

CHAPTER 9

RADAR MEASUREMENTS

9.1 GENERAL

This chapter is an elementary discussion of meteorological microwave radars – the weather radar – used mostly to observe hydrometeors in the atmosphere. It places particular emphasis on the technical and operational characteristics that must be considered when planning, developing and operating radars and radar networks in support of Meteorological and Hydrological Services. It is supported by a substantial list of references. It also briefly mentions the high frequency radar systems used for observation of the ocean surface. Radars used for vertical profiles are discussed in Part II, Chapter 5.

9.1.1 The weather radar

Meteorological radars are capable of detecting precipitation and variations in the refractive index in the atmosphere which may be generated by local variations in temperature or humidity. Radar echoes may also be produced from airplanes, dust, birds or insects. This chapter deals with radars in common operational usage around the world. The meteorological radars having characteristics best suited for atmospheric observation and investigation transmit electromagnetic pulses in the 3–10 GHz frequency range (10–3 cm wavelength, respectively). They are designed for detecting and mapping areas of precipitation, measuring their intensity and motion, and perhaps their type. Higher frequencies are used to detect smaller hydrometeors, such as cloud or even fog droplets. Although this has valuable applications in cloud physics research, these frequencies are generally not used in operational forecasting because of excessive attenuation of the radar signal by the intervening medium. At lower frequencies, radars are capable of detecting variations in the refractive index of clear air, and they are used for wind profiling. Although they may detect precipitation, their scanning capabilities are limited by the size of the antenna required to achieve effective resolution.

The returned signal from the transmitted pulse encountering a weather target, called an echo, has an amplitude, a phase and a polarization. Most operational radars worldwide are still limited to analysis of the amplitude feature that is related to the size distribution and numbers of particles in the (pulse) volume illuminated by the radar beam. The

amplitude is used to determine a parameter called the reflectivity factor (Z) to estimate the mass of precipitation per unit volume or the intensity of precipitation through the use of empirical relations. A primary application is thus to detect, map and estimate the precipitation at ground level instantaneously, nearly continuously and over large areas.

Some research radars have used reflectivity factors measured at two polarizations of the transmitted and received waveform. Research continues to determine the value and potential of polarization systems for precipitation measurement and target state, but operational systems do not exist at present.

Doppler radars have the capability of determining the phase difference between the transmitted and received pulse. The difference is a measure of the mean Doppler velocity of the particles — the reflectivity weighted average of the radial components of the displacement velocities of the hydrometeors in the pulse volume. The Doppler spectrum width is a measurement of the spatial variability of the velocities and provides some indication of the wind shear and turbulence. Doppler radars offer a significant new dimension to weather radar observation and most new systems have this capability.

Modern weather radars should have characteristics optimized to produce the best data for operational requirements, and should be adequately installed, operated and maintained to utilize the capability of the system to the meteorologists' advantage.

9.1.2 Radar characteristics, terms and units

The selection of the radar characteristics, and consideration of the climate and the application, are important for determining the acceptable accuracy of measurements for precipitation estimation (Tables 9.1, 9.2 and 9.3).

9.1.3 Meteorological applications

Radar observations have been found most useful for the following:

- (a) Severe weather detection, tracking and warning;

- (b) Surveillance of synoptic and mesoscale weather systems;
- (c) Estimation of precipitation amounts.

The radar characteristics of any one radar will not be ideal for all applications. The selection criteria of a radar system are usually optimized to meet several applications, but they can also be specified to best meet a specific application of major importance. The choices of wavelength, beamwidth, pulse length, and pulse repetition frequencies (PRFs) have particular consequences. Users should therefore carefully consider the applications and climatology before determining the radar specifications.

Severe weather detection and warning

A radar is the only realistic surface-based means of monitoring severe weather over a wide area. Radar echo intensities, area and patterns can be used to identify areas of severe weather, including thunderstorms with probable hail and damaging winds. Doppler radars that can identify and provide a measurement of intense winds associated with gust fronts, downbursts and tornadoes add a new dimension. The nominal range of coverage is about 200 km, which is sufficient for local short-range forecasting and warning. Radar networks are used to extend the coverage (Browning and others, 1982). Effective warnings require effective interpretation performed by alert and well-trained personnel.

Table 9.1. Radar frequency bands

Radar band	Frequency	Wavelength	Nominal
UHF	300-1 000 MHz	1-0.3 m	70 cm
L	1 000-2 000 MHz	0.3-0.15 m	20 cm
S ^a	2 000-4 000 MHz	15-7.5 cm	10 cm
C ^a	4 000-8 000 MHz	7.5-3.75 cm	5 cm
X ^a	8 000-12 500 MHz	3.75-2.4 cm	3 cm
K _u	12.5-18 GHz	2.4-1.66 cm	1.50 cm
K	18-26.5 GHz	1.66-1.13 cm	1.25 cm
K _a	26.5-40 GHz	1.13-0.75 cm	0.86 cm
W	94 GHz	0.30 cm	0.30 cm

^a Most common weather radar bands.

Table 9.2. Some meteorological radar parameters and units

Symbol	Parameter	Units
Z_e	Equivalent or effective radar reflectivity	mm ⁶ m ⁻³ or dBZ
V_r	Mean radial velocity	m s ⁻¹
σ_v	Spectrum width	m s ⁻¹
Z_{dr}	Differential reflectivity	dB
CDR	Circular depolarization ratio	dB
LDR	Linear depolarization ratio	dB
k_{dp}	Propagation phase	Degree km ⁻¹
ρ	Correlation coefficient	

Table 9.3. Physical radar parameters and units

Symbol	Parameter	Units
c	Speed of light	m s ⁻¹
f	Transmitted frequency	Hz
fd	Doppler frequency shift	Hz
P_r	Received power	mW or dBm
P_t	Transmitted power	kW
PRF	Pulse repetition frequency	Hz
T	Pulse repetition time (=1/PRF)	ms
Ω	Antenna rotation rate	Degree s ⁻¹ or rpm
λ	Transmitted wavelength	cm
ϕ	Azimuth angle	Degree
θ	Beamwidth between half power points	Degree
τ	Pulse width	μs
γ	Elevation angle	Degree

Surveillance of synoptic and mesoscale systems

Radars can provide a nearly continuous monitoring of weather related to synoptic and mesoscale storms over a large area (say a range of 220 km,

area 125 000 km²) if unimpeded by hills. Owing to ground clutter at short ranges and the Earth's curvature, the maximum practical range for weather observation is about 200 km. Over large water areas, other means of observation are often not available or possible. Networks can extend the coverage and may be cost effective. Radars provide a good description of precipitation. Narrower beamwidths provide better resolution of patterns and greater effectiveness at longer ranges. In regions where very heavy and extensive precipitation is common, a 10-cm wavelength is needed for good precipitation measurements. In other areas, such as mid-latitudes, 5 cm radars may be effective at much lower cost. The 3 cm wavelength suffers from too much attenuation in precipitation to be very effective, except for very light rain or snow conditions. Development work is beginning on the concept of dense networks of 3 cm radars with polarimetric capabilities that could overcome the attenuation problem of stand-alone 3 cm radars.

Precipitation estimation

Radars have a long history of use in estimating the intensity and thereby the amount and distribution of precipitation with a good resolution in time and space. Most studies have been associated with rainfall, but snow measurements can also be taken with appropriate allowances for target composition. Readers should consult reviews by Joss and Waldvogel (1990), and Smith (1990) for a comprehensive discussion of the state of the art, the techniques, the problems and pitfalls, and the effectiveness and accuracy.

Ground-level precipitation estimates from typical radar systems are made for areas of typically 2 km², successively for 5–10 minute periods using low elevation plan position indicator scans with beamwidths of 1°. The radar estimates have been found to compare with spot precipitation gauge measurements within a factor of two. Gauge and radar measurements are both estimates of a continually varying parameter. The gauge samples an extremely small area (100 cm², 200 cm²), while the radar integrates over a volume, on a much larger scale. The comparability may be enhanced by adjusting the radar estimates with gauge measurements.

9.1.4 **Meteorological products**

A radar can be made to provide a variety of meteorological products to support various applications. The products that can be generated by a weather

radar depend on the type of radar, its signal processing characteristics, and the associated radar control and analysis system. Most modern radars automatically perform a volume scan consisting of a number of full azimuth rotations of the antenna at several elevation angles. All raw polar data are stored in a three-dimensional array, commonly called the volume database, which serves as the data source for further data processing and archiving. By means of application software, a wide variety of meteorological products is generated and displayed as images on a high-resolution colour display monitor. Grid or pixel values and conversion to x-y coordinates are computed using three-dimensional interpolation techniques. For a typical Doppler weather radar, the displayed variables are reflectivity, rainfall rate, radial velocity and spectrum width. Each image pixel represents the colour-coded value of a selected variable.

The following is a list of the measurements and products generated, most of which are discussed in this chapter:

- (a) The plan position indicator: A polar format display of a variable, obtained from a single full antenna rotation at one selected elevation. It is the classic radar display, used primarily for weather surveillance;
- (b) The range height indicator: A display of a variable obtained from a single elevation sweep, typically from 0 to 90°, at one azimuth. It is also a classic radar display that shows detailed cross-section structures and it is used for identifying severe storms, hail and the bright band;
- (c) The constant altitude plan position indicator (CAPPI): A horizontal cross-section display of a variable at a specified altitude, produced by interpolation from the volume data. It is used for surveillance and for identification of severe storms. It is also useful for monitoring the weather at specific flight levels for air traffic applications. The “no data” regions as seen in the CAPPI (close to and away from the radar with reference to the selected altitude) are filled with the data from the highest and lowest elevation, respectively, in another form of CAPPI, called “Pseudo CAPPI”;
- (d) Vertical cross-section: A display of a variable above a user-defined surface vector (not necessarily through the radar). It is produced by interpolation from the volume data;
- (e) The column maximum: A display, in plan, of the maximum value of a variable above each point of the area being observed;
- (f) Echo tops: A display, in plan, of the height of the highest occurrence of a selectable reflectivity contour, obtained by searching in

the volume data. It is an indicator of severe weather and hail;

- (g) Vertically integrated liquid: An indicator of the intensity of severe storms. It can be displayed, in plan, for any specified layer of the atmosphere.

In addition to these standard or basic displays, other products can be generated to meet the particular requirements of users for purposes such as hydrology, nowcasting (see section 9.10) or aviation:

- (a) Precipitation-accumulation: An estimate of the precipitation accumulated over time at each point in the area observed;
- (b) Precipitation subcatchment totals: Area-integrated accumulated precipitation;
- (c) Velocity azimuth display (VAD): An estimate of the vertical profile of wind above the radar. It is computed from a single antenna rotation at a fixed elevation angle;
- (d) Velocity volume processing, which uses three-dimensional volume data;
- (e) Storm tracking: A product from complex software to determine the tracks of storm cells and to predict future locations of storm centroids;
- (f) Wind shear: An estimate of the radial and tangential wind shear at a height specified by the user;
- (g) Divergence profile: An estimation of divergence from the radial velocity data from which divergence profile is obtained given some assumptions;
- (h) Mesocyclone: A product from sophisticated pattern recognition software that identifies rotation signatures within the three-dimensional base velocity data that are on the scale of the parent mesocyclonic circulation often associated with tornadoes;
- (i) Tornadic vortex signature: A product from sophisticated pattern recognition software that identifies gate-to-gate shear signatures within the three-dimensional base velocity data that are on the scale of tornadic vortex circulations.

9.1.5 Radar accuracy requirements

The accuracy requirements depend on the most important applications of the radar observations. Appropriately installed, calibrated and maintained modern radars are relatively stable and do not produce significant measurement errors. External factors, such as ground clutter effects, anomalous propagation, attenuation and propagation effects, beam effects, target composition, particularly with variations and changes in the vertical,

and rain rate-reflectivity relationship inadequacies, contribute most to the inaccuracy.

By considering only errors attributable to the radar system, the measurable radar parameters can be determined with an acceptable accuracy (Table 9.4).

