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LOCAL VERTICAL PROFILE CORRECTIONS USING DATA FROM MULTIPLE SCAN ELEVATIONS

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1. INTRODUCTION

The variation of reflectivity with height is understood to be one of the most significant sources of error affecting the quantitative accuracy of surface precipitation rates derived from radar data, particularly at long range. The radar samples at increasing altitude with range and reflectivity measurements aloft require correction to account for the vertical profile of reflectivity (VPR) between the measurement height and the surface.

A new VPR correction scheme is described which aims to reduce bias errors at long range by deducing the observed VPR shape above the freezing level from reflectivity measurements at all available radar scan elevations.

The operational VPR correction method currently employed as part of the Met Office radar processing chain uses an iterative approach to fit an idealised reflectivity profile shape to data measured by the lowest usable elevation scan at each pixel (Kitchen et al 1994). Different idealised profile shapes are assumed if the sampled precipitation type is diagnosed as being associated with surface rain, graupel, snow or warm rain (Smyth and Illingworth 1998). The profile shape is constructed separately for each radar pixel using parameterisations of the bright-band and low-level orographic growth, model-derived values of the freezing level and satellite-derived cloud-top heights. The idealised profile applied to correct measurements of surface rainfall forming as ice aloft, termed the ‘bright band profile’ is illustrated in Fig 1.

In contrast to alternative VPR correction methods (e.g. Andrieu and Creutin 1995, Germann and Joss 2002, Koistinen et al 2004), this pixel-by-pixel approach using external data sources allows small-scale variations in the profile shape across the radar domain to be resolved.

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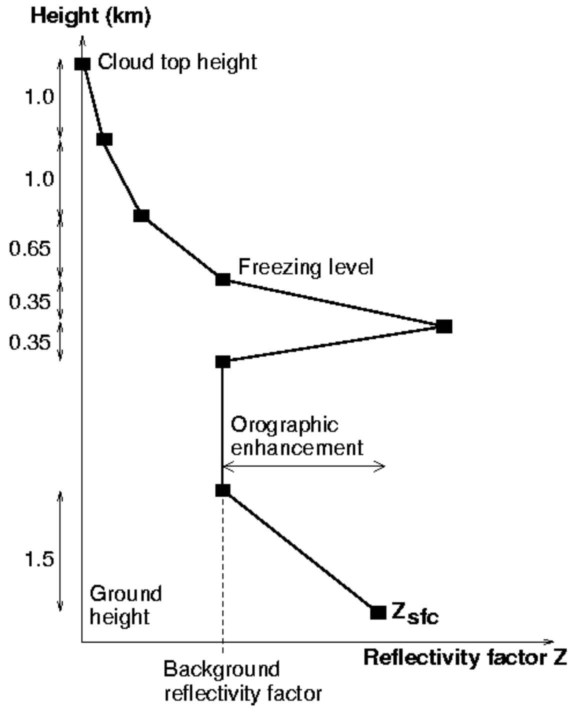

Figure 1. Idealised VPR used to correct radar data when a bright band profile is assumed (Kitchen et al 1994).

2. BRIGHT BAND PROFILE SHAPE

The idealised VPR with a bright band (Fig 1) is constructed assuming that the reflectivity of snow sampled above the bright band decreases with height at a rate of about 3.6 dBkm^{-1}. The reliance of the VPR correction scheme on a constant profile shape above the bright band, derived from observations by Kitchen et al (1994), may result in considerable bias errors at long range when the true observed profile deviates significantly from the assumed VPR.

Extensive measurements conducted by Fabry and Zawadski (1995) and Smyth and Illingworth (1998) suggest that the reflectivity of snow decreases on average by 6 to 7 dB in the first 1km above the freezing level. This is about twice the rate of decrease suggested by Kitchen et al (1994). While the operational VPR correction assumes the profile shape above the freezing level to be independent of reflectivity, Fabry and Zawadski (1995) also observed an increased gradient above the bright band with increasing measured reflectivity.

Observations by Kitchen (1997) showed reflectivity to decrease above the bright band by up to 35 $dBkm^{-1}$ but typically within a range between 0 and 15 $dBkm^{-1}$. Notably, the point-to-point scatter between the observed rates of decrease was almost as large as the total range of values observed. This indicates that it is also unrealistic to assume that the profile shape above the bright band is horizontally homogeneous across the radar domain.

