AN IMPROVED ADAPTIVE CALIBRATION TECHNIQUE FOR WEATHER RADAR

CRES, LANCASTER UNIVERSITY

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An Improved Adaptive Calibration Technique For Weather Radar

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1. INTRODUCTION

The main objective of NRA research project 315/ST, (1991-1994) has been the development of an improved method of final stage raingauge calibration of weather radar which can be used for the real-time adjustment of the radar rainfall estimates. This development is designed to replace the current operational Collier-Larke calibration technique outlined in Appendix A. Theoretical aspects of radar meteorology are to be found in Interim Report 315 / 7 / ST. The research has concentrated on data from Hameldon Hill weather radar in the North West of England, one of the conventional 'C' band radars in the UK weather radar network.

The Adaptive Radar Calibration (ARC) System we developed in the project operates on default calibrated, 2 km pixel resolution radar data from the complete 75 km range of Hameldon Hill Radar. The ARC System utilises both image processing techniques and adaptive calibration using raingauge information in order to provide real-time adjustment of the radar data. It operates on a fifteen minute time resolution, i.e. calibration model parameter values are re-estimated at the end of every fifteen minute period from the latest calibration raingauge data and image processed radar data. Calibration of the radar data over the subsequent fifteen minute period first entails the image pre-processing stages, followed by the application of a calibration parameter surface generated from the latest, adaptively updated calibration model parameters.

The ARC System has been developed and fully evaluated as a real-time simulation using archived raingauge and radar data from selected rainfall 'events' that are representative of the weather patterns observed by the Hameldon Hill radar system. A brief description of the meteorological situation for each rainfall event is given in Appendix B. Finally, the quality of the ARC calibration has been assessed statistically using data from a network of independent raingauges sited throughout the radar area.

It has been found for all the rainfall events studied that following ARC calibration the accuracy of the radar rainfall estimates is greatly improved when compared with independent tipping bucket raingauge measurements from throughout the radar region. The improvements which are observed over both the default calibrated and Collier-Larke domain calibrated radar data are assessed according to two criteria which assess the short term and long term calibration performance.

2. THE ADAPTIVE RADAR CALIBRATION (ARC) SYSTEM

The ARC System shown diagramatically in Figure 2.1 operates upon default calibrated radar rainfall intensity data from the Hameldon Hill radar. These data are from the surface beam, a combination of the radar beams of elevation 0.5 and 1.5 degrees, over the complete range of 75km. Rainfall intensity data are obtained for the whole radar area once every five minutes at a 2km grid square ('pixel') resolution and 8 bit precision. The ARC System operates on a time resolution of fifteen minutes, so that each default calibrated radar image is the mean of three successive radar scans made at five minute intervals. Tipping bucket raingauge accumulations, received every quarter hour from a network of on-line calibration raingauges, are used for the adaptive calibration. The number and location of raingauges in this network has also been the subject of research as discussed later in sections 2.2.1 and 4.2.

The ARC System consists of the following three main phases of image and data processing (where the numbers in parenthesis refer to subsequent sub-sections which discuss the item in question),

- Image processing provides automatic adjustment for the most significant anomalous geometrical patterns present in each radar image: occultation anomalies (2.1.1); cluttered pixels (2.1.2); range and bright band effects (2.1.3); and errors in the estimation of rainfall at short range (2.1.4). The area of the radar image indicating rainfall is then stored and retained for later use (2.1.5)

- Adaptive estimates of the calibration parameters are derived for sites corresponding to the locations of tipping bucket raingauges for which rainfall intensity data are available in real-time (2.2.1). Adaptive calibration of the radar image is then performed using an interpolated parameter surface generated from the point calibration parameter estimates (2.2.2).

- Final adaptive bias adjustment (2.3) minimises any remaining long term bias in the radar rainfall intensity image after all the above calibration stages have been performed.

