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CHAPTER 7. RADAR MEASUREMENTS

7.1 GENERAL

This chapter is a basic discussion of weather radars. It places particular emphasis on the technical and operational characteristics that must be considered when planning, developing and operating individual radars and radar networks in support of Meteorological and Hydrological Services. This is related to the use and application of weather radar data. Radars used for vertical wind profiling are discussed in Part II, Chapter 5.

7.1.1 The weather radar

Meteorological radars are primarily designed for detecting precipitation and associated weather phenomena. However, other objects, such as insects, birds, planes, sand and dust, ground clutter and even fluctuations in the refractive index in the atmosphere generated by local variations in temperature or humidity, can be detected by the weather radar.

This chapter deals with radars in common operational or near-operational use 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). Primarily, they are designed for detecting and mapping areas of precipitation, measuring their intensity and motion, and their type. Radar echoes due to birds, insects or Bragg scattering (the turbulent fluctuations) can also produce radial wind data with Doppler radar. Their intensity patterns can reveal the location of atmospheric boundaries that are indicative of areas of low-level convergence where thunderstorms may initiate or develop.

Higher frequencies (35 and 94 GHz) are used to detect smaller hydrometeors, such as cloud, fog, drizzle, light snow and precipitation, and are becoming prevalent in the research community. These frequencies are generally not used in operational forecasting because of excessive attenuation of the radar signal by the intervening medium and their relatively short range, particularly in Doppler mode.

At lower frequencies (915–1 440 MHz, ~400–440 MHz and ~50 MHz), radars are capable of detecting variations in the refractive index of clear air, and are used for wind profiling. Although they may detect precipitation, their scanning capabilities are limited by the size and type of the antenna, and they generally point in the vertical or near-vertical.

The returned signal from the transmitted pulse encountering any target, called an echo, has an amplitude, a phase and a polarization. Amplitude is related to the size distribution and number of particles in the (pulse) volume illuminated by the radar beam. The amplitude is used to determine the reflectivity factor ($Z$), which is used to estimate the intensity of precipitation through the use of empirical relations. A primary application is to detect, map and estimate the precipitation at ground level instantaneously, nearly continuously, and over large areas.

Doppler radars have the capability of determining the phase difference between the transmitted and received pulse which is a measure of the mean radial velocity of the particles. This is the reflectivity weighted average of the radial components of the displacement velocities of the hydrometeors within the pulse volume. The Doppler spectrum width is a measurement of the spatial variability of the Doppler velocities and provides a measure of the variation in the radial velocity that is interpreted in terms of wind shear and turbulence. An important feature of Doppler is the ability to filter out echoes due to ground targets in the signal processing.

The current generation of radars has polarization capability. Operationally, pulses are transmitted simultaneously with horizontal and vertical polarizations. In the past, the pulses were transmitted in sequence but required a high-power polarization switch that was prone to failure. Two receivers (physical or virtual) are used to measure the horizontal and vertical
components of the returned signal. The main benefits are improved data quality through the ability to identify characteristics of the target (birds, bugs, precipitation and its type, clutter), hydrometeor classification and precipitation estimation. For forecast applications, the dual-polarization capability can identify hail and the rain–snow boundary. High precipitation rates affect the horizontal and vertical phase of the transmitted and received pulses, and this can be exploited for precipitation estimation even with partially blocked beams or attenuated signals. Dual polarization can be calibrated through self-consistent relationships between parameters.

Weather radars no longer operate in isolation. Given current telecommunication capabilities, data are exchanged, resulting in networks of weather radars. This has made it possible to extend their use in local applications (e.g. severe weather warnings and nowcasting), regional (e.g. data assimilation, precipitation estimation) and global applications (e.g. climate change detection).

Modern weather radars should have characteristics optimized to produce the best data for operational requirements. They are the most complex of all the weather sensors used in operations and require special training and extensive knowledge of the instrument. The location of the radar is critical to meet the surveillance and detection requirements. There are a variety of configuration options to set up the radar, and components should be adequately installed and monitored for degradation and failure. Hence, a maintenance and support programme is needed to keep this instrument useful.

### 7.1.2 Radar characteristics, terms and units

The meteorological applications govern the selection of the characteristics of the radar (Tables 7.1, 7.2 and 7.3).

### 7.1.3 Radar accuracy requirements

Quantitative use of radar data in end-user applications relies on the accuracy and precision of the radar observations. Appropriately installed, calibrated and maintained modern radars are relatively stable and do not produce significant measurement errors due to the stability of the hardware. However, the maintenance and calibration of the radar is still a considerable challenge and requires highly qualified personnel. Measurement error still exists and requires engineering and scientific expertise to monitor, diagnose and mitigate the biases.

External physical factors, such as ground clutter effects, anomalous propagation, attenuation and propagation effects, beam effects, target composition, particularly with variations and changes in the vertical, rain rate-reflectivity relationship inadequacies and the meteorological

<table>
<thead>
<tr>
<th>Radar band</th>
<th>Frequency</th>
<th>Wavelength</th>
<th>Nominal</th>
</tr>
</thead>
<tbody>
<tr>
<td>UHF</td>
<td>300–1 000 MHz</td>
<td>1–0.3 m</td>
<td>70 cm</td>
</tr>
<tr>
<td>L</td>
<td>1 000–2 000 MHz</td>
<td>0.3–0.15 m</td>
<td>20 cm</td>
</tr>
<tr>
<td>S</td>
<td>2 000–4 000 MHz</td>
<td>15–7.5 cm</td>
<td>10 cm</td>
</tr>
<tr>
<td>C</td>
<td>4 000–8 000 MHz</td>
<td>7.5–3.75 cm</td>
<td>5 cm</td>
</tr>
<tr>
<td>X</td>
<td>8 000–12 500 MHz</td>
<td>3.75–2.4 cm</td>
<td>3 cm</td>
</tr>
<tr>
<td>K <em>u</em></td>
<td>12.5–18 GHz</td>
<td>2.4–1.66 cm</td>
<td>1.50 cm</td>
</tr>
<tr>
<td>K</td>
<td>18–26.5 GHz</td>
<td>1.66–1.13 cm</td>
<td>1.25 cm</td>
</tr>
<tr>
<td>K <em>a</em></td>
<td>26.5–40 GHz</td>
<td>1.13–0.75 cm</td>
<td>0.86 cm</td>
</tr>
<tr>
<td>W</td>
<td>94 GHz</td>
<td>0.30 cm</td>
<td>0.30 cm</td>
</tr>
</tbody>
</table>
situation, create artefacts in the data that must be removed during scientific data processing for use in quantitative applications. By considering only errors attributable to the radar system, the measurable radar parameters can be determined with an acceptable accuracy (Table 7.4).

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_e$</td>
<td>Equivalent or effective radar reflectivity factor</td>
<td>mm$^6$ m$^{-3}$ or dBZ</td>
</tr>
<tr>
<td>$V_r$</td>
<td>Mean radial velocity</td>
<td>m s$^{-1}$</td>
</tr>
<tr>
<td>$\sigma_v$</td>
<td>Spectrum width</td>
<td>m s$^{-1}$</td>
</tr>
<tr>
<td>$Z_{DR}$</td>
<td>Differential reflectivity</td>
<td>dB</td>
</tr>
<tr>
<td>$K_{DP}$</td>
<td>Specific differential phase, Differential phase</td>
<td>Degree km$^{-1}$, Degree</td>
</tr>
<tr>
<td>$\rho_{HV}$</td>
<td>Correlation coefficient</td>
<td></td>
</tr>
<tr>
<td>LDR</td>
<td>Linear depolarization ratio</td>
<td>dB</td>
</tr>
</tbody>
</table>

Table 7.3. Physical radar parameters and units

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c$</td>
<td>Speed of light</td>
<td>m s$^{-1}$</td>
</tr>
<tr>
<td>$f$</td>
<td>Transmitted frequency</td>
<td>Hz</td>
</tr>
<tr>
<td>$f_d$</td>
<td>Doppler frequency shift</td>
<td>Hz</td>
</tr>
<tr>
<td>$P_r$</td>
<td>Received power</td>
<td>mW or dBm</td>
</tr>
<tr>
<td>$P_t$</td>
<td>Transmitted power</td>
<td>kW</td>
</tr>
<tr>
<td>PRF</td>
<td>Pulse repetition frequency</td>
<td>Hz</td>
</tr>
<tr>
<td>$T$</td>
<td>Pulse repetition time</td>
<td>ms</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>Antenna rotation rate</td>
<td>Degree s$^{-1}$ or rpm</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Transmitted wavelength</td>
<td>cm</td>
</tr>
<tr>
<td>$\phi$</td>
<td>Azimuth angle</td>
<td>Degree</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Beam width between half power points</td>
<td>Degree</td>
</tr>
<tr>
<td>$\tau$</td>
<td>Pulse width</td>
<td>$\mu$s</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Elevation angle</td>
<td>Degree</td>
</tr>
</tbody>
</table>

7.2 RADAR PRINCIPLES

7.2.1 Pulse radars

The principles of radar and the observation of weather phenomena were established in the 1940s. Since then, great strides have been made in improving equipment, signal and data processing and data interpretation. The interested reader should consult some of the relevant texts for greater detail. Good references include Skolnik (1970, 1990) for engineering and equipment aspects; Battan (1973) for meteorological phenomena and applications;

Figure 7.1 shows a typical radar and radar site. The antenna (2–8.5 m) is inside the radome on top of the tower, which is of the order of 10–30 m or more in height. A tower is used to elevate the antenna above local obstructions. When determining the height of the tower, the growth of nearby trees should be taken into account. Too tall a tower will result in considerably more ground clutter due to the side of the main lobe and the side lobes. One of the buildings contains the radar electronics (transmitter/receiver and computers) and the other contains the uninterruptible power supply (UPS) and diesel generator. Radars are often located in rural locations and well-conditioned power is often not the norm. The UPS plays a critical role in removing power spikes and other anomalies in the power and is key to maintaining operations. The diesel or other kind of generator is capable of 2–3 days of operation but should be specified according to the needs. Note the lightning rod, on top of the radome, that is connected to grounding cables (not shown). This is critical as lightning can cause serious and long-term damage to the radar components. Power fluctuations due to lightning can exceed the capability of the UPS. Note also the red signal lights on top of the radome for warning aviators.

Electromagnetic waves at fixed preferred frequencies are transmitted from a directional antenna into the atmosphere in a rapid succession of short pulses. The pulse length and range processing determines the range resolution of the radar data. One emerging technology in operational radars is the use of low-power transmitters (solid state, travelling-wave tubes) that exploit a technique called pulse compression using a combination of long pulses at low power, frequency modulation and advanced signal-processing to achieve high-range resolution and high sensitivity that rival traditional pulse systems. Phased array antennas are an emerging technology that forms the beam by electronic phase shifting. They have the ability to point to different locations in an agile and non-sequential fashion. However, they all use a directional beam that can resolve targets in range, azimuth and elevation.

Figure 7.2 shows a directional radar antenna emitting a pulsed-shaped beam of electromagnetic energy over the Earth’s surface and illuminating various targets, including non-meteorological targets. Many of the physical limitations and constraints of the observation technique are immediately apparent from the figure. For example, (i) there is a limit to the minimum altitude that can be observed at far ranges due to the curvature of the Earth, (ii) there are non-

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
<th>Acceptable accuracy$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi$</td>
<td>Azimuth angle</td>
<td>0.1°</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Elevation angle</td>
<td>0.1°</td>
</tr>
<tr>
<td>$V_r$</td>
<td>Mean Doppler velocity</td>
<td>1.0 m s$^{-1}$</td>
</tr>
<tr>
<td>$Z$</td>
<td>Reflectivity factor</td>
<td>1 dBZ</td>
</tr>
<tr>
<td>$\sigma_v$</td>
<td>Doppler spectrum width</td>
<td>1 m s$^{-1}$</td>
</tr>
<tr>
<td>$Z_{DR}$</td>
<td>Differential reflectivity</td>
<td>0.2 dB</td>
</tr>
<tr>
<td>$K_{DP}$</td>
<td>Specific differential phase</td>
<td>&lt; 0.5 degree km$^{-1}$</td>
</tr>
<tr>
<td>$\rho_{HV}$</td>
<td>Cross-polar correlation</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Note:
- These figures are relative to a normal Gaussian spectrum with a standard deviation smaller than 4 m s$^{-1}$. Velocity accuracy deteriorates when the spectrum width grows, while reflectivity accuracy improves.
meteorological targets, (iii) there are other emitters (Radio Local Area Networks, the Sun),
(iv) there is anomalous propagation of the beam, (v) there is blockage and partial blockage due
to mountains, (vi) there is precipitation of different types, and (vii) there are electromagnetic–
precipitation interactions resulting in enhanced returns (bright band), etc.

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.

For a pulse radar, the short bursts of electromagnetic energy are absorbed and scattered by the
illuminated meteorological and non-meteorological targets. Some of the scattered energy is
reflected back to the radar antenna and receiver. Since the electromagnetic wave travels at the
speed of light (that is, $2.99 \times 10^8$ m s$^{-1}$), the range of the target can be determined by measuring

Figure 7.1. A typical weather radar within the Canadian network showing the major physical
components of a radar system. The tower is about 30 m high, with a radome fitted with
hazard lights and a lightning rod.

Figure 7.2. The weather radar can detect many things besides weather targets. This
schematic illustrates many of these features. The + or – signs indicate whether the radar
reflectivity is augmented or diminished by the feature. These artefacts need to be removed
for quantitative applications.
the time between the transmission of the pulse and its return. Between the transmissions of 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 time between consecutive pulses determines the maximum unambiguous range of the radar. Echoes can still be received from targets beyond this maximum range and are known as multiple-trip echoes.

For a pulse compression radar with frequency modulation, the range to target is determined by the frequency within the long pulse. However, the maximum unambiguous range is still determined by the time between consecutive pulses. With the transmission of long pulses, the radar receiver is protected from the high power of the transmit pulse, and a long blind zone (10–30 km, depending on the pulse length) is created. In this type of radar, short pulses (with corresponding short blind zones, < 2 km) are transmitted to detect objects that are within this blind zone.

The radar range equation relates the power returned from the target to the radar characteristics. The power returned provides an estimate of the amount of precipitation in the resolution volume. This estimate depends on the assumption of the type of precipitation particles and their size distribution in the resolution volume.

The power measurements are determined by the total power backscattered by the target within a volume being sampled at any one instant in time. This volume is called the pulse volume or sample volume. The pulse volume dimensions (which determine the resolution of the radar) are dependent on the radar pulse length in space ($h$) and the antenna beam widths in the vertical ($\phi_b$) and the horizontal ($\theta_b$). 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 the 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, the elevation, the range to the target and also by the non-linear propagation path of the radar beam away from the radar. For a pulse compression radar, the pulse volume is primarily determined by the resolution of the frequency modulation and the capability of the receiving system to resolve changes in frequency.

Particles within the pulse volume are continuously shuffling relative to one another. This results 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, though this will depend on the level of data quality considered as acceptable (Smith, 1995). This was formerly carried out by an electronic integrator circuit but is now done in a digital signal processor. Further averaging of pulses in range, azimuth and time is often conducted to increase the sampling size and accuracy of the estimate at the expense of coarser spatial resolution. An important difference with non-meteorological radars is that the signal processing and the interpretation of the data are based on the premise that the backscatter is from a distributed target and not from a point target (such as an aeroplane). This requires processing for quantitative measurements (not just detection) and a different range dependency of the return power (different radar equation) compared to point target detection radars (such as for air traffic control).

Doppler radars have circuitry to measure the phase shift difference from successive pulses from the same radar pulse volume. The phase shift is proportional to the radar wavelength and therefore to the distance in the time between pulses. This phase shift is used to estimate the radial or Doppler velocity.

