Weather radar technology and future developments

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Abstract Radar Hydrology is slowly coming of age and the future development of quantitative weather radar will be heavily influenced by the Hydrological community. There is controversy as to whether or not dual-polarization radar technology is going to improve the estimation of precipitation. This paper discusses some of the advantages and disadvantages of the present algorithms used to estimate precipitation, using single- and dual-polarization weather radar measurements, and gives some recommendations for future research in this area.

Keywords dual-polarization radar; hydrometeor classification; radar hydrology; rainfall estimators; vertical reflectivity profile; weather radar.

INTRODUCTION

One of the main advantages of weather radars is that they can scan large areas and take millions of measurements from a single location in real-time. A network of raingauges that can survey the same area with a similar spatial resolution would be practically impossible to maintain. However, weather radars have practical limitations and the estimation of precipitation using these devices is prone to several sources of errors. At the beginning of weather radar research during the World War II, early researchers revealed many of the problems that weather radars face in Quantitative Precipitation Estimation (QPE) (Atlas & Ulbrich, 1990). Weather radars are subject to many sources of error and in order to obtain an accurate estimation of precipitation, it is necessary to understand each process involved in the estimation of precipitation.

During the World War II, weather radar echoes were considered as annoyance rather than something of intrinsic interest (Probert-Jones, 1990). The major research work in the field of radar meteorology was carried out in the UK, where considerable work on radar propagation was carried out at the Telecommunication Research Establishment at Malvern (now the Royal Signals and Radar Establishment) and at the General Electric Research Laboratories with the research work carried out by Ryde (Probert-Jones, 1990). Ryde (1946), estimated the echo intensity and attenuation by atmospheric hydrometeors at centimetric wavelengths to determine the extent to which radars would be affected by weather. This established the basis of radar meteorology by the end of the war (Atlas & Ulbrich, 1990; Probert-Jones, 1990). Marshall et al. (1947) were the first to show an excellent correlation between the received echo power from a 10-cm radar and the reflectivity, Z, computed from the drop size distribution of samples obtained from a filter paper on the ground. They stated that “it may be possible therefore to determine with useful accuracy the intensity of rainfall at a point quite distant (say 100 km) by the radar echo from that point”. Since then, this work has stimulated many researchers to estimate precipitation using radars.
DUAL-POLARIZATION RADAR MEASUREMENTS

A radar sends a pulse of microwave energy in some specific direction. If a target (e.g. precipitation particles) lies along the path of the beam, then a small percentage of the energy is reflected back to the radar and related to the rainfall rate by using empirical equations. In order to fully exploit and interpret the backscattered electromagnetic radiation from hydrometeors, it is necessary to take into account the four fundamental properties of electromagnetic waves: amplitude, phase, frequency and polarization (Jameson & Johnson, 1990). The use of the reflectivity factor $Z_h$ exploits the amplitude property and it has been the most important parameter in the estimation of precipitation with weather radars. However, there are several sources of uncertainty using only the reflectivity factor that can be minimized by the use of dual-polarization techniques, which are sensitive to size, shape, orientation and phase of the hydrometeors (Herzegh & Jameson, 1992) and can improve the estimation of precipitation with weather radars (Zrnic & Ryzhkov, 1999).

An electromagnetic wave is produced by the interaction of time-varying electric and magnetic fields. The direction of propagation is normal to the plane formed by the electric and magnetic field vectors and both vectors are orthogonal. Polarization refers to the change of the electric field vector with time when observed along the direction of propagation (see Staelin et al., 1994). The most general type of polarization is elliptical and in this polarization the electric field is oscillating in such a way that it draws an ellipse when viewed along the direction of propagation. If the direction of propagation is the $+z$ axis in a $xyz$ coordinate system, the electric field will have components in the $x$ and $y$ directions ($E_x$ and $E_y$ respectively). Depending on the amplitude and phase of the components $E_x$ and $E_y$, the ellipse may become either circular or linear (known as either circular or linear polarization respectively). Therefore, circular and linear polarizations are special cases of the general elliptical polarization. Dual-polarization weather radars use either circular or linear horizontal/vertical polarization (see Bringi & Hendry, 1990). The electric field in linear horizontal polarization is confined to the $x$ direction and the component $E_y = 0$. On the other hand, the electric field in linear vertical polarization is confined to the $y$ direction and the component $E_x = 0$.