Flow Chart of ARC System

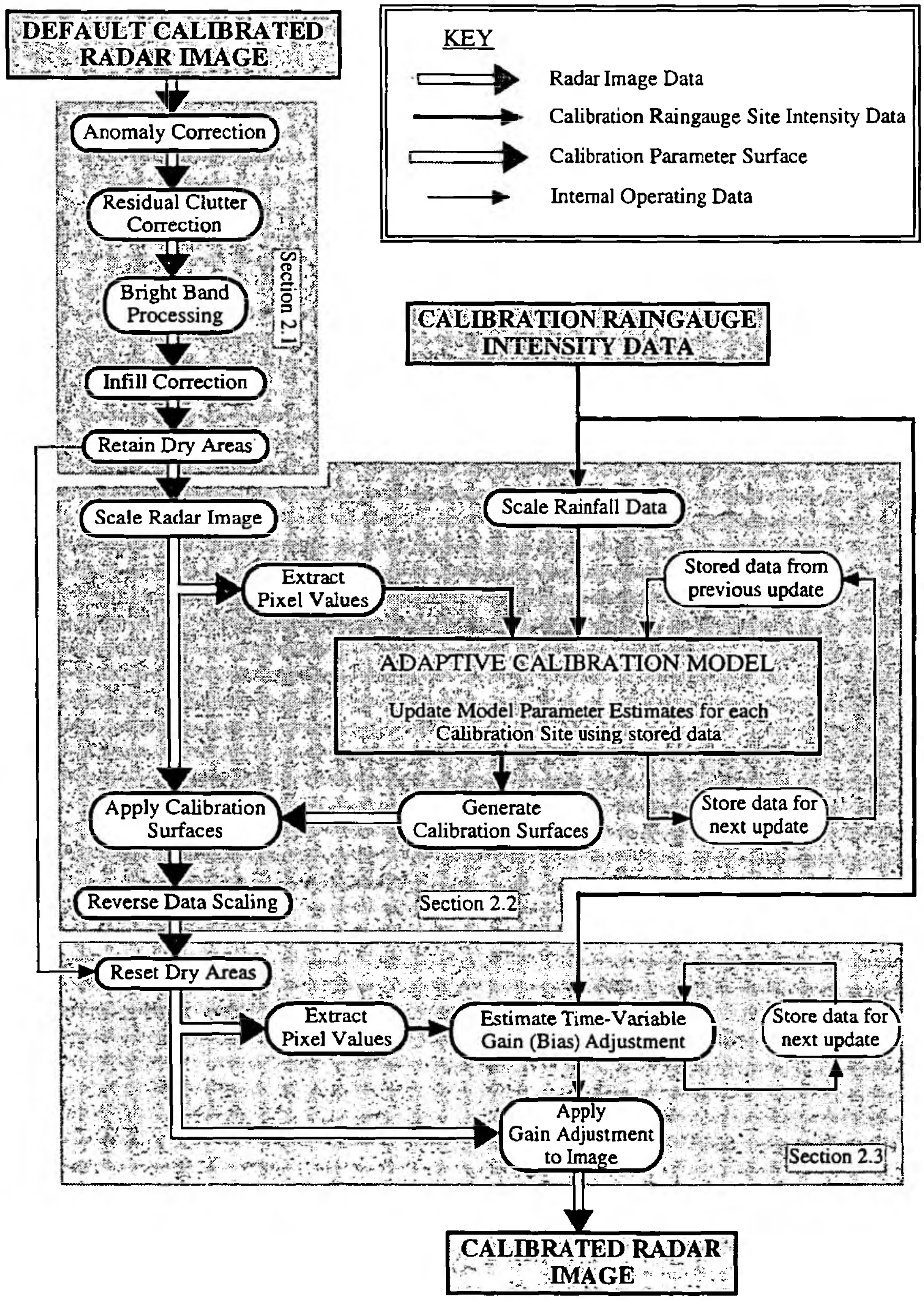

Figure 2.1

2.1 Image Processing

During the course of the research project, the nature of numerous geometrical anomalies on the default calibrated radar images has become obvious, as shown in Fig. 2.2, where radial and concentric anomalies are clearly visible. The visualisation of some of the more transient anomalies was made possible using advanced display software designed by Jim Mann in CRES (Mann, 1993) in connection with related CEC funded research. Others are revealed when the radar data are averaged over a long period of time. All of these anomalies are caused by the inherent problems associated with radar echo measurements and their subsequent conversion to rainfall intensity estimates. The problems caused by the presence of these anomalies have been overcome by introducing a set of radar image pre-processing stages in the analysis, prior to application of the adaptive calibration procedure. The stages of pre-processing as outlined below, are carried out sequentially on each default calibrated image.

