Chapter 2: Polarimetric Radar

2.1 Polarimetric radar vs. conventional radar

Conventional weather radars transmit and receive linear electromagnetic radiation whose electric field is parallel to the local horizontal. A PR can transmit and receive linear electromagnetic radiation whose electric field is oriented in either the local horizontal or the local vertical.

With a PR, orthogonally−oriented pulses of radiation may be alternated in rapid succession as the radar scans through a volume of interest. Upon examination of the differences in the backscattered power and propagation characteristics between the orthogonal pulses, bulk particle information within the sample volume can be deduced (Zrnic and Ryzhkov 1999). This information may include particle shape, particle size, ice density, and particle diversity. Using this information in unison, the bulk hydrometeor type(s) and presence of non−hydrometeorological scatterers within a radar volume can be estimated with great certainty (Zrnic et al. 2001).

2.2 Reflectivity factor (Z)

When an illuminated particle’s diameter D is at least one order of magnitude smaller than the wavelength λ of a radar, the Rayleigh approximation can be used for the backscattering cross−section, i.e., it is said to be a Rayleigh scatterer. The backscattering cross−section σ of a single spherical target in the Rayleigh regime is given by:

$$\sigma \approx (\pi^5/\lambda^4)\,|K|^2\,D^6, \tag{2.1}$$

where K is the complex refractive index of the material (Doviak and Zrnic 1993). Because many Rayleigh targets of varied diameter may be present in a volume, the backscattering cross section per unit volume, or reflectivity η, at range r is defined as:

$$\eta = (\pi^5/\lambda^4)\, |K|^2\, Z\ , \tag{2.2}$$

where:

$$Z = \int_0^\infty N(D,r)\, D^6\, dD\ . \tag{2.3}$$

N(D) in equation (2.3) refers to the number of particles of diameter D present within the volume, called the particle size distribution (PSD). The PSD cannot be measured directly by a radar and is typically not known *a priori*.

For an "S−band" ($\lambda \approx$ 10 cm) radar, rain drops act as Rayleigh scatterers. Rain drop diameter typically ranges between a fraction of a millimeter and 5 mm, with few drops observed to be more than 8 mm in diameter (Pruppacher and Klett 1997). The PSD of rain varies over time and space, but the distributions measured by Marshall and Palmer (1948) are typically used in radar applications (Figure 2.1).

Rain drops in free fall at terminal velocity tend to flatten into an oblate orientation. Wind tunnel simulations by Pruppacher and Beard (1970) found that the ratio between the minor (a) and major (b) axes of a drop falling at terminal velocity can be related to its initial diameter D (in mm) by the empirical equation:

$$a/b = 1.030 - 0.124D\ , \tag{2.4}$$

which is in agreement with observations of increasingly oblate fall orientations given larger initial drop diameter (Figure 2.2). Conventional radars typically use linear horizontal polarization so that the backscattering cross section will become larger for increasing drop size, as can be seen through examination of equations (2.1) and (2.4).

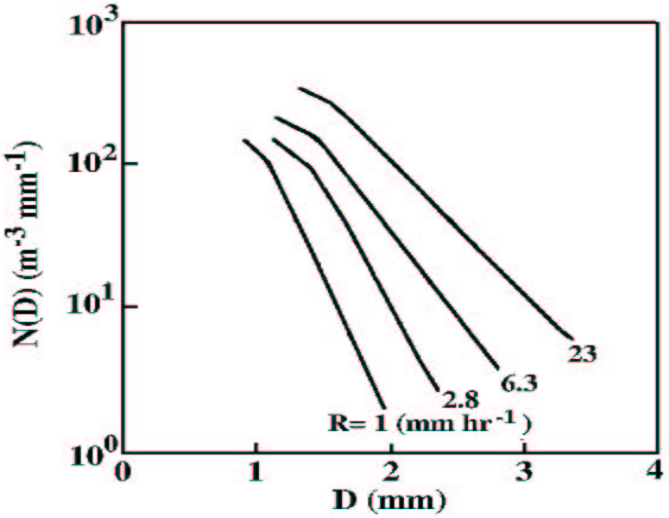

Figure 2.1. Rain drop size distributions versus drop diameter for four different rain rates. After Marshall and Palmer (1948).