Dual-polarization radar can be of several types. The polarization can be circular and, though there have been very excellent research radars with this feature, it is not generally used in weather operations. Linear dual-polarization radars can send pulses at horizontal and vertical polarization in alternating or simultaneous fashion. In the former case, a fast high-power switch (switches every pulse) is required, but it has proved to be problematic and so few exist in operations. The simultaneous transmit and receive (STAR mode) technique transmits equal powers in both the horizontal and vertical polarizations and the signal is received separately at horizontal and vertical polarizations. This has proved to be the solution for operations as the high-power, high failure fast switch is avoided. There are variations to these methods of creating...
the dual-polarization signal. The major advantage of the alternating dual-polarization mode is that it can measure the cross-polarization backscatter of the target (Linear Depolarization Ratio – LDR), and this is particularly useful for bright band detection. The major disadvantage of the STAR mode is this loss of LDR (as there is cross-polarization already in the transmitted pulse), a 3 dB loss of signal strength in both channels (due to power splitting), and cross-coupling artefacts, particularly in the ice phase of storms.

7.2.2 Propagation radar signals

Electromagnetic waves propagate in straight lines in a homogeneous medium. However, the atmosphere is vertically stratified and the rays change direction depending on the changes in the refractive index (which is a function of temperature and moisture). When the waves encounter precipitation and clouds, part of the energy is absorbed and part is scattered in all directions, including back to the radar site.

The amount of bending of electromagnetic waves can be predicted by using the vertical profile of temperature, moisture and pressure (Bean and Dutton, 1966). Under normal atmospheric conditions, the waves travel in a curve bending slightly earthward (Figure 7.3). The representation is drawn in physical space (the Earth is drawn with a radius of 6 371 km) and the figure shows that the beam bends downward, but still rises with range with respect to the Earth’s surface. In a four-thirds (4/3) Earth model, where the Earth’s surface is drawn with a radius of 8 975 km (4/3 x 6 371 km), the beams are straight lines (Figure 7.4).

This 4/3 model is most often used, but some radars (mountain top) use a 5/4 model. The height above the radar is given by the following equation:

$$h = \left[ r^2 + \left( k_e a \right)^2 + 2k_e a r \sin \theta_e \right]^{1/2} - k_e a$$

(7.1)

where $h$ is the height above the radar antenna, $r$ is the range along the beam, $a$ is the Earth’s radius, $\theta_e$ is the elevation angle above the horizon and $k_e a$ is the effective Earth radius.

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. This is known as anomalous propagation. From a precipitation measurement standpoint, the

![Figure 7.3. Schematic of beam height for selected elevation angles (-0.3, 0, 0.3 and 0.5) above the Earth’s surface, for a standard index of refraction profile in the atmosphere plotted in physical space with an Earth curvature equivalent to the Earth radius](image)
CHAPTER 7. RADAR MEASUREMENTS

The greatest problem occurs under super-refractive or “ducting” conditions, where 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. This occurs when there is an increase in temperature and a decrease in moisture with height. These echoes must be eliminated when producing a precipitation map. The sub-refraction situation, where the beam doesn’t beam as much as normal or bends in the upward direction, is not evident to identify and thus is also a problem. In actual practice, the vertical profile of the index of refraction is not known, so that the precise location of the beam is not known.

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

7.2.3 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 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 can be quite easily accomplished automatically.
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 attenuation very difficult to overcome in any quantitative way using radar observations alone, though great progress has been made using dual-polarization radar techniques.

Attenuation is dependent on wavelength. At 10 cm wavelengths, the attenuation exists but 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 7.5). Total attenuation of the signal can occur at 3 and 5 cm. Smaller wavelength radars are more sensitive to attenuation and attenuation correction, and quantitative precipitation estimation based on dual-polarization specific differential phase measurements has more impact on resulting data. These techniques are effective starting at lower precipitation rates for smaller wavelengths.

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.

7.2.4 Scattering by clouds and precipitation

The echo power detected is backscattered by the targets in the resolution volume (hydrometeors, ground, trees, etc.). The backscattering cross-section \( \sigma_b \) is defined as the area of an isotropic scatterer that would return to the emitting source by 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:

\[
\sigma_b = \frac{\pi^5 |K|^2 D^6}{\lambda^4}
\]  

which is the justification for equation 7.3. \( |K|^2 \), 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 7.2 in the form:

\[
z = \frac{C P_r r^2}{|K|^2}
\]
7.2.5 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 (Bragg scatter). The echoes are of low intensity and are detected by most modern radars unless discarded via thresholding of the data. Equivalent $Z$ values for clear air phenomena generally appear in the range of $-55$ to $-5$ dBZ, although these are not true $Z$ parameters as the physical process generating the echoes is entirely different. For precipitation measurement, these echoes are “noise” in the signal. However, they can usually be associated with some meteorological phenomenon such as a sea breeze or thunderstorm outflows and therefore are useful to identify areas of potential convective initiation. 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 7.6).

Although normal radar processing would interpret the signal in terms of $Z$, the scattering properties of the fluctuations of the index of refraction are quite different from that of hydrometeors. It is also known as Bragg scattering. The scattering is most often expressed in terms of the structure parameter of refractive index, $Cn^2$. This is a measure of the mean-square fluctuations of the refractive index as a function of distance (Gossard and Strauch, 1983).

### Table 7.6. Typical backscatter cross-sections for various targets

<table>
<thead>
<tr>
<th>Object</th>
<th>$\sigma_b$ ($m^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aircraft</td>
<td>10 to 1 000</td>
</tr>
<tr>
<td>Human</td>
<td>0.14 to 1.05</td>
</tr>
<tr>
<td>Weather balloon</td>
<td>0.01</td>
</tr>
<tr>
<td>Birds</td>
<td>0.001 to 0.01</td>
</tr>
<tr>
<td>Bees, dragonflies, moths</td>
<td>$3 \times 10^{-6}$ to $10^{-5}$</td>
</tr>
<tr>
<td>2 mm water drop</td>
<td>$1.8 \times 10^{-10}$</td>
</tr>
</tbody>
</table>

The method and problems of interpreting the reflectivity factor in terms of precipitation rate ($R$) are discussed in section 7.10.

7.3 THE RADAR EQUATION FOR PRECIPITATION TARGETS

Meteorological targets consist of ice and/or water particles 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:

$$\bar{P}_r = \frac{\pi^3}{1024 \ln 2} \frac{P_b G^2 \theta_b \phi_b}{\lambda^2} \left[ K \right]^2 \frac{10^{-18} Z}{r^2}$$

(7.4)

where $\bar{P}_r$ is the power received back at the radar, averaged over several pulses, in watts; $P_b$ is the peak power of the pulse transmitted by the radar in watts; $h$ is the pulse length in space, in metres ($h = cr/2$, where $c$ is the speed of light and $r$ is the pulse duration); $G$ is the gain of the antenna over an isotropic radiator; $\theta_b$ and $\phi_b$ are the horizontal and vertical beam widths,
respectively, of the antenna radiation pattern at the –3 dB level of one-way transmission, in radians; \( \lambda \) 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 in the third term the parameters depend on the range and characteristics of the target. The radar parameters 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:

\[
\frac{P_e}{P_r} = \frac{C|K|^2 Z}{r^2}
\]

(7.5)

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 located precipitation particles;

(c) The reflectivity factor \( Z \) is uniform throughout the sampled pulse volume and approximately 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 radar uses linear polarizations (typically \( H \) or \( V \));

(h) The main lobe of the antenna radiation pattern is Gaussian in shape;

(i) The gain of the antenna is known or can be calculated with sufficient accuracy;

(j) The contribution of the side lobes to the received power is negligible;

(k) Blockage of the transmitted signal by ground clutter in the beam is negligible;

(l) The peak power transmitted \( (P_t) \) is the actual power transmitted at the antenna, that is, all waveguide losses, and so on, and attenuation in the radar dome, are considered;

(m) 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 power returned from the target and estimating precipitation amounts from
radar measurements. Despite the many assumptions, the expression provides a reasonable estimate of the precipitation mass. This estimate can be improved by further consideration of factors in the assumptions.

7.4 BASIC WEATHER RADAR SYSTEM AND DATA

The basic weather radar consists of the following:

(a) An antenna to focus the transmitted microwaves into a narrow beam and receive the returning power;

(b) A tower to elevate the antenna above immediate obstructions;

(c) A transmitter to produce power at microwave frequency and a modulator to create the pulses and pulse rates;

(d) A receiver to detect, amplify and convert the microwave signal into a low-frequency signal;

(e) A signal processor to extract the desired information from the received signal;

(f) A system to control the radar and process the data into radar variables;

(g) A data display to visualize the information in an intelligible form;

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

A basic weather radar may be non-coherent (e.g. a magnetron or power oscillator type transmitter), that is, the phase of successive transmitted pulses is random. Doppler measurements can be made if the phase of the transmitted pulse is measured and the return signal processed with reference to this phase. This is known as a coherent-on-receive Doppler radar. A coherent-on-transmit radar (e.g. a klystron, power amplifier, solid state or travelling-wave tube type transmitter) transmits the same phase with each pulse. Power transmitted by a weather radar is typically several hundreds of kilowatts to a megawatt of peak power concentrated in a pulse of a microsecond in width, whereas the average power is typically a few hundred watts. Solid state or travelling-wave tube type transmitters send a pulse of much lower power but rely on long pulses to compensate.

7.4.1 Reflectivity

The backscattered power measured by 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 the weakest targets detectable. Compared to the transmit power, this is over 20 orders of magnitude smaller. To measure the weakest and strongest signals simultaneously, receivers with large dynamic ranges (> 90 dB) are required and are now commonly available (Heiss et al., 1990; Keeler et al., 1995). In the past, logarithmic receivers with a dynamic range of 90 dB were used for reflectivity measurements. Linear receivers (that maintain phase linearity) are needed for Doppler measurements. In the past, these had limited dynamic range (40 to 50 dB), requiring automatic gain control.

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:

$$Z = \Sigma \nu V(D) D^6$$

(7.6)

where the unit of $Z$ is mm$^6$ m$^{-3}$. In many cases, the number of particles and their composition and shape are not known and an equivalent or effective reflectivity factor $Z_e$ is defined. For example, snow and ice particles must refer to an equivalent $Z_e$, which represents $Z$, assuming the backscattering particles were all spherical drops of density $\rho$. 
Rainfall rate is given by:

\[ R = \sum \text{vol} N(D) V_T \rho \pi / 6 D^3 \]  

(7.7)

However, \( N(D) \) is not known, and empirical relationships between \( Z \) and \( R \) have been developed; the most famous being the one commonly known as the Marshall-Palmer relationship:

\[ Z = 200 R^{1.6} \]  

(7.8)

In order to cover the range of values, a common practice is to work in a logarithmic scale or dBZ units which are numerically defined as dBZ

\[ \text{dBZ}_e = 10 \log_{10} Z_e. \]

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 and phased array (through phase shifting) antennas are used to focus the waves into a pencil shaped or Gaussian shaped beam. Larger reflectors create narrower beams, greater resolution and sensitivity at increasing costs. The beam width, often defined by the half power points, is one half that at the axis, is dependent on the wavelength, and may be approximated by:

\[ \theta_e = \frac{70\lambda}{d} \]  

(7.9)

where the units of \( \theta \) are degrees; and \( d \) is the antenna diameter in the same units as \( \lambda \). Good surveillance weather radars have beam widths of 0.5° to 1°. However, broader beams are useful for short-range applications.

The useful range of weather radars is dependent on the application and nature of the weather. Depending on the time interval between pulses (characterized by the pulse repetition frequency (PRF), say 300 s\(^{-1}\)), the maximum unambiguous range of the radar can be hundreds of kilometres (e.g. 500 km). However, given the beam propagation and the curvature of the Earth, the beam, and therefore the pulse volume, is high and big (e.g. at 250 km, a 1° beam width radar pointing at an elevation angle of 1° is 9 km high and 6 km wide, Figure 7.4). The beam may overshoot the weather, the pulse volume may not be filled and the sensitivity of the radar may not be sufficient to measure the precipitation intensity accurately. However, if echoes are observed, they will indicate very intense and hazardous thunderstorms or weather. Typical weather radars operate with a maximum range of the order of 250 to 600 km.

For good quantitative precipitation measurements, a 1° beam width radar has an effective range of about 80 km. The smaller the beam width of the radar, the greater the effective range (e.g. a 0.65° beam has an effective range of about 120 km). At longer ranges, the data must be extrapolated to the ground. The beam spreads and under-filling results in under-reporting of the precipitation intensity. This is weather regime dependent, and the results discussed are for mid-latitudes.

### 7.4.2 Doppler velocity

The development of Doppler weather radars and their introduction to weather surveillance provided a new dimension to the observations (Heiss et al., 1990). Doppler radar provides a measure of the targets’ velocity along a radial from the radar. So it provides a measurement of the velocity component of the wind in the direction either towards or away from the radar.

The typical speeds of meteorological targets are less than 50 m s\(^{-1}\), except in the case of tornadoes/hurricanes. As discussed earlier, pulse-to-pulse phase changes are used to estimate the Doppler velocity. If the phase changes by more than ±180°, the velocity estimate is ambiguous. In order to unambiguously and accurately measure the Doppler velocity of meteorological targets, the pulse repetition frequency must be high (smaller time interval between pulses) such that the maximum unambiguous range is reduced from that of a typical radar, measuring reflectivity only. At higher speeds, additional processing steps are required to retrieve the correct velocity. The maximum unambiguous Doppler velocity depends on the radar wavelength (\( \lambda \)) and the PRF, and can be expressed as:
\[ V_{\text{max}} = \pm \frac{\text{PRF} \cdot \lambda}{4} \]  

(7.10)

The maximum unambiguous range can be expressed as:

\[ r_{\text{max}} = \frac{c}{\text{PRF} \cdot 2} \]  

(7.11)

Thus, \( V_{\text{max}} \) and \( r_{\text{max}} \) are related by the equation:

\[ V_{\text{max}} r_{\text{max}} = \pm \frac{\lambda c}{8} \]  

(7.12)

These relationships show the limits imposed by the selection of the wavelength and PRF (see Figure 7.5). A high PRF is desirable to increase the unambiguous velocity; a low PRF is desirable to increase the radar range. Unfortunately, these limits fall within the desired measurement space of a weather radar, and compromises in the radar operating conditions are required. This is known as the Doppler dilemma and is further discussed in the signal and data processing section of this chapter. The maximum unambiguous velocity or range is often referred to as the Nyquist velocity or Nyquist range.

One of the significant consequences of the high PRFs is that there are often still detectable echoes beyond the Nyquist range. These echoes are referred to as second- (or multiple-) trip echoes since they are received from pulses transmitted previously. If the targets are strong enough, the power of these targets can still be received by the radar. However, the targets will be located incorrectly in the first trip since the radar cannot determine whether the echo was a result of the current or previous pulse, given that the timing or range of the echo is based on the most recent transmitted pulse.

Some Doppler radars are fully coherent; their transmitters are oscillators and generate the same phase from pulse to pulse. These coherent radars typically employ klystrons, solid state or similar transmitters. Since these types of radars transmit the same phase for every pulse, the velocity of the second echoes will produce discernible mean radial velocities. This kind of radar cannot (without advanced processing) separate the range or the velocity of the multiple-trip echoes.

Figure 7.5. This illustrates the Doppler dilemma for the three common radar bands (X, C, S). The dilemma arises because one parameter, the pulse repetition frequency, which is the time between transmitted pulses, controls the maximum unambiguous velocity and the maximum unambiguous range in opposite ways. The markers and red lines indicate commonly used settings.
For coherent-on-receive Doppler radars, such as one with a magnetron amplifier transmitter, the phase from pulse to pulse is random. In this kind of radar, the phase of the most recently transmitted pulse is measured and the phases of all echoes are referenced to it. Therefore, the series of phases from the second-trip echo that referenced to the most recent phase will be random and will appear as noise in the Doppler spectrum. Figure 7.6 is a simulated example of a typical C band radar set-up. The sharp spike at zero velocity is due to stationary ground echoes and has a narrow power distribution. The broad peak on the right is the weather echo. It is broader than the ground clutter peak since it originates from a distribution of drops that are shuffling. Note that the tail of the weather contribution on the right is aliased and appears on the left edge of the graph. The signal fluctuates about the noise floor due to thermal noise in the system, and also about the weather spectrum due to the shuffling of the precipitation targets. A dynamic estimation of the noise power makes it possible to subtract the noise power from the overall power to produce a cleaner estimate of the first-trip power (Figure 7.7). This is an example showing (a) how stationary ground clutter can be filtered using a zero velocity notch filter, and (b) how second-trip echoes can be filtered using a noise type filter (signal quality index).