The sensitivity of surface rainfall values derived using the operational VPR correction scheme to the assumed rate of reflectivity decrease above the bright band is illustrated in Fig 2. Significantly, Fig 2 shows that there is greater sensitivity to differences between smaller slope values around -3.6 $dBkm^{-1}$ than if considering the impact of changes between steeper slopes around -7 $dBkm^{-1}$. The potential error in the resulting surface rainfall rates is quantified in Table 1. If an equivalent rainfall rate of 1 mmh^{-1} were measured by the lowest usable radar scan at 250 km range, the corrected surface rainfall would be overestimated by 87% by assuming a constant profile slope of -3.6 $dBkm^{-1}$ when a slope of -1.6 $dBkm^{-1}$ was observed. Assuming the operational profile slope would result in a 36% underestimate of surface rainfall when a slope of -5.6 $dBkm^{-1}$ was observed.

Rainfall rate (mmh^{-1})	Slope above bright band ($dBkm^{-1}$)			
	-1.6	-5.6	-7.6	-9.6
0.5	+94%	-33%	-51%	-58%
1.0	+87%	-36%	-49%	-56%
5.0	+79%	-25%	-39%	-44%
10.0	+61%	-29%	-37%	-43%
20.0	+62%	-22%	-33%	-37%

Table 1. Percentage error in the surface rainfall estimates at maximum range derived assuming a profile slope value of -3.6 $dBkm^{-1}$ for different observed slope values and sampled rainfall rates. Values are computed for a freezing level at 2 km.

The sensitivity increases as the freezing level approaches the surface. For a freezing level height of 1 km overestimation of up to 132% results for an observed slope of -1.6 $dBkm^{-1}$ and underestimation by 56% results if a slope of -5.6 $dBkm^{-1}$ were observed.

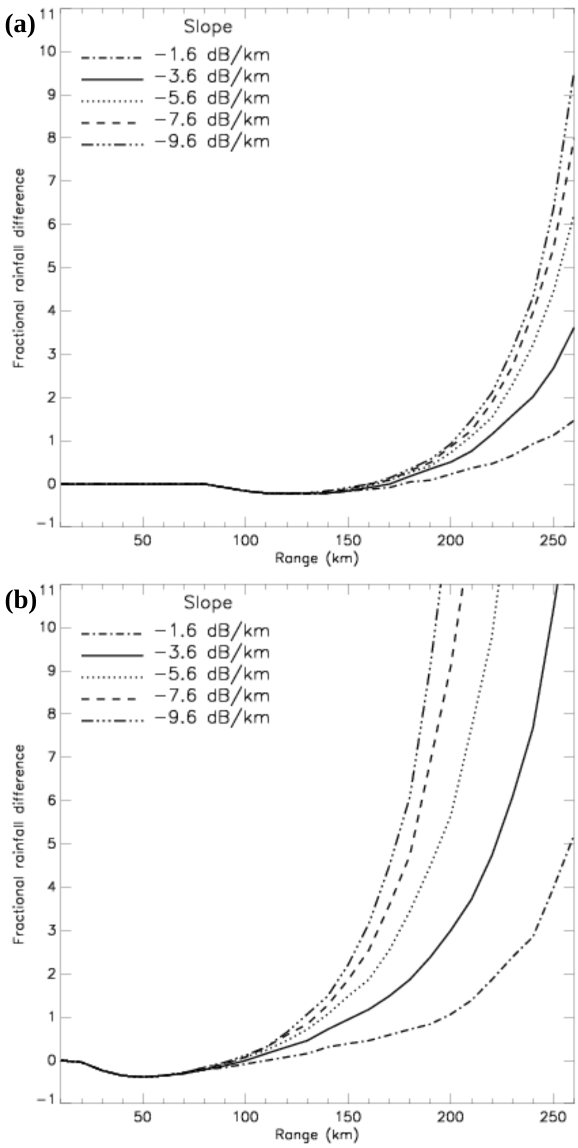

Figure 2. Fractional difference between the rainfall sampled by a radar scan (elevation 0.5°) and the corrected surface rainfall derived using the operational VPR correction scheme assuming different values for the profile slope above the bright band when the freezing level is at an altitude of (a) 2 km and (b) 1 km.

