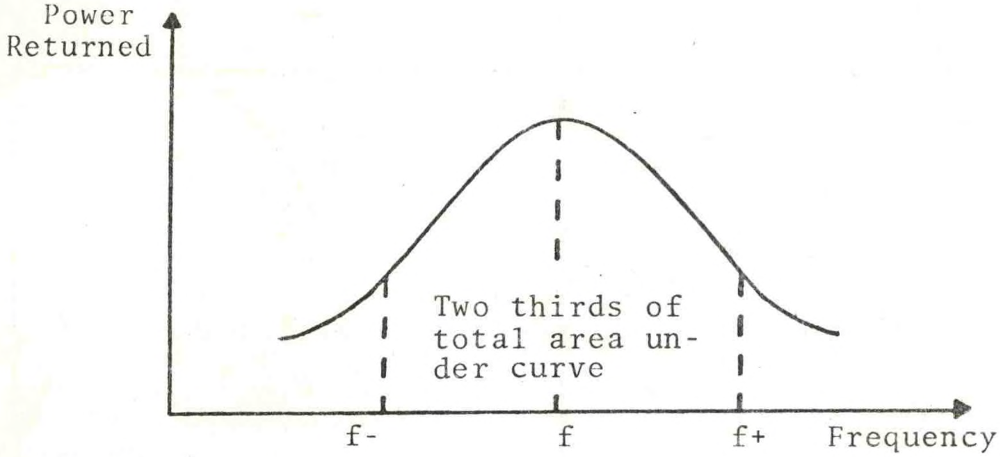

Figure 7. Standard deviation.

From earlier discussion of spectral shape, we know that wider spectra correspond generally to more turbulent targets. Similarly, large values of σ or σ^2 also correspond to more turbulent targets. Using electronic mathematical approximations similar to those used for approximating mean doppler velocity, contemporary doppler weather radars evaluate variance as an indication of spectral width. By examining patterns of mean doppler velocity and variance together in real time, both mean air flow and gustiness (turbulence) can be evaluated for various portions of a precipitation target using doppler weather radar. The most reliable doppler estimates of mean motion within or near a precipitation target are obtained from spectra which have narrow widths (small variance) and relatively sharp peaks.

For an increase of:	Spectrum change is:	Indicated by:
a. Max. Particle Size	Higher Peak (P_{max})	Higher indicated reflectivity
b. Turbulence	Wing Stretching	Larger σ
c. Wind Shear	Flattened Peak	Larger σ

Table 1. Target character changes as they may affect general spectral shape.

EFFECT OF TARGET AND RADAR CHARACTERISTICS ON SPECTRAL SHAPE

The doppler spectrum shape is determined by the nature of both target and radar. In the broadly generalized discussion of spectral shape which follows, it should be kept foremost in mind that the characteristics of precipitation targets, and thus, their doppler spectra, vary widely.

Effects of target characteristics upon spectral shape are summarized in Table 1 and Figure 8, as discussed earlier.

General effects of radar characteristics upon spectrum shape are summarized in Table 2 and Figure 9. Recall that spectra which are narrower and have sharper peaks produce more reliable ("stable") doppler estimates of mean velocity. Stabilizing the doppler velocity estimate by increasing antenna size or decreasing operational range results from the corresponding decrease of echoing