Two signal-processing 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 fast Fourier transform (FFT) processing 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.

### 7.4.3 Dual polarization

There are several basic radar polarization techniques in current usage. One system transmits a circularly polarized wave, and the co-polar and orthogonal polarization powers are measured. Another system alternately or simultaneously transmits pulses with horizontal (H) then vertical (V) polarization utilizing a high-power switch. Simultaneous H and V radars do not require a fast switch. The complexity of unravelling the microphysical characteristics of the echo is still a challenge, and manufacturing a high-quality circular polarization system can be more costly. The linear polarization system is generally preferred since the retrieval of meteorological information is less calculation intensive, and conventional radars can be converted to dual polarization.
more easily. Except in a few situations, the high-power switch has proved to be problematic for alternating polarization, and as a result the simultaneous transmit and receive system is common in operational radars.

In general, the polarization technique is based on micro-differences in the scattering particles. Raindrops are 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. This is also true for other targets such as insects, birds and ground clutter.

Table 7.2 describes the most common polarization diversity parameters. 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 precipitation may be separated as hail, rain, drizzle or snow (Seliga and Bringi, 1976).

As an electromagnetic wave propagates through a medium with oblate particles, the phase of the incident beam is altered due to attenuation differences (resulting in propagation speed differences) in the vertical and horizontal. The effect on the vertical and horizontal phase components depends on the oblateness and is embodied in an integral parameter termed the differential phase ($\phi_{DP}$). If an appropriate range derivative can be computed, the specific differential phase ($K_{DP}$) can also be estimated. For heavy rainfall measurements, $K_{DP}$ has certain advantages (Zrnić and Ryzhkov, 1995). English et al. (1991) demonstrated that the use of $K_{DP}$ for rainfall estimation is much better than $Z$ for rainfall rates greater than about 20 mm h$^{-1}$ at the S band. Since this is a phase measurement and can be localized or specific to the range bin, this parameter can be used to overcome issues of power calibration and partial beam blockage. With greater attenuation (shorter wavelengths), the effectiveness of this technique increases at lower reflectivities or precipitation rates.

The correlation of the vertical and horizontal time-series data provides a statistical measure of the dissimilarity of the $H$ and $V$ scattering cross-sections of the hydrometeors. It should be noted that this is a statistical measure, and so rain and snow, though on an individual particle basis appear to have quite different scattering characteristics, actually have high correlation in the statistical sense. Bebbington (1992) designed a parameter for a circularly polarized radar,
termed the degree of polarization, which is insensitive to propagation effects (linear correlation is independent of propagation effects also). This parameter is similar to linear correlation for linearly polarized radars and 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 et al., 1993).

7. 5  
**SIGNAL AND DATA PROCESSING**

7. 5.1  
**The Doppler spectrum**

The radar detects an electromagnetic wave returned from the target. This wave is a result of all the scatterers in the radar volume. Mathematically, a wave is characterized by an amplitude and phase or equivalently in complex numbers as the real or imaginary parts of a phasor. This is also called the in-phase or quadrature (I, Q) signals. The wave is measured several times and the results are a time series of I, Q samples. If a Fourier transform is applied to the data, then the magnitude of the Fourier transform coefficients constitutes the Doppler spectrum. The Doppler spectrum is a representation of the auto-correlation of the I, Q time series in frequency space (Wiener, 1964). The more time samples, the finer the resolution in the frequency domain. Processing in time domain is equivalent to that in the frequency domain. Figure 7.6 shows a typical Doppler spectrum and is useful to characterize the various aspects of the information within a single radar volume. The noise level (integrated over the entire spectrum) represents the minimum signal level or minimum detected signal of this range bin. The peak at zero frequency or zero velocity is the contribution of stationary echoes or ground clutter. The broader peak is due to the weather target. Note that the peak at zero velocity is broadened by the antenna motion, poor phase stability of the radar system and a fewer number of samples. The width of the ground clutter spectrum is generally smaller than the width of the weather spectrum and can, in most cases, be used to separate the ground from the weather echo. The area under the weather echo and above the noise level is the power of the weather echo. The area under the ground clutter spectrum is the power due to ground clutter.

7. 5.2  
**Power parameter estimation**

The hydrometeors are distributed within the pulse volume and shuffle relative to each other and produce a fluctuating signal. Averaging is required to reduce the variance of the measurements to within acceptable uncertainty. Generally, 30 independent pulses are required to estimate reflectivity (Doviak and Zrnić, 1993). This implies that the pulses need to be sampled at time intervals greater than the de-correlation time of the pulse volume, sampled in different locations in range or using some other technique (frequency shuffling).

Operationally, this is done in various ways depending on the application and processing philosophy. The antenna could slowly scan and the reflectivity could be estimated within one degree of azimuth and within one pulse volume, or it could rotate more quickly and range averaging could be employed in the signal or data processor. Additionally, poorer data quality could be acceptable and data smoothing could be applied at a later stage.

7. 5.3  
**Ground clutter and point targets**

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 since the sides of the main beam and the side lobes interact with the nearby terrain (Figure 7.8). The radar beam is not perfectly conical but radiates in all directions, though the main power is along the bore sight. The beam width is often defined as the half power points (~3 dB of the power along the bore sight). This radiation pattern is determined by the geometry of the feed horn, the distance from the focal point, the parabolic dish and the struts holding the feed horn. The height of the first side lobe
(marked) is more or less determined by these factors and often used as a measure of the quality of the antenna. Reducing or moving this side lobe in azimuth by shifting the feed horn results in either a broader main beam or power loss.

The intensity of ground clutter is inversely proportional to wavelength (Skolnik, 1970, 1990), whereas backscatter from rain is inversely proportional to the fourth power of wavelength. Therefore, shorter wavelength radars are less affected by ground clutter. Ground clutter echoes should be eliminated for precipitation estimation; however, clutter echo can be used for humidity measurements (Fabry, 2004). 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. 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 their relative strength.

To remove ground clutter, 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 typically 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.

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 (see Figure 7.6). The spectral widths of ground clutter and weather echo are generally much less than 0.5 m s\(^{-1}\) and generally greater than 1 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 7.6). The spike has finite width because the ground echo targets, such as swaying trees, have some associated motion.
Time domain processing to remove the zero velocity component of a finite sequence is done with a high-pass digital filter. A width and depth of the digital filter to match the clutter must be assumed for the whole scanning domain, and mismatches are inevitable as the clutter varies (Zrnić and Hamidi, 1981). Adaptive spectral (Fourier transform) processing identifies the ground clutter echo, heuristically determines the clutter echo and removes the ground clutter power from the total power, thereby separating ground clutter from the weather echoes even if they are overlapped (Passarelli et al., 1981; Crozier et al., 1991; Figure 7.7). It can be difficult to separate the weather from the clutter echo when the weather echo is narrow (as in light snow situations) and the mean Doppler velocity is near zero. In this situation, too much weather echo can be removed. When the weather echo spectrum is narrow as in the case of snow or drizzle, the zero-notch filter cannot distinguish the weather from the ground clutter. This is particularly true when the antenna spins fast, causing the ground echo spectrum to broaden, and when the mean radial velocity of the weather is near zero. Too much power is removed and results in an anomalous depression in reflectivity (Figure 7.9, left image). The arrow shows where the depressed echo corresponds to the zero line in the radial velocity image (Figure 7.9, right image). This is a minor drawback to Doppler notch filtering.

Improvements to the clutter echo identification include better techniques to identify the clutter echo (Gaussian model adaptive processing) and techniques to use texture of the data (variance of the reflectivity) associated with clutter before applying the clutter filters (Hubbert et al., 2009a; Hubbert et al., 2009b). Systems without Doppler could employ these texture techniques to remove ground clutter and anomalous propagation echoes.

An alternative approach, called micro-clutter removal, 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 et al., 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 ground clutter since the ground clutter has different polarimetric features as compared to precipitation. In addition, other kinds of clutter targets can be identified.

Clutter can be reduced by careful site selection (see below). 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 constant altitude plan position indicator (CAPPI) products, low elevation data
are rejected automatically at short ranges (Marshall and Ballantyne, 1978). Figure 7.4 shows
a geometric scan sequence proposed by Marshall and Ballantyne (1978) that is optimized to
produce constant height products such as the CAPPI and echo top.

7.5.4 Overcoming the Doppler dilemma

The Nyquist interval and sampling govern the quality of the Doppler velocity estimates. The
Nyquist interval (±180°) must be sufficiently large to span the spectrum of the weather echo.
Typically, the weather echo usually has a 4–6 m s\(^{-1}\) width and so the Nyquist interval must be at
least twice as wide. The tails of the spectrum may be aliased, but if the signal is strong the mean
velocity can still be estimated.

In order to provide a statistically stable velocity estimate about 20–30 samples are required.
These samples need to be correlated, so they need to be made quickly. Note that this is fewer
than for reflectivity, and in theory, it is possible to recover velocity at lower signal-to-noise ratios
(weaker signal strength) than reflectivity and in a shorter period of time.

To detect returns at various ranges from the radar, the echoes should be sampled periodically,
usually about every 1 µs, to obtain information about every 150 m in range. This sampling
can continue until it is time to transmit the next pulse (at about every 1 ms). A sample point in
time (corresponding to a distance from the radar) is called a range gate. The interval between
transmit pulses governs the maximum unambiguous range. The wavelength combined with the
transmit interval governs the maximum unambiguous velocity. For weather radar wavelengths
and weather scenarios, these maxima are in conflict and this is called the Doppler dilemma,
as increasing one results in reducing the other. This is shown in Figure 7.5. So, a fundamental
problem with the use of any pulse Doppler radar is to mitigate the impacts of limited range and
velocity.

Common techniques to mitigate the velocity limitation or to de-alias the velocities include
multiple PRF techniques (Doviak and Zrnić, 1993; Crozier et al., 1991) or continuity techniques
(Eilts and Smith, 1990). In the former, radial velocity estimates are collected at two or more
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 de-alias the velocity to an extended Nyquist velocity range of ±48 m s\(^{-1}\).
Figure 7.10 shows how the dual-PRF technique is able to extend the unambiguous velocity. The
top graph shows what the Doppler radar is able to measure as a function of true radial velocity
(−48 to 48 m s\(^{-1}\)). In this example, the PRFs are in 4:3 ratio; other ratios such as 7:5 and 3:2 are
possible. The bottom graph represents the unique difference in the measured Doppler velocities
as a function of true radial velocity. From this difference, the fold number can be determined and
the true velocity can be retrieved. The limit of the retrieval is determined by the unambiguous
Nyquist velocities and their ratio. This limit is called the extended Nyquist velocity and is 48 m s\(^{-1}\)
in this case. Figure 7.11 shows an example of the results of this technique.

Combinations of PRF ratios commonly in use are 5:4, 4:3 or 3:2. The maximum unambiguous
velocity commonly used is 16 m s\(^{-1}\), though it is not a strict requirement. Lower velocities would
result in larger maximum ranges. The difference in the use of the various ratios is that the
variance in the mean velocity results in the uniform velocity assumption being violated and dual-
PRF errors arising (Joe and May, 2003).

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 2\(V_{\text{max}}\)).
Fold numbers are determined starting at the zero line, and whenever a discontinuity of a Nyquist interval is encountered, the fold number is increased or decreased and the Nyquist interval is added or subtracted.

The second fundamental problem is the range limitation imposed by the use of high PRFs (greater than about 1 000 Hz). Echoes beyond the maximum range will be aliased back into the primary range. For radars with coherent transmitters (e.g. klystron or solid state), the echoes will appear within the primary range. For coherent-on-receive systems, the second-trip echoes will appear as noise (Joe et al., 1995; Passarelli et al., 1981; Figure 7.12). For the latter system, the noise

Figure 7.10. This is an example of a C band radar pulsing at 900 and 1 200 s⁻¹ with unambiguous Nyquist velocities of 12 and 16 m s⁻¹, respectively. The technique relies on the difference between measured radial velocities (ordinate on the bottom image) to determine the fold number (abscissa on the bottom image) and then use that with the corresponding measured radial velocity to estimate the true radial velocity.

Fold numbers are determined starting at the zero line, and whenever a discontinuity of a Nyquist interval is encountered, the fold number is increased or decreased and the Nyquist interval is added or subtracted.

The second fundamental problem is the range limitation imposed by the use of high PRFs (greater than about 1 000 Hz). Echoes beyond the maximum range will be aliased back into the primary range. For radars with coherent transmitters (e.g. klystron or solid state), the echoes will appear within the primary range. For coherent-on-receive systems, the second-trip echoes will appear as noise (Joe et al., 1995; Passarelli et al., 1981; Figure 7.12). For the latter system, the noise

Figure 7.11. This figure illustrates the necessity and ability of a C band radar to extend the velocity out to at least 48 m s⁻¹. This is a case of a hurricane/extratropical transition passage and velocities are near 48 m s⁻¹. In this situation, the assumptions of the dual-PRF technique (the two measured estimates at different PRFs are from the same radial velocity) are satisfied and the result has little noise (right image, compare with Figure 7.20).
is a result of the randomly transmitted phases. Doppler radars with their short Nyquist range are contaminated with second-trip echoes, regardless of whether they are coherent-on-receive (magnetron) or coherent-on-transmit (klystron) type. In Figure 7.12, from a C band magnetron radar, the second trip reveals itself as wedge-shaped echoes in reflectivity (black arrows) and this can be used to identify them. In the radial velocity field, the data are noisy (yellow arrows) and this can be used in the signal-processing stage to eliminate them as their Doppler spectrum is very broad, elevating the noise level. If these data were taken with a klystron radar, the radial velocity would appear as coherent data.

Phase coding techniques have been developed to distinguish the second-trip echoes for coherent Doppler radars. Processing can be done with respect to the current pulse for the first-trip echo and the previous pulse for the second-trip echo. This is called random phase processing. It is effective if the sensitivity of the radar is good (low) so that the second-trip echo can be detected above noise and if the phase stability is good (low) so that the phase or velocity can be recovered at long ranges. For coherent transmitters, a pseudo-random sequence can be generated. Better still is to modulate the phase in a known way to precisely separate the first from the second trip. Frush et al. (2002) developed this technique for klystron systems.

In a coherent-on-receive (e.g. magnetron) system, the phase variation is implicitly random. In a coherent-on-transmit (e.g. klystron) system, the phase variation is imposed by the modulator in a controlled fashion. An example is the SZ-2 phase modulation used in the US WSR-88D system. The two examples in Figure 7.13 (a–d, e–h) are shown to illustrate the benefits and limitations of the random phase technique. Images 7.13(a) and 7.13(e) are taken with low PRF and represent the “truth”. Images 7.13(b) and 7.13(f) are retrieved from the random phase technique. The demarcation of the first–second trip boundary is indicated by the white arrow. The gap is because the receiver is turned off while the pulse is being transmitted. In images 7.13(a–d), a squall line has not reached the radar. The echoes near the radar are weak relative to those at far ranges and the technique works well as most of the second trip is recovered (compare 7.13(a) with 7.13(b)). In images 7.13(e–h), part of the precipitation system has reached the radar and so there are relatively strong echoes near the radar relative to those at far ranges. The technique works less well as there are significant amounts of the second trip that are not recovered (compare 7.13(e) with 7.13(f)). In this implementation of the technique, only single PRF data is possible and the Nyquist is 16 m s⁻¹ (images 7.13(c) and 7.13(g)). The dual-PRF data with an extended Nyquist range of 48 m s⁻¹ are shown in images 7.13(d) and 7.13(h). While aliased, the single PRF data can still be interpreted and effectively used by a well-trained analyst. For example, a “bookend vortex” can be observed in image 7.13(c) (white and black arrows). The corresponding reflectivity images are the inner (first trip) portions of images 7.13(b) and 7.13(f). An important aspect of random phase processing is that the first trip will have higher data quality as the impacts of the second-trip echo are filtered.
An earlier technique uses a surveillance scan with low PRF to determine the location of the reflectivity echo. Then when overlapping echoes are encountered in the shorter range Doppler mode, the echo power and velocity are assigned to the location with the greater power (Figure 7.14). This works if the power is significantly different (> 5 dB). A long-range surveillance scan is used to locate the reflectivity echo. A short-range Doppler scan is used to measure the Doppler or radial velocity. The radial velocity is assigned to the reflectivity echo with the greatest power. If the powers are within 5 dB of each other, the technique does not work well and the radial velocity data are not recovered and are designated as range folded. They are marked as white in Figure 7.14. Some colour schemes are employed that mark these echoes as purple and so this is often called purple haze.