Even at a range of 150 km, relative errors in surface rainfall of up to 40% may result from assuming a constant profile slope of -3.6 $dBkm^{-1}$ when a different profile was observed.

3. MULTIPLE SCAN VPR CORRECTION

Correctly describing the rate of decrease of reflectivity with height above the bright band can therefore have a considerable impact on the quantitative accuracy of the corrected surface rainfall estimates at long range. A new VPR correction scheme has been developed to prescribe the observed profile shape above the bright band using radar data from multiple elevation scans. The method is based on assuming that the reflectivity expressed in dBZ decreases linearly with height and finding the best-fit line to reflectivity and height data measured by all radar scans.

3.1 Beam broadening

The simplest approach to derive the profile shape above the bright band from the measured reflectivity data is to treat the reflectivity values from different elevation scans as point measurements at different altitudes. This does not account for the effect of beam broadening and the finite sampling volume on the radar measurements. Rather, it must be assumed that the rate of decrease of reflectivity measured by a radar beam with power profile *f(ø)dø* given by,

$$Z_M = \int_{\alpha}^{\beta} Z(\phi) f(\phi) d\phi \qquad (1)$$

is representative of the rate of decrease of reflectivity *Z* between the freezing level and cloud top height.

Figure 3 illustrates the difference between an idealised bright band profile shape and the apparent VPR which would be obtained by a radar with 1° beamwidth sampling that profile at different elevation angles. The impact of beam broadening on the radar measurements is largest for the lower elevation scans, leading to about 3 dB under-prediction of the bright band intensity at close range (< 100 km) and up to 2 dB over-prediction of reflectivity values above the bright band at long range (> 100 km). Where the radar samples above the bright band at close range, there is good agreement between the idealised and measured reflectivity values as the beam width is relatively narrow.

Estimates of the gradient of reflectivity values between successive points in the idealised and measured profiles are also plotted in Fig 3. The results above the bright band calculated assuming the radar measures at 100 km range (Fig 3(a)) show the general trend for calculating a faster rate of decrease than observed using radar measurements below about 500 m above

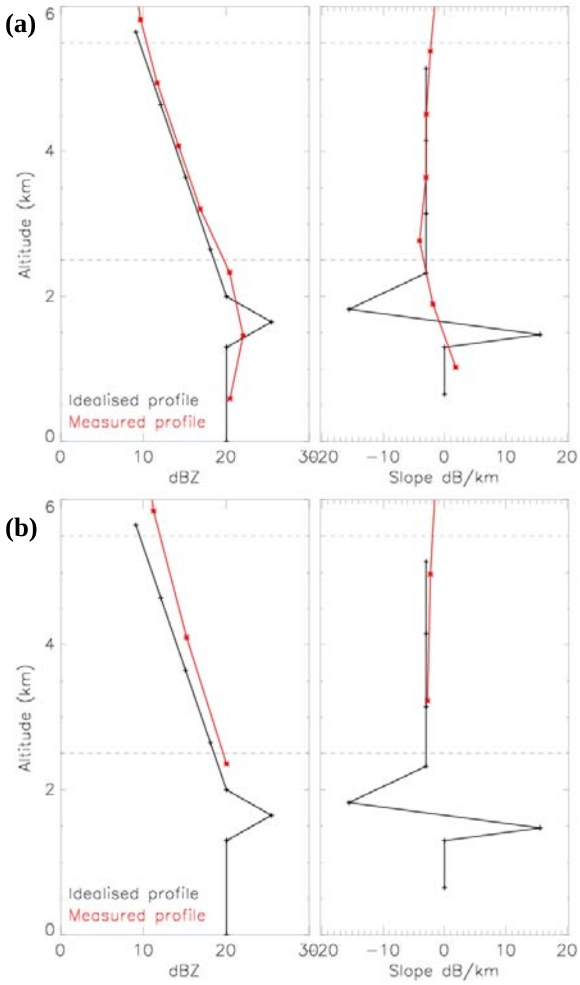

Figure 3. Comparison of an idealised VPR and the reflectivity measured by a radar with 1° beamwidth sampling that profile at elevation angles of between 0.0° and 4.0° in 0.5° increments at a range of (a) 100 km and (b) 200 km from the radar. Finite difference slope of the idealised and measured profiles between successive heights are plotted in $dBkm^{-1}$.

the freezing level and calculating a slower rate of decrease than observed using radar data above about 500 m below the assumed cloud top height.

