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Differential Phase Measurements of Precipitation

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DIFFERENTIAL PHASE MEASUREMENT OF PRECIPITATION

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1. INTRODUCTION

In this paper we present measurements of a new parameter, the differential phase shift, ϕ_{DP}, and show how it can be used to improve estimates of rainfall. Conventional radar rainrate estimates have relied on an empirical relationship between the radar reflectivity factor, Z (in $mm^6\ mm^{-3}$) and the rainfall rate, R (in mm/hr) of the form:

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

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'), the presence of large hailstones and ground clutter.

ϕ_{DP} is the difference in phase between the co-polar returns measured with vertical and horizontal polarisation ($\phi_V - \phi_H$). This phase difference is a propagation effect. 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. Seliga and Bringi (1978) first pointed out that larger values of differential phase shift should occur in heavier rain, because of the increased proportion of larger oblate raindrops. For raindrops with a Marshall-Palmer spectrum Sachidananda and Zrnic (1986) have derived the following theoretical relationship between K_{DP} (the gradient of ϕ_{DP}) and the rainrate (R):

$$K_{DP}\ (\text{deg/km}) = 0.03\ R^{1.15}\ (\text{mm/hr}) \qquad (2)$$

The advantage of K_{DP} for estimating rainrate is that it is nearly proportional to R and insensitive to drop size distribution, the disadvantage is that the phase shifts are very small. There are only a few reports of differential phase measurements, but most have phase errors of about 5° (e.g. Hubbert et al, 1991). Accordingly, it has been concluded (e.g. Sachidananda and Zrnic, 1987) that the K_{DP} technique is only useful for R > 50mm/hr.

The observations we report here have been made with the RAL S-band Chilbolton radar which transmits (prf 610Hz) and receives pulses which are alternately horizontally and vertically polarised. This radar has recently been Dopplerised and is now capable of phase measurements. The system was specifically designed so that the relative phases for the H and V returns could be estimated to better than 1°.

2. ESTIMATION OF DIFFERENTIAL PHASE SHIFT

The value of ϕ_{DP} is given by ($\phi_V - \phi_H$). A difficulty arises because the V and H samples are not taken simultaneously. If the targets had a constant Doppler velocity, then the phase would change linearly with time (for example, a phase shift of 180° would correspond to a displacement of one quarter of a wavelength), and the interpolation to correct for the staggered sampling would be straightforward. In practice, the spread of velocities (finite width of the Doppler spectrum) places a fundamental restriction on the accuracy of the ϕ_{DP} estimate. ϕ_{DP} was computed using estimator #2 from Sachidananda and Zrnic (1986).

3. OBSERVATIONS OF PRECIPITATION

A comparison of the reflectivity and phase measurements in widespread stratiform precipitation on 17 Dec 1991 is plotted in Figure 1 for a 0.4 second dwell (256 pulses 128 of each polarisation) at 512 gates with 300m spacing. Other polarisation parameters, such as the co-polar correlation, ρ, (Illingworth and Caylor, 1991) and the linear depolarisation ratio, LDR, (Illingworth and Caylor, 1989) confirm that the precipitation is in the form of rain to 55km range, the bright band from 55km to 65km, and dry ice beyond.

The steady gradient of ϕ_{DP} in the rain is clearly visible in Figure 1 over the range 20 to 50km. ϕ_{DP} also increases in the ice beyond 65km, but in this regions Z_{DR} is essentially zero, so the phase shifts probably result from

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small horizontally aligned ice particles. We suggest that ground clutter and the bright band can be identified by the increased noise in ϕ_{DP}, estimated from σ, the standard deviation of ϕ_{DP}. Sachidananda and Zrnic (1986) discuss how the Doppler width and the correlation, ρ, affect σ, but unfortunately their theory fails for the narrow Doppler widths (2m/s) of the data in Figure 1. For the rain, which has a correlation near to unity, it appears that the Doppler width limits σ to about 1° for this 0.4 second dwell. The bright band consists of a mixture of particle shapes, and so has a low ρ, which results in small random phase shifts between the horizontal and vertical returns; this is consistent with the increased value of σ to more than 2° in the bright band (55-65km range). Mie scattering from ground clutter results in large, random phase shifts, and can be readily identified in the ϕ_{DP} profile at ranges of 7, 12 and 21km.