Dual-polarization weather radars alternately transmit vertically and horizontally polarized electromagnetic waves and receive polarized backscattered signals. The backscattering characteristics of a single precipitation particle are described in terms of the backscattering matrix $S$ (Bringi & Chandrasekar, 2001). The polarimetric radar observables are related to the scattering elements of the backscattering matrix and they are defined as follows.

The reflectivity factor

The reflectivity factors at horizontal and vertical polarizations are given by:

$$Z_{h,v} = \frac{\lambda^4}{\pi^3 |K|^2} \int \sigma_{h,v}(D) N(D) dD$$

(1)

where $D$ is the drop diameter, $\lambda$ is the radar wavelength, $|K|^2$ is the refractive index of
the hydrometeors (approximately 0.93 for water and 0.20 for ice). $\sigma(D)$ is the back-scattering cross sections of the scatterers and $N(D)$ is the drop size distribution. If the scatterers are considered as small water spheres with small radii compared to the radar wavelength, then the approximation of the Rayleigh scattering applies and Equation (1) can be expressed as:

$$Z = \int D^6 N(D) dD$$

(2)

**Differential reflectivity**

Pruppacher & Beard (1970) found that large raindrops falling to the ground are distorted into oblate spheroids due to aerodynamic forces. Their maximal dimensions are horizontally oriented even when turbulence, drop collisions and aerodynamic instability may disturb their orientation. Taking advantage of this fact, Seliga & Bringi (1976) proposed the use of differential reflectivities at orthogonal polarizations to improve the estimation of precipitation. The backscattering cross-section for raindrops is larger for a horizontal polarized wave than for a vertical polarized wave. The differential reflectivity is given by:

$$Z_{dr} = 10 \log \left( \frac{Z_h}{Z_v} \right)$$

(3)

Seliga & Bringi (1976) showed that the mean volumetric diameter of raindrops is related to the value of $Z_{dr}$. Therefore $Z_{dr}$ is a measure of the mean particle shape. Large raindrops produce large values of $Z_{dr}$. On the other hand, the sensitivity of $Z_{dr}$ to particle shape for ice is less than for water (Herzegh & Jameson, 1992). Ice particles tend to wobble and spin in their descent resulting in $Z_{dr}$ values closer to zero.

**Specific differential phase**

Electromagnetic waves experience phase shifts as they propagate through regions of precipitation. The horizontally polarized wave suffers larger phase shifts than the vertically polarized wave because raindrops are horizontally oriented as they fall. The differential phase $\Phi_{dp}$ is the difference between the received phases of horizontally and vertically polarized electromagnetic waves ($\Phi_{dp} = \Phi_{hh} - \Phi_{vv}$) and the specific differential phase ($K_{dp}$) is the rate of change of $\Phi_{dp}$ along the range and it is then given by:

$$K_{dp} = \frac{1}{2} \frac{d\Phi_{dp}}{dr} \circ \text{km}^{-1}$$

(4)

It can also be expressed as (Bringi & Chandrasekar, 2001):

$$K_{dp} = \left( \frac{180^\circ}{\lambda} \right) 10^{-3} CW(0.062D_m) \text{ with } D_m = \int D^4 N(D) dD$$

(5)

where $\lambda$ is the wavelength in m, $C \approx 3.75$, $W$ is the water content in g m$^{-3}$ and $D_m$ is the mass-weighted mean diameter in mm. Equation (5) is important because $K_{dp}$ is nearly
linearly related to the liquid water content multiplied by the mean raindrop shape and therefore it provides the possibility of better estimates of the rainfall rate.

**ESTIMATION OF PRECIPITATION USING WEATHER RADARS**

Raindrops grow to a critical size and will then suffer break-up due to hydrodynamic instability (Cotton & Anthes, 1989). The different sizes of raindrops define a Drop Size Distribution (DSD) given by \( N(D) \). The DSD describes the probability density function of raindrops and it is one of the most important functions in rainfall rate algorithms. All the microphysical processes involved in the interaction between raindrops are reflected in the DSD. For a given DSD, the rain rate can be obtained by:

\[
R = 0.0006\pi \int v(D)D^3N(D)\,dD \quad \text{mm h}^{-1}
\]