The gradient values computed from reflectivity measurements within these height bounds show particularly good agreement with the idealised profile slope, even at long range where the measured reflectivity itself is several dB larger than the true reflectivity. These results show that the rate of change of reflectivity above the bright band measured by a radar is a reasonable approximation to the rate of change of the true VPR. Beam broadening does not have a significant impact on slope estimation.

3.2 Rainfall segmentation

An attempt to account for the spatial variability of profiles is made by considering the measured profile within distinct rainfall segments identified within a radar scan.

Continuous rainfall segments are identified using a recursive flood fill algorithm applied to reflectivity data from the lowest usable radar scan at each sampling volume, previously corrected for the effects of noise, clutter and anaprop (Harrison et al 2000). Figure 4 shows an example of the rainfall segments identified for a radar image.

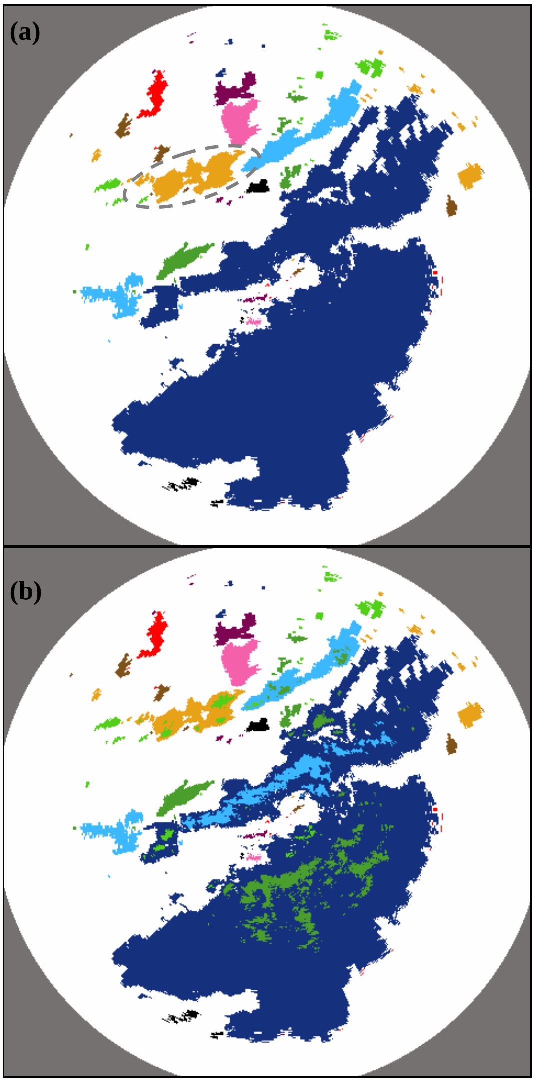

Figure 4. Rain segments derived from the lowest usable scan reflectivity measurements. (a) Results of the flood fill algorithm. Different colours represent the distinct segments identified. (b) Larger segments are divided into smaller regions using a method based on the Steiner (1995) criteria with a 30 dBZ threshold.

A lower limit on the size of a valid rainfall segment is set to be about 320 km^2. It is intended that some of the spatial variability of profile shapes within larger rainfall segments can be resolved by dividing those segments into smaller rainfall regions. Figure 3(b) illustrates the effect of applying a method based on the criteria developed by Steiner et al (1995). Regions where the reflectivity measured by the lowest usable scan exceeds the average reflectivity within the local continuous rain segment by more than a reflectivity-dependent difference or is greater than a 30 dBZ threshold are treated as new smaller rain areas.

3.3 Determining the profile shape

The multiple scan VPR correction method relies on the availability of sufficient data to derive a representative profile shape in each rainfall segment. It is also necessary that the best-fit slope is computed using only data with relevance to the local profile.

To limit the errors in the best-fit slope from reflectivity measurements below the bright band, only data within certain height range are included in the slope analysis. The analysis presented in Section 3.1 suggests that only reflectivity measurements from beam heights at least 500 m above the freezing level height and 500 m below the assumed profile top height should be included to reduce the influence of beam broadening on the derived profiles. This also allows some tolerance for errors in the prediction of the model freezing level height itself.

