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December 2000

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Summary: The Nimrod radar processing system applies a radar domain wide gauge adjustment factor to radar data in order to reduce biases in the radar data due to sensitivity problems and calibration errors. Some weaknesses have been identified in the scheme currently used and an investigation has been carried out into alternative methods based on a scheme developed under the NEXRAD program by the National Weather Service (NWS) in the US. This investigation has shown that the schemes based on the NEXRAD method are effective at reducing errors in the radar data, and perform significantly better than the current Nimrod scheme. The modified NEXRAD scheme is particularly effective at reducing errors in the radar data (the RMSf for all radars for 0-100km range is 2.28 compared with 2.36 from the Nimrod gauge adjustment scheme). It would be beneficial to Nimrod rainrate products if the modified NEXRAD scheme were implemented in place of the current Nimrod gauge adjustment scheme.

1. Introduction

Radar rainrate data is in general subject to several sources of systematic error, which can have a significant detrimental effect on the radar data quality. These systematic errors can arise from a number of sources such as calibration errors, and variations in radar sensitivity. The Nimrod radar processing scheme (Harrison *et al.* 2000) attempts to correct for these systematic errors by applying a radar domain wide adjustment factor derived from radar-raingauge comparisons. Other sources of error, such as bright band errors and orographic enhancement of rainfall, are dealt with within the Nimrod processing by physically based corrections. The scheme currently implemented in Nimrod for gauge adjustment, which has been in continuous use since January 1996, has proved to be useful in reducing radar bias errors, although until now no formal investigation into its effectiveness has been undertaken. Several weaknesses, such as an inability to respond to rapid changes in radar sensitivity, have been identified in the structure of the Nimrod scheme. Here we shall evaluate the performance of the Nimrod gauge adjustment scheme, and investigate several alternatives which should address some of the deficiencies in the Nimrod method. We shall see that the alternative methods, which are based on a scheme developed under the NEXRAD program at the NWS, are better at reducing errors in the radar data than the current Nimrod scheme. A modified version of the NEXRAD scheme is particularly effective at reducing the RMSf (root mean square factor), and in general, is the best of the schemes under consideration.

The results in this report are based on a parallel trial of the Nimrod, NEXRAD and modified NEXRAD schemes running from May–September 2000. The emphasis in the trial is on the typical performance of the schemes under operational conditions, rather than the performance under specific weather conditions. The trial was performed in real time, so similar performance can be expected under operational conditions.

2. Quality control of data

The gauge data used in this trial consists of several hundred rain gauges reporting hourly as SREWS. This corresponds to about 10–15 gauges within 100km of each radar. The gauge data was compared with hourly integrations of 5km radar data (available every 15 minutes) from the UK and Eire radar networks. In order to avoid range dependent errors affecting the gauge adjustment factors the comparisons used in calculating the gauge adjustment factors were made for data within 100km of the radar sites. An exception to this was made for the Jersey radar, due to the lack of gauge data near the radar, for which comparisons within 150km of the radar were used. We shall, however, make use of radar-gauge comparisons at all ranges in verifying the performance of the gauge adjustment schemes.

In order to make best use of the radar and gauge data it is necessary to apply some quality control to the data. Rain gauge data from gauges where the radar is subject to occlusion, frequent anaprop or clutter were excluded from the comparisons since the data is less reliable, and (in occluded areas) the probability of detection is low. Since the radar data gives rainrates every 15 minutes, and the raingauge data yields hourly accumulations some care is needed in comparing the data. The radar data is integrated over the hour, and it is required that radar data be available for most of the hour of the comparison.

The raingauges used in this trial consist of tipping bucket gauges with tip capacities of 0.2mm so a minimum threshold of 0.2mm is applied to the rain gauge data. For consistency with this thresholding, and to avoid problems associated with the radar measuring very low rainrates, the radar data is also thresholded at 0.2mm. This quality control should ensure that the radar-gauge comparisons are reliable, although there will still be large representativeness errors in the comparisons (these are essentially unavoidable, and will be considered to be random noise.)

3. Nimrod gauge adjustment scheme

The Nimrod gauge adjustment scheme (Hackett and Kitchen 1995; Harrison *et al*. 2000) calculates a radar domain wide adjustment factor on a weekly basis. Radar-gauge comparisons from the previous week are used to calculate a correction, m_i, to the previous adjustment factor given by

$$m_i = \frac{\sum G}{\sum R} \qquad (1)$$

where G and R are the gauge and radar rainfall respectively for each rainfall event. The sums are taken over all gauge-radar comparisons satisfying the quality control criteria of the previous section. The radar rainfall is given by the corrected rainfall subjected to the correction factor from the previous week. The updated correction factor, M_i is then given by the product of all previous m_i. It can be seen from the equation below that this can be written in an iteritive form allowing the scheme to be implemented in an extremely efficient way, which makes it suitable for operational use.