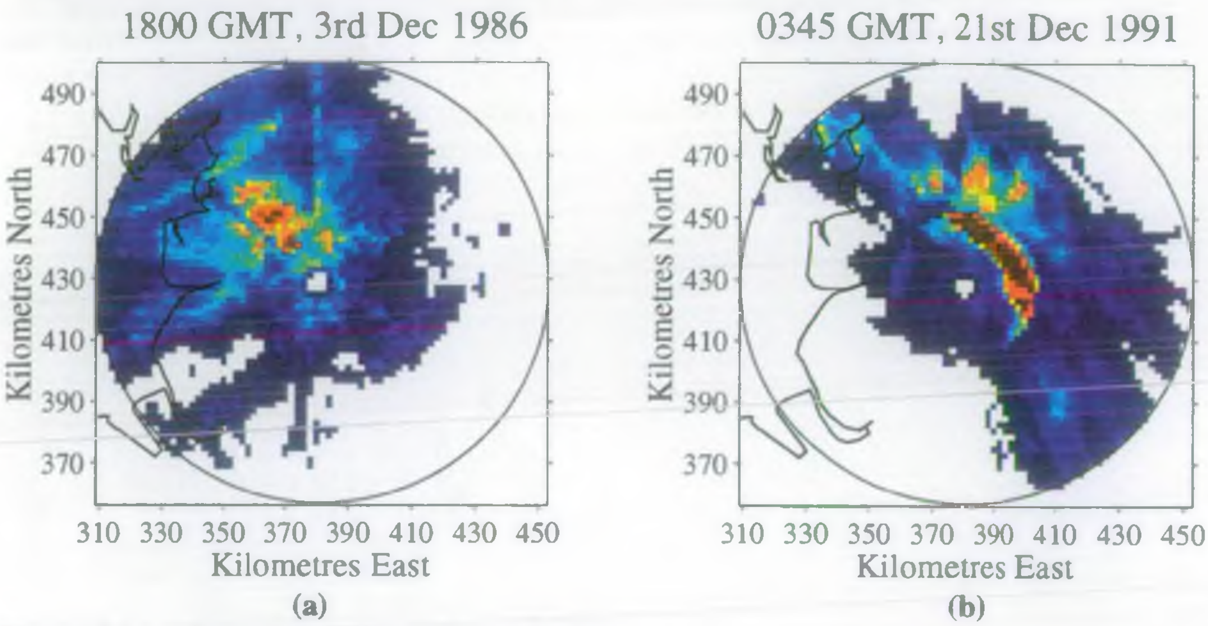

Figure 2.2 Default Calibrated Radar Images

2.1.1 Correction for occultation anomalies. Static radial errors exist in the radar images due to imperfect default correction for partial obstruction to the radar beam (occultation). The anomaly correction technique applies a fixed multiplicative correction to remedy the effect of the two worst artificial distortions, one to the north and one to the north-west of the radar caused by Pendle Hill and a transmitter mast respectively (Figure 2.2a).

2.1.2 Residual Clutter correction. A few pixels suffering from clutter often exist in each default calibrated radar image. The siting of these pixels is essentially random but they generally occur within certain specific regions of the image. An automatic processing routine has been developed to detect these cluttered pixels within the radar image, remove them and interpolate replacement rainfall intensity values from the surrounding unaffected radar pixels using an inverse distance weighting.

2.1.3 Processing for Bright band and range effects. The 'bright-band' effect causes highly overestimated radar rainfall intensity within the melting layer (where ice crystals melt to form rain drops) and underestimated rainfall intensity above the melting layer. Because the radar emits an inclined beam and the melting layer is approximately horizontal, radar rainfall estimation errors caused by bright band generally appear arcate in form within the affected radar image (Figure 2.2b). Bright-band together with imperfect beam attenuation correction and an increasing tendency for the radar beam to overshoot rainfall systems at longer ranges, cause a complex pattern of errors which are all related to the *range* from the radar. In any one radar image, one or more of these error sources may cause significant errors in the radar rainfall estimates. Within the ARC System, an automatic routine using image processing techniques has been developed to adjust each radar image for these combined range effects. This technique is described in some detail in the Second Interim Report 315 / 11 / ST.

2.1.4 Interpolation of short range data. The radar is unable to reliably estimate rainfall intensity over the shortest ranges (from 0 to about 6 km range), so data from the central area of each image are discarded and replaced, using intensity values interpolated from the surrounding radar rainfall pixel data. Figure 2.3 demonstrates the success of this procedure. This is a typical time-series plot of the raingauge rainfall intensity at Loveclough (1.2 km from the radar antenna), together with the corresponding radar pixel rainfall intensity estimate both before and after the ARC calibration.