Figure 5 shows reflectivity measurements from radar scans between 500 m above the freezing level height and 500 m below cloud top from all available scan elevations sampling the continuous rainfall segment circled in Fig 4(a). The best-fit slope computed by a linear regression of all measured data has a value of -5.67 $dBkm^{-1}$ (correlation coefficient $r^2 = 0.39$). It is also possible to compute the gradient between reflectivity measurements from different elevations scans above each pixel. In this case, the average of all gradients in the segment is -7.36 $dBkm^{-1}$, suggesting a more rapid rate of decrease than the best-fit slope. This is because the spread of reflectivity and beam height data used to determine the best-fit slope within a particular rain segment may result in a poorly defined slope which is not very representative of the trend of the measurements. It is therefore necessary to normalise the data to improve the determination of the profile shape.

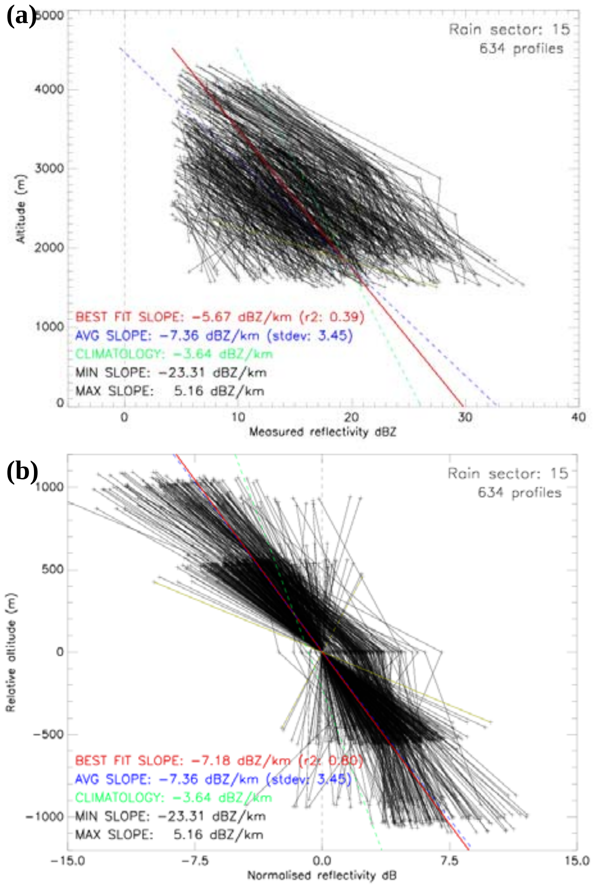

Figure 5. (a) Measured reflectivity profiles above the bright band within the rainfall segment circled in Fig 4. Profiles of data measured above the same horizontal location (i.e. radar pixel) are connected. (b) The data are normalised according to reflectivity and beam height. The red line shows the line of best-fit to the data, the blue line shows the average of gradients computed above each individual pixel in the segment.

Figure 5(b) shows the result of normalising both the height and reflectivity data by the subtracting the average measurement above each radar pixel. This leads to more representative best-fit slope values and a correlation coefficient which describes the consistency of the profile shape within the rainfall segment rather than the spread of the measured reflectivity or beam height values. Normalising the height data may lead to unrepresentative results if two or more sections of a profile are sampled at different locations within a rainfall segment and different profile slopes are observed at those different heights. The potential for deriving more representative profile slopes when the data are consistent and in cases when only one section of a profile is sampled by the available data suggests that it is desirable to normalise both reflectivity and height data in the majority of cases.

While the average of the gradients computed at each pixel in this case is well matched with the trend of the data, it is more appropriate to compute the best-fit profile to reduce the dependence of the calculation on individual profiles and the impact of errors such as wind drift. Note that the requirement to normalise the data to produce representative profile slopes does introduce some dependence of the method on consistent measurements between successive scan elevations at each location. In addition, this restricts the measurements suitable to use in the calculation to those data at locations where valid measurements are available from at least two different scan elevations.

