Joint Centre for Mesoscale Meteorology, Reading, UK

Recent Advances in the Measurement of Precipitation by Radar

A. J. Illingworth

Internal Report No. 20

April 1993

Met Office Joint Centre for Mesoscale Meteorology Department of Meteorology
University of Reading PO Box 243 Reading RG6 6BB United Kingdom
Tel: +44 (0)118 931 8425 Fax: +44 (0)118 931 8791
www.metoffice.com

RECENT ADVANCES IN THE MEASUREMENT OF PRECIPITATION BY RADAR

Anthony J. Illingworth

JCMM, Dept of Meteorology,
University of Reading, Reading, RG6 2AU UK.

1. INTRODUCTION

Conventional meteorological radars measure the radar reflectivity factor, Z, which is proportional to ΣND^6, where N is the concentration of particles of size D summed over all particle sizes. From Z alone it is not possible to derive unambiguously the phase (liquid or ice), size, concentration, shape or density of the reflecting precipitation particles. The reflectivity is usually expressed in units of $mm^6\ m^{-3}$ relative to the reflectivity of a single mm sized raindrop per cubic meter.

The phase is important for predicting attenuation on communication links. For meteorological and hydrological applications, the rainfall rate at the ground (R in mm/hr) is estimated using an empirical relationship of the form:

$$Z = 200\, R^{1.6} \qquad (1).$$

An ice sphere has a value of Z which is 7dB less than the same sized liquid water sphere; when a low density ice particle starts to melt it reflects microwaves like a giant raindrop and Z may 10dBZ higher than for the equivalent raindrop. Values of R from equation 1 are prone to error, due to, for example: variation in the raindrop size distribution, the enhanced return from melting snowflakes ('the bright band'), overshooting of the low level precipitation at large ranges, the presence of large hailstones and ground clutter, and the spurious returns due to anomalous propagation.

This brief review will consider how polarisation parameters can be used to provide additional information on the types of precipitation present. The survey will concentrate on the parameters derived from radiation linearly polarised in the horizontal and vertical directions. Holt (1988) has shown how the linear parameters may be derived from circularly polarised observations once corrections are made for the propagation effects. Many of the results quoted have been made with the SERC/RAL Chilbolton radar in Hampshire which has a 25m antenna and operates at S-band (3GHz). Similar S-band radars, but with smaller antennae, are CP-2, operated by the National Center for Atmospheric Research (NCAR) (Herzegh and Jameson, 1992), and the CHILL radar at Colorado State University (Rutledge et al, 1993). Technical details on the implementation of polarisation diversity can be found in Atlas (1990).

8th International Conference on Antennas and Propagation, Edinburgh, UK. 30 March - 2 April 1993

2. DIFFERENTIAL REFLECTIVITY

The differential reflectivity, Z_{DR}, was one of the first polarisation parameters to be implemented and provides a measure of the mean particle shape. It is defined as:

$$Z_{DR} = 10 \log (Z_H/Z_V) \qquad (2)$$

where Z_H and Z_V are the reflectivities measured at horizontal and vertical polarisation. Hall et al (1980) showed how Z_{DR} could be used to measure the mean shape and hence, because raindrops are oblate to a degree which depends upon their size, the diameter of raindrops. Once a mean drop size is derived from Z_{DR} the concentration can be derived from Z, and a better estimate made of the drop size distribution.

Melting snowflakes are oblate and fall with their major axes aligned in the horizontal, so the melting layer is associated with a band of high Z_{DR} values. Graupel and hail particles tumble as they fall and give rise to Z_{DR} values very close to zero, and this provides the most reliable means of detecting hail falling to the ground; the regions of zero Z_{DR} close to the ground are clearly distinguishable from the positive values of Z_{DR} associated with rain (e.g. Illingworth et al, 1986). In the upper levels of stratiform clouds, where Z is low, positive values of Z_{DR} can be found, indicating the presence of very oblate ice crystals.