$$M_i = \prod_i m_i = M_{i-1} m_i \qquad (2)$$

The correction factor is only updated if it is considered that there is sufficient evidence for a change in adjustment factor. The uncertainty in *m* is estimated from the goodness of fit of a straight line of gradient *m* to the gauge-radar comparisons. If this uncertainty is greater than a specified amount ($\sigma_{max} = 0.17$) then the adjustment factor is left unchanged. The change to the adjustment factor is also subjected to a sensitivity test. If the change in adjustment factor in adjustment factor is less than σ_{max} the change to the adjustment factor is not considered to be significant. It is also required that at least 50 gauge-radar comparisons satisfying the criteria of section 2 be generated in the previous week before the gauge adjustment factor is updated.

This scheme has proved to be necessary and useful (see figure 1) in reducing bias errors in Nimrod radar data. However, there are several weaknesses inherent in the scheme. As a result of the adjustment factor being updated only on a weekly basis (or less often if there is little rainfall in previous weeks) the scheme is rather slow at responding to any changes in radar sensitivity. Even if there is strong evidence for a change in radar calibration or sensitivity the adjustment factor will not update for at least a week unless manual intervention occurs. Also, if a detrimental gauge adjustment factor is in use (this could possibly occur if a particular type of precipitation, such as drizzle, dominated in the previous week leading to a non-representative adjustment factor) then this will remain in use until at least a week has passed and sufficient evidence has accumulated for a change in adjustment factor.

A further problem is that it is not simple to obtain verification of the Nimrod gauge adjustment scheme using operational data, because the adjustment scheme is applied as part of the Nimrod VPR corrections. It is not possible to simply separate out the effects of the correction scheme and the gauge adjustment scheme. From a verification point of view it would be preferable if this were possible. The schemes discussed in the next two sections, based upon Seo et al.1999, address these problems.

4. NEXRAD adjustment scheme

The NEXRAD gauge adjustment scheme, Seo et al. 1999, updates gauge adjustment factors on an hourly basis. The scheme uses a Kalman filter which assumes a simple model of errors in the gauge and radar observations. It is assumed that the errors in readings at different sites (or pixels) and at different times are uncorrelated. the scheme also assumes that the errors in the radar observations are not correlated with the errors in the gauge reading. The errors are treated as zero-mean random noise about the mean gauge and radar rainrates, which are assumed to change only slowly. The Kalman filter then assumes that the best estimate (assuming the above observation model), at hour k, of the average gauge rainfall is provided by a linear combination of currently observed gauge rainfall, and the previous estimate of the mean gauge rainfall. The filter is similarly applied to the radar rainfall. The gauge adjustment factor is then taken to be the ratio of the estimates of gauge and radar mean rainfall,

$$\beta(k\mid k)=\frac{g_m(k\mid k)}{r_m(k\mid k)}, \qquad (3)$$

where $\beta(k|k)$ is the best estimate of the gauge adjustment factor at hour k, given available data up to hour k, and $g_m(k|k)$ and $r_m(k|k)$ are the best estimates of the mean gauge and radar rainfall respectively.

To estimate the mean gauge rainfall the Kalman filter minimises the following penalty function (in the sense of minimising the expectation value):

$$J(k)=\sum_{j=1}^{k} e^{[-(j-k)/\alpha]}\sum_{i=1}^{n(j)}\{g(j,u_i)-g_m(k)\}^2 \qquad (4)$$

where $g(j,u_i)$ is the gauge rainfall at site u_i and hour j, and $g_m(k)$ is the mean gauge rainfall. The best estimate of the mean gauge rainfall is then given by:

$$g_m(k\mid k)=\{1-w(k)\}g_m(k-1\mid k-1)+w(k)g_a(k) \qquad (5)$$

where

$$g_a(k\mid k)=\frac{1}{n(k)}\sum_{i=1}^{n(k)} g(k,u_i) \qquad (7)$$

and n(k) is the number of gauge-radar comparisons available at hour k. The weighting applied in the Kalman filter is given by

$$w(k)=n(k)p(k\mid k) \qquad (6)$$

where

$$p^{-1}(k\mid k)=\exp\{-(T_k-T_{k-1})/\alpha\}p^{-1}(k-1\mid k-1)+n(k) \qquad (8)$$

is essentially an age weighted number of gauge-radar comparisons available up to hour k, and T_k is the time (in hours) since the *k*th hour. The equations for estimating the mean radar rainfall are exactly analogous. α is a parameter relating to the size of the temporal window used in exponential smoothing of the data.