A combination of multiple PRF and phase diversity techniques can be used to mitigate both problems simultaneously (WMO, 2012; Yamauchi et al., 2013).

Figure 7.13. Example of random phase range extension: the example on the left (a–d) shows a situation where the first-trip echo is weak and much of the second-trip echo is recoverable. In the example on the right (e–h), there is significant first-trip echo which precludes recovering the second-trip echo.

Figure 7.14. Without the advanced phase coded signal processing, multiple PRF techniques are used to recover the second trip. Low PRF scans with long-range capability are used to locate the reflectivity echo. High PRF but short-range scans are used to measure radial velocity. The radial velocity is assigned to the range bin with the highest power.
7.6 OPTIMIZING RADAR CHARACTERISTICS

7.6.1 Selecting a radar

A radar is a highly effective observation system. However, the application, the climatology, the local environment (blockage) and the network design determine the effectiveness of any particular radar or radar system. Everything about radar is a trade-off. 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 a few applications, such as tornado detection or snow squall detection, but not all applications (compared with long-range surveillance). Cost is a significant consideration. Much of the interdependence can be referenced to the radar range equation.

An important consideration is the radar network design and the application. Networks of X band radars are being proposed for a variety of local applications where the range requirement is of the order of 50 km or less and where low-level coverage is critical – as in low-level snow squall, tornado detection, microburst detection, complex terrain (mountainous), urban hydrology and perhaps wind turbine mitigation. The original intention of these networks was for adaptive sensing of the atmosphere for multiple applications – from weather to air traffic control. This is accomplished in conjunction with phased array antennas that have pointing agility and can scan in a cooperative fashion (McLaughlin et al., 2009). An innovation of this technology is the low requirements in terms of infrastructure of the phased array antenna that can be mounted on a side of a building or on an existing tower.

7.6.2 Wavelength and beam width

The larger the wavelength, the greater the cost of the radar system, particularly antenna costs for comparable beam widths (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 interest for weather radars (S, C and X), the sensitivity of the radar or its ability to detect a target is strongly dependent on the wavelength. However, this dependence is pragmatically mitigated by transmit power. It is also significantly related to antenna size, which impacts gain, beam width and beam filling. Smaller wavelength radars (35 GHz and 94 GHz) are becoming available for specialized applications, such as fog or cloud detection, or used from space-based platforms for cloud or precipitation measurements (e.g. Tropical Rainfall Measuring Mission (TRMM); Global Precipitation Measurement (GPM); CloudSat; and Earth Clouds, Aerosols and Radiation Explorer (EarthCARE)).

Considerations of Doppler range within a radar network have a great impact on the wavelength chosen. For the same Nyquist velocity, an S band will have twice the Nyquist range compared to a C band radar and hence have a significant impact on unambiguous coverage. This may be mitigated with the velocity and range extension techniques discussed earlier.

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. 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.

The great disadvantage is that smaller wavelengths have much larger attenuation. It remains to be seen whether the dual-polarization K\_\text{dp} techniques can compensate for the attenuation until total attenuation occurs (which is very infrequent) and whether ignoring attenuation at S band is justified. If K\_\text{dp} techniques prove to be superior for precipitation estimation than reflectivity techniques, the smaller wavelength is more sensitive to attenuation and so may be more effective.

The radar signal may be totally lost at C and X band, particularly if the radome is wet. While this may seem disastrous, the key question is whether the loss of signal (typically for tens of minutes
for propagating storms) results in actual missed severe storm warnings or missed flash flooding. Experience indicates that warnings will have usually been already issued and the loss of one or two data points for hydrological purpose is not a devastating situation.

7.6.3 **Transmitters and transmit 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 and pulse width. Improvements in sampling, receiver sensitivity, antenna gain, pulse width or choice of wavelength may be better means of increasing detection capability.

Magnetrons and klystrons are common power sources. Magnetrons cost less but are power oscillators and so they are less stable in frequency. Many Doppler radars today are based on magnetrons, and with co-axial magnetrons and digital technology, the phase noise of these systems can be comparable to that of klystron systems. Smaller phase noise results in greater capability for clutter rejection (Figure 7.15). Phase noise of less than 0.5° is a minimum performance level of modern radars. 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 and 1 000 kW or greater in the C band and S band, respectively.

Solid state transmitters have recently been deployed operationally. They have the promise of reduced maintenance with the high reliability of solid state technology, excellent phase stability and electronic stability for dual-polarization measurements. Solid state transmitters are typically low power and require multiple long pulse lengths and pulse compression to attain the required sensitivities. They are a combination of pulse and frequency-modulated continuous wave radars. Range side lobes are an issue with pulse compression modulation schemes and it remains to be seen whether they are significant in the weather application.

7.6.4 **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

![Figure 7.15. Coherency (phase noise) is a measure of the quality of a Doppler radar and is directly related to the ability to remove ground clutter and retrieve second-trip echoes using phase coding techniques.](image)
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 µs. A pulse length
of 2 µs has a resolving power of 300 m, and a pulse of 0.5 µs 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 but decreases 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.

7.6.5  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 reflectivity-only 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 (~1 200 s⁻¹) are used to increase the Doppler unambiguous
velocity measurement limit. This results in the Doppler dilemma, where there is a trade-off
between maximum range and maximum velocity. 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 (~300 s⁻¹) are desirable to
increase the maximum unambiguous range that can be measured, and to provide a lower duty
cycle.

7.6.6  The antenna subsystem

Weather radars normally use a horn fed antenna with a parabolic reflector to produce a
focused narrow conical beam. Three important considerations are the beam width (angular
resolution), the antenna gain and the side lobes. For common weather radars, the size of the
antenna increases with wavelength for a fixed beam width and with the narrowness of the
beam required. A common target for weather radar antenna beam width is 1°, though there is
inherently nothing special about this number.

Phased array antenna technologies are being explored in research and are now commercially
available at X band at an affordable price. These antennas consist of phase controllable radiating
elements that form the beam. Adaptable target specific or dependent scan strategies can
be developed such that rapid scan or high-quality data requirements can be simultaneously
satisfied in theory, but this is still to be demonstrated in operations. Ground clutter rejection may
be superior as these systems do not scan but essentially momentarily stare at each radial and so
the beam smearing of the ground clutter echo does not occur.

Antenna size and beam width

Weather radars normally have beam widths 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 at least 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 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 widths at 50, 100 and 200 km range are 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 beam width at the longer ranges is substantially large.
The gain of the antenna is also inversely proportional to the beam width 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 therefore 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 0.5 to 6 rpm.

Most single polarization weather radars are linearly polarized, with the direction of the electric field vector transmitted being horizontal and sometimes vertical. Reasons for favouring horizontal polarization include: (a) sea and ground echoes are generally less with horizontal polarization; (b) lesser side lobes in the horizontal provide more accurate measurements in the vertical; and (c) there is greater backscatter from rain due to the drop ellipticity. However, at low elevation angles, better reflection of horizontally polarized waves from plane ground surfaces may produce an unwanted range-dependent effect.

Most if not all operational dual-polarization radar employ the STAR mode of transmission, with equal amount of power at two orthogonal linear polarizations (typically horizontal and vertical). This eliminates the need for a high-power, high failure polarization switch.

### 7.6.7 Illumination

Side lobes are an inherent property of any antenna. Side lobes also include the sides of the main lobe. The beam width is usually defined as the half power points of the main beam and there is power at angular distances away from the main beam. A major contributor to the side lobes is the feed horn and the struts supporting the feed horn. Side lobes may be mitigated by over-illuminating the dish; however, this results in a broader beam and less sensitivity.

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

### 7.6.8 Typical weather radar characteristics

The characteristics of typical radars used in general weather applications are given in Table 7.7. 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 non-coherent pulsed radars that have been in use for decades. The Doppler radars are de rigueur and add a new dimension to the observations. They provide estimates of radial velocity. Specialized Doppler radars have been developed for better detection of small-scale microbursts and tornadoes over very limited areas, such as for air-terminal protection. Dual-polarization radars are deployed and applications for data quality, target classification and quantitative precipitation estimation are finding their way into operations – including in hydrology, numerical weather prediction, and climate change studies.
### Table 7.7. Specifications of typical meteorological radars

<table>
<thead>
<tr>
<th>Type</th>
<th>S</th>
<th>S</th>
<th>S</th>
<th>S</th>
<th>C</th>
<th>C</th>
<th>C</th>
<th>C</th>
<th>C</th>
<th>C</th>
<th>X</th>
</tr>
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<td>Frequency (GHz)</td>
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<td>2 700–3 000</td>
<td>2 700–3 000</td>
<td>2 700–3 000</td>
<td>5 400–5 900</td>
<td>5 600–5 650</td>
<td>5 600–5 650</td>
<td>5 500–5 700</td>
<td>5 300–5 850</td>
<td>9 300–9 500</td>
<td></td>
</tr>
<tr>
<td>Wavelength (cm)</td>
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<td>10.7</td>
<td>10.7</td>
<td>10.7</td>
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<td>5.3</td>
<td>5.3</td>
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<td>3</td>
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<td>Peak power (kW) per channel</td>
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<td>850</td>
<td>750</td>
<td>20</td>
<td>500</td>
<td>1 000</td>
<td>250</td>
<td>250</td>
<td>12</td>
<td>75</td>
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<td>Pulse lengths (μs)</td>
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<td>0.2–2.0</td>
<td>0.4–4.5</td>
<td>0.5–200</td>
<td>0.2–3.0</td>
<td>0.4–4.5</td>
<td>0.4–4.5</td>
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<td>0.3–3.3</td>
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<td>PRF (/s)</td>
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<td>200–2 400</td>
<td>250–2 000</td>
<td>100–20 000</td>
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<td>200–2 400</td>
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<td>100–20 000</td>
<td>250–3 000</td>
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<td>–19.5</td>
<td>–15</td>
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<td>115</td>
<td>99</td>
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<td>0.95</td>
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<td>Solid state</td>
<td>Co-axial magnetron</td>
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<td>Co-axial magnetron</td>
<td>Solid state</td>
<td>Co-axial magnetron</td>
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</table>
7.6.9 Radar volume scan strategy

Most modern radars automatically perform a volume scan consisting of a number of full azimuth rotations of the antenna at several elevation angles. This is called the scan strategy and there are a variety of strategies for different purposes (Marshall and Ballantyne, 1978; Brown et al., 2005; Crum and Alberty, 1993; Germann et al., 2006; Seltmann et al., 2013).

Long-range scans of 500 km or more (that result in limited Nyquist velocity) are needed for long-range surveillance. Rapid update of the order of 5 min is required to capture the evolving morphology of the convective thunderstorm. In aviation downburst applications, even shorter cycle times are required (Michelson et al., 1990). Research radars scan limited areas or sectors with 1 min or less cycle times (Wurman et al., 1996). Slow low-level scans with long pulse lengths are needed to maximize the capture of clear air echoes. Slow scanning will optimize the Doppler filtering of ground echoes. Multiple PRF techniques require the assumption of uniformity of radial velocity and can be implemented on a ray by ray or scan by scan basis.

Scans as low in elevation as possible are needed for optimizing the retrieval of quantitative precipitation estimates and also to optimize the detection of low-level and shallow weather. A geometric sequence of elevation angles are required to generate optimal CAPPI or echo top products (Marshall and Ballantyne, 1978). The emerging X band phased array radar networks, such as that of the Collaborative Adaptive Sensing of the Atmosphere (CASA) project or the Multifunction Phased Array Radar (MPAR) project, are revolutionizing the scan strategy concept as the electronic scanning can adapt to the weather or application (McLaughlin et al., 2009; Weber et al., 2007), or weaknesses may be mitigated with data from neighbouring radars.

The trade-off is the quality of the data. For example, slow scans for high spectral resolution for ground clutter mitigation or low data variance preclude scan strategies with very many elevation angles and hence result in poor vertical resolution. Data quality is a nebulous concept as it qualitatively refers to trade-offs in timeliness or temporal resolution (cycle time), spatial resolution (azimuth, range, elevation), data bias (velocity or reflectivity bias) and data variance. This is difficult to objectively optimize as the success metrics are quite diverse and setting the number of elevation angle sequence is not an exact science.

Of prime consideration is the nature of the weather and the location that requires the coverage. For example, the scan sequence for a radar located in a valley used for local and short-range application will or can be quite different from a radar that is used for long-range surveillance for land-falling hurricanes (Joe et al., 2014).

While it is attractive conceptually to set the elevation angle changes equal to the beam width, small changes in the elevation angle of even 0.1° degrees can produce significant views of the data, due to the stratified nature of the precipitation (snow, bright band, rain profiles) and the wind profile.

Raw polar data are stored in a three (range, azimuth, elevation) or multiple (radar parameter) dimensional array, commonly called the volume scan. This serves as the data source for further data processing and archiving. There can be several versions of raw data due to different data quality processing.

7.6.10 Radar performance

Minimum detectable signal

The minimum detectable signal (MDS) is a performance measure of the aggregate of the transmit power, antenna size, beam width or gain, pulse length, wavelength and other factors. This is often described in power units or system noise temperature. However, for a radar analyst, reflectivity at a fixed range provides a more intuitive measure of the performance of a radar. High sensitivity is highly desired in order to detect clear air echoes and light precipitation and to enhance the retrieval of second-trip echoes. Table 7.8 shows some MDS of typical high-performance radars.
Phase stability

Phase stability or phase jitter is a measure of the average change of phase from pulse to pulse. Some radar test software can provide this measurement using an acoustic delay line or from external targets. The advantage of the latter is that it tests the stability at different ranges or time delays and the entire processing change. Good phase stability (< 0.5°) results in better velocity estimation, ground clutter rejection and better second-trip retrieval with magnetron systems.

Cross-polar correlation and ZDR

A measure of the quality of a dual-polarization radar is the cross-polar correlation ($\rho_{HV}$). If the radar is pointed at light rain or drizzle that is generally uniformly round, the correlation should be very close to 1.0. Good radars report values typically of 0.995 or better. This indicates that the dual polarization is very good and well configured.

If vertical scans are performed during stratiform conditions, the $Z_{DR}$ values should be 0 and have no azimuthal dependence.

7.7 MAINTENANCE AND CALIBRATION

Radar is arguably the most complex of instruments that a meteorological service or service provider must service and maintain. It requires a very high level of training and skill development. Maintenance is critical to keeping the radar operating, and calibration is critical to the quality of the data. Both should follow the manufacturer's prescribed procedures. The following is an outline.

7.7.1 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. Mechanical and electronic failures are the most prevalent (Sireci et al., 2010; Figure 7.16).

It should be noted that factors external to the radar can result in data not reaching the users. These include failures or poor quality of the main power, or there may be too many spikes or fluctuations in the power. The power grid may fail due to lightning or other reasons. Telecommunications may fail. Air conditioning systems may fail and result in the shutdown of sensitive electronic systems.

<table>
<thead>
<tr>
<th>Radar</th>
<th>MDS at 50 km</th>
</tr>
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<tbody>
<tr>
<td>Z9110</td>
<td>-8.0 dBZ (few days in August)</td>
</tr>
<tr>
<td></td>
<td>-10.0 dBZ (2 months)</td>
</tr>
<tr>
<td>Z9220</td>
<td>-1.0 dBZ</td>
</tr>
<tr>
<td>King City CONVOL (2 $\mu$s)</td>
<td>-11.0 dBZ</td>
</tr>
<tr>
<td>King City DOPVOL (0.5 $\mu$s)</td>
<td>-5.0 dBZ</td>
</tr>
<tr>
<td>Twin Lakes, OK</td>
<td>-7.5 dBZ</td>
</tr>
<tr>
<td>Lake Charles, LA</td>
<td>-8.5 dBZ</td>
</tr>
</tbody>
</table>
Preventive maintenance should include at least a quarterly 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 facility 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. Basic record keeping is a must.