Z_{DR} was the first technique to be able to distinguish liquid precipitation from ice and has been very valuable in deriving attenuation statistics for communication links. The hail detection technique may find application in operational radars. The use of Z_{DR} to improve rainfall estimates in networks of operational radars scanning at low levels in elevation is more questionable. Firstly, the major source of error in deriving R from Z is not the uncertainty in the drop size distribution, but arises because the radar beam is not actually in the rain but is penetrating the bright band and the ice. Secondly, Z_{DR} needs to be measured to a precision of 0.1dB if the drop size distribution is to be accurately estimated. This relies on precise matching of the horizontal and vertical channels, and well matched antenna side lobes for the two polarisations to prevent spurious signals when strong reflectivity gradients are present. This accuracy can be achieved with a research radar with good antenna properties but is more difficult for an operational radar network.

3. LINEAR DEPOLARISATION RATIO, LDR.

The linear depolarisation ratio, LDR, provides an estimate of the fall mode of the precipitation particles. It is particularly sensitive to the presence of wet ice and is a reliable indicator of the wet snow flakes responsible for the bright band. It is defined as:

$$LDR = 10 \log (Z_{VH}/Z_H) \qquad (3)$$

where Z_{VH} is the cross-polar return for radiation transmitted with vertical polarisation but received in the horizontal, and Z_H is the conventional co-polar reflectivity.

Theoretical considerations suggest that a cross-polar return should occur only when oblate particles fall with their axes canted with respect to the vertical. The highest values of LDR will occur for particles which are the most oblate and are also wet. Wet tumbling particle with an axial ratio of 0.5 should be associated with an LDR of about -15dB, whereas those with an axial ratio of 0.85 would have an LDR of about -24dB.

Observations with the Chilbolton radar and simultaneous in-situ particle sampling with an aircraft (Frost et al, 1991) confirm that the highest values of LDR are about -15dB and are associated with the melting snow in the bright band. Values of LDR in rain are close to the antenna limit of -32dB. Melting graupel has a value of about -24dB consistent with the axial ratio of about 0.85 measured by the aircraft instruments. Dry ice has a much lower value of LDR because of its lower dielectric constant, but in stratiform clouds moderate Z regions are sometimes accompanied by LDR values of about -25dB, presumably due to oblate but tumbling crystals.

The bright band is very clear from LDR observations, having a value about 10dB higher than that from other precipitation particles. It would appear to be a prime candidate for installation on operational radars to identify the enhanced return from the bright band. LDR has the advantage that it is relatively easy to implement. No rapid switching of the polarisation of the transmitted radiation is required, but only a parallel receiver channel is needed. The cross-polar discrimination of the antenna should exceed the value of the LDR being measured, so this should be at least 20dB for bright band detection.

4. THE CO-POLAR CORRELATION, ρ^2_{HV}.

This parameter is the correlation between the time series of successive estimates of Z_H and Z_V and reflects the distribution of shapes and sizes present in the radar beam (Illingworth and Caylor, 1991). Values are unity in drizzle, fall slightly in heavy rain and can be as low as 0.5 in the bright band. Anaprop returns fluctuate just like precipitation, but they can be detected by their ρ^2_{HV} values which are close to zero.

5. DIFFERENTIAL PHASE SHIFT, K_{DP}.

For a Doppler radar additional information is available from the phase difference of the returns measured with the two polarisations, ϕ_{DP}. As the radar wave propagates through a region in which the precipitation particles have some degree of horizontal alignment, the horizontally polarised wave progressively lags behind the vertical one, and ϕ_{DP} should increase. Sachidananda and Zrnic (1986) have derived the following theoretical relationship between K_{DP} (the gradient of ϕ_{DP} and the rainrate (R):

$$K_{DP}\ (\mathrm{deg/km}) = 0.03\ R^{1.15}\ (\mathrm{mm/hr}) \qquad (4)$$

K_{DP} has many potential advantages. It is nearly proportional to R and insensitive to drop size distribution. Because of the near linearity of equation 4, if changes in ϕ_{DP} are measured at two particular range-gates it should be possible to estimate the integrated rainfall over the distance between these gates, even when heavy ground clutter completely dominates the reflectivity measurements at the intervening gates. In vigorous convective storms the estimates of rainfall from Z are very error prone because the value of Z is dominated by the contribution of the hail, however, K_{DP} should only detect the component due to the rainfall and be insensitive the tumbling hailstones.

6.GROUND CLUTTER ANOMALOUS PROPAGATION

These phenomena can be difficult to recognise from their reflectivity alone. In both cases the target is essentially the ground rather than a distributed precipitation target, and so they can be recognised by their zero value of ρ^2_{HV} as opposed to precipitation which has a ρ^2_{HV} above 0.5.