Figure 2.2. Typical shapes of rain drops falling at terminal velocity. From Pruppacher and Beard (1970).

Moderate to large hailstones tend to tumble while in free fall (Knight and Knight 1970). Statistically, therefore, a large population of hailstones may appear to have a nearly isotropic fall orientation. This does not imply the individual hailstones are spherical; Knight (1986) observed that most hailstones are not spherical.

In typical hailstorms, the hailstone PSD can be well−estimated by a decaying exponential function (Figure 2.3). This implies that the vast majority of hailstones in a sample volume will lie within the Rayleigh scattering regime for an S−band radar. Still, the presence of giant hailstones will result in Mie scattering. A simple function describing backscattering characteristics of large spheres in the Mie regime cannot be written easily (Battan 1973), though observational evidence suggests reflectivity is larger for an ice sphere than a water sphere of the same diameter when D > 0.8λ (Atlas et al. 1960).

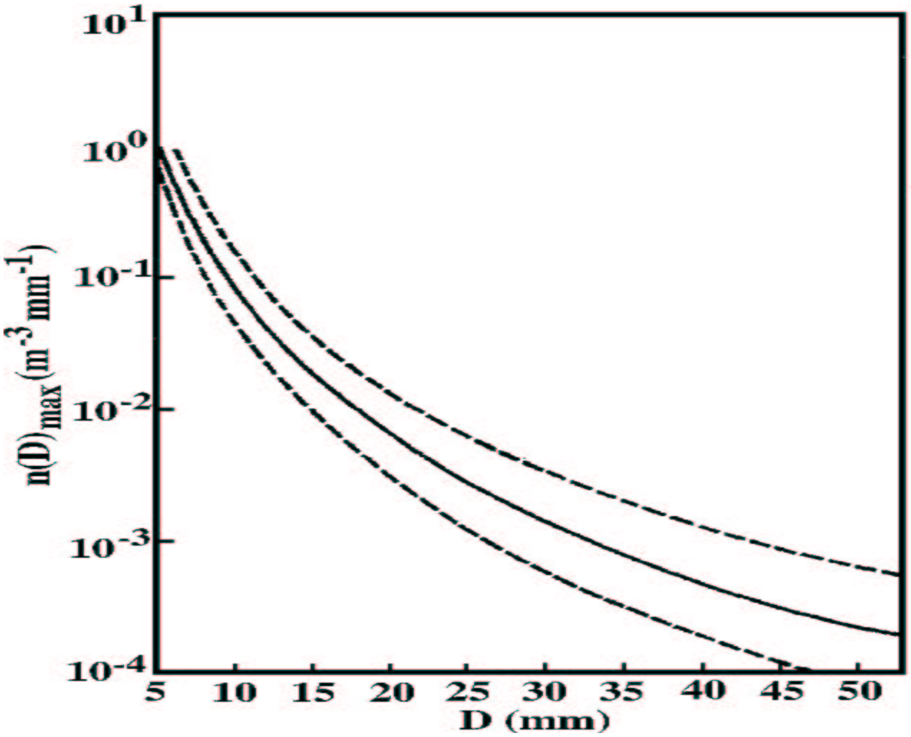

Figure 2.3. Hailstone number concentration as a function of hailstone diameter. After Cheng and English (1983).

For an S−band radar, theoretical calculations suggest backscattering increases as melting hailstones develop a water coat (Herman and Battan 1961). This is explained by the larger complex refractive index K for water than for ice in equation (2.1). While dry hail would have a small K and a large D, water−coated hail would have both a large K and a large D. Observations have shown that water−coated hailstones may have such complex scattering properties that some of the radiation is returned to the radar via three body scattering with the ground (Lemon 1998).