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

(a) Spare parts for all of the most sensitive and long lead item 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% 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%, 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% of the radar value;

(c) Well-trained personnel capable of identifying problems and making repairs rapidly and efficiently are critical.

Competent maintenance organization should result in radar availability 96% 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;
CHAPTER 7. RADAR MEASUREMENTS

(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.

7.7.2 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 waveguides have their nominal characteristics. However, this method is very rarely used because of the practical difficulties in flying a sphere and multiple ground reflections, as well as the time and skill required (Brunkow, 2001).

A standard procedure is to use the sun as a calibration source for power and pointing accuracy. The sun is a microwave source and appears as a disk of about 0.5 degrees (Tapping, 2001). However, by maximizing the power, greater precision can be achieved. Beam propagation effects may affect low elevation angles and so higher angles are often used for solar calibration. Repeated measurements will statistically improve the precision of the results. It should be noted that antenna elevation pointing accuracy and precision may be a function of angle and so a variety of angles should be measured.

Routine electronic calibration generally ignores the antenna but includes the waveguide 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, out-of-band power should be filtered;

(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 azimuthal antenna pointing and 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 six months. Emerging systems may be designed to perform this automatically. Simple comparative checks on echo strength and location can be made frequently, using two or more overlapping radars viewing an appropriate target (Zhang et al., 2005).
Data techniques such as reflectivity accumulations, probability distributions of reflectivity as a function of range for the minimum detectable signal, transmit–receive cell monitoring, and checking readback and command elevation angles can be used to monitor the health of the radar. Biases in radial velocity accumulations may reveal clutter filtering issues – generally under-filtering which results in biases in radial velocity towards zero (Joe, 2010).

Dual-polarization radars require two receivers that must be matched. Tolerances for all the components need to be tighter since small values are measured. Then, self-consistency and birdbath scans for $Z_{DR}$ nulling can be used to check this. Self-consistency calibration refers to computing $Z$ from $K_{DP}$ using an empirical relationship derived from disdrometer measurements (Figure 7.17) and computed from theoretical formulae. Then, the reflectivity (calibration bias) is adjusted until the $K_{DP}$ derived reflectivity matches the adjusted reflectivity. Given the quality (tightness of the scatter) of the $Z$–$K_{DP}$ relationship, one could consider using $K_{DP}$ as the dependent parameter for rainfall estimation. If the radar is pointed vertically (the antenna dish appears like a birdbath) in stratiform rain conditions, the $Z_{DR}$ should be zero, and adjustments are needed if it is not. Monitoring the maximum reported $\rho_{HV}$ will provide a check on the overall system performance – good radars should report 0.995 or better.

An innovative technique is the use of the TRMM or GPM space-borne radar for the calibration of ground-based weather radars. It is a single and stable downward-looking instrument that overflies the ground-based weather radars. Comparisons of echo top height, at a fixed and moderately low sensitivity, where attenuation is not significant, are used as the success metric for consistency in cross-radar calibration (Anagnostou et al., 2001).

### 7.8 RADAR INSTALLATION

#### 7.8.1 Optimum site selection

Optimum site selection for installing a weather radar depends 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 et al., 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 other. 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 adequacy and availability of digital elevation datasets such as GTOPO30 (https://lta.cr.usgs.gov/GTOPO30), SRTM30 and SRTM03 (http://www2.jpl.nasa.gov/srtm/) have resulted in software applications to help select a site. The basic product is a radar horizon plot where the elevation angle of the horizon, taking into account atmospheric beam propagation, is plotted against radar azimuth angle (Figure 7.18). In this figure, the range to terrain is colour coded as a function of azimuth and elevation angle. The colour indicates the range to which a radar beam (in this case, a 4/3 Earth model is assumed) will collect usable data. This is particularly useful in complex terrain where a radar located in the valley must provide coverage at low levels (in the valley) but with limited range as precipitation changes considerably from mountain crest to mountain valley. For example, the radar can see to 50 or 60 km along the 190° azimuth at elevations of 1° or 2°. This analysis cannot account for trees or artificial towers.

With this plot, the scan angles can be specified for optimal surveillance of the required critical areas. The datasets cannot take into account local blockage due to trees, buildings or towers.

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 beam width above the horizon, or with a horizontal width greater than a half beam width;
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 side lobes 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 et al., 1990);

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 hilltop. It will see a great deal of clutter, which may not be so important at long ranges (see section 7.5.3 for clutter suppression);

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, 1990; Leone et al., 1989).

7.8.2 Data exchange, networking, database and processing

Advancements in telecommunications and computer technology allow the transmission of radar data from a large number of sites to a central site for processing and visualization with common computer systems. Given current internet, cell phone and even satellite data rates and costs, global data exchange of at least limited but useful and usable radar data is conceivable – though the details of telecommunication networks need to be investigated. It should be kept in mind that radars are often located at remote sites where advanced telecommunication systems are not available or the initial capital investments are needed to minimize operating and maintenance costs.

In some countries, multiple radar networks exist to address different applications – weather, aviation hazards at airports, hydrological resource management, air traffic control and even customs and immigration. Data exchange is conceivable given the caveat that the applications are very specific resulting in very specific data collection methodologies and perhaps even technologies. In some locales, this is operational but requires substantial effort to integrate and interpret.

WMO has existing standards for a few radar products. Anticipating the need for radar data for regional and global numerical weather prediction, WMO has initiated a WMO radar data exchange project to define standards for raw radar data (Michelson et al., 2013). In addition, a WMO radar database has been created that attempts to provide basic metadata information about radars and radar networks on a global basis (Sireci et al., 2010).

Radar products are exchanged to generate multi-radar composite or mosaic products that are generally intended to represent surface precipitation over a vast area for long-range weather surveillance. This is common within but also between countries. The OPERA (European Operational Programme for the Exchange of Weather Radar Information) consortium is a centralized networking and processing multinational model (Dupuy et al., 2010). The BALTRAD consortium (http://baltrad.eu) is another networking and processing model for handling heterogeneous radar networks that is open source with a peer-to-peer data exchange and processing software concept that allows individual members to receive or send data, and configure and process the software as they choose (Michelson et al., 2010). A particular challenge is the compositing of heterogeneous radars consisting of products derived from different geographical projection, spatial and temporal resolution and processing. This has led to the concept of exchanging the polar raw radar data to mitigate these issues. However,
depending on the radar and the configuration, various processing steps have already been applied to the raw data to different degrees. These issues also apply to radar data exchange within a country as radars may be of different generations.

In terms of processing, there are many choices these days. Each manufacturer provides their own radar data processing and visualization systems usually with various features, such as networking capability included or for licence. There are also systems such as TITAN (Thunderstorm Identification, Tracking, Analysis and Nowcasting), which is a popular and freely available software used in many research and several meteorological services (Dixon and Wiener, 1993). It initially started as a tool for weather modification activities but has evolved to be multi-purpose. There are many sophisticated commercial systems that are radar system independent and that specialize in advance severe weather applications, such as Warning Decision Support System – Integrated Information (WDSS II) (Lakshmanan et al., 2007; http://www.wdssii.org/). One could build a radar system using tools provided by BALTRAD, or the NASA Radar Software Library (Wolff and Kelley, 2009). One could potentially negotiate or collaborate with an NMHS or a government agency for their system. Functionality varies from very basic decoders, to those generating basic products, to those with sophisticated data quality or automated severe storm detection and classification capability. The system to adopt should be based not only on the functionality, but also on the application and the available scientific and technical support and maintenance capacity.

7.9 SOURCES OF ERROR

Errors in the radar data need to be viewed within the context of the application. Precipitation estimation has often been the objective, and stringent data quality procedures need to be applied to remove and correct for the artefacts. There are different levels of data quality control. Hydrological applications require estimates even when the data are poor quality, whereas data assimilation is tolerant of missing data but not of poor data quality. Many of the issues of poor quality radar data are due to the external environment and not to the radar itself (Figure 7.2). It should be noted that these quantitative applications of weather radar are still in development, whereas the qualitative use of radar data for understanding and detecting severe storms is mature, which fully justifies the existence of radar networks.

The radar equation is developed with many assumptions. Whenever these assumptions are not satisfied, the reflectivity may be considered in error. For example, if the target is not uniform or completely filled or is mixed, the equation is not appropriate. Also, if the parameters in the equation, such as antenna gain, waveguide loss or pulse length, are incorrect then the radar constant will be in error and this will result in systematic biases in the conversion from power to reflectivity. In the following, various sources of error are discussed with respect to qualitative and quantitative applications.

Radar beam filling

In many cases, and especially at long ranges from the radar, the pulse width is large and the pulse volume is not completely filled with homogeneous precipitation, i.e. it can be only partially filled. This is particularly true with shallow weather systems (< 1 km in height, as in lake effect snow storms), where the beam completely overshoots the precipitation and no precipitation echoes can be seen beyond about 50 km. At long ranges, the pulse volume is very large, and considerable smoothing naturally occurs as the radar beam is convolved with the target. In this situation, the beam is also very high above the Earth’s surface and does not quantitatively reflect the surface precipitation very well. With taller systems (say 15 km), the radar will be able to detect these systems at long range (> 250 km) and has considerable value to the forecaster as these systems will be very intense. In general, the radar measurements may be quantitatively useful for ranges of less than about 80 km for a 1° beam width radar and about 110 km for a 0.65° beam width radar without additional adjustments to the data (see Figure 7.33).
Non-uniformity of the vertical distribution of precipitation

Related to radar beam filling is the non-uniformity of the precipitation intensity as a function of height. The first parameter of interest when taking radar measurements is usually precipitation at ground level. As with horizontal variability, the vertical variability or profile plays a significant role in the estimation of surface precipitation. Because of the effects of beam width, beam tilting and the Earth’s curvature, radar measurements of precipitation at long ranges or equivalently in height are lower than at the surface (see section 7.10.4.1).

Attenuation by intervening precipitation

Attenuation by rain may be significant, especially at the shorter radar wavelengths (5 and 3 cm). Attenuation by snow is less than that of rain but may still be significant over long path lengths. Contrary to common thought, attenuation at S band radar exists, but it is more difficult to identify. Dual-polarization techniques use the specific differential phase ($K_{DP}$) parameter, which is independent of attenuation and more effective at the shorter wavelengths. $K_{DP}$ is a noisy parameter and the techniques are still being refined (see section 7.10.4.4).

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 underestimates of reflectivity and, hence, of rainfall rate. The $K_{DP}$ is a local parameter; it is a measure of the differential attenuation (revealed in phase) within a radar volume, and so it is independent of beam blocking. In the case of narrow blockage, data interpolation may be sufficient for quantitative application. For qualitative usage, beam blockage is a nuisance that the analyst can overcome. When the beam is totally blocked, vertical adjustments using the profile of reflectivity may be used to a degree of success.

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.

Combined with precipitation attenuation and at short wavelengths, the radar echoes may be totally suppressed. While this may seem disastrous, pragmatically, it occurs for a limited time (about 10 min), and for qualitative use, warnings will likely already have been issued. For data assimilation, dual-polarization data ($K_{DP}$) will be available that indicate that severe attenuation has occurred and data beyond will be unusable. For hydrological applications that operate on timescales of hours or days, short-term loss of data for flood forecasting is not significant. Depending on the weather regime, flash flooding prediction may be affected.

Electromagnetic interference

Electromagnetic interference from other radars or devices, such as Radio Local Area Networks (RLANs), is becoming increasingly significant, requiring substantial diligence to protect against it. Interference among adjacent radars is mitigated through the use of slightly different frequencies (but still in the same band) with appropriate filters on the transmitter and receiver. There may be occasional interference from airborne and ground-based C band radars using the same frequency.

Use of the electromagnetic spectrum is determined by agreement and managed through the International Telecommunication Union. At the World Radiocommunication Conference 2003,
following demand for spectrum by the wireless community, the C band frequencies were opened up to the telecommunication industry on a regulated secondary non-interfering non-licensed basis to be shared with the meteorological community. In order to be non-interfering, the RLAN devices are supposed to implement Dynamic Frequency Selection, which is designed to vacate a C band channel if a weather radar is detected. However, the algorithms used to detect the weather radar are not sufficient to prevent interference before they vacate the channel. The Doppler spectra of RLAN signals appear as white noise and can be removed with adaptive noise techniques. However, they increase the noise level and reduce the sensitivity of the weather radar where the RLAN is detected. WMO has issued guidance statements relating to the co-use of the C band frequencies. Figure 7.19 shows some examples of this interference for sources at different ranges. Interference patterns like these are increasingly being observed. The image on the left shows a total reflectivity (no Doppler ground clutter filtering) plan position indicator (PPI) image at 0.42° elevation angle from a controlled study where the C band radar with an RLAN was specifically located at 6.4 km at about 40° azimuth. The RLAN is observed at 7°–10° of azimuth. Nearer (or farther) positioning of the RLAN would result in broader (or narrower) patterns. In the experiment, an RLAN could be observed as far away as 16.7 km (maximum value in a vertical column within the volume scan). The image on the right is a “max reflectivity” product from the operational Ezeiza radar in Argentina and shows a pattern of perhaps 12 RLANs that are within 5 km of the radar. This is an extreme interference example. Also, if nearby, the interference can affect the three-dimensional radar data.

Extreme diligence is needed as these systems will be deployed massively and on a non-licensed basis where violations will be difficult to control. Cooperation and collaboration is expected, required and encouraged. Interference also occurs at S band due to wireless 4G technology and also other S band radars (air traffic control). WMO has prepared guidelines or statements on spectrum sharing with these new technologies (see Annex 7.A).

**Ground clutter**

The contamination of rain echoes by ground clutter may cause very large errors in precipitation and wind estimation. Most modern radar antennas have standard side lobe performance that is difficult to improve as it is a geometric issue. Side lobes can be improved or moved to different angular locations, but moving the feed horn away from the focal point results in poorer antenna gain or beam width. The primary method to minimize ground clutter is a good choice of radar location. Ideally, the radar should be located in a slight depression or there should be trees to absorb and scatter the side lobes without blocking the main lobe. Signal and data suppression techniques have been extensively discussed.
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. These echoes are eliminated in the same manner as ground clutter.

It should be noted that in general the location of the beam is not known since the atmospheric profile of the index of refraction is an idealization (Joe, 1999). Assimilation of radar volume data with the typical number of elevation angles (10–24) is problematic since the numerical weather prediction models now typically have 50–80 model levels. The lack of precise knowledge of the beam location and the mismatch between the number of radar data and model levels preclude the use of the data for assimilation beyond about 100 km.

Antenna accuracy

The antenna position may be known within 0.1° with a well-engineered system. However, positioning errors may arise due to a tilted antenna platform or instability in the feedback loop or mechanism due to wear and tear. This is particularly important at low elevation angles as small changes in elevation angle can result in large changes in coverage of shallow weather.

Electronics stability

Modern electronic systems are subject to small variations with time and have significantly improved since the early days of weather radar where receiver calibrations needed to be done daily. A well-engineered radar can be stable (< 1 dB variation) for months. The addition of a built-in test equipment monitoring system can activate an alarm or issue an e-mail when a fault is detected, and minimize the downtime for weather radars.

Variations in the \( Z-R \) relationship

To convert reflectivity to precipitation rate, an empirical relationship between \( Z \) and \( R \) is needed. The most famous and most frequent relationship used in operational radars is that of Marshall-Palmer (1948, actually reported in Marshall and Gunn, 1952). The uncertainty of this relationship was reported to be a factor of two. It also applies to snow. Reflectivity is a function of the drop size distribution, and different drop size distributions can produce the same \( Z \). Hence, a variety of \( Z-R \) relationships have been formulated for different precipitation types – convective, stratiform and snow – with varying degrees of success (see section 7.10.4.2). With dual-polarization radar, techniques have now been developed using the \( K_{dp} \) dual-polarization parameter. It remains to be seen whether vertical profile adjustment can rival the \( K_{dp} \) technique in partially blocked situations.