Table 9.4. Accuracy requirements

<i>Parameter</i>	<i>Definition</i>	<i>Acceptable accuracy^a</i>
ϕ	Azimuth angle	0.1°
γ	Elevation angle	0.1°
V_r	Mean Doppler velocity	1.0 m s ⁻¹
Z	Reflectivity factor	1 dBZ
σ_v	Doppler spectrum width	1 m s ⁻¹

^a These figures are relative to a normal Gaussian spectrum with a standard deviation smaller than 4 m⁻¹. Velocity accuracy deteriorates when the spectrum width grows, while reflectivity accuracy improves.

9.2 RADAR TECHNOLOGY

9.2.1 Principles of radar measurement

The principles of radar and the observation of weather phenomena were established in the 1940s. Since that time, great strides have been made in improving equipment, signal and data processing and its interpretation. The interested reader should consult some of the relevant texts for greater detail. Good references include Skolnik (1970) for engineering and equipment aspects; Battan (1981) for meteorological phenomena and applications; Atlas (1964; 1990), Sauvageot (1982) and WMO (1985) for a general review; Rinehart (1991) for modern techniques; and Doviak and Zrnic (1993) for Doppler radar principles and applications. A brief summary of the principles follows.

Most meteorological radars are pulsed radars. Electromagnetic waves at fixed preferred frequencies are transmitted from a directional antenna into the atmosphere in a rapid succession of short pulses. Figure 9.1 shows a directional radar antenna emitting a pulsed-shaped beam of electromagnetic

energy over the Earth's curved surface and illuminating a portion of a meteorological target. Many of the physical limitations and constraints of the observation technique are immediately apparent from the figure. For example, there is a limit to the minimum altitude that can be observed at far ranges due to the curvature of the Earth.

A parabolic reflector in the antenna system concentrates the electromagnetic energy in a conical-shaped beam that is highly directional. The width of the beam increases with range, for example, a nominal 1° beam spreads to 0.9, 1.7 and 3.5 km at ranges of 50, 100, and 200 km, respectively.

The short bursts of electromagnetic energy are absorbed and scattered by any meteorological targets encountered. Some of the scattered energy is reflected back to the radar antenna and receiver. Since the electromagnetic wave travels with the speed of light (that is, $2.99 \times 10^8 \text{ m s}^{-1}$), by measuring the time between the transmission of the pulse and its return, the range of the target is determined. Between successive pulses, the receiver listens for any return of the wave. The return signal from the target is commonly referred to as the radar echo.

The strength of the signal reflected back to the radar receiver is a function of the concentration, size and water phase of the precipitation particles that make up the target. The power return, P_r , therefore provides a measure of the characteristics of the meteorological target and is, but not uniquely, related to a precipitation rate depending on the form of precipitation. The "radar range equation"

relates the power-return from the target to the radar characteristics and parameters of the target.

The power measurements are determined by the total power backscattered by the target within a volume being sampled at any one instant — the pulse volume (i.e. sample volume). The pulse volume dimensions are dependent on the radar pulse length in space (h) and the antenna beam widths in the vertical (ϕ_b) and the horizontal (θ_b). The beam width, and therefore the pulse volume, increases with range. Since the power that arrives back at the radar is involved in a two-way path, the pulse-volume length is only one half pulse length in space ($h/2$) and is invariant with range. The location of the pulse volume in space is determined by the position of the antenna in azimuth and elevation and the range to the target. The range (r) is determined by the time required for the pulse to travel to the target and to be reflected back to the radar.

Particles within the pulse volume are continuously shuffling relative to one another. This results in phase effects in the scattered signal and in intensity fluctuations about the mean target intensity. Little significance can be attached to a single echo intensity measurement from a weather target. At least 25 to 30 pulses must be integrated to obtain a reasonable estimation of mean intensity (Smith, 1995). This is normally carried out electronically in an integrator circuit. Further averaging of pulses in range, azimuth and time is often conducted to increase the sampling size and accuracy of the estimate. It follows that the space resolution is coarser.

9.2.2 The radar equation for precipitation targets

Meteorological targets consist of a volume of more or less spherical particles composed entirely of ice and/or water and randomly distributed in space. The power backscattered from the target volume is dependent on the number, size, composition, relative position, shape and orientation of the scattering particles. The total power backscattered is the sum of the power backscattered by each of the scattering particles.

Using this target model and electromagnetic theory, Probert-Jones (1962) developed an equation relating the echo power received by the radar to the parameters of the radar and the targets' range and scattering characteristics. It is generally accepted as being a reliable relationship to provide quantitative reflectivity measurements with good accuracy, bearing in mind the generally realistic assumptions made in the derivation:

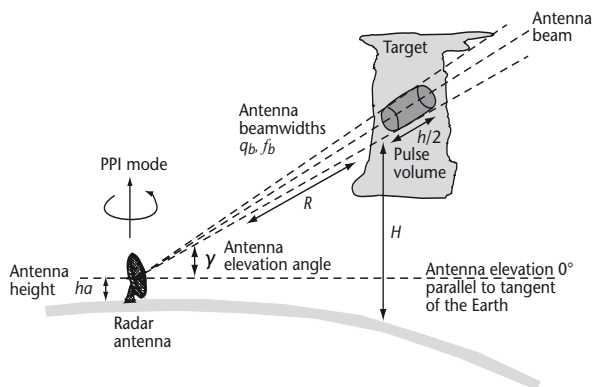


Figure 9.1. Propagation of electromagnetic waves through the atmosphere for a pulse weather radar; h_a is the height of the antenna above the Earth's surface, R is the range, h is the length of the pulse, $h/2$ is the sample volume depth and H is the height of the pulse above the Earth's surface

$$\bar{P}_r = \frac{\pi^3}{1024 \ln 2} \cdot \frac{P_t h G^2 \theta_b \phi_b}{\lambda^2} \cdot \frac{|K|^2 10^{-18} Z}{r^2} \quad (9.1)$$

where \bar{P}_r is the power received back at the radar, averaged over several pulses, in watts; P_t is the peak power of the pulse transmitted by the radar in watts; h is the pulse length in space, in metres ($h = c\tau/2$ where c is the speed of light and τ is the pulse duration); G is the gain of the antenna over an isotropic radiator; θ_b and ϕ_b are the horizontal and vertical beamwidths, respectively, of the antenna radiation pattern at the -3 dB level of one-way transmission, in radians; λ is the wavelength of the transmitted wave, in metres; $|K|^2$ is the refractive index factor of the target; r is the slant range from the radar to the target, in metres; and Z is the radar reflectivity factor (usually taken as the equivalent reflectivity factor Z_e when the target characteristics are not well known), in $\text{mm}^6 \text{m}^{-3}$.

The second term in the equation contains the radar parameters, and the third term the parameters depending on the range and characteristics of the target. The radar parameters, except for the transmitted power, are relatively fixed, and, if the transmitter is operated and maintained at a constant output (as it should be), the equation can be simplified to:

$$\bar{P}_r = \frac{C |K|^2 Z}{r^2} \quad (9.2)$$

where C is the radar constant.

There are a number of basic assumptions inherent in the development of the equation which have varying importance in the application and interpretation of the results. Although they are reasonably realistic, the conditions are not always met exactly and, under particular conditions, will affect the measurements (Aoyagi and Kodaira, 1995). These assumptions are summarized as follows:

- (a) The scattering precipitation particles in the target volume are homogeneous dielectric spheres whose diameters are small compared to the wavelength, that is $D < 0.06 \lambda$ for strict application of Rayleigh scattering approximations;
- (b) The pulse volume is completely filled with randomly scattered precipitation particles;
- (c) The reflectivity factor Z is uniform throughout the sampled pulse volume and constant during the sampling interval;
- (d) The particles are all water drops or all ice particles, that is, all particles have the same refractive index factor $|K|^2$ and the power scattering by the particles is isotropic;

- (e) Multiple scattering (among particles) is negligible;
- (f) There is no attenuation in the intervening medium between the radar and the target volume;
- (g) The incident and backscattered waves are linearly co-polarized;
- (h) The main lobe of the antenna radiation pattern is Gaussian in shape;
- (i) The antenna is a parabolic reflector type of circular cross-section;
- (j) The gain of the antenna is known or can be calculated with sufficient accuracy;
- (k) The contribution of the side lobes to the received power is negligible;
- (l) Blockage of the transmitted signal by ground clutter in the beam is negligible;
- (m) The peak power transmitted (P_t) is the actual power transmitted at the antenna, that is, all wave guide losses, and so on, and attenuation in the radar dome, are considered;
- (n) The average power measured (P_r) is averaged over a sufficient number of pulses or independent samples to be representative of the average over the target pulse volume.

This simplified expression relates the echo power measured by the radar to the radar reflectivity factor Z , which is in turn related to the rainfall rate. These factors and their relationship are crucial for interpreting the intensity of the target and estimating precipitation amounts from radar measurements. Despite the many assumptions, the expression provides a reasonable estimate of the target mass. This estimate can be improved by further consideration of factors in the assumptions.

9.2.3 Basic weather radar

The basic weather radar consists of the following:

- (a) A transmitter to produce power at microwave frequency;
- (b) An antenna to focus the transmitted microwaves into a narrow beam and receive the returning power;
- (c) A receiver to detect, amplify and convert the microwave signal into a low frequency signal;
- (d) A processor to extract the desired information from the received signal;
- (e) A system to display the information in an intelligible form.

Other components that maximize the radar capability are:

- (a) A processor to produce supplementary displays;

- (b) A recording system to archive the data for training, study and records.

A basic weather radar may be non-coherent, that is, the phase of successive pulses is random and unknown.

Almost exclusively current systems use computers for radar control, digital signal processing, recording, product displays and archiving.

The power backscattered from a typical radar is of the order of 10^{-8} to 10^{-15} W, covering a range of about 70 dB from the strongest to weakest targets detectable. To adequately cover this range of signals, a logarithmic receiver was used in the past. However, modern operational and research radars with linear receivers with 90 dB dynamic range (and other sophisticated features) are just being introduced (Heiss, McGrew and Sirmans, 1990; Keeler, Hwang and Loew, 1995). Many pulses must be averaged in the processor to provide a significant measurement; they can be integrated in different ways, usually in a digital form, and must account for the receiver transfer function (namely, linear or logarithmic). In practice, for a typical system, the signal at the antenna is received, amplified, averaged over many pulses, corrected for receiver transfer, and converted to a reflectivity factor Z using the radar range equation.

The reflectivity factor is the most important parameter for radar interpretation. The factor derives from the Rayleigh scattering model and is defined theoretically as the sum of particle (drops) diameters to the sixth power in the sample volume:

$$Z = \sum_{vol} D^6 \quad (9.3)$$

where the unit of Z is $\text{mm}^6 \text{m}^{-3}$. In many cases, the numbers of particles, composition and shape are not known and an equivalent or effective reflectivity factor Z_e is defined. Snow and ice particles must refer to an equivalent Z_e which represents Z , assuming the backscattering particles were all spherical drops.

A common practice is to work in a logarithmic scale or dBZ units which are numerically defined as $\text{dBZ} = 10 \log_{10} Z_e$.

Volumetric observations of the atmosphere are normally made by scanning the antenna at a fixed elevation angle and subsequently incrementing the elevation angle in steps at each revolution. An important consideration is the resolution of the targets. Parabolic reflector antennas are used to

focus the waves into a pencil shaped beam. Larger reflectors create narrower beams, greater resolution and sensitivity at increasing costs. The beamwidth, the angle subtended by the line between the two points on the beam where the power is one half that at the axis, is dependent on the wavelength, and may be approximated by:

$$\theta_e = \frac{70\lambda}{d} \quad (9.4)$$

where the units of θ_e are degrees; and d is the antenna diameter in the same units as λ . Good weather radars have beamwidths of 0.5 to 1°.