This scheme is sufficiently economical that it can be run with several time window sizes in parallel. The gauge adjustment factor can then be chosen from the set of adjustment factors that have been calculated according to some criterion. Following Seo et al. 1999 we shall require that the age weighted number of gauge-radar comparisons n(k) be greater than some cutoff, N_{cutoff}. This means that if there have been a sufficient number of recent gauge radar comparisons the scheme can respond rapidly to any changes in radar sensitivity. However, if only a small number of gauge-radar comparisons are available then the scheme will revert to using a long term adjustment factor. This should avoid the problems of the Nimrod gauge adjustment scheme.

One further difference between the NEXRAD scheme and the Nimrod scheme is that the NEXRAD gauge adjustment factor is applied after all other (physically based) corrections have been made to the radar data. This has advantages when evaluating the radar data, as it is then possible to separate out the effects of the gauge adjustment and the correction scheme.

A possible disadvantage of the NEXRAD scheme is that it estimates the gauge and radar average rainfall separately and then calculates the gauge adjustment factor from these estimates. One of the assumptions in this is that the spatial averages of the gauge and radar rainfalls do not change rapidly (with respect to the size of the temporal window). This assumption is not expected to be well met, at least for short time window sizes. Also, the penalty function is not directly related to errors in radar rainfall, although it would be expected that it would lead to a reduction in radar bias.

5. Modified NEXRAD adjustment scheme

As a result of the potential disadvantages of the NEXRAD scheme a modified version of this scheme was developed (Gibson 2000) which attempts to resolve these problems. In this scheme the penalty function

$$J(k) = \sum_{j=1}^{k} e^{[-(j-k)/\alpha]} \sum_{i=1}^{n(j)} \left\{ \log\left[\frac{g(j,u_i)}{r(j,u_i)}\right] - \log\left[\beta_m(k)\right] \right\}^2 \qquad (9)$$

is used to directly estimate the gauge adjustment factor, using a function which is closely related to the root mean square factor (RMSf) error statistic. Essentially the same assumptions are made for the error model as were made for the NEXRAD method. However, it should be noted that in this case it is assumed that the gauge adjustment factor is slow changing (compared with the assumption in the original scheme that the mean gauge and radar rainfall are slow changing). This should be a more realistic assumption.

The equations for this scheme are exactly analogous to the equations for the original NEXRAD scheme, and can be obtained by making the substitutions,

$$\begin{aligned} g_m(k \mid k) &\rightarrow \log\left[\beta_m(k \mid k)\right] \\ &= \{1 - w(k)\}\log\left[\beta_{\mathrm{m}}(k-1 \mid k-1)\right] + w(k)\log\left[\beta_a(k)\right] \end{aligned} \qquad (10)$$

and

$$g_a(k) \rightarrow \log\left[\beta_a(k)\right] = \frac{1}{n(k)} \sum \log\left[\frac{g(k,u_{i)}}{r(k,u_{i)}}\right]. \qquad (11)$$

The scheme is applied in the same way as the original NEXRAD scheme, with several values of α being used in parallel, and using the most appropriate adjustment factor according to a cutoff for n(k). The primary advantage of the modified NEXRAD scheme is that it should be more effective than either the Nimrod scheme or the NEXRAD scheme in reducing RMSf errors.

6. Results

The above schemes were run as a trial between May and September 2000. Preliminary results have previously been given in Gibson 2000, and this report provides complete results for the full trial period. In the operational Nimrod correction scheme the gauge adjustment is performed in conjunction with the physically based correction scheme. For this trial the correction scheme has been run twice; once including the Nimrod gauge adjustment, and once without gauge adjustment. We shall refer to the data from these two runs as Nimrod adjusted data and corrected data. Note that this differs from the usual terminology employed when discussing Nimrod data, in which corrected data usually refers to data with both gauge adjustment and physically based corrections applied. The NEXRAD and modified NEXRAD schemes have then been applied to the corrected radar data. The input data to the correction schemes have been subjected to the quality control measures discussed in section 2, as well as removal of clutter and anaprop, and will be referred to as quality controlled (QC) data.

The NEXRAD and modified NEXRAD schemes were both run using the set of values for the temporal window of α(hours) $\in$ [1,5,10,20,50,100,200,500,1000,2000]. A previous trial of the schemes using historical gauge-radar data suggested that a cut-off for the number of age-weighted gauge-radar pairs of n_{cutoff}=15-20 tended to yield the best results. Hence in this trial n_{cutoff} =15 was used for both schemes. In order to avoid potentially poorer performance by the NEXRAD based schemes during the startup of the schemes the first few weeks of the trial period were not used for evaluation puroposes (the Nimrod adjustment factors used were the operational adjustment factors, and hence were not subject to the same problem).