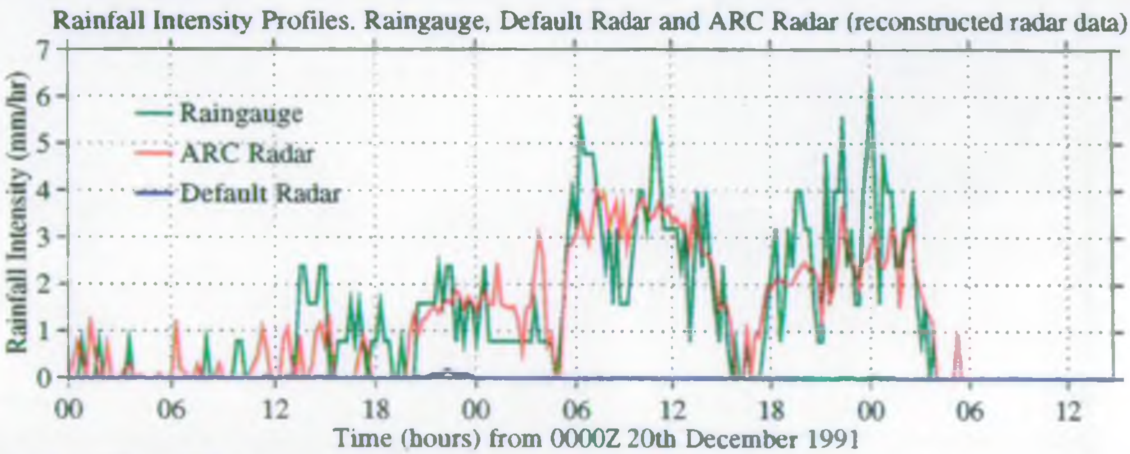

Figure 2.3 Rainfall intensity estimates close to the radar site.

2.1.5 Retain Dry Regions In Image. Here, a map of radar pixels that have no rain and those which have some radar rainfall intensity is constructed. Processing is carried out on the map to filter out isolated non-dry radar pixels within dry regions of the radar image. This is an effective means of reducing the noise level in the radar image without significantly affecting the extent of the measured radar rainfall. This technique is described in detail in the Second Interim Report. The resulting map is retained until after the adaptive raingauge calibration, when it is used as a mask to ensure all pixels that were previously dry are reset to zero. This is in recognition that the radar is usually very accurate in measuring the *extent* of a rainfall area.

2.2 Adaptive Raingauge Calibration

Following the application of the above image processing stages, the radar intensity data are less affected by range dependent, random and static error sources, so that the radar image is in a more suitable form for the application of the adaptive calibration procedure. In particular, adaptive updates of the calibration parameters are more likely to be due to real changes in the calibration relationship and less likely to be caused by image aberrations.

A number of different calibration models have been evaluated in the project (see First Interim Report, 315 / 7 / ST) but the following relationship was found to provide the best overall performance;

$$\gamma + \delta . CRr_{(k)} = \hat{A}_{(k-1)} . \{\gamma + \delta . Rr_{(k)}\}$$

where $CRr_{(k)}$ and $Rr_{(k)}$ are the ARC calibrated and default calibrated radar (after image processing) rainfall intensities respectively during the (k)th quarter hour, γ and δ are data scaling factors, and $\hat{A}_{(k-1)}$ is the estimate of the calibration parameter, A, made at the end of the previous, $(k - 1)$th, quarter hour.

As soon as each radar image is received, the image processing stages are performed and the pre-processed image then calibrated according to the relationship above. The calibration parameter surface used is generated from the calibration parameter estimates for each of the calibration raingauge sites (see subsection 2.2.2) from the previous quarter hour. Subsequently, rainfall data from each of the remote calibration raingauges is collected and compared with the single pixel radar rainfall intensity values for the geographical points corresponding to these sites from within the calibrated radar image. The difference between the two estimates is used to update the calibration parameter at that site.

2.2.1 Calibration Parameter Estimation. The adaptive calibration model produces recursive estimates of the calibration parameter, $\hat{A}$, every quarter hour for each of a set of remote calibration raingauge sites. At the end of the quarter hour period the parameter estimates at each site are recursively updated using the information provided by the difference between the calibrated radar, $CRr_{(k)}$, and the calibration raingauge, $G_{(k)}$, rainfall intensity estimates. In effect, the recursive estimation uses an exponential weighting into the past (memory) such that the parameter estimate returned at any particular time is dependent on all the previous radar and raingauge intensity data at that site, with the most recent data given the greatest weighting. In this manner, a smoothly changing estimate of the calibration parameter is obtained for each calibration raingauge location: this estimate reflects previous changes in the parameter and avoids rapid fluctuations caused by inevitable noise effects in the data.