The useful range of weather radars, except for long-range detection only of thunderstorms, is of the order of 200 km. The beam at an elevation of, for example, 0.5° is at a height of 4 km above the Earth's surface. Also, the beamwidth is of the order of 1.5 km or greater. For good quantitative precipitation measurements, the range is less than 200 km. At long ranges, the beam is too high for ground estimates. Also, beam spreading reduces resolution and the measurement can be affected by underfilling with target. Technically, there is a maximum unambiguous range determined by the pulse repetition frequency (equation 9.6) since the range must be measured during the listening period between pulses. At usual PRFs this is not a problem. For example, with a PRF of 250 pulses per second, the maximum range is 600 km. At higher PRFs, typically 1 000 pulses per second, required for Doppler systems, the range will be greatly reduced to about 150 km. New developments may ameliorate this situation (Joe, Passarelli and Siggia, 1995).

9.2.4 Doppler radar

The development of Doppler weather radars and their introduction to weather surveillance provide a new dimension to the observations (Heiss, McGrew and Sirmans, 1990). Doppler radar provides a measure of the targets' velocity along a radial from the radar in a direction either towards or away from the radar. A further advantage of the Doppler technique is the greater effective sensitivity to low reflectivity targets near the radar noise level when the velocity field can be distinguished in a noisy Z field.

At the normal speeds of meteorological targets, the frequency shift is relatively small compared with the radar frequency and is very difficult to measure. An easier task is to retain the phase of the transmitted pulse, compare it with the phase of the received pulse and then determine the change in phase between successive pulses. The time rate

of change of the phase is then directly related to the frequency shift, which in turn is directly related to the target velocity – the Doppler effect. If the phase changes by more than $\pm 180^\circ$, the velocity estimate is ambiguous. The highest unambiguous velocity that can be measured by a Doppler radar is the velocity at which the target moves, between successive pulses, more than a quarter of the wavelength. At higher speeds, an additional processing step is required to retrieve the correct velocity.

The maximum unambiguous Doppler velocity depends on the radar wavelength (λ), and the PRF and can be expressed as:

$$V_{max} = \pm \frac{PRF \cdot \lambda}{4} \quad (9.5)$$

The maximum unambiguous range can be expressed as:

$$r_{max} = \frac{c}{PRF \cdot 2} \quad (9.6)$$

Thus, V_{max} and r_{max} are related by the equation:

$$V_{max} r_{max} = \pm \frac{\lambda c}{8} \quad (9.7)$$

These relationships show the limits imposed by the selection of the wavelength and PRF. A high PRF is desirable to increase the unambiguous velocity; a low PRF is desirable to increase the radar range. A compromise is required until better technology is available to retrieve the information unambiguously outside these limits (Doviak and Zrnic, 1993; Joe, Passarelli and Siggia, 1995). The relationship also shows that the longer wavelengths have higher limits. In numerical terms, for a typical S-band radar with a PRF of 1 000 Hz, $V_{max} = \pm 25 \text{ m s}^{-1}$, while for an X-band radar $V_{max} = \pm 8 \text{ m s}^{-1}$.

Because the frequency shift of the returned pulse is measured by comparing the phases of the transmitted and received pulses, the phase of the transmitted pulses must be known. In a non-coherent radar, the phase at the beginning of successive pulses is random and unknown, so such a system cannot be used for Doppler measurements; however, it can be used for the basic operations described in the previous section.

Some Doppler radars are fully coherent; their transmitters employ very stable frequency sources, in which phase is determined and known from pulse to pulse. Semi-coherent radar systems, in which the

phase of successive pulses is random but known, are cheaper and more common. Fully coherent radars typically employ klystrons in their high-power output amplifiers and have their receiver frequencies derived from the same source as their transmitters. This approach greatly reduces the phase instabilities found in semi-coherent systems, leading to improved ground clutter rejection and better discrimination of weak clear-air phenomena which might otherwise be masked. The microwave transmitter for non-coherent and semi-coherent radars is usually a magnetron, given that it is relatively simple, cheaper and provides generally adequate performance for routine observations. A side benefit of the magnetron is the reduction of Doppler response to second or third trip echoes (echoes arriving from beyond the maximum unambiguous range) due to their random phase, although the same effect could be obtained in coherent systems by introducing known pseudo-random phase disturbances into the receiver and transmitter.

Non-coherent radars can be converted relatively easily to a semi-coherent Doppler system. The conversion should also include the more stable coaxial-type magnetron.

Both reflectivity factor and velocity data are extracted from the Doppler radar system. The target is typically a large number of hydrometeors (rain drops, snow flakes, ice pellets, hail, etc.) of all shapes and sizes and moving at different speeds due to the turbulent motion within the volume and due to their fall speeds. The velocity field is therefore a spectrum of velocities — the Doppler spectrum (Figure 9.2).

Two systems of different complexity are used to process the Doppler parameters. The simpler pulse pair processing (PPP) system uses the comparison of successive pulses in the time domain to extract mean velocity and spectrum width. The second and more complex system uses a fast Fourier transform (FFT) processor to produce a full spectrum of velocities in each sample volume. The PPP system is faster, less computationally intensive and better at low signal-to-noise ratios, but has poorer clutter rejection characteristics than the FFT system. Modern systems try to use the best of both approaches by removing clutter using FFT techniques and subsequently use PPP to determine the radial velocity and spectral width.

9.2.5 Polarization diversity radars

Experiments with polarization diversity radars have been under way for many years to determine their potential for enhanced radar observations of

the weather (Bringi and Hendry, 1990). Promising studies point towards the possibility of differentiating between hydrometeor types, a step to discriminating between rain, snow and hail. There are practical technical difficulties, and the techniques and applications have not progressed beyond the research stage to operational usage. The potential value of polarization diversity measurements for precipitation measurement would seem to lie in the fact that better drop size distribution and knowledge of the precipitation types would improve the measurements. Recent work at the United States National Severe Storms Laboratory (Melnikov and others, 2002) on adding polarimetric capability to the NEXRAD radar has demonstrated a robust engineering design utilizing simultaneous transmission and reception of both horizontally and vertically polarized pulses. The evaluation of polarimetric moments, and derived products for rainfall accumulation and hydrometeor classification, has shown that this design holds great promise as a basis for adding polarization diversity to the entire NEXRAD network.

There are two basic radar techniques in current usage. One system transmits a circularly polarized wave, and the copolar and orthogonal polarizations are measured. The other system alternately transmits pulses with horizontal then vertical polarization utilizing a high-power switch. The linear system is generally preferred since meteorological information retrieval is less calculation intensive. The latter technique is more common as conventional radars

are converted to have polarization capability. However, the former type of system has some distinct technological advantages. Various polarization bases (Holt, Chandra and Wood, 1995) and dual transmitter systems (Mueller and others, 1995) are in the experimental phase. The main differences in requirements from conventional radars relate to the quality of the antenna system, the accuracy of the electronic calibration and signal processing. Matching the beams, switching polarizations and the measurement of small differences in signals are formidable tasks requiring great care when applying the techniques.

The technique is based on micro-differences in the scattering particles. Spherical raindrops become elliptically shaped with the major axis in the horizontal plane when falling freely in the atmosphere. The oblateness of the drop is related to drop size. The power backscattered from an oblate spheroid is larger for a horizontally polarized wave than for a vertically polarized wave assuming Rayleigh scattering. Using suitable assumptions, a drop size distribution can be inferred and thus a rainfall rate can be derived.

The differential reflectivity, called Z_{DR} , is defined as 10 times the logarithm of the ratio of the horizontally polarized reflectivity Z_H and the vertically polarized reflectivity Z_V . Comparisons of the equivalent reflectivity factor Z_e and the differential reflectivity Z_{DR} suggest that the target may be separated as being hail, rain, drizzle or snow (Seliga and Bringi, 1976).

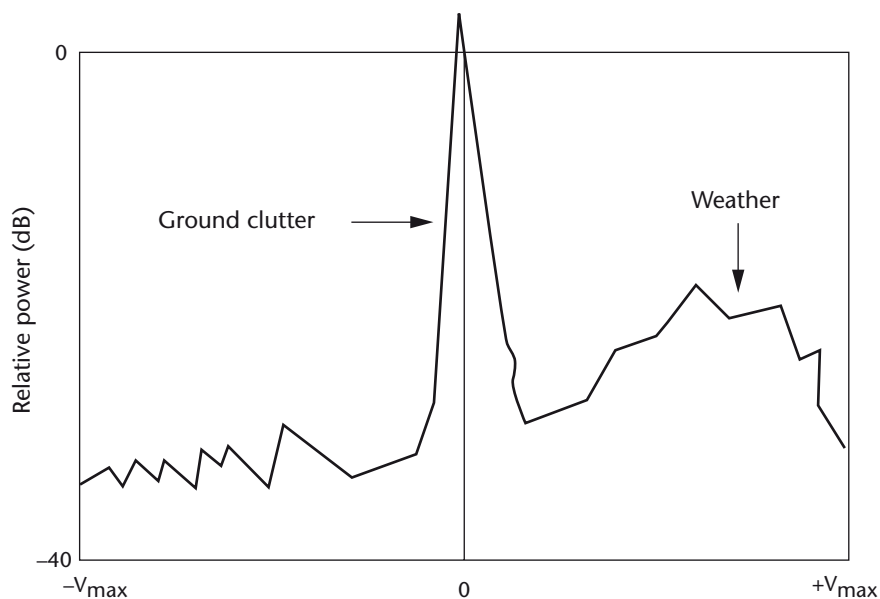


Figure 9.2. The Doppler spectrum of a weather echo and a ground target. The ground target contribution is centred on zero and is much narrower than the weather echo.

As an electromagnetic wave propagates through a medium with oblate particles, the phase of the incident beam is altered. The effect on the vertical and horizontal phase components depends on the oblateness and is embodied in a parameter termed the specific differential phase (K_{DP}). For heavy rainfall measurements, K_{DP} has certain advantages (Zrnich and Ryzhkov, 1995). English and others (1991) demonstrated that the use of K_{DP} for rainfall estimation is much better than Z for rainfall rates greater than about 20 mm hr^{-1} at the S-band.

Propagation effects on the incident beam due to the intervening medium can dominate target backscatter effects and confound the interpretation of the resulting signal. Bebbington (1992) designed a parameter for a circularly polarized radar, termed the degree of polarization, which was insensitive to propagation effects. This parameter is similar to linear correlation for linearly polarized radars. It appears to have value in target discrimination. For example, extremely low values are indicative of scatterers that are randomly oriented such as those caused by airborne grass or ground clutter (Holt and others, 1993).

9.2.6 Ground clutter rejection

Echoes due to non-precipitation targets are known as clutter, and should be eliminated. Echoes caused by clear air or insects which can be used to map out wind fields are an exception. Clutter can be the result of a variety of targets, including buildings, hills, mountains, aircraft and chaff, to name just a few. Good radar siting is the first line of defence against ground clutter effects. However, clutter is always present to some extent. The intensity of ground clutter is inversely proportional to wavelength (Skolnik, 1970), whereas backscatter from rain is inversely proportional to the fourth power of wavelength. Therefore, shorter wavelength radars are less affected by ground clutter.

Point targets, like aircraft, can be eliminated, if they are isolated, by removing echoes that occupy a single radar resolution volume. Weather targets are distributed over several radar resolution volumes. The point targets can be eliminated during the data-processing phase. Point targets, like aircraft echoes, embedded within precipitation echoes may not be eliminated with this technique depending on relative strength.

Distributed targets require more sophisticated signal and data-processing techniques. A conceptually attractive idea is to use clutter maps. The patterns of radar echoes in non-precipitating conditions are

used to generate a clutter map that is subtracted from the radar pattern collected in precipitating conditions. The problem with this technique is that the pattern of ground clutter changes over time. These changes are primarily due to changes in meteorological conditions; a prime example is anomalous propagation echoes that last several hours and then disappear. Micro-changes to the environment cause small fluctuations in the pattern of ground echoes which confound the use of clutter maps. Adaptive techniques (Joss and Lee, 1993) attempt to determine dynamically the clutter pattern to account for the short-term fluctuations, but they are not good enough to be used exclusively, if at all.