7. ACKNOWLEDGEMENTS. The research at Chilbolton is supported by RA, NERC, SERC and the Meteorological Office. I thank colleagues at RAL, UMIST, JCMM and NCAR for useful discussions.

8. REFERENCES

Atlas D. (1990) Radar in Meteorology. Amer Meteorol Soc, Boston

Frost I.R., Goddard J.W.F. and Illingworth A.J. (1991) 25th Conf on Radar Met, Amer Meteorol Soc, Boston.

Hall M.P.M., Cherry S.M., Goddard J.W.F., & Kennedy G.R.(1980) Nature, **285**, 195-198.

Herzegh P.H. and Jameson A.R. (1992) Bull Amer Meteorol Soc, **73**, 1365-1374.

Holt A.R. (1988) Electron Lett, **24**, 1241-1242.

Illingworth A.J., Goddard J.W.F. and Cherry S.M. (1986) Nature, **320**, 431-433.

Illingworth A J and Caylor I.J. (1991) 25th Conf on Radar Met, Amer Meteorol Soc, Boston.

Rutledge S.A., Kennedy P.R. and Brunkwo D.A. (1993) Bull Amer Meteorol Soc, **74**, 25-31.

Sachidananda M. and Zrnic D.S. (1986) Rad.Sci., **21**, 235-247.

CURRENT JCMM INTERNAL REPORTS

This series of JCMM Internal Reports, initiated in 1993, contains unpublished reports and also versions of articles submitted for publication. The complete set of Internal Reports is available from the National Meteorological Library on loan, if required.

1. **Research Strategy and Programme.**
   K A Browning et al
   January 1993

2. **The GEWEX Cloud System Study (GCSS).**
   GEWEX Cloud System Science Team
   January 1993

3. **Evolution of a mesoscale upper tropospheric vorticity maximum and comma cloud from a cloud-free two-dimensional potential vorticity anomaly.**
   K A Browning
   January 1993

4. **The Global Energy and Water Cycle**
   K A Browning
   July 1993

5. **Structure of a midlatitude cyclone before occlusion.**
   K A Browning and N Roberts
   July 1993

6. **Developments in Systems and Tools for Weather Forecasting.**
   K A Browning and G Szejwach
   July 1993

7. **Diagnostic study of a narrow cold frontal rainband and severe winds associated with a stratospheric intrusion.**
   K A Browning and R Reynolds
   August 1993

8. **Survey of perceived priority issues in the parametrizations of cloud-related processes in GCMs.**
   K A Browning
   September 1993

9. **The Effect of Rain on Longwave Radiation.**
   I Dharssi
   September 1993

10. **Cloud Microphysical Processes - A Description of the Parametrization used in the Large Eddy Model.**
    H Swann
    October 1993

11. **An Appreciation of the Meteorological Research of Ernst Kleinschmidt.**
A J Thorpe
May 1992

12. **Potential Vorticity of Flow Along the Alps.**
A J Thorpe, H Volkert and Dietrich Heimann
August 1992

13. **The Representation of Fronts.**
A J Thorpe
January 1993

14. **A Parametrization Scheme for Symmetric Instability: Tests for an Idealised Flow.**
C S Chan and A J Thorpe
February 1993

15. **The Fronts 92 Experiment: a Quicklook Atlas.**
Edited by T D Hewson
November 1993

16. **Frontal wave stability during moist deformation frontogenesis.**
Part 1. Linear wave dynamics.
C H Bishop and A J Thorpe
May 1993

17. **Frontal wave stability during moist deformation frontogenesis.**
Part 2. The suppression of non-linear wave development.
C H Bishop and A J Thorpe
May 1993

18. **Gravity waves in sheared ducts.**
S Monserrat and A J Thorpe
October 1993

19. **Potential Vorticity and the Electrostatics Analogy: Quasi-Geostrophic Theory.**
C Bishop and A J Thorpe
November 1993

20. **Recent Advances in the Measurement of Precipitation by Radar.**
A J Illingworth
April 1993

Met Office Joint Centre for Mesoscale Meteorology Department of Meteorology
University of Reading PO Box 243 Reading RG6 6BB United Kingdom
Tel: +44 (0)118 931 8425 Fax: +44 (0)118 931 8791
www.metoffice.com