This adaptive approach to estimation is based on recursive estimation techniques developed in CRES over the past few years (Young, 1984) and used successfully in numerous other practical applications (Lees et al., 1994). A complete description of these recursive parameter estimation techniques is given in the First Interim Report on this project, 315 / 7 / ST.

2.2.2 Calibration Surface Generation. Following the recursive update made to the parameter estimate at each site, the parameter estimates from all the calibration sites are used to derive a calibration parameter surface. This surface is used to calibrate the pre-processed radar image obtained at the end of the next fifteen minute period. Several different techniques for generating the calibration surface have been explored, as discussed in the Second Interim Report, 315 / 11 / ST, however, the most suitable interpolation method found so far is based on an inverse distance weighting of the calibration site parameter estimates. Here, the parameter value at each pixel in the radar area is generated from a weighting of each calibration site's parameter value. The weightings are calculated as the inverse of the distance from that point to each calibration site. Thus, at the calibration sites themselves, the greatest weighting is given to the local parameter value, while the weighted parameter estimates regress towards the mean of all the point estimates in the network at locations far from the calibration sites. This approach avoids the domain based anomalies which can be seen on the images generated by the Collier-Larke technique.

The surface generation technique uses parameter estimates derived using raingauge data from a network of remote calibration raingauge sites. In this research programme, the number of calibration raingauges used has been as few as five, but the quality of the calibration has been found to improve greatly if the number is increased to about ten or twelve raingauges (see later, Section 4.2). The network of five calibration gauges is identical to that used for the current Collier-Larke, final stage, raingauge calibration technique (Appendix A). The various extensions we have made to this network are shown in Figure 2.4: each of these networks has been used to perform adaptive calibration and the comparative results are discussed later in Section 4.