Radial velocity

The velocities measured by the Doppler radar are in the radial direction only, which can cause ambiguities. Automated interpretation is still an active area of research, but interpretations are possible in certain situations – large-scale synoptic flows and small-scale convective flows – with knowledgeable and well-trained analysts.

The velocities are reflectivity weighted estimates of the precipitation/target motion. If the radial components of the vertical motions are negligible (e.g. low elevation angles), they can represent the precipitation motion which can often be interpreted as wind. However, care should be taken to not interpret the velocity as motion of the precipitation echo or system itself. In the example...
of a lenticular flow over a mountain peak, the echo motion (as indicated by reflectivity) may be stationary but the precipitation particles move through the feature and the echo will have non-zero Doppler. Insects and birds may bias the radial velocities. In general, the biases are relatively small (Wilson et al., 1994) if the birds or insects are not migrating. Ground clutter can also bias the radial velocities towards zero velocity (underestimation) if not enough of the ground echo is removed.

If the wind within a radar volume is not uniform and highly sheared, inaccurate estimates of the radial velocity will result. Consider the extreme case of a tornado that is totally or partially encompassed by radar volume. In the former case, a mean radial velocity of zero with very high spectral width is expected. In the latter case, a non-zero velocity may be expected if the Nyquist velocity is sufficiently high. If the Nyquist is relatively small, the mean velocity may be aliased several times and any velocity may be produced (Fabry et al., 2013). In addition, the weather spectrum may also be aliased, confounding retrieval of both the mean velocity and its spectral width. Dual-PRF techniques also fail in this instant as the uniformity assumption of the two dual-PRF estimates is violated. The antenna rotates as well and so this assumption can be violated in high shear areas, where the two velocity samples at the different PRFs are made at different azimuthal locations and where the velocity has large variance or spectral width. In the latter situation, the error in the technique is determined by this variance and the difference in the unambiguous Nyquist velocities (hence, the ratio of the PRFs). Correction techniques can alleviate the situation of high Doppler variance (Joe and May, 2003). Figure 7.20 shows a simulation. The top image shows a prescribed simulated field with a step in the velocity field. The middle figure shows what a C band Doppler radar would measure. The bottom figure shows the results of the mitigation technique.

Side lobe contamination

When strong reflectivity gradients are present, as in the case of thunderstorms with large wet hail, the side lobes can produce an echo while the main lobe is pointing at a significantly low or no reflectivity target. The side lobes are typically 25 dB or more lower (one way, or 50 dB two way) than the main beam (Figure 7.8). So if the side lobe is pointing at a target that is 60 dBZ

Figure 7.20. The dual-PRF technique assumes that the measurements are made from a volume with the same radial velocity. The images show the prescribed field, the measured and the corrected data. (Figure adapted from Joe and May, 2003)
in strength, as in the case of wet hail, and the main beam is pointing at a target that is 10 dBZ or lower, the radar will report an echo with reflectivity, radial velocity and dual-polarization characteristics assuming that the power originated in the main beam. Side lobe echoes appear as annular artefacts both in azimuth and elevation at constant range. This can appear as "wings" or "high echo top spikes" near areas of high reflectivities (left and right images in Figure 7.21, respectively). Multiple scattering effects appear as radial artefacts at constant azimuth but with increasing range. These are caused by high reflectivity zones plus reflection effects from a highly reflective surface (ground wetted by rain, for example) and are used as hail indicators in S band radars. Note that in the figure on the right there may have been azimuthal side lobe and/or three-body scattering but this would likely have been obscured by the stronger weather echoes. This is not evident within the thunderstorm area itself as the reflectivity will be dominated by the echo in the main lobe. However, it can be evident in the vertical and result in falsely high echo tops that have been called the hail spike and can be used to qualitatively diagnose hail in a thunderstorm (see Figure 7.21). This type of echo could also occur in the weak echo region that abuts the hail curtain of a thunderstorm, which can confound the interpretation of rotation signatures indicative of the presence of a mesocyclone.

**Multiple scattering**

The radar beam may be reflected multiple times due to the propagation conditions (see Figure 7.22). It may also be multiply scattered within a highly reflective thunderstorm (wet hail), to a wet underlying surface and back to the radar. This has been called three-body scattering and it results in an elongated echo in range beyond the strong reflectivity core (Zrnić et al., 2010). At S band radars, this is used as a hail signature, which is called the hail flare to distinguish it from the side lobe hail signature (Lemon, 1998). Multiple scattering is more prevalent as the wavelength decreases and the signature could occur in heavy rain at C or X band.

**Second/multiple-trip echo**

With the high PRFs used in Doppler radars, multiple-trip echoes may occur. This has already been discussed earlier and the differences between coherent-on-transmit and coherent-on-receive
CHAPTER 7. RADAR MEASUREMENTS

radars were highlighted. Figure 7.7 shows an example of second-trip echoes in reflectivity and radial velocity for a coherent-on-receive radar. In a coherent-on-transmit radar, the second-trip echo algorithm paints the overlapping echoes as range folded.

Wind turbines

An increasing issue is the proliferation of wind turbines and its impact on weather radar. Wind turbines are a source of natural power and sited in remote windy areas. These targets appear in the ground echo (and hence at the lower beams), but the turbine blades provide a moving target and hence generate a varying Doppler signature, and so are difficult to remove. In addition, the turbines are deployed in clusters of 100 or more, creating wind farms. Thus, significant areas will be affected. Figure 7.23 shows two different impacts of wind turbines. If the turbines are located close to the radar, they can create blocked sectors (left image). They may appear as somewhat isolated echoes (not shown). Multiple scattering may be observed (right image). In this example, the wind turbines are about 80–100 km from the radar. WMO has developed guidelines for mutual proximal operation.

Clutter maps may be one technique to remove the echoes. However, this removes the weather echo as well and therefore will require other mitigation strategies to infill the missing data (Figure 7.23). These may include interpolation from the sides or from above or with the use of gap filling data sources. As wind farms are proliferating, ongoing modification or adaptive strategies need to be developed to be able to maintain the data quality for weather applications. If the wind turbines are situated very near the radar, they can be an obstruction to the radar beam not only in the lower beams but also in the higher elevation beams through direct blockage and also due to multipath. WMO has developed guidelines regarding their deployment (see Annex 7.B).

Figure 7.22. This schematic describes how three-body scattering occurs. The echo extending to the right (bright yellow) is an artefact due to the three-body scattering.
OVERVIEW OF METEOROLOGICAL APPLICATIONS

Radar observations have been found most useful for the following:

(a) Surveillance of synoptic and mesoscale weather systems;
(b) Severe weather detection, tracking and warning, including severe wind hazard detection;
(c) Nowcasting;
(d) Estimation of precipitation intensity, echo classification;
(e) Wind profiling and wind mapping;
(f) Initiation of numerical weather prediction models;
(g) Humidity estimation.

7.10.1 General weather surveillance

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 and an area of 125 000 km$^2$) if unimpeded by buildings, hills, mountains, etc. Generally, only a single low-level sweep of the radar scanning at approximately 10–30 min is required. Owing to the Earth’s curvature and the propagation of the radar beam, the maximum practical range for weather observation is about 250 to 350 km, as the radar will overshoot the weather at longer ranges. While radars have sufficient sensitivity to detect to farther ranges, the limit of modern radars is due to the beam height location. A radar with a 1° beam width antenna pointed at 0.5° elevation angle above the horizon is approximately 10 km above the Earth’s surface at a range of 350 km. In addition, the beam width at that range is about 7 km wide. Shorter storms would not be detected or would be distorted in their representation. So storms must be substantial in size to be detected at that range. Pragmatically, scans of even 500 km or more are operationally used, particularly at the edges of radar networks. If echoes are detected, the forecaster will be provided with substantial information of a large and intense storm. Satellites and lightning detection networks may provide information on the clouds and the electric activity that produce or are associated with the precipitation. Exchange of radar data to create a radar network is de rigueur and mandatory to create mosaic products for surveillance.

Another surveillance application is the detection of shallow weather (< 1 km), such as lake effect snow squalls, drizzle or even duststorms. Narrower beam widths provide better resolution...
and greater effectiveness at longer ranges as they can scan at lower elevation angles without additional ground clutter effects, can provide a filled beam to longer ranges and have greater sensitivity due to greater gain. Networks of low maintenance, low infrastructure and low cost X band radars are emerging which can fill this low-level scanning gap of large S and C band radars.

The cooperative exchange of weather radar data among various operators is now important in radar applications. It can achieve broader views of large-scale precipitation systems, such as synoptic scale fronts and typhoons. Standard radar data formats would enable and facilitate the efficient development of inter-network products. A leading example is that done in the OPERA consortium.

Radar networks employing adaptive and collaborative scanning strategies are emerging (McLaughlin et al., 2009; Weber et al., 2007). Phased array radars with electronic steering capability are being developed that can scan in non-contiguous azimuthal and elevation directions to provide high temporal sampling of rapidly changing weather phenomena, such as tornadoes and downbursts, and even other targets such as aeroplanes. Adjacent radars may also fill low-level gaps in coverage due to beam propagation effects at long range and perhaps the “cone of silence” due to limited elevation scanning.

7.10.2 Severe weather detection and warning

A radar is the only realistic means of monitoring severe weather over a wide area (hundreds of kilometres of range) due to the temporal resolution (minute), spatial resolution (kilometres) and detected weather elements (reflectivity from precipitation). Radar echo intensities, area and patterns are used to identify areas of severe weather, including thunderstorms with probable hail and damaging winds. Doppler radars can identify and provide a measurement of intense winds associated with gust fronts, downbursts and tornadoes to add an additional dimension (Lemon, 1978). Dual-polarization radars have the capability to separate echoes due to different types of scatterers and can distinguish hail from heavy rain and rain from snow (Zrnić et al., 2001). The nominal range of coverage of a single radar is about 250 km, which is sufficient for local short-range forecasting of about 1–2 h lead time and warning. Radar networks extend the coverage and lead time (Germann et al., 2006). Effective warnings require effective interpretation performed by alert and well-trained personnel.

Technique for thunderstorm warning by radar

The technique for using radar for the provision of warnings is attributed to Lemon (1978), who outlined the reflectivity features to identify for the provision of severe thunderstorm warnings that include tornadoes, strong wind, heavy rain, flash flooding and hail. Since then, Doppler and dual-polarization features as well as additional reflectivity features have been added to the list of criteria. Figure 7.24 lists (on the left) and provides an example (on the right) of the severe weather features (Lemon, 1978; Lemon et al., 1978). These features include strong reflectivities aloft, high echo tops, weak echo regions aloft indicative of strong updraughts, strong low-level reflectivity gradients and low-level hook patterns. A set of the multi-panel images (shown on the right in Figure 7.24) is called a cell view and is automatically created once a cell has been identified in radar data-processing software. The sub-images are derived radar products that a severe weather analyst would use to decide on the storm severity, its stage in the life cycle and whether to issue a warning. Given the location of various features of the thunderstorm (e.g. location of the echo top, location of the storm centroid or location of the bounded weak echo region), cross-section lines can be configured and vertical cross-sections can be automatically created.

The temporal and three-dimensional spatial relationship is important to diagnose the life cycle phase of the storm for anticipating its evolution and hence for its warnings. This is a challenging problem and not every thunderstorm produces weather reaching the severity threshold for warnings (see Table 7.9). The original technique, that is still used today, was applied by examining various radar products and interrogating the data in various ways (Figure 7.24).
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 et al., 1980; JDOP, 1979). This vortex is known as a mesocyclone, which is a vertical column of rising rotating air typically 2 to 10 km in diameter. The mesocyclone signature is a small anomalous Doppler velocity pattern and is first observed in the mid-levels of a storm that descends to cloud base and may be coincident with the presence of severe weather (Markowski, 2002; Burgess, 1976; Burgess and Lemon, 1990; Figure 7.25). Mesocyclonic rotation in severe storms indicates a strong and long-lived storm deserving of a severe weather warning. This is identified as small quasi-circular areas of away and toward radial velocities aligned approximately at constant range in an azimuthal direction, as can be seen in Figure 7.25. It should be noted that storm motion should be removed to easily see the away/toward couplet. In the northern hemisphere, the rotation is generally (but not always) counterclockwise and vice versa in the southern hemisphere. This behaviour has led to improved severe storm and tornado warning lead times of 20 min or longer during quasi-operational experiments in Oklahoma (JDOP, 1979). During these experiments, roughly 50% 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).

Figure 7.24. The severe storm features are listed on the left (Lemon, 1978). The cell-view product is an image centred on the automatically detected thunderstorm cell and shows relevant products for decision-making (number in cell view matches the list number).

<table>
<thead>
<tr>
<th>Thresholds</th>
<th>Rank weight</th>
<th>Rank (0–8)</th>
<th>Bounded weak echo region (BWER) count</th>
<th>Mesoscale shear (m/s/km)</th>
<th>Hail size (cm)</th>
<th>Downdraught (m/s)</th>
<th>VIL density (kg m²/km)</th>
<th>Max Z (dBZ)</th>
<th>45 dBZ echo top height (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>1</td>
<td>0–2</td>
<td>5–11</td>
<td>4</td>
<td>0.5</td>
<td>10</td>
<td>2.2</td>
<td>30</td>
<td>5.5</td>
</tr>
<tr>
<td>Weak</td>
<td>2</td>
<td>3–4</td>
<td>12–17</td>
<td>6</td>
<td>1.3</td>
<td>15</td>
<td>3.0</td>
<td>45</td>
<td>8.5</td>
</tr>
<tr>
<td>Moderate</td>
<td>3</td>
<td>5–6</td>
<td>18–21</td>
<td>8</td>
<td>2.3</td>
<td>20</td>
<td>3.5</td>
<td>50</td>
<td>10.5</td>
</tr>
<tr>
<td>Severe</td>
<td>4</td>
<td>7+</td>
<td>22–26</td>
<td>10</td>
<td>5.0</td>
<td>25</td>
<td>4.0</td>
<td>60</td>
<td>12.5</td>
</tr>
</tbody>
</table>

Table 7.9. Thunderstorm characteristics for different warning thresholds
A tornado is approximately 200–500 m in diameter. This is often at the resolution of the radar data and so difficult to consistently detect unless a high zoom magnification is employed. When detected, it is observed as a large difference in radial velocity in adjacent radar data volumes and called the tornado vortex signature, and this is embedded within the mesocyclone (Figure 7.26). In some cases, the tornado vortex signature has been detected aloft nearly half an hour or more before a tornado touched the ground. Several years of experience with the tornado vortex signature have demonstrated its great utility for determining tornado location, usually within ±1 km. It is estimated that 50% to 70% 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. In the reflectivity image (Figure 7.26, left image), a classic hook echo is observed and is indicative of precipitation associated with a strong downdraught in the rear of the strong thunderstorm.

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 updraught 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

Figure 7.25. Multiple mesocyclones (A–D) are observed along a squall line and are identified as couplets of relative away and toward velocities at constant range. Symmetric velocity signatures observed in the storm are not evident or have been removed.

Figure 7.26. A tornado vortex signature is identified as an away/toward couplet on adjacent range bins (see arrow on right image), embedded within a mesocyclone. The image on the left shows a classic hook echo.
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 (see Figure 7.27). This is an example of a wet downdraught and has a strong associated reflectivity. Dry downdraughts may not be identifiable in the radar data if the precipitation evaporates and if there are no other targets for the radar to detect. In this case, a highly sensitive radar is required or a Doppler lidar or anemometer network. In this application, the radar computer system automatically provides warnings to the air-traffic control tower (Michelson et al., 1990). Mesoscale winds (40–50 km in scale) are difficult to interpret with Doppler radar as the orientation of the flows confounds the assumption of uniformity. Assumptions have to be made of the wind direction based on research studies and conceptual models of the airflow within these systems (Smull and Houze, 1987). Fortunately, in some cases, the flows and the reflectivity structure are distinctive and strong winds can be identified and warnings provided. Figure 7.28 shows a system moving to the east, and hence the full strength of the straight line winds (also known as a derecho) is evident in the away (orange) radial velocities (marked A). In this case, the away velocities are moving into toward velocities. This is also shown in the bowing of the reflectivity echo (left image). At other azimuths, the radial wind is not perpendicular to the system motion (marked B) and the analyst must take this into account.