One method of deriving rainfall rate from K_{DP} would be to estimate the gradient of a least squares fit of ϕ_{DP} against range, but this assumes a constant rain rate and no ground clutter noise. We have used an alternative approach and computed K_{DP} from $\Delta\phi_{DP}$, the change in the average value of ϕ_{DP} at two ranges, and then relied on the near linearity of Equation 2 to derive an integrated average rain rate over a distance. At 16.2km (point A in the figure) the average value of ϕ_{DP} was -11.80° $\pm$ 0.18°, where the error term is the standard error, s, obtained by averaging over 16 neighbouring gates so that in this case s is one quarter of σ. At 47.8km (point B) the average ϕ_{DP} is -6.85° $\pm$ 0.57°. This leads to a mean value of K_{DP} of 0.15$\pm$0.02 deg/km between A and B, which yields R = 4.20 $\pm$ 0.43 mm/hr from Equation 2; this is consistent with the average R = 4.44 mm/hr derived from Equation 1 using the Z value at each gate.

Figure 2 shows data for lighter rain and illustrates how K_{DP} can integrate rainfall rate over a path in the presence of ground clutter. The beam is dwelling in the rain below the bright band, with a Doppler width of about 1 m/s leading to a standard deviation, σ, of 0.7° for a 0.4 second dwell. The polarisation parameters confirm that the high value of reflectivity at 14km range is due to ground clutter, but this inference would not be obvious from the reflectivity alone. The rainfall rate derived by measuring the mean values of ϕ_{DP} (using 32 gates with 75m separation) centred at 10km (point A) and 19km (point B), that is on either side of the clutter, yield an essentially zero rainrate of 0.51 $\pm$ 0.62 mm/hr. The rainrate of 4.84 mm/hr, from a gate by gate integration of the reflectivity, is in error because the ground clutter dominates the return.

5.CONCLUSIONS

These observations suggest that the differential phase technique can be used to derive rainfall rates down to a few mm/hr, provided that the standard error in ϕ_{DP} can be reduced to 0.1° by careful design of the phase detection circuitry and by suitable spatial and temporal averaging. The standard deviation of ϕ_{DP} is limited by the Doppler width and the correlation of the precipitation targets. The increase in noise for low correlation targets could be used to identify both clutter and the bright band.

The rainfall values derived from the phase measurement are consistent with those from the reflectivity in the absence of ground clutter, but for quantitative verification we plan a statistical series of measurements above ground based rain gauges. Ideally these will include occasions when there is a mixture of rain and hail, and it will be possible to quantify the usefulness of K_{DP} in isolating the component of the reflectivity due to rain in conditions when the reflectivity is dominated by large hailstones.

The phase technique has the advantage that it is not directly affected by attenuation and this suggests that it should be applicable at X-band; much narrower beams would be feasible and so the beam could sample the rain to much greater distances. In heavy rain the large raindrops would scatter in the Mie regime, but if the phase measurements are made in the lighter rain on either side of the heavy precipitation core, then it should be possible to isolate the propagation phase shift from the differential phase shift on backscatter.

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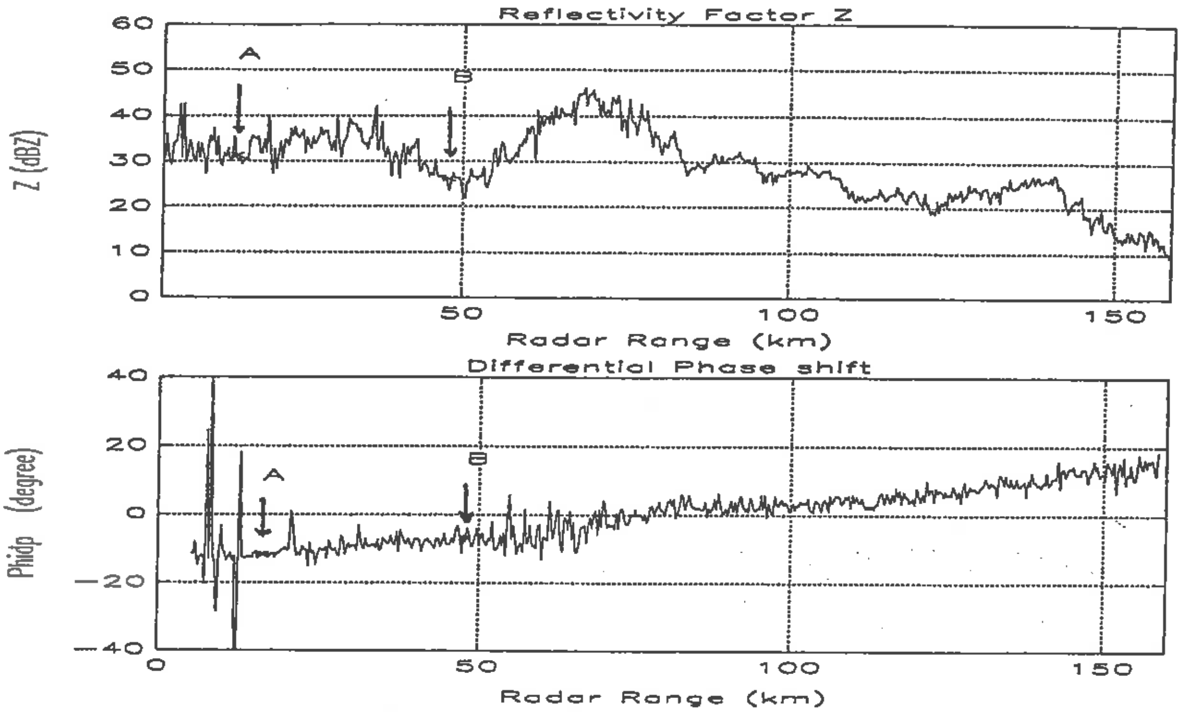