The statistics used to evaluate these schemes for this trial are mean gauge-radar bias, root mean square error (RMS), and root mean square factor (RMSf). The mean gauge-radar bias is defined as

$$\text{Bias} = \frac{1}{N}\sum(G-R) \tag{12}$$

where N is the number of gauge-radar pairs in the trial period (or month for a monthly bias), G and R are the gauge and radar rainfall respectively at a given hour. The sum is taken over all available gauge-radar pairs. The RMS is defined as

$$\text{RMS} = \left[\frac{1}{N}\sum(G-R)^2\right]^{1/2}. \tag{13}$$

The RMSf is defined as

$$\text{RMSf} = \exp\left\{\frac{1}{N}\sum\left[\ln\left(\frac{R}{G}\right)\right]^2\right\}^{1/2}. \tag{14}$$

RMSf is ill defined for rainfall (gauge or radar) of 0. However, as discussed in section 2, rainfall rates used are subject to a threshold of 0.2mm.

We shall place the most emphasis on the RMSf statistic because the bias and RMS are subject to some difficulties in interpretation. The primary problem with mean bias is that it is possible to have extremely small bias even if the scheme is performing very badly, as a result of accidental cancellations (*e.g.* the scheme could badly over-adjust the data for the first half of a month, and then badly under-correct the data for the second half of the month, but still have a small bias over the entire month.) This clearly means that bias alone is an insufficient indicator of the effectiveness of the adjustment schemes. Both the RMS and the mean bias are also un-normalised statistics and so the absolute value of them is dependent upon the rainfall during the period. This would mean that some months would contribute more than others, even if there there are the same number of (non-zero) rainfall events in the same period. The RMSf is, however, dependent only upon the ratio of gauge to radar rainfall and is thus not subject to this problem.

The trial was run for the 15 radars in the UK and Eire network. Data was subdivided into range bins, covering 0-50km, 50-100km, 100-150km, 150-200km to allow some examination of the effectiveness of the schemes at different ranges. Since the gauge adjustment factors are calculated using (for most of the radars) data from 0-100km only, it would be expected that the best results will be obtained at shorter range. At long range it would be likely that range effects will play a significant part. We shall see that this is indeed the case.

The RMSf and RMS taken over all of the radars and over the entire trial range are given in figures 2 and 3. For the RMSf it can be seen that at long range all of the gauge adjustment schemes have a neutral effect. This is presumably a result of range dependent effects dominating to the point where a radar domain wide adjustment factor is unable to lead to significant improvement. However, at short range the NEXRAD and modified NEXRAD schemes give a significant reduction in RMSf, with the better performance being produced by the modified scheme. This is consistent with the nature of the schemes, with the modified scheme minimising a penalty function related to the RMSf statistic. Similar results are given by the RMS statistic in figure 3, although the Nimrod gauge adjustment scheme has a detrimental effect between 100 and 150km. This contrasts with a marginal benefit from the Nimrod gauge adjustment scheme apparent in the RMSf at this range. The reasons for this discrepancy are not clear. Although not the primary purpose of this report it is interesting to note that the correction scheme leads to substantial benefits, particularly at long range.

It is not really appropriate to take the bias over all radars as cancellations between the biases of different radars will occur. Hence, we shall look at the root mean square of the biases for each of the radars *i.e.* if Bias_i= (Bias for radar i) then we have

$$\text{RMS(Bias)} = \frac{1}{N_{radars}} \sum_i (\text{Bias}_i)^2 . \tag{15}$$

This RMS(Bias) is plotted in figure 4, from which it can be seen that the NEXRAD and modified NEXRAD schemes are effective at reducing bias at all ranges, with the NEXRAD scheme being marginally better. The Nimrod scheme is significantly less successful at reducing gauge-radar bias at short range.

The benefits of the NEXRAD base scheme can clearly be seen in figure 5 which is a plot of radar versus gauge accumulation for the period of June 2000. The closer the gradient of the gauge-radar curves to having a gradient of one the better thethe scheme is performing. It can be seen that at the start of the period none of the gradient for all of the schemes differs significantly from one iimplying poor performance. However, the NEXRAD based schemes pick up on the bias early on with little bias during most of the period. In contrast the Nimrod scheme does not respond quickly to the large bias in the corrected radar data and continues to apply too small an adjustment factor for much of June, although it does eventually respond to the bias. This illustrates the primary advantage of the NEXRAD based schemes over the Nimrod gauge adjustment scheme.

An example of the gauge adjustment factor for the Ingham radar is shown in figure 6. The gauge adjustment factor is given for October 2000. It can be seen that there is some variation in the adjustment factor over relatively short timescales. This is likely to reflect the adjustment factor changing for particular precipitation types (e.g. drizzle) rather than due to instability in the radar calibration. During a period of precipitation the adjustment scheme will sometimes use a short term adjustment factor if there have been a sufficient number of gauge-radar comparisons. When there is a gap in the precipitation the adjustment factor will revert to using a longer time window. This prevents a detrimental adjustment factor (resulting from applying an adjustment factor based only on one type of precipitation) from being applied generally. Hence these short term changes in adjustment factor should not cause any problems.