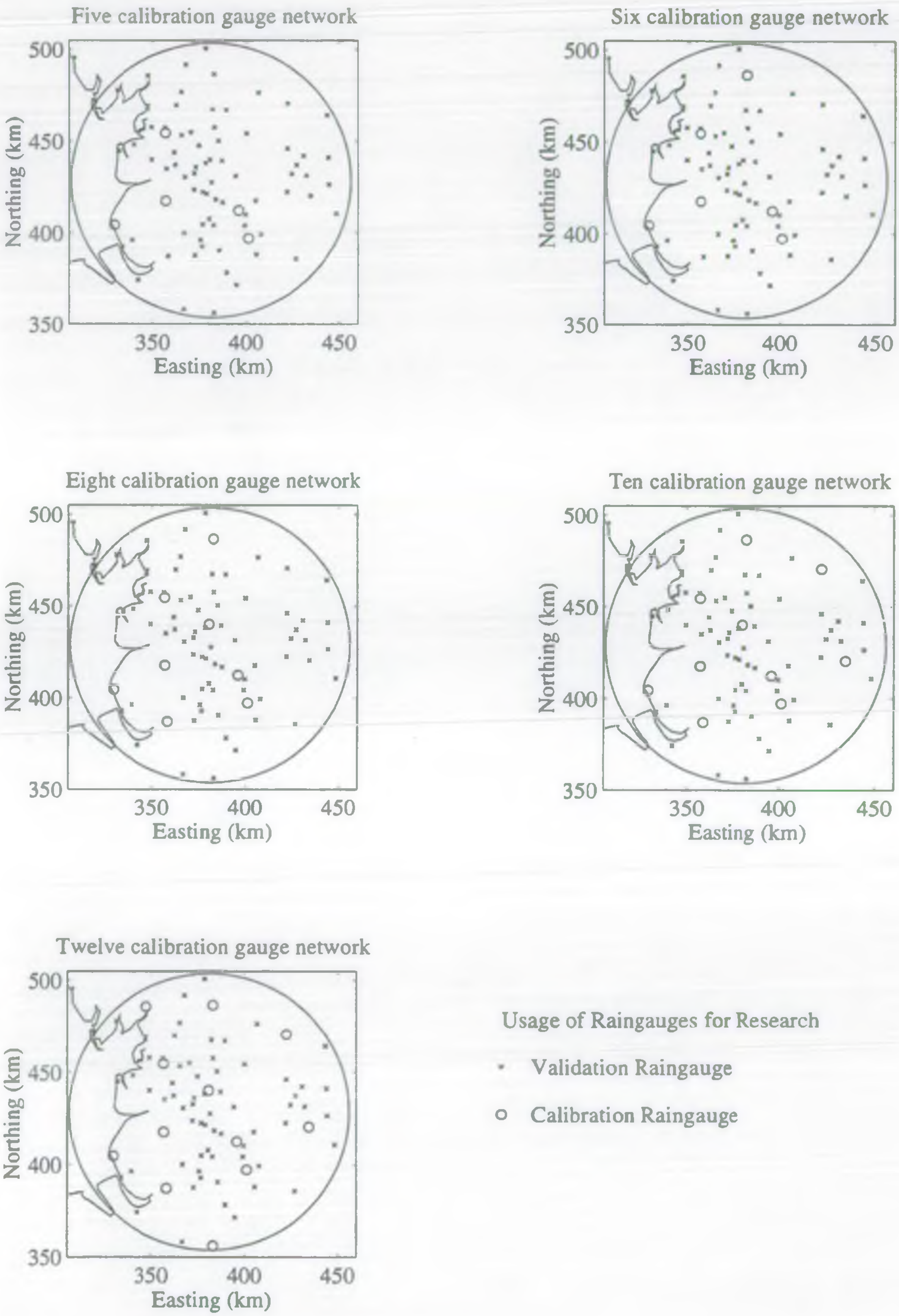

Figure 2.4 Experimental Calibration Raingauge Networks

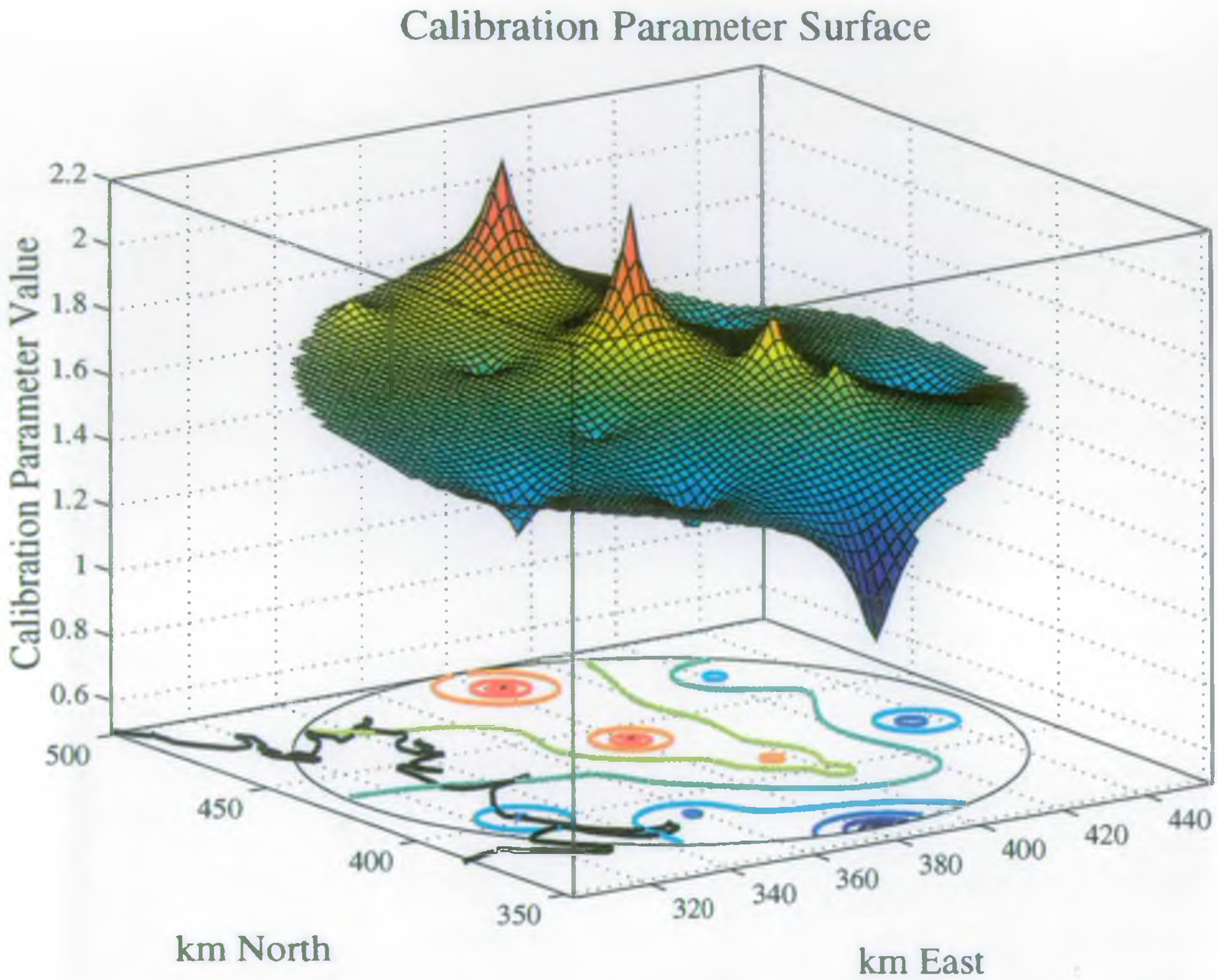

Figure 2.5 Typical calibration parameter surface for a twelve raingauge network.

This calibration surface is created from a set of parameter estimates calculated at points corresponding to the sites of the remote calibration raingauges. This surface is used to calibrate the following radar image (after image processing) and is then recreated from the parameter estimates updated using raingauge rainfall measurements from that fifteen minute period.

Of course, surface fitting based on inverse-distance weighting is only one of a wide variety of surface fitting procedures that could be exploited. For example, we have also investigated statistically-based procedures, where the surface fitting is related to the spatio-temporal correlation structure in the data (see Interim Report 315 / 11 / ST). This appears to be a promising approach but the research has not advanced far enough for practical application. However, research on such statistically based methods is continuing and the current ARC System could be modified easily in future if the promise of the new approaches is realised in practice. We anticipate, for example, that the present individual site calibration parameter estimation algorithm can be improved by converting it to a *multi-site* recursive algorithm which exploits the spatio-temporal correlation structure. And similarly, the surface fitting based on these multi-site estimates will also benefit from the enhanced information resulting from the exploitation of identifiable *spatio-temporal* patterns in the data.