The derived gradient of reflectivity with height γ is then applied to construct the idealised VPR profile at all heights h_+ located between the freezing level height and the cloud top for each pixel in that region.

$$dBZ(h_+) = dBZ(h_{0^oC}) + \gamma(h_+ - h_{0^oC}) \quad (2)$$

The multiple scan VPR correction method therefore applies a statistical approach to account for the observed profile slope above the bright band, but maintains the parameterised methods developed by Kitchen et al (1994) to enable a different profile to be defined for each sampling volume within the radar domain.

3.4 The need for non-local slopes

The spatial variability of the best-fit slopes and correlation coefficients computed for the example shown in Fig 4(b) are illustrated in Fig 6. Best-fit slopes range between -4.54 $dBkm^{-1}$ (r^2=0.75) and -9.07 $dBkm^{-1}$ (r^2=0.83). This example is typical in that there are several rainfall segments where a best-fit slope value cannot be derived using radar data within that segment. This may be because there are insufficient measurements from at least two different scan elevations within the height range of interest. Even if there are sufficient data to define a best-fit value, the measurements may be poorly described by a linear fit. In rainfall segments where the correlation is particularly low, below some defined threshold, it may prove necessary to adopt an alternative profile shape rather than assume that the derived profile slope is representative. The rainfall segments where a best-fit slope cannot be derived are shown in Fig 6(b) as regions with a correlation coefficient of 0.1 (blue segments).

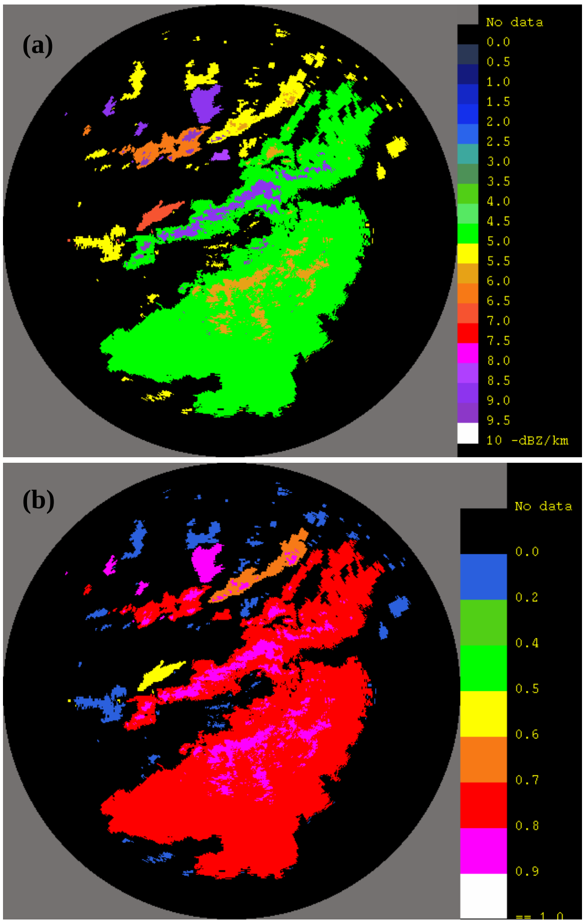

Figure 6. (a) Best-fit slope values in each rainfall segment identified in Fig 4(b). (b) Correlation coefficient r^2 for the best-fit slope in each segment. Regions where no local slope could be derived are shown with r^2=0.1.

The profile slope above the bright band in those segments where a local slope is not defined is prescribed by applying a scan-averaged slope value, weighted by the number of data points included and the correlation coefficient.

For cases when it is not possible to define a best-fit slope value in any sector, such as when the radar first detects a region of rainfall at long range after a dry period, the constant slope value used in the current operational scheme is used to correct the measured data. This is likely to introduce temporal discontinuities between radar images as a radar begins to detect a larger area of a rain band as it crosses into the radar domain. Alternative solutions are to be investigated.

3.5 Quality information

The parameters which result from the calculation of the best-fit slope in the multiple scan VPR correction method are potentially of great value to describe the quality of the resulting surface rainfall estimates. For example, the correlation coefficient for each rainfall segment indicates how much of the variability of profile shapes within that segment is represented by the best-fit slope. Surface rainfall estimates within segments where the correlation is high (r^2>0.9) are likely to be more accurate than in segments where there is a large variability of measured data and the best-fit slope is not well constrained.