where \( D \) is the raindrop diameter and \( v(D) \) is the terminal velocity of the raindrops. Atlas & Ulbrich (1977) expressed the terminal velocity as a function of the particle diameter, given by \( v(D) = 3.78D^{0.67} \text{ m s}^{-1} \), assuming the absence of vertical air motions. Thus, \( R \) represents the 3.67th moment of the DSD whereas \( Z \) represents the 6th moment (see Equation 2), with \( Z \) more sensitive to large drops than \( R \). Knowledge of the DSD is important because it establishes the interaction between the radar reflectivity and the rainfall rate. Marshall & Palmer (1948) (MP) observed an exponential DSD using dyed filter paper to measure the density of drop diameters at the surface. The exponential form of the DSD can always be applied when a large number of DSD are averaged in space or time (Bringi & Chandrasekar, 2001). The MP DSD can be expressed as:

\[
N(D) = N_0 \exp\left(-3.67D/D_0\right)
\]

where \( N_0 \) is 8000 m\(^{-3}\) mm\(^{-1}\) and \( D_0 \) is the median drop diameter, which is defined as the drop diameter such that 50% the water content is comprised of drops with diameters less than \( D_0 \) (Doviak & Zrnic, 1993). According to Marshall & Palmer (1948) the exponential DSD is slightly overestimated for raindrop diameters less than 1.5 mm. In reality there are larger variations in the shape of the DSD not represented by the MP DSD. Ulbrich (1983) proposed a more general three-parameter gamma DSD given by:

\[
N(D) = N_0D^\mu\exp\left(-\frac{(3.67+\mu)D}{D_0}\right)
\]

where the parameter \( \mu \) can take values between \(-3\) and 8. For \( \mu = 0 \), Equation (8) takes the form of the MP DSD. The shape of the gamma DSD is determined by the exponent \( \mu \), that is, for positive values of \( \mu \) the gamma DSD is concave down whereas for negative values it is concave upward. A gamma DSD can describe many of the natural variations in the shape of the DSD. When there is a substantial depth between the melting level and the ground surface, the parameterization of a gamma DSD appears to be suitable for stratiform and convective rainfall events (Bringi & Chandrasekar, 2001). In addition, Testud et al. (2001) proposed the normalization of the DSD to avoid any assumption about the shape of the DSD.
Algorithms to estimate rain from radar measurements

The most commonly used polarimetric radar measurements for rainfall estimation are the reflectivity factor \((Z_h)\), the differential reflectivity \((Z_{dr})\) and the specific differential phase \((K_{dp})\). For many years, radar meteorologists have tried to find a useful equation relating the reflectivity factor to the rainfall rate. The rainfall rate given by Equation (6) can be obtained assuming a drop size distribution and terminal velocity of raindrops. By comparing the rainfall rate with the actual reflectivity measured by the radar, it is possible to derive \(Z–R\) relationships of the form:

\[
Z = aR^b \quad \text{or} \quad R = a^{-\frac{1}{b}}Z^{\frac{1}{b}}
\]

where \(Z\) is the reflectivity factor in \(mm^6 m^{-3}\), \(R\) is the rainfall rate in \(mm h^{-1}\) and \(a\) and \(b\) are the parameters obtained from a regression analysis. Atlas & Ulbrich (1990) showed that the first \(Z-R\) relationship can be traced back to the research work carried out by Ryde (1946). They showed that this relationship is approximately \(Z = 320R^{1.44}\). This relationship is very similar to that employed to estimate the rainfall rate from reflectivity measurements in the WSR-88D radar network, which is \(Z = 300R^{1.4}\) (Serafin & Wilson, 2000). Marshall et al. (1947) reported one of the first \(Z-R\) relationships \((Z = 190R^{1.72})\), which was slightly modified to \(Z = 220R^{1.6}\) (Marshall & Palmer, 1948). Years later, Marshall et al. (1955) carried out a slight revision of the 1948 relationship, obtaining the well known Marshall-Palmer formula \(Z = 200R^{1.6}\).

The UK Meteorological Office’s Nimrod system estimates the precipitation rate using this equation (Harrison et al., 2000). Unfortunately, there is no single \(Z–R\) relationship that can be applied in every part of the world. Battan (1973) listed 69 different \(Z–R\) relationships derived from different climatological regions by several researchers. This variability is due to the fact that the coefficient and exponent of the \(Z–R\) relationship depend on the shape of the DSD. Therefore, it is necessary to estimate in real-time the parameters of the DSD to allow flexibility in the variation of the parameters \(a\) and \(b\) of the \(Z–R\) relationship.