Figure 7.27. A downburst (micro or macro) is observed as a couplet of away and toward radial velocities aligned along a radial (see arrows on the right image). This is a rapidly evolving feature of thunderstorms, and can emanate from very ordinary and small thunderstorms.

Figure 7.28. Another signature of strong intense hazardous winds can be observed as a linear or curvilinear feature in the reflectivity (left) or radial velocity data (right).
The best method for measuring winds inside precipitation is the multiple Doppler method, which has been deployed since the mid-1970s for scientific research field programmes of limited duration. However, real-time operational use of dual- or triple-Doppler analyses is not anticipated because of the need of relatively closely spaced radars (~40 km). An exception may be the limited area requirements of airports, where a network of X band radars may be useful (McLaughlin et al., 2009; Wurman et al., 1995).

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 et al., 1970; Lemon et al., 1978). Empirical but limited studies have shown the ability to predict hail size (Treloar, 1998; Joe et al., 2004; Witt et al., 1998). Federer et al. (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 et al., 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 \( (Z_{\text{DR}}) \) as measured by a dual-polarization Doppler radar (Seliga and Bringi, 1976; Figure 7.29). The image on the left shows a classification of the radar echo using dual-polarization signatures of a hail situation. Fuzzy logic techniques are commonly used to combine various dual-polarization parameters such as \( Z, Z_{\text{DR}}, \rho_{\text{HV}}, \text{and } K_{\text{DP}} \) to identify the nature of the radar echo. In this case, the classification scheme is indicated in the left image and includes (from top to bottom): hail, heavy rain, rain, big drops, graupel, ice crystals, wet snow, dry snow, biological scatters and ground clutter. The inset image is a hail size estimate based on combining vertically integrated liquid (VIL), MAX reflectivity and freezing level (Treloar, 1998; Joe et al, 2004). A maximum hail size of 3.2 cm is indicated. The image on the right compares, in detail, the dual-polarization hail detection using data at two different resolutions (plus signs for 1 km resolution and diamond symbols for 250 m resolution) and slightly different times compared to the older reflectivity only technique (crosses). The blue ellipse corresponds to the blue ellipse in the left image. All three algorithms verified with the 3+ cm hail reported at the airport (yellow mark, middle of the red grid lines).

Recent advances include the automated detection and classification of thunderstorms through advanced processing techniques (Lakshmanan et al., 2007; Joe et al., 2002; Joe et al., 2012).
Thunderstorms evolve on a temporal scale of minutes and precipitation initiates aloft. So, radar features both aloft and near the surface are used for identification of severe weather. Hence, the radar should scan in multiple elevation angles with a cycle time of the order of 5 min.

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

### 7.10.3 Nowcasting

A strict definition of nowcasting is that it is a prediction in the 0–2 h timescale and, traditionally, it refers to automated linear extrapolation of the current situation as revealed by observations. The original nowcasting system was based on doing a cross-correlation analysis of two radar images (CAPPI) for the echo motion (Bellon and Austin, 1978). The motion analysis was done in nine sectors of the image and used to extrapolate the echoes up to 90 min into the future. Points were identified for the nowcasts and a meteogram was created that indicated the most likely and probable values (Figure 7.30). The figure on the left is a single image of weather, presented as a CAPPI, that is moving to the north-east. The figure on the right shows the nowcast (the most likely, left column, and the most probable reflectivity, right column) for various points. Only two points are indicated in this example for clarity of presentation. This is a meteogram presented as an image (current time is at the top, and future time increments are presented downward in 10 min steps). An inherent assumption in this nowcast is that the precipitation system persists for the next 90 min. This illustrates the specificity characteristic of nowcasts and their precision in terms of time, space and weather element. The skill of this nowcast is very high for the first 20–30 min and it is used as a call to action or warning service. No evolution is assumed.

Using continental composite of radar data and a scaling approach to filter out the high-frequency or small-scale reflectivity patterns, nowcasts of the large-scale patterns have skill out to six or more hours that exceeds the skill of the numerical weather prediction models at this time. This is compared to the 2 to 3 h for the smaller scales. However, the skill levels are not capable of providing the precision needed for call-to-action type warning services.

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).

![Figure 7.30. An example of a cross-correlation nowcast; the weather is moving from the south-west (left image) and the meteogram on the right shows the most likely and most probable precipitation intensities at different locations (only KRA and ADL are shown on the left, which are the sixth and tenth sites on the right image).](image)
An important nowcasting application is the analysis of the radar fields for the initiation of convection. Recent scientific studies have shown that airmass thunderstorms, which were previously thought to be random and unpredictable, actually form on small-scale atmospheric boundaries (Wilson et al., 1998). These boundaries can be detected in both the reflectivity and radial velocity fields in the clear air echoes as line features or convergence lines (Figure 7.31). The boundaries are formed by a variety of mechanisms including lake breezes (A), thunderstorm outflows (B), drainage flows from mountain valleys, dry lines and others. Enhanced lift occurring at the intersection of these boundaries can initiate thunderstorms. Note the distinctive convergence signature in the radial velocity image (white arrow, right image).

The source of the clear air echoes can be turbulent fluctuations or insects. Polarization radar studies indicate that insects are the primary source of these radar returns. Extensions to the traditional nowcasting systems include the prediction of convective initiation and dissipation, modelling the life cycle of thunderstorms, and using numerical weather prediction models in the analysis (Wilson et al., 1998; Sun et al., 2013). In addition to the radar data, associated model fields, such as temperature and humidity, are also extrapolated (Crook and Sun, 2002; Sun et al., 2013). Increasing the cycle time (rapid update to 1 h or better), reducing the spin up and improving the physics of high-resolution models are improvements that are anticipated (Sun et al., 2013). Another emerging nowcasting application is the development of ensemble precipitation nowcasts where the small scales are both filtered and re-created using a family of statistically consistent estimates (Seed, 2003).

7.10.4 Precipitation estimation

Radars have a long history in estimating the distribution, the intensity and thereby the amount 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. The retrieval of precipitation intensity is mainly based on empirical relationships from the returned power or reflectivity (Marshall and Palmer, 1948; Marshall and Gunn, 1952; Wilson and Brandes, 1979; Chandrasekar et al., 2003). Dual-polarization radars use additional information based on the shift in the phase of the attenuated propagating wave and on the differential scatter due to the large non-spherical particles. Comprehensive hail studies are rare due to difficulty in gathering ground truth information. Readers should consult reviews by Joss and Waldvogel (1990), and Smith (1990) for a comprehensive discussion of the problems and pitfalls, and the effectiveness and accuracy. Emerging radar processing systems are able to remove ground clutter (including anomalous propagation) in a variety of ways, and mitigate the vertical profile of reflectivity problem by adjustment with gauges or disdrometers in quasi-real-time.
7.10.4.1  **Vertical profile of reflectivity**

At long ranges, errors caused by the inability to observe the precipitation close to the ground and the lack of beam filling are usually dominant. 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. 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. Figure 7.32 shows three idealized vertical profiles of reflectivity for different weather situations. They are shown at zero range. These profiles are increasingly smoothed with range due to the broadening of the beam. The beam propagation effect also occurs, and the lower part of the profile no longer contributes to the measured value. 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. The effective range for quantitative precipitation estimation is about 80 km for a 1° beam width radar (Figure 7.33) and longer for smaller beam width radars (120 km for 0.65° beam width radar) without adjustment.

In shallow weather that is prevalent in winter conditions, the beam smoothing effect (illustrated in Figure 7.32) reduces the reflectivity with range. This results in accumulations (radar reflectivity or derived precipitation rate) that take on an annular pattern shown in the left image of Figure 7.33. Non-uniform filling of the radar volume with range also contributes to the rapid reduction in the reflectivity. Comparisons with values measured with gauges over a season are shown on the right (ratio of the radar versus in situ gauge measurements), illustrating this degradation in measured precipitation amounts. In this particular location, with this 1° beam width radar and this weather regime (Finland in winter), the effective range (the flat part of the curve) is about 80 km for direct precipitation estimates. Since the effect is geometric, a smaller beam width would extend this effective range. This is illustrated for a 0.65° beam width, where the effective range is extended to about 110–120 km.

![Figure 7.32. Beam smoothing and beam propagation modify the appearance of the vertical profile of reflectivity with range. Three situations are depicted with the maximum reflectivity in the column as a percentage of the surface precipitation taking into account the bright band (adapted from Joss and Waldvogel, 1990).](image)
No one method of compensating for the effects of the vertical reflectivity profile in real time is widely accepted. 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;

(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).

Figure 7.34 shows an example of the latter method of correcting for the vertical profile of reflectivity with range effect, which is now routinely used on a radar network basis. The figure on the left shows a 24 h accumulation of radar-derived precipitation rate during a stationary front passage. The pattern would be expected to be broadly uniform. The figure on the right is created with an adjustment for the vertical profile effect at long ranges, and hence the accumulations at the edges are enhanced. The difference in the images also illustrates the benefits of a network approach to generating precipitation products, as the vertical profile effect of the individual radars is not so evident in the interior of the network.

Improvements in digital radar data processing and real-time integration with gauge networks 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 (Berenguer et al., 2012; Cluckie and Owens, 1987). 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 $Z$–$R$ 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.

7.10.4.2 The $Z$–$R$ relation

In ideal conditions (close to the radar, no artefacts), precipitation is usually estimated by using the $Z$–$R$ relation:

$$Z = A R^b$$

(7.13)

where $A$ and $b$ are constants. The relationship is not unique and 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). This can be applied to an accuracy of a factor of two for both rain and snow. 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 (Figure 7.35). A survey of the $Z$–$R$ relationships in worldwide use indicated that the Marshall-Palmer relationship is used in 80% of the operational weather radars – a remarkable achievement considering the very few data points used to form the original relationship (Sireci et al., 2010). The red line in Figure 7.35 represents the original Marshall-Palmer relationship (reported in Marshall and Gunn, 1952, and Marshall and Palmer, 1948). Attempts at improvements have been made throughout the years and the black lines represent these other relationships (Battan, 1973). It is remarkable that the original relationship, made with few measurements and in a specific weather regime, has stood the test of time.

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 ($Z > 57$ dBZ
is often taken as the boundary between rain and hail). 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 ($Z$ 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). However, snowfall gauge measurements are problematic and there are few comprehensive studies of radar–snowfall relationships.

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 when other factors are taken into account.

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, particularly for storm event studies. A $Z$–$R$ relation can be obtained by calculating values of $Z$ and $R$ from measured drop size distributions produced by an instrument known as a disdrometer. 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. Disdrometers are now being deployed in operational networks for determining the $Z$–$R$ relationship for climatology, storm studies and real-time adjustment, and are very sensitive and can detect very light precipitation.

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. 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.

Figure 7.35. A plot of a plethora of $Z$–$R$ relationships from Battan (1973)
7.10.4.3  **Gauge adjustment**

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. However, this needs to be done judiciously as tuning the adjustment for one situation may create problems in other situations. In situations where radar estimates are far from the mark due to radar calibration or other problems, such adjustments can bring about significant improvements.

Ground level precipitation estimates from radar systems are made for areas of typically 1–4 km$^2$ spatial resolution and successively for 5–15 min periods using low elevation (elevation angles of < 1°) plan position indicator scans, constant altitude PPI synthetic products or even more sophisticated products. The radar estimates have been found to compare with spot precipitation gauge measurements within a factor of two. The gauge samples an extremely small area (100 cm$^2$, 200 cm$^2$), while the radar integrates over a volume, on a much larger scale (1–4 km$^2$). This difference accounts for a considerable amount of the discrepancy. 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). An important consideration is the success metric. Seasonal averages may be acceptable in some applications and a single $Z$–$R$ relationship may be sufficient. However, for flash flood warnings, real-time adjustments may be required.

Note that these 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 (i.e. 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.

7.10.4.4  **Dual-polarization precipitation techniques**

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 ($Z_{\text{HV}}$) or the phase shift ($\phi_{\text{DP}}$ or $K_{\text{DP}}$) can provide useful information about drop size distributions (Seliga and Bringi, 1976). These methods depend on the hydrodynamic distortions of the shapes of large raindrops, with more intense rainfalls with larger drops giving a stronger polarization signature. The attenuation must be first corrected and again dual-polarization techniques are applicable here. There is still considerable research on whether this technique has promise for operational use for precipitation measurement (English et al., 1991). At long wavelengths, the rain rate thresholds where $K_{\text{DP}}$ techniques are effective are higher (for example, at S band it is about 20 mm h$^{-1}$, and at X band it is about 4 mm h$^{-1}$).

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 multi-parameter techniques worked perfectly well, the error caused by $Z$–$R$ could be reduced only from 33% to 17%, 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.
Dual-polarization radars can overcome attenuation, partial beam filling and partially blocked beams. Figure 7.36 shows a C band radar where the polarization technique is used to correct for attenuation. The dual-polarization parameters are sensitive to the size and shape of the large particles, and the smaller the wavelength, the more sensitive the radar. In this example, a precipitation system that caused localized flooding was observed by a C band radar and an S band radar. The C band (King City with a 0.65° beam) was about 40 km from the flooding and the S band (Buffalo with a 1° beam) was about 100 km away. Images (a) and (b) show one instance of the low-level radar reflectivity from both radars. The red grid lines are reference lines. The location of the raingauge is about 7 km to the south-west. The C band radar data are attenuated compared to the S band data (image (b) is more intense than image (a)). During the event, the C band radar experienced a wet radome which also strongly attenuated the signal. Images (c) and (d) are accumulations based on their respective dual-polarization-derived precipitation products from over the 8 h period of the event (see also Figure 7.37). The resolution difference is evident, but the accumulation patterns are very similar. This illustrates the great potential for a dual-polarized C band radar to overcome significant attenuation. Interestingly, the dual-polarization precipitation estimate from the S band radar was actually lower and closer to the raingauge value (not shown) than using the traditional \(Z-R\) relationship, as the particle classification of hail versus rain was used to prevent the overestimation.

Figure 7.37 shows the comparison of various rainfall estimates from C and S band radars and a raingauge. The bottom (C1) and top (S1) lines are accumulations based on traditional simple reflectivity converted to rain rate \((Z = 300 R^{1.4})\) from the King City C band (40 km from the gauge site) and the Buffalo S band (100 km from the gauge site) radars. Both radars are well calibrated and only Doppler ground clutter rejection has been applied to the data. The \(Z_{DR}\)-only attenuation corrected reflectivity converted to rain rate and accumulated. The dashed (S2) and dark blue (C3) lines are the precipitation estimates using a mix of dual-polarization techniques from the S band radar (S2) and from the \(K_{DP}\)-\(R\) technique from the C band radar (C3), respectively. The improved Buffalo S band results are attributed to removing the hail bias using the dual-polarization particle classification technique. The specific differential phase \(K_{DP}\) technique, which is insensitive to attenuation, partial beam blockage and partial beam
filling, improves the King City C band estimates. This illustrates the impact of dual polarization on the quantitative use of both S and C band radars. It also illustrates the larger impact of dual polarization on C band radars.

Rain/snow/hail discrimination and other target classification

With conventional or reflectivity-only radars, the pattern and intensity of the echo were used to roughly estimate the nature of the target. In summer, reflectivities less than about 12 dBZ were considered to be non-precipitating echoes, light rain was up to about 30 dBZ and heavy rain up to about 50 dBZ or so. Reflectivities above 57 dBZ were considered to be hail. Snow is not generally separable with these kinds of radars in the horizontal. In the vertical, the bright band (a region of enhanced reflectivity due to large wet snow aggregates) delineated snow aloft from rain below. Dual-polarization radars characterize the target using reflectivity information from orthogonal channels, their cross-polar signal and changes in propagation phase. Surface temperature and humidity and soundings from numerical weather prediction models are also used. Fuzzy logic techniques use independent estimates from a variety of dual-polarization parameters to classify the echo type into a variety of categories including: ground clutter, rain, snow, hail, biological scatters and even big and small drops (Figure 7.29).

Aeroplanes were identified as isolated point anomalies and ground echoes were identified as stationary or permanent echoes at short range around the radar. The reflectivities of aeroplanes and ground echoes can vary greatly because small changes in aspect angle result in substantial changes in backscatter.