7. Conclusions

The Nimrod, NEXRAD and modified NEXRAD schemes have been investigated in this report. A clear benefit, in terms of RMSf, RMS and bias, can be seen from the Kalman filter schemes when compared with the current Nimrod gauge adjustment scheme. The difference in effectiveness for the NEXRAD and modified NEXRAD schemes is less clear, with the modified NEXRAD scheme being slightly more effective at reducing RMSf, but marginally worse at reducing bias. As we consider the RMSf to be a more reliable statistic for evaluating performance we would recommend that the modified NEXRAD scheme be implemented in place of the current Nimrod gauge adjustment scheme.

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Harrison, D.L., Driscoll, S. J. and Kitchen, M.: Improving precipitaton estimates from weather radar using quality control and correction techniques. *Meteorol. Appl. 6, 135-144 (2000).*

Seo D.-J., Breidenbach J.P. and Johnson, E.R.: Real-time estimation of mean field bias in radar rainfall data. *Journal of Hydrology 223, 131-147 (1999).*

Appendix: Tables and figures

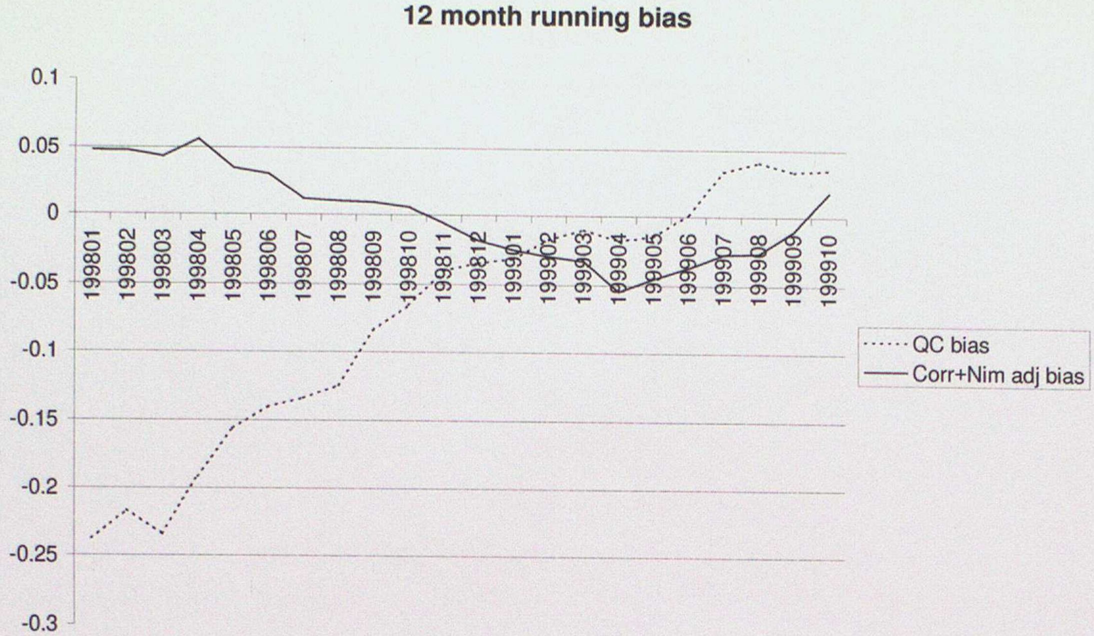

Figure 1: Long term running bias for QC and Nimrod adjusted radar data

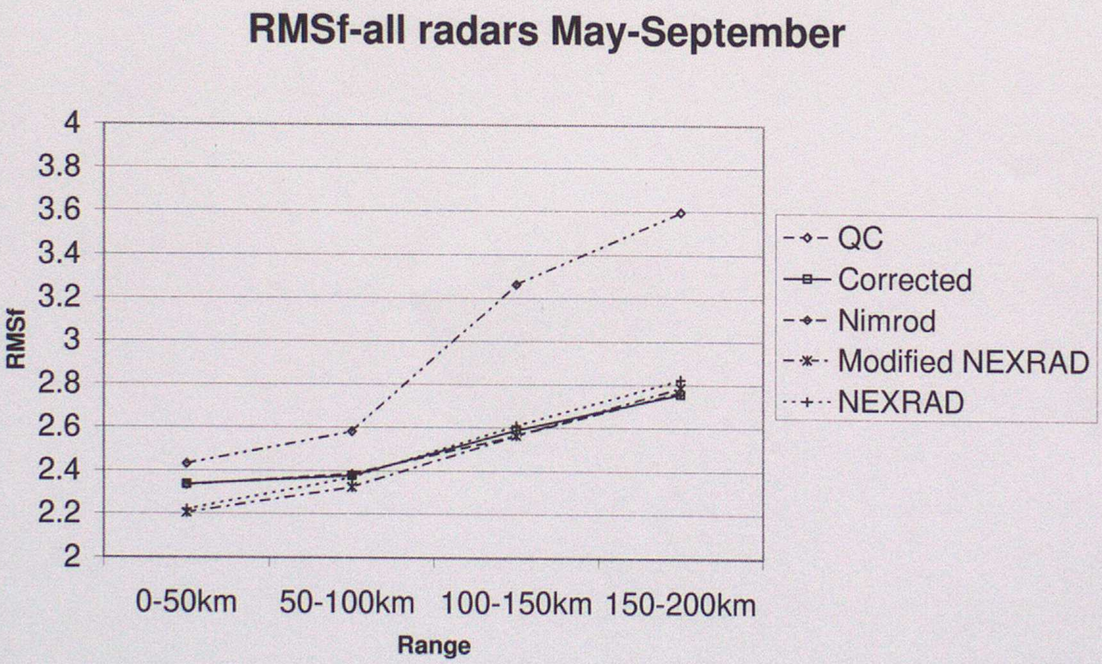

Figure 2: RMSf for 15 UK and Eire radars over trial period

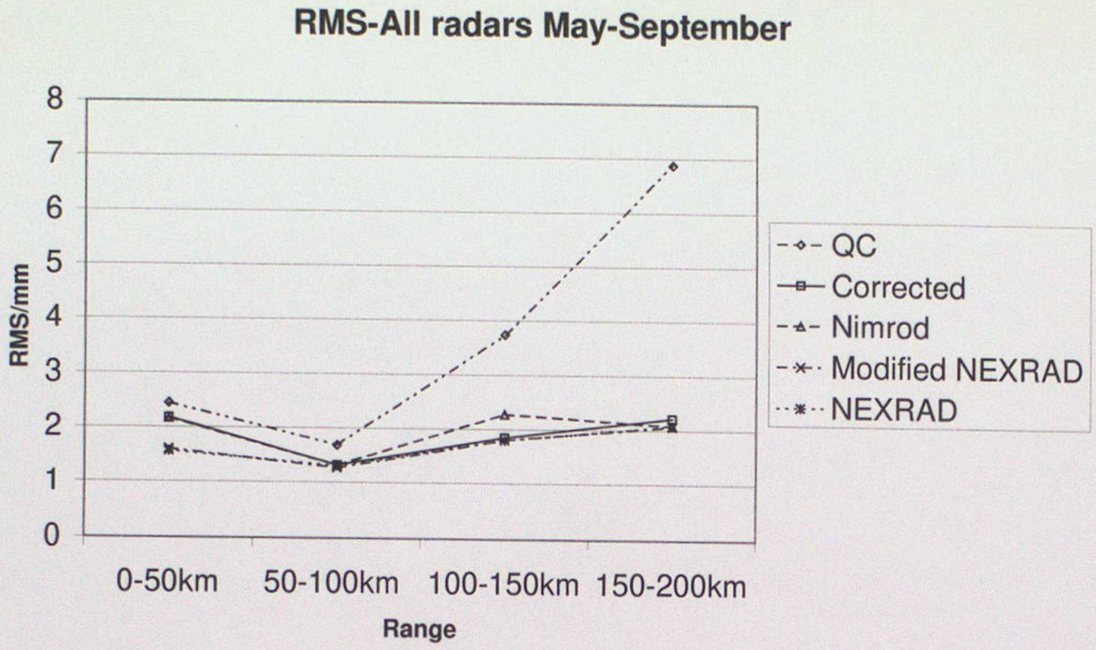