One of the main goals of dual-polarization radars is the improvement in QPE. Seliga & Bringi (1976) proposed the use of differential reflectivities at orthogonal polarizations to estimate the parameters of an exponential DSD (Equation 7). They suggested that the parameter \(D_0\) is obtained with \(Z_{dr}\) whereas \(N_0\) is obtained with \(Z_h\) and \(D_0\). The main advantage of using the differential reflectivity \(Z_{dr}\), is that the median raindrop diameter \(D_0\) is related to the value of \(Z_{dr}\). The advantage of using differential reflectivity measurements has been exploited by several researchers to obtain the shape of the DSD.

In order to derive relationships between the rainfall rate and the polarimetric radar measurements, a common method is based on varying the parameters \(N_0\), \(D_0\) and \(\mu\) of a theoretical gamma DSD and then calculating \(R\), \(Z_h\), \(Z_{dr}\) and \(K_{dp}\) assuming a scattering model. In addition, the mean raindrop axis ratio \(r(D)\) or degree of deformation as a function of the diameter \(D\) must be specified. The coefficients and exponents of the different rainfall rate algorithms are obtained by performing a nonlinear regression between the rainfall rate and the polarimetric variables (Bringi & Chandrasekar, 2001). The deformation of raindrops is an important relationship that leads to different rainfall estimators. Further research has to be done to reach a consensus on raindrop deformation.
Table 1 Summary of relationships for rainfall estimation using polarimetric radar measurements at different frequencies. \( f \) is in mm h\(^{-1} \), \( Z_h \) is in m\(^2\) m\(^{-3} \), \( Z_{dr} \) is in dB, \( K_{dp} \) is in ° km\(^{-1} \) and \( \lambda \) in cm.

<table>
<thead>
<tr>
<th>Rain estimator</th>
<th>( f ) (GHz)</th>
<th>( c )</th>
<th>( a )</th>
<th>( b )</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R = a^{-1/2}Z_h^{1/b} )</td>
<td>&gt;3</td>
<td>-</td>
<td>200</td>
<td>1.6</td>
<td>Marshall et al. (1955)</td>
</tr>
<tr>
<td>( R = cZ_h^a10^{bZ_{dr}} )</td>
<td>3</td>
<td>0.0067</td>
<td>0.93</td>
<td>-3.43</td>
<td>Bringi &amp; Chandrasekar (2001)</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.0058</td>
<td>0.91</td>
<td>-2.09</td>
<td>Bringi &amp; Chandrasekar (2001)</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.0039</td>
<td>1.07</td>
<td>-5.97</td>
<td>Bringi &amp; Chandrasekar (2001)</td>
</tr>
<tr>
<td>( R = cK_{dp}^b )</td>
<td>3–10</td>
<td>5.17(^{0.86} )</td>
<td>-</td>
<td>0.866</td>
<td>Sachidananda &amp; Zrnic (1987)</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>50.7</td>
<td>-</td>
<td>0.85</td>
<td>Bringi &amp; Chandrasekar (2001)</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>40.5</td>
<td>-</td>
<td>0.85</td>
<td>Bringi &amp; Chandrasekar (2001)</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>50.1</td>
<td>-</td>
<td>0.70</td>
<td>Illingworth (2003)</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>31.4</td>
<td>-</td>
<td>0.70</td>
<td>Illingworth (2003)</td>
</tr>
<tr>
<td>( R = cK_{dp}^a10^{bZ_{dr}} )</td>
<td>3</td>
<td>90.8</td>
<td>0.93</td>
<td>-1.69</td>
<td>Bringi &amp; Chandrasekar (2001)</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>37.9</td>
<td>0.89</td>
<td>-0.72</td>
<td>Bringi &amp; Chandrasekar (2001)</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>28.6</td>
<td>0.95</td>
<td>-1.37</td>
<td>Bringi &amp; Chandrasekar (2001)</td>
</tr>
</tbody>
</table>

Gorgucca et al. (1994) proposed an algorithm to estimate the rainfall rate based on \( Z_h \) and \( Z_{dr} \) (Table 1). The disadvantage of the algorithm \( R(Z_h, Z_{dr}) \) is that \( Z_h \) and \( Z_{dr} \) are prone to attenuation of the horizontal reflectivity and differential attenuation respectively at frequencies higher than 3 GHz, quite apart from the fact that \( Z_h \) is subject to radar miscalibration. The use of the differential phase \( K_{dp} \) may overcome these difficulties. The main advantages of rainfall estimation based on \( K_{dp} \) are its immunity to attenuation by precipitation, its immunity to radar miscalibration and \( K_{dp} \) is also less affected by partial blockage of the radar beam (Zrnic & Ryzhkov, 1996). Thus, rainfall estimators based on \( K_{dp} \) (Sachidananda & Zrnic, 1987) and \( K_{dp}Z_{dr} \) (Bringi & Chandrasekar, 2001) have been proposed (Table 1).