Doppler processing techniques attempt to remove the clutter from the weather echo from a signal-processing perspective. The basic assumption is that the clutter echo is narrow in spectral width and that the clutter is stationary. However, to meet these first criteria, a sufficient number of pulses must be acquired and processed in order to have sufficient spectral resolution to resolve the weather from the clutter echo. A relatively large Nyquist interval is also needed so that the weather echo can be resolved. The spectral width of ground clutter and weather echo is generally much less than $1\text{--}2 \text{ m s}^{-1}$ and greater than 1^{-2} m s^{-1} , respectively. Therefore, Nyquist intervals of about 8 m s^{-1} are needed. Clutter is generally stationary and is identified as a narrow spike at zero velocity in the spectral representation (Figure 9.2). The spike has finite width because the ground echo targets, such as swaying trees, have some associated motions. Time domain processing to remove the zero velocity (or DC) component of a finite sequence is problematic since the filtering process will remove weather echo at zero velocity as well (Zrnich and Hamidi, 1981). Adaptive spectral (Fourier transform) processing can remove the ground clutter from the weather echoes even if they are overlapped (Passarelli and others, 1981; Crozier and others, 1991). This is a major advantage of spectral processing. Stripped of clutter echo, the significant meteorological parameters can be computed.

An alternative approach takes advantage of the observation that structures contributing to ground clutter are very small in scale (less than, for example, 100 m). Range sampling is carried out at a very fine resolution (less than 100 m) and clutter is identified using reflectivity and Doppler signal processing. Range averaging (to a final resolution of 1 km) is performed with clutter-free range bins. The philosophy is to detect and ignore range bins with clutter, rather than to correct for

the clutter (Joss and Lee, 1993; Lee, Della Bruna and Joss, 1995). This is radically different from the previously discussed techniques and it remains to be seen whether the technique will be effective in all situations, in particular in anomalous propagation situations where the clutter is widespread.

Polarization radars can also identify clutter. However, more work is needed to determine their advantages and disadvantages.

Clutter can be reduced by careful site selection (see section 9.7). Radars used for long-range surveillance, such as for tropical cyclones or in a widely scattered network, are usually placed on hilltops to extend the useful range, and are therefore likely to see many clutter echoes. A simple suppression technique is to scan automatically at several elevations, and to discard the data at the shorter ranges from the lower elevations, where most of the clutter exists. By processing the radar data into CAPPI products, low elevation data is rejected automatically at short ranges.

9.3 PROPAGATION AND SCATTERING OF RADAR SIGNALS

Electromagnetic waves propagate in straight lines, in a homogeneous medium, with the speed of light. The Earth's atmosphere is not homogeneous and microwaves undergo refraction, absorption and scattering along their path. The atmosphere is usually vertically stratified and the rays change direction depending on the changes in height of the refractive index (or temperature and moisture). When the waves encounter precipitation and clouds, part of the energy is absorbed and a part is scattered in all directions or back to the radar site.

9.3.1 Refraction in the atmosphere

The amount of bending of electromagnetic waves can be predicted by using the vertical profile of temperature and moisture (Bean and Dutton, 1966). Under normal atmospheric conditions, the waves travel in a curve bending slightly earthward. The ray path can bend either upwards (sub-refraction) or more earthward (super-refraction). In either case, the altitude of the beam will be in error using the standard atmosphere assumption.

From a precipitation measurement standpoint, the greatest problem occurs under super-refractive or "ducting" conditions. The ray can bend sufficiently

to strike the Earth and cause ground echoes not normally encountered. The phenomenon occurs when the index of refraction decreases rapidly with height, for example, an increase in temperature and a decrease in moisture with height. These echoes must be dealt with in producing a precipitation map. This condition is referred to as anomalous propagation (AP or ANAPROP).

Some "clear air" echoes are due to turbulent inhomogeneities in the refractive index found in areas of turbulence, layers of enhanced stability, wind shear cells, or strong inversions. These echoes usually occur in patterns, mostly recognizable, but must be eliminated as precipitation fields (Gossard and Strauch, 1983).

9.3.2 Attenuation in the atmosphere

Microwaves are subject to attenuation owing to atmospheric gases, clouds and precipitation by absorption and scattering.

Attenuation by gases

Gases attenuate microwaves in the 3–10 cm bands. Absorption by atmospheric gases is due mainly to water vapour and oxygen molecules. Attenuation by water vapour is directly proportional to the pressure and absolute humidity and increases almost linearly with decreasing temperature. The concentration of oxygen, to altitudes of 20 km, is relatively uniform. Attenuation is also proportional to the square of the pressure.

Attenuation by gases varies slightly with the climate and the season. It is significant at weather radar wavelengths over the longer ranges and can amount to 2 to 3 dB at the longer wavelengths and 3 to 4 dB at the shorter wavelengths, over a range of 200 km. Compensation seems worthwhile and can be quite easily accomplished automatically. Attenuation can be computed as a function of range on a seasonal basis for ray paths used in precipitation measurement and applied as a correction to the precipitation field.

Attenuation by hydrometeors

Attenuation by hydrometeors can result from both absorption and scattering. It is the most significant source of attenuation. It is dependent on the shape, size, number and composition of the particles. This dependence has made it very difficult to overcome in any quantitative way using radar observations alone. It has not been satisfactorily overcome for automated operational measurement systems yet. However, the phenomenon must be recognized and

the effects reduced by some subjective intervention using general knowledge.

Attenuation is dependent on wavelength. At 10 cm wavelengths, the attenuation is rather small, while at 3 cm it is quite significant. At 5 cm, the attenuation may be acceptable for many climates, particularly in the high mid-latitudes. Wavelengths below 5 cm are not recommended for good precipitation measurement except for short-range applications (Table 9.5).

Table 9.5. One-way attenuation relationships

Wavelength (cm)	Relation (dB km ⁻¹)
10	0.000 343 R ^{0.97}
5	0.00 18 R ^{1.05}
3.2	0.01 R ^{1.21}

After Burrows and Attwood (1949). One-way specific attenuations at 18°C. R is in units of mm hr⁻¹.

For precipitation estimates by radar, some general statements can be made with regard to the magnitude of attenuation. Attenuation is dependent on the water mass of the target, thus heavier rains attenuate more; clouds with much smaller mass attenuate less. Ice particles attenuate much less than liquid particles. Clouds and ice clouds cause little attenuation and can usually be ignored. Snow or ice particles (or hailstones) can grow much larger than raindrops. They become wet as they begin to melt and result in a large increase in reflectivity and, therefore, in attenuation properties. This can distort precipitation estimates.

9.3.3 Scattering by clouds and precipitation

The signal power detected and processed by the radar (namely, echo) is power backscattered by the target, or by hydrometeors. The backscattering cross-section (σ_b) is defined as the area of an isotropic scatterer that would return to the emitting source the same amount of power as the actual target. The backscattering cross-section of spherical particles was first determined by Mie (1908). Rayleigh found that, if the ratio of the particle diameter to the wavelength was equal to or less than 0.06, a simpler expression could be used to determine the backscatter cross-section:

$$\sigma_b = \frac{\pi^5 |K|^2 D^6}{\lambda^4} \tag{9.8}$$

which is the justification for equation 9.3. $|K|^2$, the refractive index factor, is equal to 0.93 for liquid water and 0.197 for ice.

The radar power measurements are used to derive the scattering intensity of the target by using equation 9.2 in the form:

$$z = \frac{C \bar{P}_r r^2}{|K|^2} \tag{9.9}$$

The method and problems of interpreting the reflectivity factor in terms of precipitation rate (R) are discussed in section 9.9.

9.3.4 Scattering in clear air

In regions without precipitating clouds, it has been found that echoes are mostly due to insects or to strong gradients of refractive index in the atmosphere. The echoes are of very low intensity and are detected only by very sensitive radars. Equivalent Z_e values for clear air phenomena generally appear in the range of -5 to -55 dBZ, although these are not true Z parameters, with the physical process generating the echoes being entirely different. For precipitation measurement, these echoes are a minor "noise" in the signal. They can usually be associated with some meteorological phenomenon such as a sea breeze or thunderstorm outflows. Clear air echoes can also be associated with birds and insects in very low concentrations. Echo strengths of 5 to 35 dBZ are not unusual, especially during migrations (Table 9.6).

Table 9.6. Typical backscatter cross-sections for various targets

Object	σ_b (m ²)
Aircraft	10 to 1 000
Human	0.14 to 1.05
Weather balloon	0.01
Birds	0.001 to 0.01
Bees, dragonflies, moths	3 x 10 ⁻⁶ to 10 ⁻⁵
2 mm water drop	1.8 x 10 ⁻¹⁰

Although normal radar processing would interpret the signal in terms of Z or R, the scattering properties of the clear atmosphere are quite different from that of hydrometeors. It is most often expressed in terms of the structure parameter of refractive index, C_n^2 . This is a measure of the mean-square fluctuations

of the refractive index as a function of distance (Gossard and Strauch, 1983).

9.4 VELOCITY MEASUREMENTS

9.4.1 The Doppler spectrum

Doppler radars measure velocity by estimating the frequency shift produced by an ensemble of moving targets. Doppler radars also provide information about the total power returned and about the spectrum width of the precipitation particles within the pulse volume. The mean Doppler velocity is equal to the mean motion of scatterers weighted by their cross-sections and, for near horizontal antenna scans, is essentially the air motion towards or away from the radar. Likewise, the spectrum width is a measure of the velocity dispersion, that is, the shear or turbulence within the resolution volume.

A Doppler radar measures the phase of the returned signal by referencing the phase of the received signal to the transmitter. The phase is measured in rectangular form by producing the in-phase (I) and quadrature (Q) components of the signal. The I and Q are samples at a fixed range location. They are collected and processed to obtain the mean velocity and spectrum width.

9.4.2 Doppler ambiguities

To detect returns at various ranges from the radar, the returning signals are sampled periodically, usually about every μs , to obtain information about every 150 m in range. This sampling can continue until it is time to transmit the next pulse. A sample point in time (corresponding to a distance from the radar) is called a range gate. The radial wind component throughout a storm or precipitation area is mapped as the antenna scans.

A fundamental problem with the use of any pulse Doppler radar is the removal of ambiguity in Doppler mean velocity estimates, that is, velocity folding. Discrete equi-spaced samples of a time-varying function result in a maximum unambiguous frequency equal to one half of the sampling frequency (f_s). Subsequently, frequencies greater than $f_s/2$ are aliased ("folded") into the Nyquist co-interval ($\pm f_s/2$) and are interpreted as velocities within $\pm \lambda f_s/4$, where λ is the wavelength of transmitted energy.

Techniques to dealias the velocities include dual PRF techniques (Crozier and others, 1991; Doviak

and Zrnic, 1993) or continuity techniques (Eilts and Smith, 1990). In the former, radial velocity estimates are collected at two different PRFs with different maximum unambiguous velocities and are combined to yield a new estimate of the radial velocity with an extended unambiguous velocity. For example, a C band radar using PRFs of 1 200 and 900 Hz has nominal unambiguous velocities of 16 and 12 m s^{-1} , respectively. The amount of aliasing can be deduced from the difference between the two velocity estimates to dealias the velocity to an extended velocity range of $\pm 48 \text{ m s}^{-1}$ (Figure 9.3).

Continuity techniques rely on having sufficient echo to discern that there are aliased velocities and correcting them by assuming velocity continuity (no discontinuities of greater than $2V_{max}$).

There is a range limitation imposed by the use of high PRFs (greater than about 1 000 Hz) as described in section 9.2. Echoes beyond the maximum range will be aliased back into the primary range. For radars with coherent transmitters (e.g. klystron systems), the echoes will appear within the primary range. For coherent-on-receive systems, the second trip echoes will appear as noise (Joe, and Passarelli and Siggia, 1995; Passarelli and others 1981).