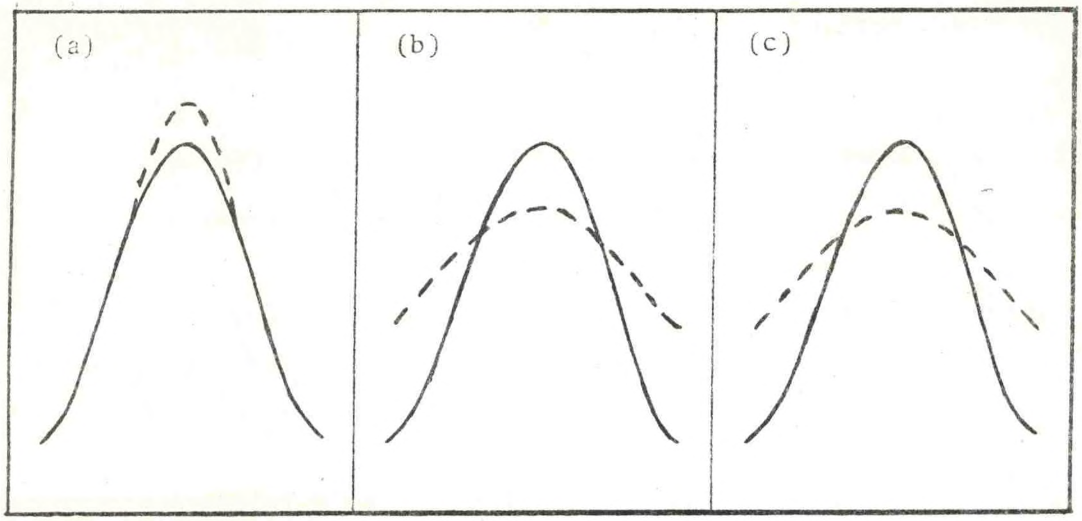

Figure 8. Effect of target character changes listed in Table 1 on doppler spectrum
——Before ‐ ‐ ‐ After

	For an increase of:	Spectrum Width Change is:	Effect on Mean Velocity Estimate is:
a.	Antenna Size	Decrease	Increase Accuracy
b.	Rotation Rate	Increase	Decrease Accuracy
c.	Operational Range	Increase*	Decrease Accuracy*

Table 2. Effect of radar characteristic changes on spectrum width and resulting mean doppler velocity estimate.

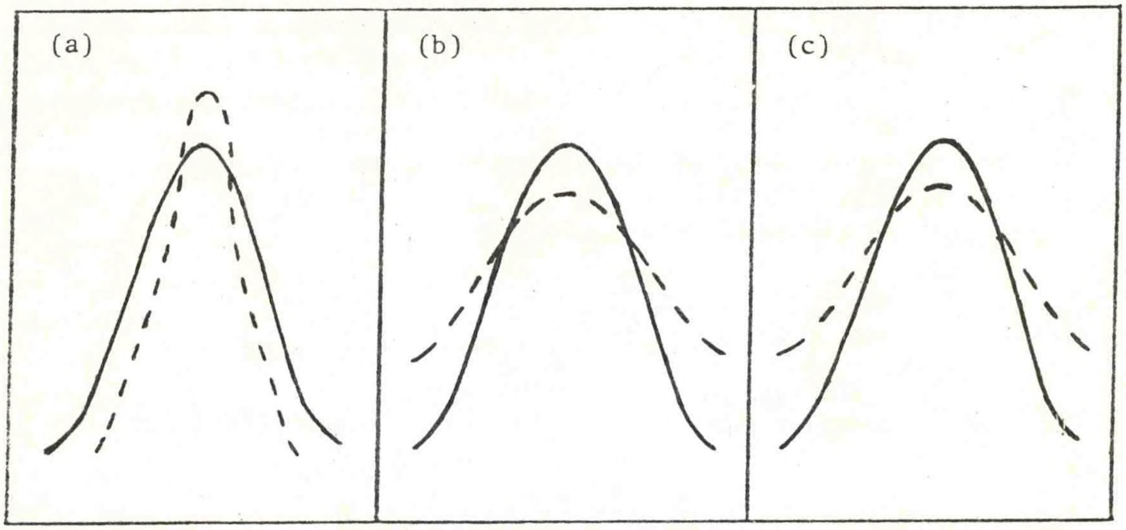

Figure 9. Effect of radar characteristic changes listed in Table 2 on doppler spectrum.
—— Before --- After

volume size due to beamwidth considerations. Obviously, the variability of particle motion within the echoing volume decreases as the volume size decreases. Stabilizing doppler velocity estimates by decreasing rotation rate results from the fact that the pulsed doppler weather radar actually samples a given volume of atmosphere repeatedly to produce a spectral estimate of velocity within that volume. Slower rotation allows more DWELL TIME, or sequential samples, and thus, a more reliable estimate of mean velocity.

DOPPLER WEATHER RADAR OPERATING CHARACTERISTICS

Contemporary doppler weather radars generally portray the atmosphere in terms of three types of two-dimensional (PPI) displays:

1. Equivalent Reflectivity Factor
2. Radial Velocity
3. Spectrum Width (Variance)

These are commonly color-enhanced to aid in interpretation.