Doppler radars can identify non-moving targets, such as ground clutter and anomalous propagation echoes, even in the presence of weather phenomena. These ground targets can be effectively filtered out in signal processing to produce “corrected (for ground clutter) reflectivity”. Most if not all modern radars have Doppler and thus have this capability. Before Doppler radars, a variety of techniques were used to remove ground clutter including: (i) CAPPI, (ii) ground clutter maps, and (iii) the statistical fluctuation of the reflectivity statistics.
7.10.5 Wind estimation/wind mapping

Doppler velocities are radial velocities, and a family of true velocities can create the same radial velocity. Hence, radial velocities alone are ambiguous and require simplifying assumptions to interpret. On typical colour displays, velocities between $\pm V_{\text{max}}$ are generally assigned warm/cool colours to indicate away/toward motions. Velocities extending beyond the Nyquist (unambiguous or extended) velocity enter the scale of colours at the opposite end. This process may be repeated if the velocities are aliased more than one Nyquist interval.

7.10.5.1 Wind profiling

Doppler radar can be used to derive vertical profiles of synoptic scale 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 assumed to be relatively uniform or linear over the area of the scan. The winds at zero radial velocity bins 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. See Figure 7.12 for a sample of synoptic Doppler wind fields.

If uniformity can be assumed, then divergence estimates can also be obtained using the VAD technique by fitting a curve with a constant term to the equation. This technique cannot be accurately applied during periods of convective precipitation around the radar as the uniformity assumption is not satisfied. 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.

7.10.5.2 Convective wind features

In the case of convection, small-scale wind features are due to divergence, convergence and rotation as observed in gust fronts, downbursts, mesocyclones, etc. These appear as small anomalies of one kilometre to tens of kilometres in scale embedded in mean flows of hundred kilometre scales. Taking into account assumptions about the flow, and in combination with conceptual models and an understanding of the thunderstorm or mesoscale convective system wind flows, colour displays of single-Doppler radial velocity patterns can aid in the real-time interpretation and diagnosis of thunderstorm severity (Burgess and Lemon, 1990). Lemon (1978) listed the features and diagnostic procedure to identify severe thunderstorms (see section 7.10.2). Convective wind features confound the interpretation of radial velocity fields in particular when there are mesoscale flows on the scale of 40 to 100 km and three-dimensional regimes, as in complex mountainous terrain.

7.10.5.3 Wind mapping

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). However, for accurate velocity estimation, the radars must be relatively close together (40–80 km) and the target area must be in two lobes perpendicular to the radar baselines. Operationally, it is unusual to find radars situated so close to one another.
7.10.6 **Initiation and numerical weather prediction models**

A variety of radar data and products are used for data assimilation in some numerical weather prediction centres. Not all models use the same products. Precipitation is a derived parameter in numerical weather prediction models, and so it is difficult to directly assimilate precipitation or reflectivity fields. Winds are direct model variables and radial velocities may be assimilated with less contrivance. These include VAD wind profiles, composited radar-derived surface precipitation fields in global models and, in some cases, three-dimensional reflectivity and radial velocity fields for local area or small-scale models in polar coordinates. Lopez (2011) has demonstrated the value of assimilating the US Stage IV surface precipitation product on the weather in Europe and Asia. These and other applications (typhoon tracking) are prime drivers for the global weather radar data exchange initiative.

7.10.7 **Humidity estimation**

An emerging innovation is the retrieval of humidity from beam propagation differences of echoes from the omnipresent ground targets (Fabry, 2004). This innovation is counter-intuitive to the siting of weather radars since they are sited to minimize ground clutter. Index of refraction fluctuations cause beam propagation path length changes which can be detected as changes in the phase of the signal or the Doppler shift. By comparing the shift in dry versus moist conditions and accounting for range ambiguities, the path length change can be estimated and then related to the index of refraction change using Snell’s law. The index of refraction is dependent on temperature, pressure and humidity but primarily on the latter, and hence the humidity can be retrieved very near the radar. Several research radars have this capability and some operational systems (in France and the UK) are prototyping this for operational deployment.

7.11 **METEOROLOGICAL PRODUCTS**

The radar data can be processed to provide a variety of meteorological products to support various applications. The quality of these products depends on the type of radar, the scan strategy, its signal processing characteristics and the associated radar control and data analysis/production system. These products include grids of raw or derived radar parameters, vertical wind profiles, location and characteristics of analysed thunderstorm cells, their historical tracks, nowcasts, etc. Polar coordinate data are converted to two- or three-dimensional Cartesian coordinates using interpolation techniques onto grids with different geographical projections. Several of the products listed below are illustrated in Figure 7.24. A list of typical radar products is presented in Table 7.10.

<table>
<thead>
<tr>
<th>Table 7.10. List of typical radar products</th>
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<tbody>
<tr>
<td>Plan position indicator of basic parameters (low level)</td>
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<tr>
<td>Maximum reflectivity in a column</td>
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<tr>
<td>Echo top</td>
</tr>
<tr>
<td>Derived thunderstorm severity products</td>
</tr>
<tr>
<td>Surface precipitation rate</td>
</tr>
<tr>
<td>Surface accumulation products</td>
</tr>
<tr>
<td>Basin products</td>
</tr>
<tr>
<td>Hydrometeor classification – hail, rain, snow, etc.</td>
</tr>
<tr>
<td>Arbitrary cross-sections of various parameters</td>
</tr>
</tbody>
</table>
The following is a list of common generated products:

(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 for weather surveillance. This is the most basic of products. Note that it is made at constant elevation angle, and so increasing range means that the data are taken at increasing height. Any parameter can be displayed in this format.

(b) The constant altitude plan position indicator: 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. One of the rationales for the CAPPI is that by judicious selection of the altitude, a near clutter-free product can be produced in the absence of the Doppler zero velocity notch filter.

(c) The pseudo range–height indicator (RHI): A display of a variable obtained from a volume scan where the data from the same azimuth are extracted and collated to provide vertical information on the structure of the weather. Classically, this was done with an antenna doing a physical vertical sweep, typically from $0^\circ$ to $90^\circ$, at one azimuth. Manual intervention was required to select the azimuth and decide when to do the scan. The advantage of this classic technique is that the density of information is much higher. Typically, very fine elevation angle changes ($\sim 0.1^\circ$) can be used. The quality of the pseudo RHI technique depends on the scan strategy, but it has the great advantage of flexibility. It is used for identifying severe storms, hail and the bright band.

(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 horizontal plane, of the maximum value of a variable (usually reflectivity) above each point of the area being observed. This is useful to identify the maximum reflectivity in a storm to assess its severity or to estimate the maximum precipitation that could be expected. In some cases, due to radar siting issues, where the low levels could not be observed (mountainous terrain), this was used to estimate surface precipitation. Sometimes, there is a minimum altitude threshold to the data, so that the high reflectivities in the bright band do not overly influence the use of this product. A variation is to limit the altitude of the data to quickly provide insight into the vertical structure of the storm.

(f) Vertically integrated liquid: An indicator of the intensity of severe storms. It can be displayed, in horizontal plane, for any specified layer of the atmosphere. As this is dominated by the highest reflectivities, it is very similar to the maximum reflectivity product in pattern but in different units.

(g) Echo tops: A display, in horizontal plane, of the height of the highest occurrence of a selectable reflectivity contour, obtained by searching in the volume data. It is an indicator of the strength of the updraught and therefore an indicator of severe weather and hail.

(h) Often the reflectivity products are converted to precipitation products by an empirical relationship between $Z$ and $R$. These precipitation products are aggregated into accumulation products of varying time duration.

(i) Modern computing systems have significant processing capabilities. Techniques or algorithms have been developed to search the three-dimensional data to locate and quantify the characteristics of contiguous areas of high reflectivity which are related to severe weather thunderstorms for the analyst (Figure 7.24).
In addition to these standard or basic displays, other products can be generated to meet the particular requirements of various users (hydrology, nowcasting or aviation):

(a) Precipitation accumulation: An estimate of the precipitation accumulated over time at each point in the area observed;

(b) Precipitation sub-catchment totals: Area-integrated accumulated precipitation;

(c) Velocity azimuth display: 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 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 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) Tornado 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;

(j) Particle type: The echo is classified according to precipitation type and derived from dual-polarization data.

In addition, radar network processing results in a radar mosaic. The products mentioned above apply on a network basis; in fact, this is standard practice. Considerations for radar products include: (i) projections are used for visualization of the data; (ii) for areas of overlapping radar coverage, various algorithms are used – based either on the nearest radar, the maximum value or a sophisticated estimation of data quality. If the overlap is significant, a neighbouring radar may fill the void in the "cone of silence". The development of networked radar products needs also to consider intra-network and inter-network homogenization of the data. This includes temporal and spatial harmonization, mutual calibration of the radar data, and examination of the radar sensitivities which can result in discontinuities in the network products.
ANNEX 7.A. WMO GUIDANCE STATEMENT ON WEATHER RADAR/RADIO FREQUENCY SHARED SPECTRUM USE

WMO expresses concern over increasing pressure on weather radar related radio-frequency bands and stresses the need for adequate protection and mitigation efforts against the loss and shared use of this spectrum. WMO addresses its concern to policymakers, to national radio-frequency administration agencies, to national hydrological and meteorological societies, to commercial vendors of telecommunication equipment and to the meteorological community.

Protection of traditional weather radar related radio frequencies is critical to the continued function and improvement of weather sensing, monitoring, forecasting, and warning, and is therefore in the best interests of public safety and security. The meteorological community increasingly relies on remote-sensing technologies for both routine and experimental observations of weather and climate. These activities require global access to the radio-frequency spectrum by not only radars but also wind profilers, microwave radiometers, and telemetry systems, as well as satellite-based passive and active sensors. The progress in weather warning services and other meteorological predictions made in recent years is largely attributable to these technologies.

Weather prediction models and localized operational forecasts increasingly depend on national networks of ground-based Doppler radars for severe weather warnings such as tornadoes, flash flooding, land-falling hurricanes, precipitation (rain, snow, hail) forecasts, aircraft icing and air traffic/weather avoidance. Worldwide, Doppler radar networks are now contending with increasing pressures on shared spectrum usage with unlicensed broadband wireless applications. As already experienced in Europe, the impacts of radio-frequency interference by wireless communications can render weather radars blind in particular directions or even over large portions of their coverage. The situation is exacerbated by the ubiquitous and unlicensed nature of these wireless applications that could lead to a total loss of the related spectrum for weather radars.

Development of new radar technologies, including adaptive scanning strategies, shorter pulses, polarization, pulse compression, frequency and phase agility is ongoing. Current and planned satellite radar systems measure clouds and precipitation, which is important for weather forecasting and global climate change research and assessment. Varieties of other space-based and ground-based radio technologies are currently in experimental use and may require future radio spectrum allocations.

New communication applications make the radio-frequency spectrum an extremely valuable commodity, and so the frequency bands used for operational meteorology and research are in increasing jeopardy. WMO and the meteorological community rely on and support mandated international and national radio-frequency agencies and promote cooperation with the telecommunication authorities and industries to continue to protect or to appropriately share these radio frequencies. WMO is intensively working with these agencies, through the International Telecommunication Union (ITU), to establish appropriate mechanisms to protect meteorological uses of the radio-frequency spectrum. WMO encourages the development of a clear definition of interference, permissible or otherwise, and a remedial process or solution if shared use becomes a problem. WMO encourages funding and implementation of studies to determine the impact of the total or partial loss of one or more frequency bands used by current operational observing systems and by planned systems. Further, WMO recommends that the results of these studies be made available to ITU radiocommunication groups and to national radio-frequency agencies and the telecommunications industry to encourage dialogue between active and passive users of the spectrum. Vigilance is necessary, as degradations of meteorological data due to intrusions or shared usage will evolve over time. Cooperation with national radio-frequency agencies, the telecommunications industry, and with other spectrum users is encouraged both to advocate support for critically important meteorological use of radio spectrum and to mitigate potential problems.
It is in all nations’ best interests to protect radio frequencies essential for meteorological activities that are critical to the accurate forecasting of adverse weather. Global solutions are sought and should be advocated. WMO is actively participating in international frequency management activities, through a group of experts with global representation, to protect current frequency bands used in meteorology, climatology and Earth observations, as well as to obtain new bands required for research and operations.

Further information is available in a guide entitled *Use of Radio Spectrum for Meteorology: Weather, Water and Climate Monitoring and Prediction*, produced jointly by WMO and ITU.
ANNEX 7.B. WMO GUIDANCE STATEMENT ON WEATHER RADAR/WIND TURBINE SITING

WMO expresses concern over increasing deployment of wind turbine farms and stresses the need for adequate consultation, protection and mitigation efforts. WMO addresses its concern to policymakers, to national radio administration agencies, to national hydrological and meteorological societies, to wind turbine farm developers, to commercial vendors of wind turbine equipment and to the meteorological community.

Protection of weather radar data is critical to the continued function and improvement of weather sensing, monitoring, forecasting, and warning, and is therefore in the best interests of public safety and security. Weather prediction models and localized operational forecasts increasingly depend on national networks of ground-based Doppler weather radars and wind profilers for severe weather warnings such as tornadoes, flash flooding, land-falling hurricanes, precipitation (rain, snow, hail) forecasts, aircraft icing and air traffic/weather avoidance. Worldwide, Doppler radar and wind profile networks are now contending with increasing pressures by wind farms.

Wind farms have already had an impact on operational weather radar networks, creating confounding ground echoes that create a significant loss of data or create false precipitation for hydrological applications. The rotating blades can create velocities which could potentially be mistaken to be severe weather such as a tornado. While weather radars have been voluntarily moved by the wind farm developers, generally, the meteorological community has no jurisdiction on the location of the wind farms and relies on cooperative “good neighbour” policies for mitigation.

Development of new radar and wind profiler networks and wind farms will require strategic planning for mitigation by the meteorological and wind farm communities. WMO and the meteorological community rely on and support mandated international and national radio agencies and will proactively encourage and support these agencies’ efforts to promote and to protect the meteorological use of unobstructed space. WMO encourages national radio agencies to develop acceptable obstruction criteria and to provide tools to help the wind farm developer on site selection.

The range between wind turbines and the weather radar can be used to generally describe the impact on radar quality and also used to provide a mitigation strategy for cooperative siting of weather radars and wind turbines. Below are the general guidelines for typical radars and flat terrain situations, which may require modifications for specific situations and for particular radars. Higher powered radars such as S band (10 cm wavelength) radars with less attenuation may necessitate increasing the range limits in the table.

WMO encourages funding and implementation of studies to develop technologies to mitigate the impact. Weather radar signal processing techniques or use of other materials to construct wind turbines may be able to mitigate clutter at long ranges. Further, WMO recommends that the results of these studies be made available to commercial weather radar and wind turbine manufacturers.

It is in all nations’ best interests to protect unobstructed space for weather radars and wind profilers that are essential and critical to the accurate forecasting of adverse weather. Local, national and technological solutions are sought. WMO will support and provide guidance material and tools to protect unobstructed space for weather radars and wind profilers.
<table>
<thead>
<tr>
<th>Range</th>
<th>Potential impact</th>
<th>Guideline</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–5 km</td>
<td>The wind turbine may completely or partially block the radar and can result in significant loss of data that cannot be recovered.</td>
<td>Definite impact zone: Wind turbines should not be installed in this zone.</td>
</tr>
<tr>
<td>5–20 km</td>
<td>Multiple reflection and multi-path scattering can create false echoes and multiple elevations. Doppler velocity measurements may be compromised by rotating blades.</td>
<td>Moderate impact zone: Terrain effects will be a factor. Analysis and consultation is recommended. Reorientation or re-siting of individual turbines may reduce or mitigate the impact.</td>
</tr>
<tr>
<td>20–45 km</td>
<td>Generally visible on the lowest elevation scan ground like echoes will be observed in reflectivity Doppler velocities may be compromised by rotating blades.</td>
<td>Low impact zone: Notification is recommended.</td>
</tr>
<tr>
<td>&gt; 45 km</td>
<td>Generally not observed in the data but can be visible due to propagation conditions.</td>
<td>Intermittent impact zone: Notification is recommended.</td>
</tr>
</tbody>
</table>
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