9.4.3 Vertically pointing measurements

In principle, a Doppler radar operating in the vertically-pointing mode is an ideal tool for obtaining accurate cloud-scale measurements of vertical wind speeds and drop-size distributions (DSDs). However, the accuracy of vertical velocities and DSDs derived from the Doppler spectra have been limited by the strong mathematical interdependence of the two quantities. The real difficulty is that the Doppler spectrum is measured as a function of the scatterers' total vertical velocity – due to terminal hydrometeor fall speeds, plus updrafts or downdrafts. In order to compute the DSD from a Doppler spectrum taken at vertical incidence, the spectrum must be expressed as a function of terminal velocity alone. Errors of only $\pm 0.25 \text{ m s}^{-1}$ in vertical velocity can cause errors of 100 per cent in drop number concentrations (Atlas, Scrivastava and Sekhon, 1973). A dual-wavelength technique has been developed (termed the Ratio method) by which vertical air velocity may be accurately determined independently of the DSD. In this approach, there is a trade-off between potential accuracy and potential for successful application.

9.4.4 Measurement of velocity fields

A great deal of information can be determined in real time from a single Doppler radar. It should be noted that the interpretation of radial velocity estimates from a single radar is not always unambiguous. Colour displays of single-Doppler radial velocity patterns aid in the real-time interpretation of the associated reflectivity fields and can reveal important features not evident in the reflectivity structures alone (Burgess and Lemon, 1990). Such a capability is of particular importance in the identification and tracking of severe storms. On typical colour displays, velocities between $\pm V_{max}$ are assigned 1 of 8 to 15 colours or more. Velocities extending beyond the Nyquist interval enter the scale of colours at the opposite end. This process may be repeated if the velocities are aliased more than one Nyquist interval.

Doppler radar can also be used to derive vertical profiles of horizontal winds. When the radar's antenna is tilted above the horizontal, increasing range implies increasing height. A profile of wind with height can be obtained by sinusoidal curve-fitting to the observed data (termed velocity azimuth display (VAD) after Lhermitte and Atlas, 1961) if the wind is relatively uniform over the area of the scan. The winds along the zero radial velocity contour are perpendicular to the radar beam axis. The colour display may be used to easily interpret VAD data obtained from large-scale precipitation systems. Typical elevated conical scan patterns in widespread

precipitation reveal an S-shaped zero radial velocity contour as the mean wind veers with height (Wood and Brown, 1986). On other occasions, closed contours representing jets are evident.

Since the measurement accuracy is good, divergence estimates can also be obtained by employing the VAD technique. This technique cannot be accurately applied during periods of convective precipitation around the radar. However, moderately powerful, sensitive Doppler radars have successfully obtained VAD wind profiles and divergence estimates in the optically clear boundary layer during all but the coldest months, up to heights of 3 to 5 km above ground level. The VAD technique seems well suited for winds from precipitation systems associated with extratropical and tropical cyclones. In the radar's clear-air mode, a time series of measurements of divergence and derived vertical velocity is particularly useful in nowcasting the probability of deep convection.

Since the mid-1970s, experiments have been made for measuring three-dimensional wind fields using multiple Doppler arrays. Measurements taken at a given location inside a precipitation area may be combined, by using a proper geometrical transformation, in order to obtain the three wind components. Such estimations are also possible with only two radars, using the continuity equation. Kinematic analysis of a wind field is described in Browning and Wexler (1968).

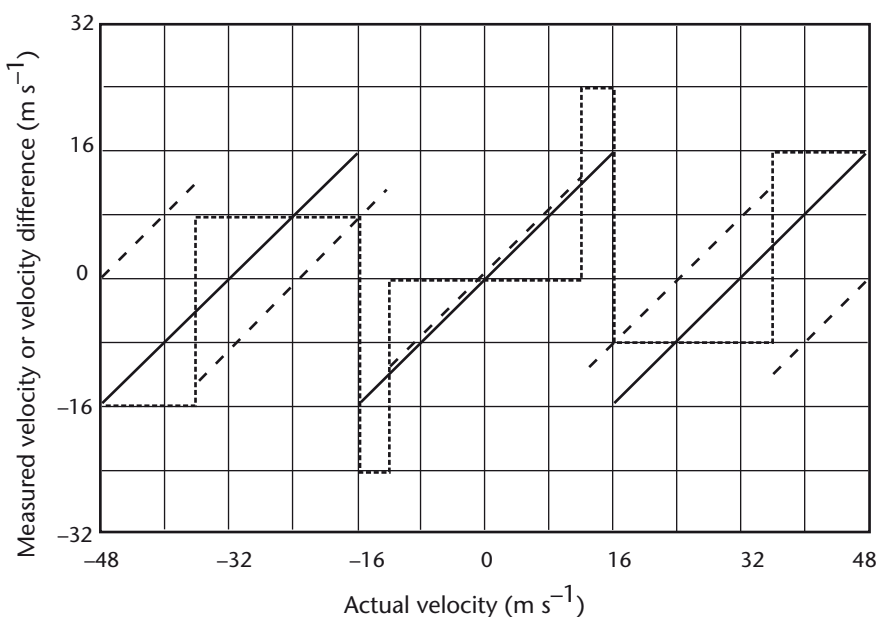


Figure 9.3. Solid and dashed lines show Doppler velocity measurements taken with two different pulse repetition frequencies (1 200 and 900 Hz for a C band radar). Speeds greater than the maximum unambiguous velocities are aliased. The differences (dotted line) between the Doppler velocity estimates are distinct and can be used to identify the degree of aliasing.

9.5 SOURCES OF ERROR

Radar beam filling

In many cases, and especially at large ranges from the radar, the pulse volume is not completely filled with homogeneous precipitation. Precipitation intensities often vary widely on small scales; at large distances from the radar, the pulse volume increases in size. At the same time, the effects of the Earth's curvature become significant. In general, measurements may be quantitatively useful for ranges of less than 100 km. This effect is important for cloud-top height measurements and the estimation of reflectivity.

Non-uniformity of the vertical distribution of precipitation

The first parameter of interest when taking radar measurements is usually precipitation at ground level. Because of the effects of beam width, beam tilting and the Earth's curvature, radar measurements of precipitation are higher than average over a considerable depth. These measurements are dependent on the details of the vertical distribution of precipitation and can contribute to large errors for estimates of precipitation on the ground.

Variations in the Z-R relationship

A variety of Z-R relationships have been found for different precipitation types. However, from the radar alone (except for dual polarized radars) these variations in the types and size distribution of hydrometeors cannot be estimated. In operational applications, this variation can be a significant source of error.

Attenuation by intervening precipitation

Attenuation by rain may be significant, especially at the shorter radar wavelengths (5 and 3 cm). Attenuation by snow, although less than for rain, may be significant over long path lengths.

Beam blocking

Depending on the radar installation, the radar beam may be partly or completely occulted by the topography or obstacles located between the radar and the target. This results in underestimations of reflectivity and, hence, of rainfall rate.

Attenuation due to a wet radome

Most radar antennas are protected from wind and rain by a radome, usually made of fibreglass. The

radome is engineered to cause little loss in the radiated energy. For instance, the two-way loss due to this device can be easily kept to less than 1 dB at the C band, under normal conditions. However, under intense rainfall, the surface of the radome can become coated with a thin film of water or ice, resulting in a strong azimuth dependent attenuation. Experience with the NEXRAD WSR-88D radars shows that coating radomes with a special hydrophobic paint essentially eliminates this source of attenuation, at least at 10 cm wavelengths.

Electromagnetic interference

Electromagnetic interference from other radars or devices, such as microwave links, may be an important factor of error in some cases. This type of problem is easily recognized by observation. It may be solved by negotiation, by changing frequency, by using filters in the radar receiver, and sometimes by software.

Ground clutter

The contamination of rain echoes by ground clutter may cause very large errors in precipitation and wind estimation. The ground clutter should first be minimized by good antenna engineering and a good choice of radar location. This effect may be greatly reduced by a combination of hardware clutter suppression devices (Aoyagi, 1983) and through signal and data processing. Ground clutter is greatly increased in situations of anomalous propagation.

Anomalous propagation

Anomalous propagation distorts the radar beam path and has the effect of increasing ground clutter by refracting the beam towards the ground. It may also cause the radar to detect storms located far beyond the usual range, making errors in their range determination because of range aliasing. Anomalous propagation is frequent in some regions, when the atmosphere is subject to strong decreases in humidity and/or increases in temperature with height. Clutter returns owing to anomalous propagation may be very misleading to untrained human observers and are more difficult to eliminate fully by processing them as normal ground clutter.

Antenna accuracy

The antenna position may be known within 0.2° with a well-engineered system. Errors may also be produced by the excessive width of the radar beam

or by the presence of sidelobes, in the presence of clutter or of strong precipitation echoes.

Electronics stability

Modern electronic systems are subject to small variations with time. This may be controlled by using a well-engineered monitoring system, which will keep the variations of the electronics within less than 1 dB, or activate an alarm when a fault is detected.

Processing accuracy

The signal processing must be designed to optimize the sampling capacities of the system. The variances in the estimation of reflectivity, Doppler velocity and spectrum width must be kept to a minimum. Range and velocity aliasing may be significant sources of error.

Radar range equation

There are many assumptions in interpreting radar-received power measurements in terms of the meteorological parameter Z by the radar range equation. Non-conformity with the assumptions can lead to error.

9.6 OPTIMIZING RADAR CHARACTERISTICS

9.6.1 Selecting a radar

A radar is a highly effective observation system. The characteristics of the radar and the climatology determine the effectiveness for any particular application. No single radar can be designed to be the most effective for all applications. Characteristics can be selected to maximize the proficiency to best suit one or more applications, such as tornado detection. Most often, for general applications, compromises are made to meet several user requirements. Many of the characteristics are interdependent with respect to performance and, hence, the need for optimization in reaching a suitable specification. Cost is a significant consideration. Much of the interdependence can be visualized by reference to the radar range equation. A brief note on some of the important factors follows.

9.6.2 Wavelength

The larger the wavelength, the greater the cost of the radar system, particularly antenna costs for comparable beamwidths (i.e. resolution). This is

due both to an increase in the amount of material and to the difficulty in meeting tolerances over a greater size. Within the bands of weather radar interest (S, C, X and K), the sensitivity of the radar or its ability to detect a target is strongly dependent on the wavelength. It is also significantly related to antenna size, gain and beamwidth. For the same antenna, the target detectability increases with decreasing wavelength. There is an increase in sensitivity of 8.87 dB in theory and 8.6 dB in practice from 5 to 3 cm wavelengths. Thus, the shorter wavelengths provide better sensitivity. At the same time, the beamwidth is narrower for better resolution and gain. The great disadvantage is that smaller wavelengths have much larger attenuation.

9.6.3 Attenuation

Radar rays are attenuated most significantly in rain, less in snow and ice, and even less in clouds and atmospheric gases. In broad terms, attenuation at the S band is relatively small and generally not too significant. The S band radar, despite its cost, is essential for penetrating the very high reflectivities in mid-latitude and subtropical severe storms with wet hail. X-band radars can be subject to severe attenuation over short distances, and they are not suitable for precipitation rate estimates, or even for surveillance, except at very short range when shadowing or obliteration of more distant storms by nearer storms is not important. The attenuation in the C band lies between the two.

9.6.4 Transmitter power

Target detectability is directly related to the peak power output of the radar pulse. However, there are practical limits to the amount of power output that is dictated by power tube technology. Unlimited increases in power are not the most effective means of increasing the target detectability. For example, doubling the power only increases the system sensitivity by 3 dB. Technically, the maximum possible power output increases with wavelength. Improvements in receiver sensitivity, antenna gain, or choice of wavelength may be better means of increasing detection capability.

Magnetrons and klystrons are common power tubes. Magnetrons cost less but are less frequency stable. For Doppler operation, the stability of klystrons was thought to be mandatory. An analysis by Strauch (1981) concluded that magnetrons could be quite effective for general meteorological applications; many Doppler radars today are based on magnetrons. Ground echo rejection techniques and clear air detection applications may favour

klystrons. On the other hand, magnetron systems simplify rejecting second trip echoes.

At normal operating wavelengths, conventional radars should detect rainfall intensities of the order of 0.1 mm h^{-1} at 200 km and have peak power outputs of the order of 250 kW or greater in the C band.