The most common equivalent reflectivity display is of the type presently available in the form of remote CRT-type monitors of equivalent reflectivity from NWS network radars (i.e., Kavouras), but with better display resolution. Radial velocity is generally displayed using different colors for motion toward the radar and away from the radar. Varying shades of the respective colors are used for indicating magnitudes of the radial velocities, with brighter shades generally associated with relatively stronger velocities. Velocities <u>away</u> from the radar in direction are normally considered <u>positive</u>, and those <u>toward</u> the radar are normally considered <u>negative</u>. Spectrum width is also typically presented in various shades and colors, with the most visually pronounced colors portraying the relatively larger spectral widths and thus, the areas where the probability of wind shear and/or turbulence is highest.

Typically, the rotation rate of currently operating doppler weather radars is slower, the PRF higher, and the antenna larger than for conventional network radars; for reasons discussed earlier. Available combinations of unambiguous range and velocity are expanded beyond PRF limitations through the use of electronic computer POSTPROCESSING equipment interfaced to the radar for "unfolding" range and/or velocity ambiguities prior to display. However, the combination of slower antenna rotation rate and time required for sophisticated postprocessing may result in as much as one to three minutes between complete display unpdates on future doppler radars compared to approximately 20 seconds for current network models.

OPERATIONAL DOPPLER WEATHER RADAR ADVANTAGES

The most widely known doppler weather radar advantage is in the area of vortex detection; for locating mesoscale cyclones and/or tornado votices. Lead times of up to 20 minutes prior to tornado occurrence appear to be possible with doppler weather radar, based upon studies at NSSL during the 1970's. Specifically, this is because rotation aloft within the tornado-producing Plains thunderstorm frequently precedes tornado occurrence. Doppler spectra from the Binger, Oklahoma tornado of 1981 (mentioned previously) are shown in Figure 10 as a function of range along the azimuth of the tornado.

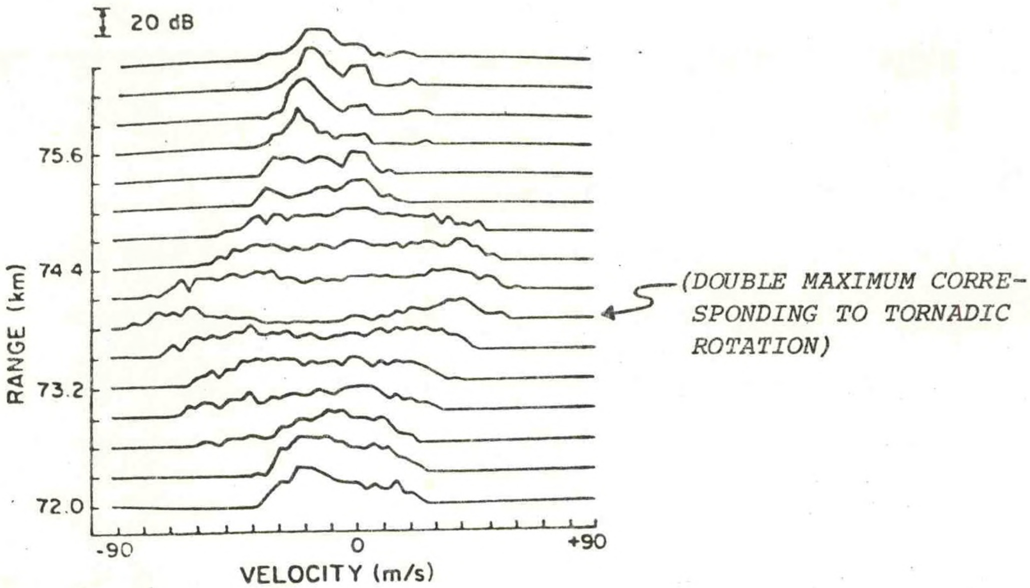

Figure 10. Doppler spectra from Binger, Oklahoma tornado on May 22, 1981. (Courtesy NSSL)

Recall here that the doppler radar, through analysis of the doppler shift, detects and displays only motions toward and away from the radar in the horizontal plane. Components of motion across the beam are not recognized. The radar thus "sees" a vortex (rotating system of small scale) turning cyclonically (counter-clockwise) as a reversal in mean wind direction within a small distance (see Figure 11).