Alternative data quality measures can be derived by assessing how well the idealised profile matches the measured data. Figure 7 compares the idealised profiles constructed using the current operational and multiple scan VPR correction methods with the reflectivity measurements within the rainfall segment circled in Fig 4(a). The bias and root mean square (RMS) statistics listed for each method in Fig 7 quantify the total error between measured reflectivity values from all available radar scans in the rainfall segment and the corresponding beam-weighted reflectivity derived from the idealised profile at that location (Equation 1).

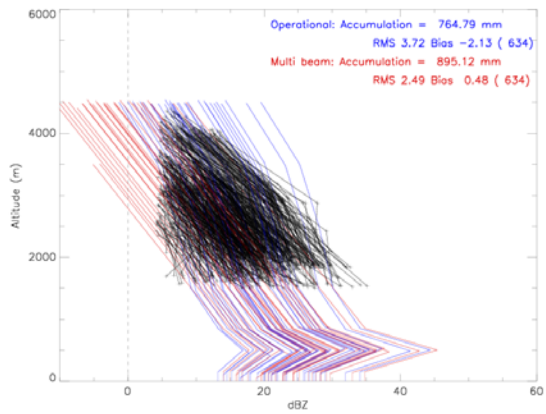

Figure 7. Available reflectivity measurements within the rainfall segment circled in Fig 4 and the idealised profiles constructed for each sampling volume using the current operational (blue) and multiple scan (red) VPR correction methods. RMS and bias statistics are computed from the difference between all reflectivity measurements and the corresponding beam-integrated reflectivity across the idealised profile.

The reduction of the RMS error from 3.7 to 2.5 quantifies the improved agreement between the reflectivity measured at all heights and the profiles generated using the observed reflectivity gradient above the bright band rather than using climatology. A bias of 0.48 shows that, on average, the idealised profiles generated by the multiple scan method correspond to slightly higher reflectivity values than measured. This information could contribute to an estimation of the quality of the derived surface rainfall estimates in this rainfall segment.

4. RESULTS

The multiple scan VPR correction algorithm has been running in a non-operational development mode to process data from one of the radars in the UK network since May 2007.

Figure 8 shows the number of distinct rainfall segments identified during a period of 12 consecutive days with rainfall within the radar domain. The local slope values computed for each of these sectors is also plotted along with the scan-averaged slope for each time-interval.

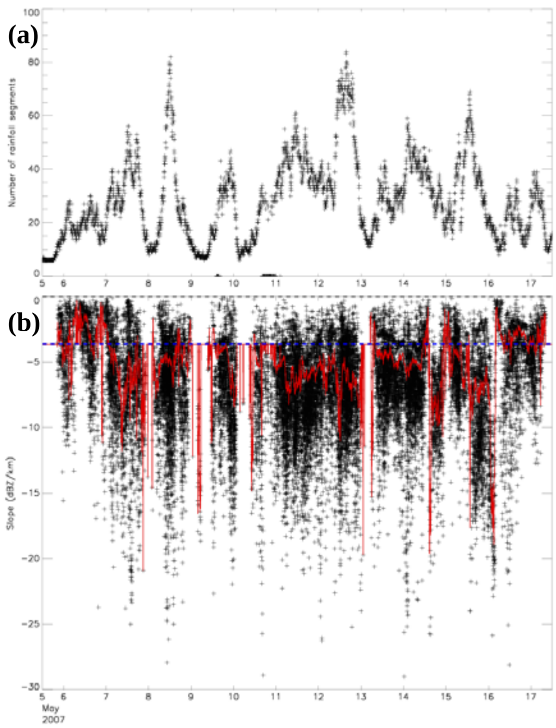

Figure 8. (a) Number of rainfall segments identified within the radar domain at each time interval. (b) Time series of the local slope value computed in each segment. The scan-averaged slope is plotted in red.

Results show slope values generally within a range between -1 dBkm^{-1} and -15 dBkm^{-1}, similar to the values observed by Kitchen (1997). The scan-averaged slope tends to be higher than the assumed climatology, with a mean value over the time shown of -5.0 dBkm^{-1}.

The quantitative accuracy of the results obtained using the multiple scan VPR correction algorithm is assessed by comparing hourly precipitation accumulations derived from corrected radar data with reports from co-located surface rain gauges. Figure 9 shows the variation of bias, RMS and root mean square factor (RMSF) statistics with range for comparisons between the radar data and measurements by 149 rain gauges across the radar domain over the period plotted in Fig 8.