9.6.5 Pulse length

The pulse length determines the target resolving power of the radar in range. The range resolution or the ability of the radar to distinguish between two discrete targets is proportional to the half pulse length in space. For most klystrons and magnetrons, the maximum ratio of pulse width to PRF is about 0.001. Common pulse lengths are in the range of 0.3 to $4 \mu\text{s}$. A pulse length of $2 \mu\text{s}$ has a resolving power of 300 m, and a pulse of $0.5 \mu\text{s}$ can resolve 75 m.

Assuming that the pulse volume is filled with target, doubling the pulse length increases the radar sensitivity by 6 dB with receiver-matched filtering, while decreasing the resolution; decreasing the pulse length decreases the sensitivity while increasing the resolution. Shorter pulse lengths allow more independent samples of the target to be acquired in range and the potential for increased accuracy of estimate.

9.6.6 Pulse repetition frequency

The PRF should be as high as practical to obtain the maximum number of target measurements per unit time. A primary limitation of the PRF is the unwanted detection of second trip echoes. Most conventional radars have unambiguous ranges beyond the useful range of weather observation by the radar. An important limit on weather target useful range is the substantial height of the beam above the Earth even at ranges of 250 km.

For Doppler radar systems, high PRFs are used to increase the Doppler unambiguous velocity measurement limit. The disadvantages of higher PRFs are noted above.

The PRF factor is not a significant cost consideration but has a strong bearing on system performance. Briefly, high PRFs are desirable to increase the number of samples measured, to increase the maximum unambiguous velocity that can be measured, and to allow higher permissible scan rates. Low PRFs are desirable to increase the maximum unambiguous range that can be measured, and to provide a lower duty cycle.

9.6.7 Antenna system, beamwidth, and speed and gain

Weather radars normally use a horn fed antenna with a parabolic reflector to produce a focused narrow conical beam. Two important considerations are the beamwidth (angular resolution) and the power gain. For common weather radars, the size of the antenna increases with wavelength and with the narrowness of the beam required.

Weather radars normally have beamwidths in the range of 0.5 to 2.0° . For a 0.5 and 1.0° beam at a C band wavelength, the antenna reflector diameter is 7.1 and 3.6 m, respectively; at S band it is 14.3 and 7.2 m. The cost of the antenna system and pedestal increases much more than linearly with reflector size. There is also an engineering and cost limit. The tower must also be appropriately chosen to support the weight of the antenna.

The desirability of having a narrow beam to maximize the resolution and enhance the possibility of having the beam filled with target is particularly critical for the longer ranges. For a 0.5° beam, the azimuthal (and vertical) cross-beam width at 50, 100 and 200 km range is 0.4, 0.9 and 1.7 km, respectively. For a 1.0° beam, the widths are 0.9, 1.7 and 3.5 km. Even with these relatively narrow beams, the beamwidth at the longer ranges is substantially large.

The gain of the antenna is also inversely proportional to the beamwidth and thus, the narrower beams also enhance system sensitivity by a factor equal to differential gain. The estimates of reflectivity and precipitation require a nominal minimal number of target hits to provide an acceptable measurement accuracy. The beam must thus have a reasonable dwell time on the target in a rotating scanning mode of operation. Thus, there are limits to the antenna rotation speed. Scanning cycles cannot be decreased without consequences. For meaningful measurements of distributed targets, the particles must have sufficient time to change their position before an independent estimate can be made. Systems generally scan at the speed range of about 3 to 6 rpm.

Most weather radars are linearly polarized with the direction of the electric field vector transmitted being either horizontal or vertical. The choice is not clear cut, but the most common polarization is horizontal. Reasons for favouring horizontal polarization include: (a) sea and ground echoes are generally less with horizontal; (b) lesser sidelobes

in the horizontal provide more accurate measurements in the vertical; and (c) greater backscatter from rain due to the falling drop ellipticity. However, at low elevation angles, better reflection of horizontally polarized waves from plane ground surfaces may produce an unwanted range-dependent effect.

In summary, a narrow beamwidth affects system sensitivity, detectability, horizontal and vertical resolution, effective range and measurement accuracy. The drawback of small beamwidth is mainly cost. For these reasons, the smallest affordable beamwidth has proven to improve greatly the utility of the radar (Crozier and others, 1991).

9.6.8 Typical weather radar characteristics

The characteristics of typical radars used in general weather applications are given in Table 9.7.

Table 9.7. Specifications of typical meteorological radars

Type	Z only	Doppler	Z only	Doppler	Micro-Doppler
Band	C	C	S	S	C
Frequency (GHz)	5.6	5.6	3.0	2.8	5.6
Wavelength (cm)	5.33	5.33	10.0	10.7	5.4
Peak power (kw)	250	250	500	1 000	250
Pulse length (µs)	2.0	0.5, 2.0	0.25, 4.0	1.57, 4.5	1.1
PRF (Hz)	250-300	250-1 200	200-800	300-1 400	235-2 000
Receiver	Log	Log/Lin	Log	Log/Lin	Log/Lin
MDS (dBm)	-105	-105	-110	-113	-106
Antenna diameter (m)	3.7	6.2	3.7	8.6	7.6
Beamwidth (°)	1.1	0.6	1.8	1.0	0.5
Gain (dB)	44	48	38.5	45	51
Polarization	H	H	H	H	H
Rotation rate (rpm)	6	1-6	3	6	5

As discussed, the radar characteristics and parameters are interdependent. The technical limits on the radar components and the availability of manufactured components are important considerations in the design of radar systems.

The Z only radars are the conventional non-coherent pulsed radars that have been in use for decades and are still very useful. The Doppler radars are the new generation of radars that add a new dimension to the observations. They provide estimates of radial velocity. The micro-Doppler radars are radars developed for better detection of small-scale microbursts and tornadoes over very limited areas, such as for air-terminal protection.

9.7 RADAR INSTALLATION

9.7.1 Optimum site selection

Optimum site selection for installing a weather radar is dependent on the intended use. When there is a definite zone that requires storm warnings, the best compromise is usually to locate the equipment at a distance of between 20 and 50 km from the area of interest, and generally upwind of it according to the main storm track. It is recommended that the radar be installed slightly away from the main storm track in order to avoid measurement problems when the storms pass over the radar. At the same time, this should lead to good resolution over the area of interest and permit better advance warning of the coming storms (Leone and others, 1989).

In the case of a radar network intended primarily for synoptic applications, radars at mid-latitudes should be located at a distance of approximately 150 to 200 km from each another. The distance may be increased at latitudes closer to the Equator, if the radar echoes of interest frequently reach high altitudes. In all cases, narrow-beam radars will yield the best accuracy for precipitation measurements.

The choice of radar site is influenced by many economic and technical factors as follows:

- (a) The existence of roads for reaching the radar;
- (b) The availability of power and telecommunication links. It is frequently necessary to add commercially available lightning protection devices;

- (c) The cost of land;
- (d) The proximity to a monitoring and maintenance facility;
- (e) Beam blockage obstacles must be avoided. No obstacle should be present at an angle greater than a half beamwidth above the horizon, or with a horizontal width greater than a half beamwidth;
- (f) Ground clutter must be avoided as much as possible. For a radar to be used for applications at relatively short range, it is sometimes possible to find, after a careful site inspection and examination of detailed topographic maps, a relatively flat area in a shallow depression, the edges of which would serve as a natural clutter fence for the antenna pattern sidelobes with minimum blockage of the main beam. In all cases, the site survey should include a camera and optical theodolite check for potential obstacles. In certain cases, it is useful to employ a mobile radar system for confirming the suitability of the site. On some modern radars, software and hardware are available to greatly suppress ground clutter with minimum rejection of weather echoes (Heiss, McGrew and Sirmans, 1990);
- (g) When the radar is required for long-range surveillance, as may be the case for tropical cyclones or other applications on the coast, it will usually be placed on a hill-top. It will see a great deal of clutter, which may not be so important at long ranges (see section 9.2.6 for clutter suppression);
- (h) Every survey on potential sites should include a careful check for electromagnetic interference, in order to avoid as much as possible interference with other communication systems such as television, microwave links or other radars. There should also be confirmation that microwave radiation does not constitute a health hazard to populations living near the proposed radar site (Skolnik, 1970; Leone and others, 1989).

9.7.2 Telecommunications and remote displays

Recent developments in telecommunications and computer technology allow the transmission of radar data to a large number of remote displays. In particular, computer systems exist that are capable of assimilating data from many radars as well as from other data sources, such as satellites. It is also possible to monitor and to control remotely the operation of a radar which allows unattended operation. Owing to these technical

advances, in many countries, “nowcasting” is carried out at sites removed from the radar location.

Pictures may be transmitted by almost any modern transmission means, such as telephone lines (dedicated or not), fibre optic links, radio or microwave links, and satellite communication channels. The most widely used transmission systems are dedicated telephone lines, because they are easily available and relatively low in cost in many countries. It should be kept in mind that radars are often located at remote sites where advanced telecommunication systems are not available.

Radar pictures may now be transmitted in a few seconds due to rapid developments in communication technology. For example, a product with a 100 km range with a resolution of 0.5 km may have a file size of 160 kBytes. Using a compression algorithm, the file size may be reduced to about 20 to 30 kBytes in GIF format. This product file can be transmitted on an analogue telephone line in less than 30 s, while using an ISDN 64 kbps circuit it may take no more than 4 s. However, the transmission of more reflectivity levels or of additional data, such as volume scans of reflectivity or Doppler data, will increase the transmission time.

9.8 CALIBRATION AND MAINTENANCE

The calibration and maintenance of any radar should follow the manufacturer’s prescribed procedures. The following is an outline.

9.8.1 Calibration

Ideally, the complete calibration of reflectivity uses an external target of known radar reflectivity factor, such as a metal-coated sphere. The concept is to check if the antenna and wave guides have their nominal characteristics. However, this method is very rarely used because of the practical difficulties in flying a sphere and multiple ground reflections. Antenna parameters can also be verified by sun flux measurements. Routine calibration ignores the antenna but includes the wave guide and transmitter receiver system. Typically, the following actions are prescribed:

- (a) Measurement of emitted power and waveform in the proper frequency band;
- (b) Verification of transmitted frequency and frequency spectrum;

- (c) Injection of a known microwave signal before the receiver stage, in order to check if the levels of reflectivity indicated by the radar are correctly related to the power of the input;
- (d) Measurement of the signal to noise ratio, which should be within the nominal range according to radar specifications.

If any of these calibration checks indicate any changes or biases, corrective adjustments need to be made. Doppler calibration includes: the verification and adjustment of phase stability using fixed targets or artificial signals; the scaling of the real and imaginary parts of the complex video; and the testing of the signal processor with known artificially generated signals.

Levelling and elevation are best checked by tracking the position of the sun in receive-only mode and by using available sun location information; otherwise mechanical levels on the antenna are needed. The presence or absence of echoes from fixed ground targets may also serve as a crude check of transmitter or receiver performance.

Although modern radars are usually equipped with very stable electronic components, calibrations must be performed often enough to guarantee the reliability and accuracy of the data. Calibration must be carried out either by qualified personnel, or by automatic techniques such as online diagnostic and test equipment. In the first case, which requires manpower, calibration should optimally be conducted at least every week; in the second, it may be performed daily or even semi-continuously. Simple comparative checks on echo strength and location can be made frequently, using two or more overlapping radars viewing an appropriate target.

9.8.2 Maintenance

Modern radars, if properly installed and operated, should not be subject to frequent failures. Some manufacturers claim that their radars have a mean time between failures (MTBF) of the order of a year. However, these claims are often optimistic and the realization of the MTBF requires scheduled preventive maintenance. A routine maintenance plan and sufficient technical staff are necessary in order to minimize repair time.

Preventive maintenance should include at least a monthly check of all radar parts subject to wear, such as gears, motors, fans and infrastructures. The results of the checks should be written in a radar logbook by local maintenance staff and, when appropriate, sent to the central maintenance facility. When there are

many radars, there might be a centralized logistic supply and a repair workshop. The latter receives failed parts from the radars, repairs them and passes them on to logistics for storage as stock parts, to be used as needed in the field.