As will be discussed in Chapter 3, melting hail particles shed large numbers of water drops of varied diameter. Therefore, the presence of water−coated hail may also imply the presence of a mixture of rain and hail in the same radar volume. The above equations do not provide means for determining the relative proportions of rain and hail in such a situation.

2.3 Differential reflectivity (Z_{DR})

For a PR, the characteristics of the backscattered radiation differs between the horizontally and vertically polarized transmitted pulses. The differential reflectivity describes the ratio between the reflectivity factor measured by the horizontally−oriented pulse (Z_H) and that measured by the vertically−oriented pulse (Z_V):

$$Z_{DR} = 10 \log (Z_H/Z_V) \; . \tag{2.5}$$

Z_{DR} values in meteorological echoes typically range between −2 and 6 dB (Straka et al. 2000).

Z_{DR} values well above zero dB indicate the bulk presence of oblate hydrometeors ($Z_H > Z_V$). Likewise, the bulk presence of spherical hydrometeors will result in near zero dB Z_{DR}, and significantly negative Z_{DR} indicates prolate hydrometeors. As noted in section 2.2, rain drops tend to fall in an oblate orientation, so the Z_{DR} measured in a volume of rain drops should be significantly above zero dB. On the other hand, the nearly isotropic bulk orientation of falling hailstones suggests Z_{DR} measurements in that case would be near zero dB.

It should be noted that Z_{DR} is a reflectivity−weighted measure. As a result, the Z_{DR} measured in a volume of mixed hydrometeors will be biased toward the shape of the more reflective hydrometeors. This can be seen through examination of equations (2.2) and (2.3); the addition of only a few hydrometeors of large D in a radar volume will quickly increase Z. Therefore, in a bulk mixture of rain and hail, the Z_{DR} measured should be nearly that which would be measured if only the hail was present. This characteristic makes the discrimination between hail and a rain/hail mixture difficult using a Z, Z_{DR} pair alone.

2.4 Specific differential phase (K_{DP})

While Z and Z_{DR} depend on the characteristics of backscattered radiation from illuminated particles, additional useful information can be obtained by examining the propagation characteristics of radar pulses. Microwave radiation propagates more slowly through hydrometeors than through air, i.e., the phase of the wave changes more rapidly over a given distance. The difference ϕ_{DP} in the returned phase constant between the horizontally (ϕ_H) and vertically (ϕ_V) polarized pulses, for a scatterer at a given range, is given by:

$$\phi_{DP} = \phi_H - \phi_V \ . \tag{2.6}$$

As anisotropic constituents are encountered along the radiation propagation path, the orthogonally−polarized pulses will become increasingly unphased, i.e., ϕ_{DP} will continue to increase with range. The location and magnitude of relative phase shifts along the propagation path can be more readily determined by calculating the range derivative of ϕ_{DP}, called the specific differential phase K_{DP}, over a given range interval $r_1 - r_2$ (where $r_1 < r_2$):

$$K_{DP} = [\phi_{DP}(r_1) - \phi_{DP}(r_2)] \ / \ 2(r_2 - r_1) \ . \tag{2.7}$$

In a field of rain drops, K_{DP} will be well above zero deg km^{-1}. This is due to the bulk oblate orientation of falling rain drops. A larger cross section of water content in the horizontal than in the vertical will cause the horizontally oriented pulse to propagate more slowly through the field of drops. As discussed in section 2.2, hailstones tend to tumble while in free fall, with a bulk isotropic orientation. Therefore, we should expect

K_{DP} to be near zero deg km^{-1} in a field of falling hailstones. The orthogonally−oriented pulses will intersect nearly the same hydrometeor content over a given range interval.