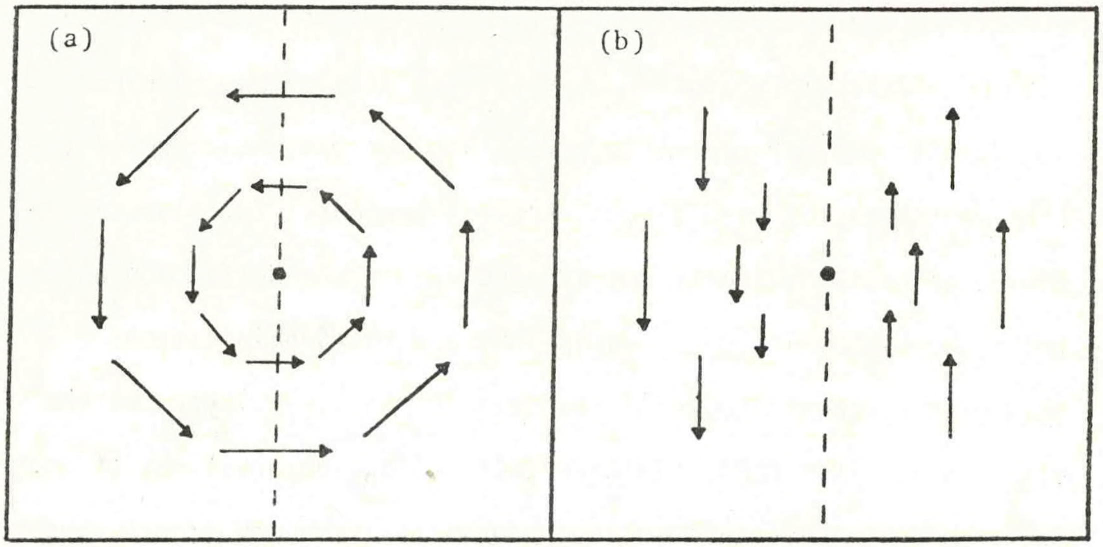

Figure 11. (a) Vortex circulation
(b) Associated radial velocity field
(Dashed line represents radial from transmitter site)

The double maximum in the spectrum at 73.8 Km. in Figure 10 corresponds to radial velocities in opposite directions and is known as a TORNADIC VORTEX SIGNATURE (TVS). In real time, with current doppler radars, this feature is typically visible as adjacent areas of bright contrasting colors in the radial velocity field, corresponding to directional reversal of strong winds within a small area. Presence of a vortex is also reflected in high spectrum widths.

Existing doppler weather radars generally have antenna systems of large size and thus, high gain compared to conventional weather radars. This decreases contamination of radial velocity and reflectivity fields by side lobe return and results in relatively high resolution in azimuth. High antenna gain allows some existing doppler weather radars to detect air motions where precipitation particles, or even clouds, are not present. In these cases, fields of radial velocity and spectrum width are based upon energy reflected by small density variations and non-precipitation particles which are typically present in the lower layers of the atmosphere. This CLEAR AIR CAPABILITY allows observations of such features as thunderstorm outflow boundaries, and dry fronts, and thus shows great potential for bridging a significant gap in our current operational meteorological intelligence. Analysis of radial velocity fields in clear air allows monitoring of convergent/divergent areas for forecasting of mesoscale development/dissipation as well as profiles of vertical wind shear for aviation forecasting and warning applications.

Other inherent advantages of contemporary doppler weather radar include the elimination of ground clutter in the radial velocity field. Lack of motion by the targets typically responsible for ground clutter eliminates them from the radial velocity display, allowing more detailed inspection of precipitation targets at close range than is possible with conventional radars.

Finally, doppler weather radar shows promise in depicting wind patterns associated with landfalling hurricanes, for use in assessing wind damage potential and determining areas of strong shear where the potential for tornadoes is relatively high. Much research and development remains to be done in this area.

OPERATIONAL DOPPLER WEATHER RADAR LIMITATIONS

Operating doppler weather radars provide a tremendous amount of observational information about the atmosphere, but at the same time require more sophisticated interpretation of radar return in terms of atmospheric structure and processes than is presently required with conventional radars. Contoured displays of radial velocity do not show motions directed across the beam ... called TRANSVERSE MOTIONS ... and may be NOISY (contaminated by insignificant or non-weather information). Optimum interpretation of the radial velocity field must be done in conjunction with both spectrum width and equivalent reflectivity displays to produce the most accurate picture of atmospheric events. Automated unfolding is not capable of removing range and/or velocity folding in extreme cases, and may instead complicate the problem of operator/user interpretation. Slow rotation rate and postprocessing, as discussed earlier, may substantially delay updates of data displays compared to conventional radars. Finally, even with the comparatively high resolution capabilities of existing doppler weather radars, the small size of some types of tornadic vortices may preclude detection.