For corrective maintenance, the Service should be sufficiently equipped with the following:

- (a) Spare parts for all of the most sensitive components, such as tubes, solid state components, boards, chassis, motors, gears, power supplies, and so forth. Experience shows that it is desirable to have 30 per cent of the initial radar investment in critical spare parts on the site. If there are many radars, this percentage may be lowered to about 20 per cent, with a suitable distribution between central and local maintenance;
- (b) Test equipment, including the calibration equipment mentioned above. Typically, this would amount to approximately 15 per cent of the radar value;
- (c) Well-trained personnel capable of identifying problems and making repairs rapidly and efficiently.

Competent maintenance organization should result in radar availability 96 per cent of the time on a yearly basis, with standard equipment. Better performances are possible at a higher cost.

Recommended minimum equipment for calibration and maintenance includes the following:

- (a) Microwave signal generator;
- (b) Microwave power meter;
- (c) MHz oscilloscope;
- (d) Microwave frequency meter;
- (e) Standard gain horns;
- (f) Intermediate frequency signal generator;
- (g) Microwave components, including loads, couplers, attenuators, connectors, cables, adapters, and so on;
- (h) Versatile microwave spectrum analyser at the central facility;
- (i) Standard electrical and mechanical tools and equipment.

9.9 PRECIPITATION MEASUREMENTS

The measurement of precipitation by radars has been a subject of interest since the early days of radar meteorology. The most important advantage of using radars for precipitation measurements is the coverage of a large area with high spatial and temporal resolution from a single observing point and in real time.

Furthermore, the two-dimensional picture of the weather situation can be extended over a very large area by compositing data from several radars. However, only recently has it become possible to take measurements over a large area with an accuracy that is acceptable for hydrological applications.

Unfortunately, a precise assessment of this accuracy is not possible – partly because no satisfactory basis of comparison is available. A common approach is to use a network of gauges as a reference against which to compare the radar estimates. This approach has an intuitive appeal, but suffers from a fundamental limitation: there is no reference standard against which to establish the accuracy of areal rainfall measured by the gauge network on the scale of the radar beam. Nature does not provide homogeneous, standard rainfall events for testing the network, and there is no higher standard against which to compare the network data. Therefore, the true rainfall for the area or the accuracy of the gauge network is not known. Indeed, there are indications that the gauge accuracy may, for some purposes, be far inferior to what is commonly assumed, especially if the estimates come from a relatively small number of raingauges (Neff, 1977).

9.9.1 **Precipitation characteristics affecting radar measurements: The Z-R relation**

Precipitation is usually measured by using the Z-R relation:

$$Z = A R^b \quad (9.10)$$

where A and b are constants. The relationship is not unique and very many empirical relations have been developed for various climates or localities and storm types. Nominal and typical values for the index and exponent are $A = 200$, $b = 1.60$ (Marshall and Palmer, 1948; Marshall and Gunn, 1952).

The equation is developed under a number of assumptions that may not always be completely valid. Nevertheless, history and experience have shown that the relationship in most instances provides a good estimate of precipitation at the ground unless there are obvious anomalies. There are some generalities that can be stated. At 5 and 10 cm wavelengths, the Rayleigh approximation is valid for most practical purposes unless hailstones are present. Large concentrations of ice mixed with liquid can cause anomalies, particularly near the melting level. By taking into account the refractive index factor for ice (i.e., $|K|^2 = 0.208$) and by choosing an appropriate relation between the reflectivity

factor and precipitation rate (Z_e against R), precipitation amounts can be estimated reasonably well in snow conditions (the value of 0.208, instead of 0.197 for ice, accounts for the change in particle diameter for water and ice particles of equal mass).

The rainfall rate (R) is a product of the mass content and the fall velocity in a radar volume. It is roughly proportional to the fourth power of the particle diameters. Therefore, there is no unique relationship between radar reflectivity and the precipitation rate since the relationship depends on the particle size distribution. Thus, the natural variability in drop-size distributions is an important source of uncertainty in radar precipitation measurements.

Empirical Z-R relations and the variations from storm to storm and within individual storms have been the subject of many studies over the past forty years. A Z-R relation can be obtained by calculating values of Z and R from measured drop-size distributions. An alternative is to compare Z measured aloft by the radar (in which case it is called the “equivalent radar reflectivity factor” and labelled Z_e) with R measured at the ground. The latter approach attempts to reflect any differences between the precipitation aloft and that which reaches the ground. It may also include errors in the radar calibration, so that the result is not strictly a Z-R relationship.

The possibility of accounting for part of the variability of the Z-R relation by stratifying storms according to rain type (such as convective, non-cellular, orographic) has received a good deal of attention. No great improvements have been achieved and questions remain as to the practicality of applying this technique on an operational basis. Although variations in the drop-size distribution are certainly important, their relative importance is frequently overemphasized. After some averaging over time and/or space, the errors associated with these variations will rarely exceed a factor of two in rain rate. They are the main sources of the variations in well-defined experiments at near ranges. However, at longer ranges, errors caused by the inability to observe the precipitation close to the ground and beam-filling are usually dominant. These errors, despite their importance, have been largely ignored.

Because of growth or evaporation of precipitation, air motion and change of phase (ice and water in the melting layer, or bright band), highly variable vertical reflectivity profiles are observed, both within a given storm and from storm to storm. Unless the beam width is quite narrow, this will

lead to a non-uniform distribution of reflectivity within the radar sample volume. In convective rainfall, experience shows that there is less difficulty with the vertical profile problem.

However, in stratiform rain or snow, the vertical profile becomes more important. With increasing range, the beam becomes wider and higher above the ground. Therefore, the differences between estimates of rainfall by radar and the rain measured at the ground also increase. Reflectivity usually decreases with height; therefore, rain is underestimated by radar for stratiform or snow conditions.

At long ranges, for low-level storms, and especially when low antenna elevations are blocked by obstacles such as mountains, the underestimate may be severe. This type of error often tends to dominate all others. This is easily overlooked when observing storms at close ranges only, or when analysing storms that are all located at roughly the same range.

These and other questions, such as the choice of the wavelength, errors caused by attenuation, considerations when choosing a radar site for hydrological applications, hardware calibration of radar systems, sampling and averaging, and meteorological adjustment of radar data are discussed in Joss and Waldvogel (1990), Smith (1990) and Sauvageot (1994). The following considers only rainfall measurements; little operational experience is available about radar measurements of snow and even less about measurements of hail.

9.9.2 Measurement procedures

The basic procedure for deducing rainfall rates from measured radar reflectivities for hydrological applications requires the following steps:

- (a) Making sure that the hardware is stable by calibration and maintenance;
- (b) Correcting for errors using the vertical reflectivity profile;
- (c) Taking into account all the information about the Z_e - R relationship and deducing the rainfall;
- (d) Adjustment with raingauges.

The first three parts are based on known physical factors, and the last one uses a statistical approach to compensate for residual errors. This allows the statistical methods to work most efficiently. In the past, a major limitation on carrying out these steps was caused by analogue circuitry and photographic techniques for data recording and analyses. It was, therefore, extremely difficult to determine and make the necessary adjustments, and certainly not

in real time. Today, the data may be obtained in three dimensions in a manageable form, and the computing power is available for accomplishing these tasks. Much of the current research is directed towards developing techniques for doing so on an operational basis (Ahnert and others, 1983).

The methods of approach for (b) to (d) above and the adequacy of results obtained from radar precipitation measurement greatly depend on the situation. This can include the specific objective, the geographic region to be covered, the details of the application, and other factors. In certain situations, an interactive process is desirable, such as that developed for FRONTIERS and described in Appendix A of Joss and Waldvogel (1990). It makes use of all pertinent information available in modern weather data centres.

To date, no one method of compensating for the effects of the vertical reflectivity profile in real time is widely accepted ((b) above). However, three compensation methods can be identified:

- (a) Range-dependent correction: The effect of the vertical profile is associated with the combination of increasing height of the beam axis and spreading of the beam with range. Consequently, a climatological mean range-dependent factor can be applied to obtain a first-order correction. Different factors may be appropriate for different storm categories, for example, convective versus stratiform;
- (b) Spatially-varying adjustment: In situations where the precipitation characteristics vary systematically over the surveillance area, or where the radar coverage is non-uniform because of topography or local obstructions, corrections varying with both azimuth and range may be useful. If sufficient background information is available, mean adjustment factors can be incorporated in suitable look-up tables. Otherwise, the corrections have to be deduced from the reflectivity data themselves or from comparisons with gauge data (a difficult proposition in either case);
- (c) Full vertical profiles: The vertical profiles in storms vary with location and time, and the lowest level visible to the radar usually varies because of irregularities in the radar horizon. Consequently, a point-by-point correction process using a representative vertical profile for each zone of concern may be needed to obtain the best results. Representative profiles can be obtained from the radar volume scan data themselves, from climatological summaries, or from storm models. This is the most complex approach but can be implemented

with modern data systems (Joss and Lee, 1993).

After making the profile corrections, a reflectivity/rain-rate relationship should be used which is appropriate to the situation, geography and season, in order to deduce the value of R ((c) in the first paragraph of this section). There is general agreement that comparisons with gauges should be made routinely, as a check on radar performance, and that appropriate adjustments should be made if a radar bias is clearly indicated ((d) in the first paragraph of this section). In situations where radar estimates are far from the mark due to radar calibration or other problems, such adjustments can bring about significant improvements.

However, the adjustments do not automatically ensure improvements in radar estimates, and sometimes the adjusted estimates are poorer than the original ones. This is especially true for convective rainfall where the vertical extent of echo mitigates the difficulties associated with the vertical profile, and the gauge data are suspect because of unrepresentative sampling. Also, the spatial decorrelation distance may be small, and the gauge-radar comparison becomes increasingly inaccurate with distance from the gauge. A general guideline is that the adjustments will produce consistent improvements only when the systematic differences (that is, the bias) between the gauge and radar rainfall estimates are larger than the standard deviation of the random scatter of the gauge versus radar comparisons. This guideline makes it possible to judge whether gauge data should be used to make adjustments and leads to the idea that the available data should be tested before any adjustment is actually applied. Various methods for accomplishing this have been explored, but at this time there is no widely accepted approach.

Various techniques for using polarization diversity radar to improve rainfall measurements have been proposed. In particular, it has been suggested that the difference between reflectivities measured at horizontal and vertical polarization (Z_{DR}) can provide useful information about drop-size distributions (Seliga and Bringi, 1976). An alternate method is to use K_{DP} that depends on large oblate spheroids distorting the shape of the transmitted wave. The method depends on the hydrodynamic distortions of the shapes of large raindrops, with more intense rainfalls with larger drops giving stronger polarization signatures. There is still considerable controversy, however, as to whether

this technique has promise for operational use for precipitation measurement (English and others, 1991).

At close ranges (with high spatial resolution), polarization diversity radars may give valuable information about precipitation particle distributions and other parameters pertinent to cloud physics. At longer ranges, it is impossible to be sure that the radar beam is filled with a homogeneous distribution of hydrometeors. Consequently, the empirical relationship of the polarimetric signature to the drop-size distribution increases uncertainty. Of course, knowing more about $Z-R$ will help, but, even if multiparameter techniques worked perfectly well, the error caused by $Z-R$ could be reduced only from 33 to 17 per cent, as shown by Ulbrich and Atlas (1984). For short-range hydrological applications, the corrections for other biases (already discussed) are usually much greater, perhaps by an order of magnitude or more.

9.9.3 State of the art and summary

Over the years, much research has been directed towards exploring the potential of radars as an instrument for measuring rain. In general, radar measurements of rain, deduced from an empirical $Z-R$ relation, agree well with gauge measurements for ranges close to the radar. Increased variability and underestimation by the radar occur at longer ranges. For example, the Swiss radar estimates, at a range of 100 km on average, only 25 per cent of the actual raingauge amount, despite the fact that it measures 100 per cent at close ranges.