Figure 3: RMS for 15 UK and Eire radars over trial period

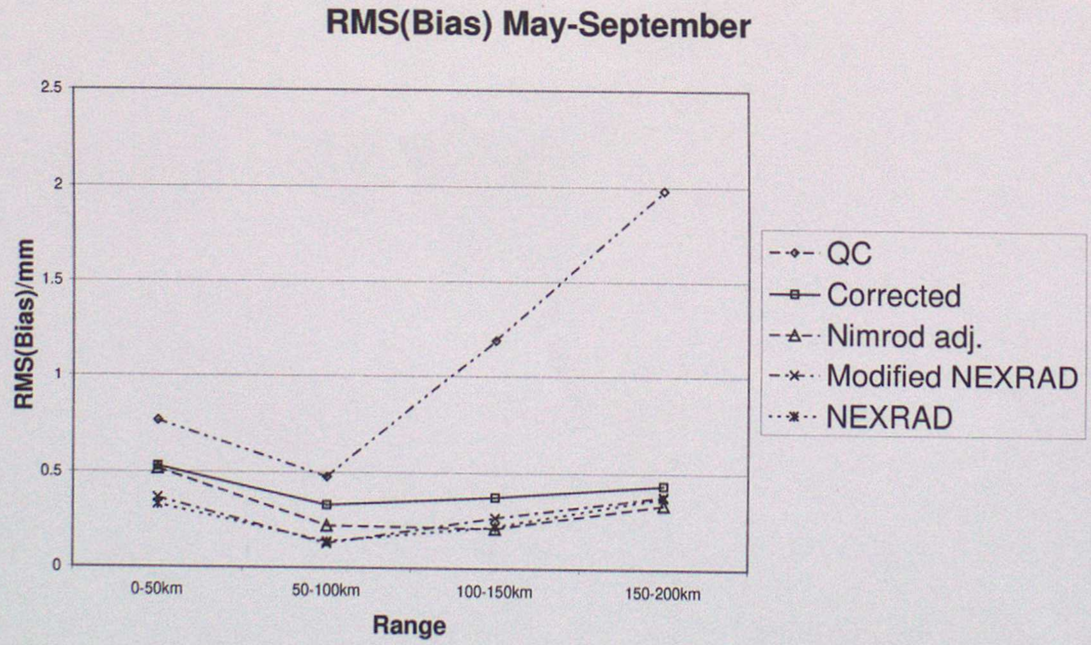

Figure 4: RMS(Bias) for 15 UK and Eire radars over trial period

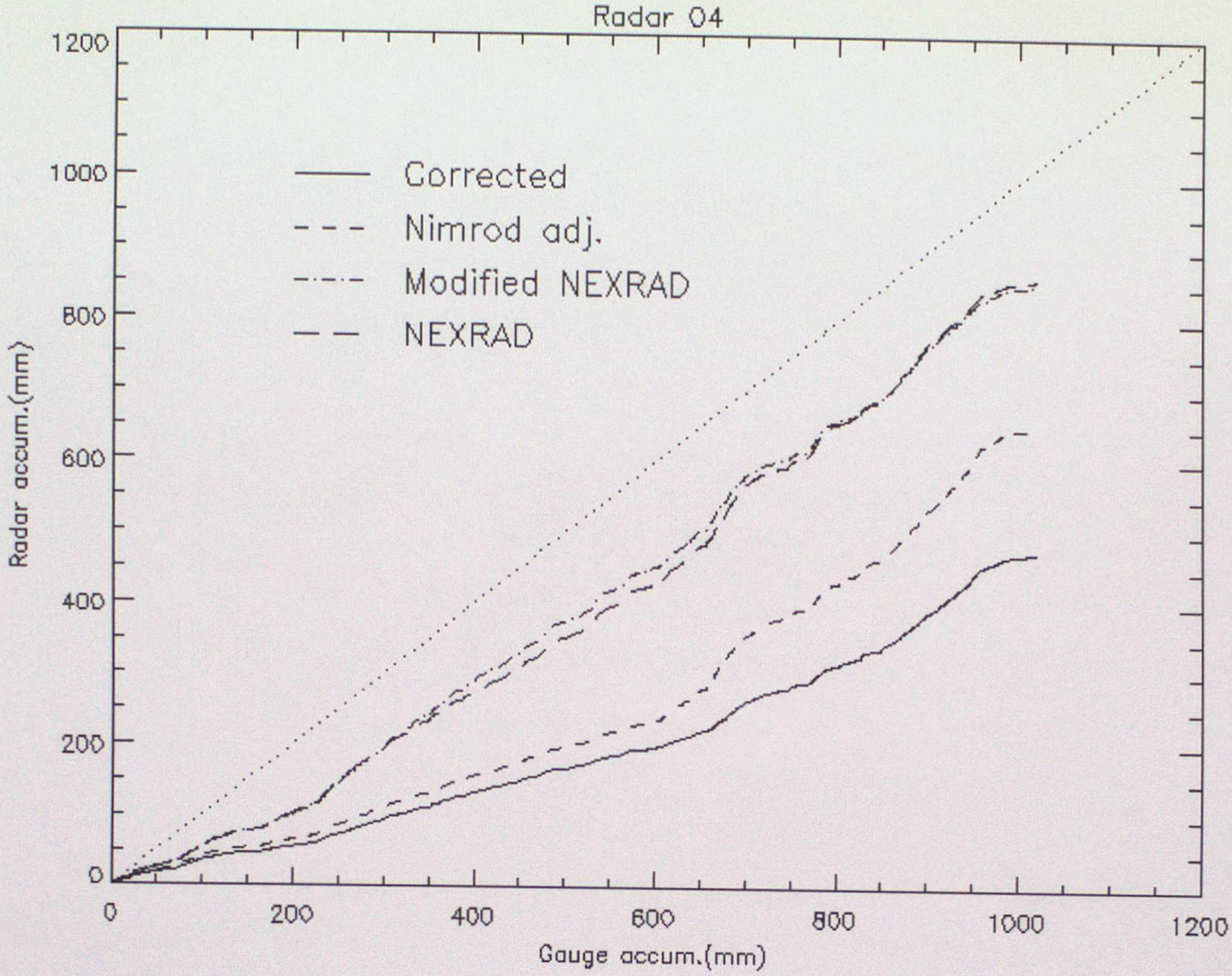

Figure 5: Radar vs. gauge rainfall accumulation for the Hameldon radar, June 2000.

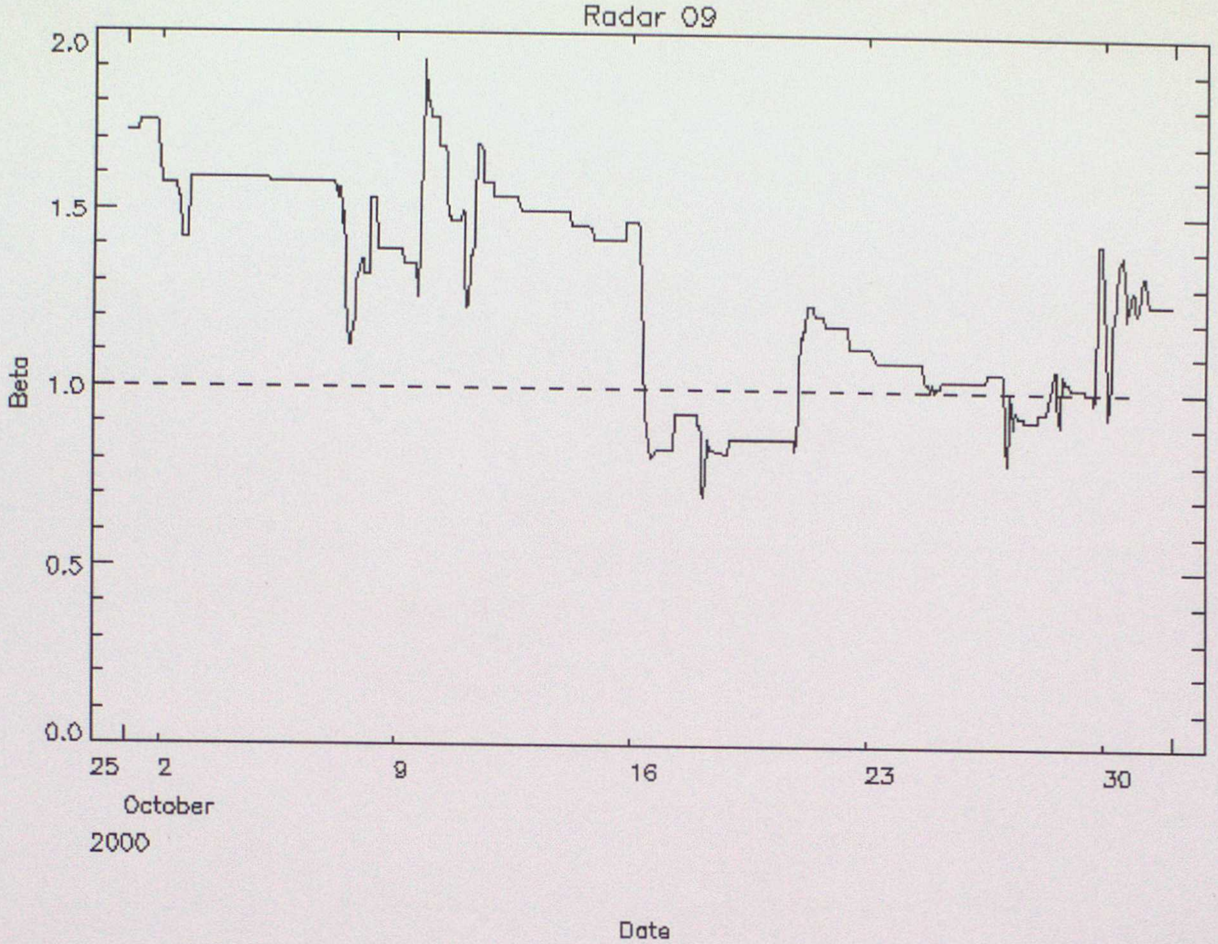

Figure 6: Gauge adjustment factor for Ingham radar using modified NEXRAD scheme for October 2000