It is clear that the different algorithms to estimate the rainfall rate have advantages and disadvantages. Relationships of the form \( R(Z_h) \) have been used since just after World War II. However, this type of relationship presents uncertainty in the coefficients \( a \) and \( b \) because they are related to the shape of the DSD. Without extra information, apart from the reflectivity factor, \( a \) and \( b \) have to be obtained empirically by establishing a single climatological \( Z–R \) relationship. Even if the DSD is known, the \( R(Z_h) \) relationship is critically dependent on the calibration of the radar system. To avoid any bias in the measurement of \( Z_h \), it is necessary to calculate accurately the radar constant. In addition, \( Z_h \) is not immune to propagation effects and it is subject to attenuation due to rain at frequencies higher than 3 GHz.

Relationships involving \( Z_{dr} \) are also questionable because although \( Z_{dr} \) is independent of radar calibration, it is not immune to propagation effects, being subject to differential attenuation in heavy precipitation and the depolarization of the polarized waves. Illingworth (2003) discussed the accuracy of rainfall estimates using \( Z_h \) and \( Z_{dr} \). He argued that the accuracy of \( R(Z_h, Z_{dr}) \) depends on several factors such as the accuracy of \( Z_{dr} \) to 0.2 dB for \( R > 10 \) mm h\(^{-1} \) and less for lower rainfall rates. In practice, this is very difficult to achieve because there are other factors limiting the accuracy of \( Z_{dr} \). For instance, \( Z_{dr} \) may be contaminated by the power of the sidelobes of the beam radiation pattern due to reflectivity gradients, and it may also be affected.
by the mismatch between the horizontal and vertical beam radiation patterns causing the sampling of different volumes of precipitation (Illingworth, 2003).

On the other hand, relationships of the form $R(K_{dp})$ present several advantages as mentioned previously. However, $\Phi_{dp}$ is extremely noisy and consequently $K_{dp}$ will be even noisier (see equation 4). To decrease the noise, $K_{dp}$ is averaged for several kilometers along the beam. Ryzhkov & Zrnic (1996) suggested to average $K_{dp}$ in a window of 2-4 km for high-reflectivity regions ($Z_h > 40$ dBZ) and 7-11 km for low-reflectivity regions ($Z_h < 40$ dBZ). This obviously leads to a considerable loss in resolution over the conventional $R(Z_h)$ rainfall estimator. Brandes et al. (2001) carried out an analysis between raingauge observations and rainfall rates estimated from $K_{dp}$ and $Z_h$. They found similar bias factors and correlation coefficients between both estimators, concluding that no obvious benefit is obtained using $K_{dp}$ to estimate rainfall rates over using $Z_h$ from a well-calibrated radar.

There is controversy whether or not polarimetry is going to improve radar rainfall estimates. Illingworth (2003) suggested that at the 2 km scale needed for an operational environment, the additional information provided by $Z_{dr}$ and $K_{dp}$ is not sufficiently accurate to improve rainfall estimates. However, some improvement in the QPE from polarimetric radar measurements may be realized by applying not only one particular rain estimator, but exploiting the attributes of the different polarimetric algorithms available depending on the circumstance. Ryzhkov & Giangrande (2004) proposed a “synthetic” algorithm, which makes use of different combinations of rain rate algorithms depending on the rain rate estimated using only the conventional $R(Z_h)$ relationship. They proposed the use of an algorithm of the form $R(R(Z_h), Z_{dr})$ for low rain rates ($R < 6$ mm h$^{-1}$), and of the form $R(R(K_{dp}), Z_{dr})$ for medium rain rates ($6 < R < 50$ mm h$^{-1}$) and the algorithm $R(K_{dp})$ for high rain rates ($R > 50$ mm h$^{-1}$). Although the algorithms proposed by Ryzhkov & Giangrande (2004) are slightly different from the rainfall rate estimators presented in this section, it is clear that by exploiting the performance of different relationships $R(Z_h)$, $R(Z_h, Z_{dr})$, $R(K_{dp})$ and $R(K_{dp}, Z_{dr})$, it may be possible to improve the estimation of rainfall using dual-polarization radars.