2.3 Bias Adjustment

As described in subsection 2.1.5, areas of the radar image that are dry in the default calibrated image are preserved as being dry following the pre-processing and adaptive calibration stages. While this process retains one of the most important properties of the radar image, namely the accurate measurement of the extent of the rainfall, it also introduces a slight bias between the calibrated radar and surface raingauge storm totals. Consequently, a final adaptive stage has been introduced to remedy this bias. Here, an adaptive gain parameter is estimated from the mean of all the calibration raingauge rainfall intensities and the mean of all the corresponding radar pixel rainfall intensity estimates obtained from the most recent calibrated image. This is updated recursively using a procedure similar to that employed for the calibration parameters. Clearly the nominal value of the adaptive gain parameter is unity, which applies if the bias is zero. However the inevitable bias errors that occur in practice induce changes in the gain parameter, such as those shown in Figure 2.6: this is a typical example of the adaptive gain adjustments over one complete study period (December 20th, 1991).

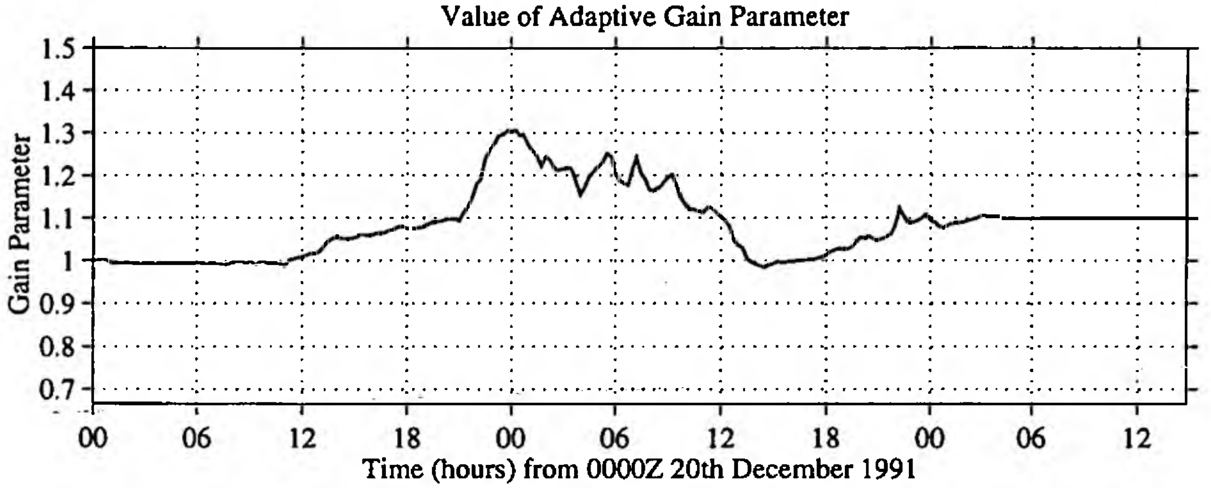

Figure 2.6 Variation in adaptive gain parameter during December 1991 event.