Figure 1. Ray profile of Z and K_{DP} with range for a 0.4 sec. dwell on 17/12/1991 at 22:44:43 UT, azimuth 370°, and elevation 0.5°. The gate spacing is 300m.

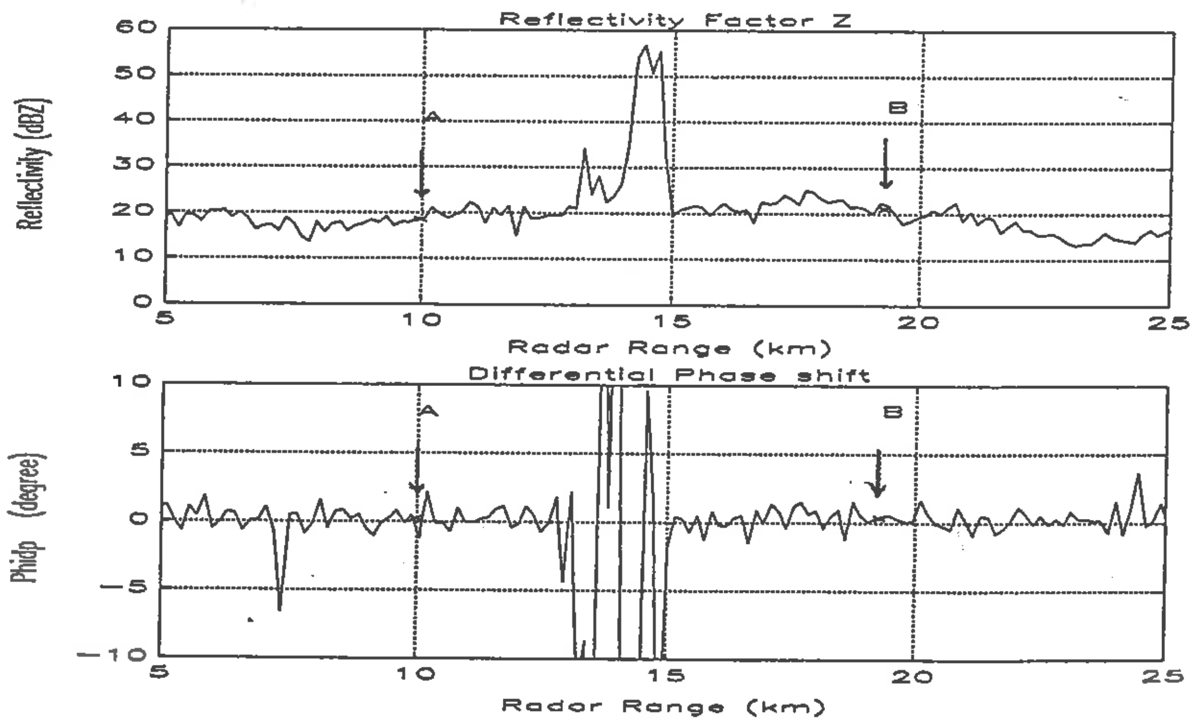

Figure 2. Ray profile of Z and K_{DP} for 0.4 sec dwell on 8/11/91 at 9:54:55 UT, azimuth 406°, and elevation 0.5°. The gate spacing is 75m.

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