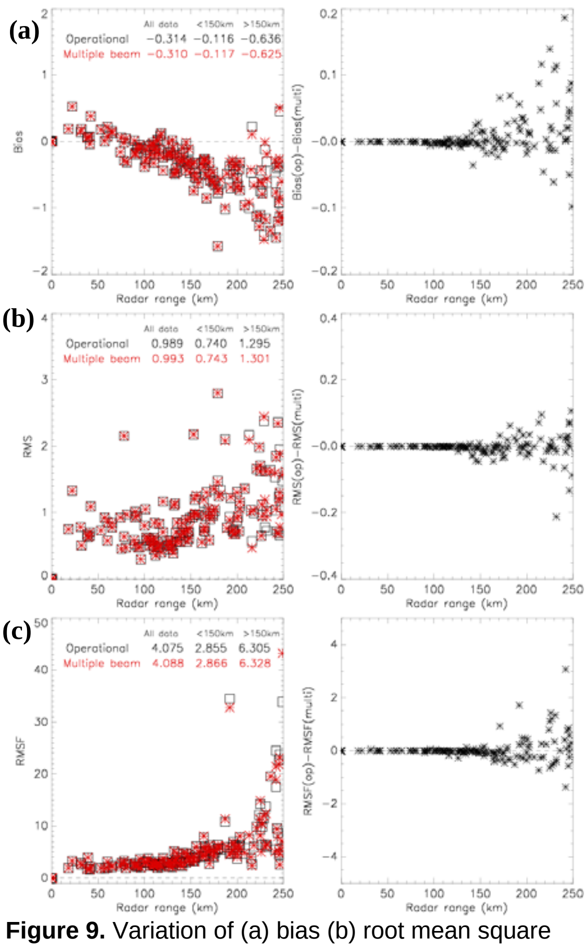

Figure 9. Variation of (a) bias (b) root mean square (RMS) and (c) root mean square factor (RMSF) statistics with range from the radar computed from differences between surface gauge measurements of hourly precipitation accumulations and radar data corrected using the operational (black) and multiple scan (red) VPR schemes. The difference between results obtained by each method is also plotted. Positive differences show the multiple scan method to perform better than current operational.

The results plotted in Fig 9 show that the multiple scan VPR correction method leads to a general reduction of the bias between gauges and radars compared with the current operational method at long range. The multiple scan VPR correction leads to reduced bias values at 46 of the 73 available gauges located more than 150 km from the radar site. In contrast, the RMS and RMSF statistics are improved by applying the multiple scan method at less than half of the available gauge locations. Computation of the RMSF gives a more robust measure of the agreement between the radar and gauge data, which is independent of the magnitude of rainfall measured.

5. CONCLUSIONS

A new VPR correction algorithm has been developed with the aim of improving the quantitative accuracy of radar-derived rainfall values at long range. The new algorithm uses radar data from multiple scan elevations to describe the reflectivity profile above the bright band, removing the dependence of the current operational method on climatology.

Preliminary results indicate that the application of the multiple scan VPR correction method has limited impact on the quantitative accuracy of the corrected surface rainfall estimates compared with the current operational method. While the idealised profiles applied to the data as part of the new method show substantially better agreement with the radar measurements from several elevation scans than climatology, there is variable impact on the resulting surface rainfall values.

A more extensive testing and evaluation period is proposed to assess the prospects for applying the multiple scan VPR correction scheme to improve the quantitative accuracy of surface rainfall estimates. It is hoped that its performance can be improved by optimising the tuning parameters used, such as the threshold minimum correlation coefficient for a valid local slope to be defined. Analysis of the performance of the new scheme during winter will be of particular benefit, when the freezing level is closer to the surface and the profile shape above the bright band affects the quantitative accuracy of surface rainfall values at closer range to the radar.

Testing the scheme over a longer period may also show the benefit of a multiple scan method for improving the value of applying a gauge adjustment scaling to the corrected rainfall data (Seo et al 1999). If capturing the spatial variability of profile shapes across the radar domain reduces the variability between radar and gauge rainfall values across the radar domain, the gauge adjustment scaling is likely be a more representative measure of the overall bias of a given radar.

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