This characteristic of K_{DP} allows the presence of a mixture of rain and hail in the same radar volume to be deduced. While the bulk isotropic nature of the hailstones in the mixture cause ϕ_H and ϕ_V to change at approximately the same rate, the presence of oblate rain drops causes ϕ_H to change more rapidly than ϕ_V. It should also be noted that the power of the backscattered signal is not involved in the calculation of K_{DP}, so this variable is also immune to partial beam blockage and signal attenuation. These characteristics of K_{DP} have be exploited to develop reliable rainfall accumulation algorithms (e.g., Zrnic and Ryzhkov 1996) that are immune to hail contamination.

2.5 Co−polar correlation coefficient at zero lag ($\rho_{HV}(0)$)

The co−polar correlation coefficient ($\rho_{HV}(0)$) describes the differences between the backscattering matrices of the horizontally and vertically polarized echoes at zero time lag. A full theoretical development of $\rho_{HV}(0)$ can be found in Balakrishnan and Zrnic (1990b). In general, correlation coefficient may be influenced by differences in eccentricities, differential phase shifts on scattering, canting angles, irregular shapes of hydrometeors, and a mixture of two types of hydrometeors (Doviak and Zrnic 1993).

Decorrelation has been known to occur in large hail, wet or spongy hail, and mixtures of rain and hail (Balakrishnan and Zrnic 1990b). In general, an equal mixture of two different hydrometeor types will yield the lowest values of $\rho_{HV}(0)$, especially when the size of one varies predominantly in the horizontal and the other varies in the vertical (Straka et al. 2000).

The standard error for $\rho_{HV}(0)$ is approximately ±0.01 in hail and rain/hail mixtures (Balakrishnan and Zrnic 1990b), where correlation coefficient values as low as 0.95 and 0.90 are typical, respectively (Doviak and Zrnic 1993). In the case of pure rain, $\rho_{HV}(0)$ is typically in excess of 0.97 (Doviak and Zrnic 1993), with a standard error near ±0.002 (Illingworth and Caylor 1991).

2.6 Use of polarimetric radar to classify particle type

These PR variables may be used in conjunction with Z to deduce hydrometeor type, and the presence of non−meteorological (e.g., biological) scatterers. Hydrometeor classification algorithms (e.g., Zrnic et al. 2001), which use a "fuzzy logic" approach to determine hydrometeor type from PR variables, have been written for this purpose. Table 1 provides an overview of typical values of polarimetric variables for different hydrometeor types.

Hydrometeor type	Z_H (dBZ)	Z_{DR} (dB)	$\rho_{HV}(0)$	K_{DP} (deg km^{-1})
Rain	25 to 60	0.5 to 4	> 0.97	0 to 10
Wet hail (< 2 cm)	50 to 60	−0.5 to 0.5	> 0.95	−0.5 to 0.5
Wet hail (> 2 cm)	55 to 70	< −0.5	> 0.96	−1 to 1
Rain/hail mixture	50 to 70	−1 to 1	> 0.90	0 to 10

Table 1. Values of polarimetric radar variables for precipitation types (after Doviak and Zrnic 1993).

2.7 Mie scattering

Differential phase shifts upon scattering (δ, in deg) are a result of the presence of Mie scatterers. Mie scattering occurs when the hydrometeors with diameters on the order of the radar wavelength are illuminated. δ contributes to the total measured differential phase shift ϕ_{DP} according to the equation:

$$\phi_{DP} = 2 \int_0^r K_{DP}\, dr + \delta \,. \qquad (2.8)$$

Therefore, the measured ϕ_{DP} will be greater than zero deg km^{-1} in the presence of isotropic Mie scatterers. Balakrishnan and Zrnic (1990b) also found that δ will decrease the value of $\rho_{HV}(0)$.

At S−band radar wavelengths, very large hailstones may result in Mie scattering. The presence of very large hail may be accompanied by very high Z, near−zero dB or negative Z_{DR}, and low $\rho_{HV}(0)$ (Zrnic et al. 1993). Attenuation of the radar signal may also occur due to large hail (Doviak and Zrnic 1993). In such areas, observed values of ϕ_{DP} and $\rho_{HV}(0)$ must be used with caution.