In addition, polarimetric radar measurements offer the possibility to classify hydrometeors (Zrnic & Ryzhkov, 1999; Vivekanandan et al., 1999; Liu & Chandrasekar, 2000; Zrnic et al., 2001), which provides the possibility of applying different rainfall estimators depending on the classification. However, the operational performance of such radars in practice is still to be established.

**PROBLEMS ASSOCIATED WITH THE ESTIMATION OF PRECIPITATION**

The estimation of precipitation using weather radars is subject to many error sources, which become important for QPE. In the previous section the importance of the DSD has been described in relating the reflectivity factor $Z_h$ (or any of the polarimetric variables $Z_{dr}, K_{dp}$) to the rainfall rate $R$. However, uncertainties in the knowledge of the DSD may not be the largest source of errors in radar rainfall measurements (Joss & Waldvogel, 1990) and there are additional errors that may require even more attention. Atlas et al. (1984) concluded that the average deviation in the rain rate estimation from reflectivity measurements due to DSD variability would be 33% whereas Doviak &
Zrnic (1993) suggest errors of 30–35%. Joss & Waldvogel (1990) suggest that after averaging over space and time, the errors in rainfall estimates due to the variability of the DSD rarely exceeds a factor of 2.

On the other hand, problems associated with the variation of the vertical reflectivity profile of precipitation may be one of the largest sources of error in QPE (Fig. 1). As the range increases from the radar, the radar beam is at some height above the ground. The hydrometeors intercepted by the radar beam may be composed of raindrops, melting snowflakes, snowflakes, hail, etc. This variability affects reflectivity measurements and the estimation of precipitation is not representative of the rainfall rate at the ground. This variation is due to the growth or evaporation of precipitation, change of phase, in particular melting, where a layer of enhanced reflectivity caused by melting snowflakes produces errors up to a factor of 5 (Joss & Waldvogel, 1990). Some correction algorithms have been proposed to correct for the variation of the VRP (Kitchen et al., 1994; Gray et al. 2002), but further research has to be done to account for small-scale variations of the melting level.

Partial blockage of the beam is especially problematic in hilly terrains. The radar usually scans at low elevation angles to obtain measurements closer to the ground. Echoes from nearby mountains can be misinterpreted as heavy precipitation and therefore overestimations may occur. Correction for partial beam blockage is difficult because not only the power from the mainlobe is reflected back to the radar, but also from the sidelobes. By knowing the shape of the antenna radiation pattern it may be possible to apply a correction for the partial blocking of the radar beam, but in conditions where this slightly departs from the standard propagation it is not straightforward. The use of $K_{dp}$ for rainfall estimation may overcome problems due to partial blocking to some extent, but as mentioned in the previous section, $K_{dp}$ is very

![Fig. 1 Variation of the vertical reflectivity profile of precipitation. The data were obtained with a vertically pointing radar during HYREX (see Cluckie et al., 2000).](image-url)
noisy and it is only useful in very heavy precipitation. Therefore, it is important to establish accurate corrections to overcome the effects of partial blockage of the beam.

Attenuation by precipitation is another source of error, especially at frequencies higher than 3 GHz. To some extent this is now recognized as posing a problem at C-band frequencies as well as X-band. It has been shown that the attenuation is directly proportional to the rain rate $R$ and expressions of the form $A = aR^b$ have been obtained. Attenuation correction algorithms have been developed using the specific differential phase (Bringi et al., 2001) when the radar beam passes through rain-filled media, but additional research has to be done to correct for attenuation when the radar beam passes through melting snow or mixed-phase precipitation.

**CONCLUSIONS**

Current research has sought to improve QPE using single- and dual-polarization radar measurements. However, additional work has to be done to account for the variation of the vertical reflectivity profile, in particular, when the melting layer is at lower altitudes. This may not be a problem in regions where the melting level is at higher altitudes, but it is a real problem in regions such as the UK. Polarimetric radar measurements offer the possibility to classify hydrometeors, which provides the possibility of applying different rainfall estimators and attenuation corrections within the rain region. However, the difficulty still remains in estimating rainfall rates in snow and melting snow. It is concluded that polarimetric radar measurements potentially provide important advantages over the conventional reflectivity factor. Such advantages have to be exploited in the best way to improve the estimation of precipitation from weather radars and its quantitative use in operational hydrology. Hydrologically, the concentration of future effort on “flood producing” storms may also focus research effort.

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**REFERENCES**