Similar, but not quite so dramatic, variations are found in flat country or in convective rain. The reasons are the Earth curvature, shielding by topography and the spread of the radar beam with range. Thus, the main shortcoming in using radars for precipitation measurements and for hydrology in operational applications comes from the inability to measure precipitation close enough to the ground over the desired range of coverage. Because this problem often does not arise in well-defined experiments, it has not received the attention that it deserves as a dominant problem in operational applications.

Thanks to the availability of inexpensive, high-speed data-processing equipment, it is now possible to determine the echo distribution in the whole radar coverage area in three dimensions. This knowledge, together with knowledge about the position of the radar and the orography around it, makes it possible

to correct in real time for a large fraction of – or at least to estimate the magnitude of – the vertical profile problem. This correction allows extension of the region in which accuracy acceptable for many hydrological applications is obtained.

To make the best possible use of radars, the following rules should be respected:

- (a) The radar site should be chosen such that precipitation is seen by the radar as close as possible to the ground. “Seen” means here that there is no shielding or clutter echoes, or that the influence of clutter can be eliminated, for instance by Doppler analysis. This condition may frequently restrict the useful radar range for quantitative work to the nearest 50 to 100 km;
- (b) Wavelength and antenna size should be chosen such that a suitable compromise between attenuation caused by precipitation and good spatial resolution is achieved. At longer ranges, this may require a shorter wavelength to achieve a sufficiently narrow beam, or a larger antenna if S band use is necessary, due to frequent attenuation by huge intense cells;
- (c) Systems should be rigorously maintained and quality controlled, including by ensuring the sufficient stability and calibration of equipment;
- (d) Unless measurements of reflectivity are taken immediately over the ground, they should be corrected for errors originating from the vertical profile of reflectivity. As these profiles change with time, reflectivity should be monitored continuously by the radar. The correction may need to be calculated for each pixel, as it depends on the height of the lowest visible volume above the ground. It is important that the correction for the vertical reflectivity profile, as it is the dominant one at longer ranges, should be carried out before any other adjustments;
- (e) The sample size must be adequate for the application. For hydrological applications, and especially when adjusting radar estimates with gauges, it is desirable to integrate the data over a number of hours and/or square kilometres. Integration has to be performed over the desired quantity (the linear rainfall rate R) to avoid any bias caused by this integration.

Even a crude estimate of the actual vertical reflectivity profile can produce an important improvement. Polarimetric measurements may provide some further improvement, but it has yet to be demonstrated that the additional cost and

complexity and risk of misinterpreting polarization measurements can be justified for operational applications in hydrology.

The main advantages of radars are their high spatial and temporal resolution, wide area coverage and immediacy (real-time data). Radars also have the capability of measuring over inaccessible areas, such as lakes, and of following a “floating target” or a “convective complex” in a real-time sequence, for instance, to make a short-term forecast. Although it is only to a lesser degree suited to giving absolute accuracy in measuring rain amounts, good quantitative information is already obtained from radar networks in many places. It is unlikely that radars will ever completely replace the rain gauge, since gauges provide additional information and are essential for adjusting and/or checking radar indications. On the other hand, as many specialists have pointed out, an extremely dense and costly network of gauges would be needed to obtain a resolution that would be easily attainable with radars.

9.9.4 **Area-time integral technique**

Climatological applications not requiring real-time data can take advantage of the close relationship between the total amount of rainfall and the area and duration of a rain shower (Byers, 1948; Leber, Merrit and Robertson, 1961). Without using a Z - R relationship, Doneaud and others (1984; 1987) found a linear relationship between the rained-upon area and the total rainfall within that area with a very small dispersion. This relationship is dependent on the threshold selected to define the rain area. While this has limited use in real-time short-term forecasting applications, its real value should be in climatological studies and applications.

9.10 **SEVERE WEATHER DETECTION AND NOWCASTING APPLICATIONS**

9.10.1 **Utilization of reflectivity information**

The most commonly used criterion for radar detection of potentially severe thunderstorms today is reflectivity intensity. Operational forecasters are advised to look for regions of high reflectivities (50 dBZ or greater). These include the spiral-bands and eyewall structures that identify tropical cyclones. Hook or finger-like echoes, overhangs and other echo shapes obtained from radar volume scans are used to warn of tornadoes or severe thunderstorms

(Lemon, Burgess and Brown, 1978), but the false alarm rate is high.

Improved severe thunderstorm detection has been obtained recently through the processing of digital reflectivity data obtained by automatic volume-scanning at 5 to 10 minute update rates. Reflectivity mass measurements such as vertically integrated liquid and severe weather probability have led to improved severe thunderstorm detection and warning, especially for hail.

Many techniques have been proposed for identifying hail with 10 cm conventional radar, such as the presence of 50 dBZ echo at 3 or 8 km heights (Dennis, Schock and Koscielski, 1970; Lemon, Burgess and Brown, 1978). However, verification studies have not yet been reported for other parts of the world. Federer and others (1978) found that the height of the 45 dBZ contour must exceed the height of the zero degree level by more than 1.4 km for hail to be likely. An extension of this method has been verified at the Royal Netherlands Meteorological Institute and is being used operationally (Holleman, and others, 2000; Holleman, 2001). A different approach towards improved hail detection involves the application of dual-wavelength radars – usually X and S bands (Eccles and Atlas, 1973). The physics of what the radar sees at these various wavelengths is crucial for understanding the strengths and limitations of these techniques (hydrometeor cross-section changes or intensity distribution). Studies of polarization diversity show some promise of improved hail detection and heavy rainfall estimation based upon differential reflectivity (Z_{DR}) as measured by a dual-polarization Doppler radar (Seliga and Bringi, 1976).

Since the late 1970s, computer systems have been used to provide time lapse and zoom capabilities for radar data. The British FRONTIERS system (Browning and Collier, 1982; Collier, 1989), the Japanese AMeDAS system, the French ARAMIS system (Commission of the European Communities, 1989) and the United States PROFS system allow the user to interact and produce composite colour displays from several remote radars at once, as well as to blend the radar data with other types of information.

The synthesis of radar data with raingauge data provides a powerful nowcasting product for monitoring rainfall. “Radar-AMeDAS Precipitation Analysis” is one of the products provided in Japan (Makihara, 2000). Echo intensity obtained from a radar network is converted into precipitation rate using a Z_e - R relationship, and 1 h precipitation amount is estimated from the precipitation rate.

The estimated amounts are then calibrated using raingauge precipitation amounts to provide a map of 1 h precipitation amount with high accuracy.

9.10.2 Utilization of Doppler information

The best method for measuring winds inside precipitation is the multiple Doppler method, which has been deployed since the mid-1970s for scientific field programmes of limited duration. However, real-time operational use of dual- or triple-Doppler analyses is not anticipated at present because of spatial coverage requirements. An exception may be the limited area requirements of airports, where a bistatic system may be useful (Wurman, Randall and Burghart, 1995).

The application of Doppler radar to real-time detection and tracking of severe thunderstorms began in the early 1970s. Donaldson (1970) was probably the first to identify a vortex flow feature in a severe thunderstorm. Quasi-operational experiments have demonstrated that a very high percentage of these single-Doppler vortex signatures are accompanied by damaging hail, strong straight wind or tornadoes (Ray and others, 1980; JDOP, 1979).

Since then, the existence of two useful severe storm features with characteristic patterns or “signatures” has become apparent. The first was that of a mesocyclone, which is a vertical column of rising rotating air typically 2 to 10 km in diameter. The mesocyclone signature (or velocity couplet) is observed forming in the mid-levels of a storm and descending to cloud base, coincident with tornado development (Burgess, 1976; Burgess and Lemon, 1990). This behaviour has led to improved tornado warning lead times, of 20 min or longer, during quasi-operational experiments in Oklahoma (JDOP, 1979). Most of the Doppler observations have been made in the United States, and it is not known if this signature can be generalized yet. During experiments in Oklahoma, roughly 50 per cent of all mesocyclones produced verified tornadoes; also, all storms with violent tornadoes formed in environments with strong shear and possessed strong mesocyclones (Burgess and Lemon, 1990).

The second signature – the tornado vortex signature (TVS) – is produced by the tornado itself. It is the location of a very small circulation embedded within the mesocyclone. In some cases, the TVS has been detected aloft nearly half an hour or more before a tornado touched the ground. Several years of experience with TVS have demonstrated its great utility for determining tornado location, usually

within ± 1 km. It is estimated that 50 to 70 per cent of the tornadoes east of the Rocky Mountain high plains in the United States can be detected (Brown and Lemon, 1976). Large Doppler spectrum widths (second moment) have been identified with tornado location. However, large values of spectrum width have also been well correlated with large values during storm turbulence.

Divergence calculated from the radial velocity data appears to be a good measure of the total divergence. Estimations of storm-summit radial divergence match those of the echo-top height, which is an updraft strength indicator. Quasi-operational Doppler experiments have shown that an increase in divergence magnitude is likely to be the earliest indicator that a storm is becoming severe. Moreover, large divergence values near the storm top were found to be a useful hail indicator.

Low-level divergence signatures of downbursts have been routinely made with terminal Doppler weather radars for the protection of aircraft during take off and landing. These radars are specially built for limited area surveillance and repeated rapid scanning of the air space around the airport terminals. The microburst has a life cycle of between 10 to 20 min, which requires specialized radar systems for effective detection. In this application, the radar-computer system automatically provides warnings to the air-traffic control tower (Michelson, Schrader and Wieler, 1990).

Doppler radar studies of the role of boundary layer convergence lines in new thunderstorm formations support earlier satellite cloud-arc studies. There are indications that mesoscale boundary-layer convergence lines (including intersecting gust fronts from prior convection) play a major role in determining where and when storms will form. Wilson and Schreiber (1986) have documented and explained several cases of tornado genesis by non-precipitation induced wind shear lines, as observed by Doppler radar (Mueller and Carbone, 1987).

Recent improvements in digital radar data-processing and display techniques have led to the development of new quantitative, radar-based products for hydrometeorological applications. A number of European countries and Japan are using such radar products with numerical models for operational flood forecasting and control (for example, see Cluckie and Owens, 1987).

Thus, major advances now appear possible in the 0 to 2 h time-specific forecasts of thunderstorms. The development of this potential will require

the efficient integration of Doppler radar, high-resolution satellite data, and surface and sounding data.

Doppler radars are particularly useful for monitoring tropical cyclones and providing data on their eye, eyewall and spiral-band dynamic evolution, as well as the location and intensity of hurricane-force winds (Ruggiero and Donaldson, 1987; Baynton, 1979).

9.11 HIGH FREQUENCY RADARS FOR OCEAN SURFACE MEASUREMENTS

Radio signals in the high-frequency radio band (from 3 to 30 MHz) are backscattered from waves on the sea surface, and their frequency is Doppler shifted. They can be detected by a high-frequency radar set-up to observe them. The strength of the returned signal is due to constructive interference of the rays scattered from successive sea waves spaced so that the scattered rays are in resonance, as occurs in a diffraction grating. In the case of grazing incidence, the resonance occurs when the sea wavelength is half the radio wavelength. The returned signal is Doppler shifted because of the motion of the sea waves. From the Doppler spectrum it is possible to determine the direction of motion of the sea waves, with a left-right ambiguity across the direction of the beam that can be resolved by making use of other information, such as a first-guess field. If the sea waves are in equilibrium with the surface wind, this yields the wind direction; this is the basic sea measurement taken with high-frequency radar. Analysis of the returned spectrum can be developed further to yield the spectrum of sea waves and an indication of wind speed.

Measurements can be obtained up to 200 km or more with ground-wave radars, and up to 3 000 km or more with sky-wave radars (using reflection from the ionosphere). The latter are known as over-the-horizon radars.

Most operational high frequency radars are military, but some are used to provide routine wind direction data, over very wide areas, to Hydrometeorological Services.

Accounts of high frequency radars with meteorological applications, with extensive further references, are given in Shearman (1983), Dexter, Heron and Ward (1982), Keenan and Anderson (1987), and Harlan and Georges (1994).

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