We see that the adaptive correction is predominantly greater than unity (indicating that the calibrated radar intensity is biased *below* the calibration raingauge rainfall intensity) and it changes quite smoothly over the period. The adaptive gain estimated in this manner is applied multiplicatively to the whole radar image to provide a final adjustment to the image prior to calibration.

2.4 Output from the ARC System

The final output from the ARC System is a calibrated radar image with, on average, a much more accurate estimate of the surface rainfall intensity at all points in the image. The *whole* ARC System requires only about 10 seconds of computing time to perform all the required image processing and adaptive calibration on each default calibrated radar image. At the end of each quarter hour period, an additional period of less than five seconds of computing time is required to perform the update of the calibration parameter estimates and re-estimation of the model parameter surface. During our research this processing was performed on a Sun SPARC 10 workstation. Although somewhat longer processing times would be required for less powerful computers, this is unlikely to cause any problems in the present context.

3. PERFORMANCE ASSESSMENT

To assess the performance of the ARC System, we have used raingauge rainfall data from all the available tipping bucket raingauges (TBR) throughout the radar area. Although there are almost eighty such raingauges within 75 km range of Hameldon Hill radar, data from some of these have had to be discarded because they are severely affected by un-correctable measurement errors. Because the raingauge data are used both by the ARC System and the subsequent assessment, it is important that as much as possible of any poor quality data are removed. As such, a rigorous quality control of the raingauge data has proven necessary.

3.1 Sources of Error in Raingauge Measurements

All raingauge data used in this study were taken from electronically logged, tipping bucket raingauges. These raingauges are more reliable and less subject to human error than the mechanical autographic raingauges which they have replaced. In addition, the digital data produced by the TBR's is easily handled by computers. Despite this superiority, measurement errors still exist in the raingauge rainfall measurements. These may be related to the incorrect mechanical operation of the gauge, i.e. a blocked or partially blocked funnel or an incorrectly calibrated tipping bucket mechanism; or they may be connected with the incorrect logging of the data or incorrectly set clock time on the logger. Further errors are caused by incorrect raingauge exposure; certain meteorological conditions, i.e. hail, snow and/or strong winds; and of course, the quantization error inherent in the tipping bucket method.

The raingauges maintained by the NRA (North-West) are regularly re-calibrated, and the incorrect calibration of the TBR mechanism is not believed to be a problem. Similarly, in our experience the clock times have been on the whole very accurate, when comparing gauge data with radar data. Exposure problems are naturally very difficult to detect purely from the data and so the extent of these errors is unknown but assumed to be relatively small. The quantization errors are known to be zero mean and approximately random so that they do not pose any serious problems to parameter estimation (see below). The most severe detectable errors are caused by partial blockage of the raingauge funnel and by the attempted measurement of snow by an *unheated* raingauge.

For all our research, the TBR data are transformed from the electronically logged clock times of each of the tips of the TBR mechanism into time series of quarter hourly rainfall estimates for each raingauge site. First, the data are transformed into time series of fifteen minute rainfall accumulations at each site. The fifteen minute rainfall accumulations are then converted into fifteen minute mean rainfall intensities, using the assumption that the rainfall intensity is constant throughout each fifteen minute period. Although this process generates quantized intensity estimates (0.8 mm hr^{-1} intensity quanta for a 0.2 mm TBR) the introduced quantization error is of zero mean, i.e. the long-term accuracy of the rainfall measurement is maintained. Most significantly, this technique for performing the conversion to rainfall intensity from the times of the individual tips of the TBR may be used in real-time operation. More advanced techniques for generating rainfall intensity time series from TBR tip time data require knowledge of the timing of a pair of consecutive tips of the tipping bucket mechanism. However, these techniques may not be used in real time because knowledge of future tip data are required.

3.2 Quality Control Methods

Raingauge rainfall intensity time series are compared with time series obtained from the default calibrated radar at the geographical locations corresponding to the raingauge sites. This permits the detection of a partially blocked raingauge funnel due to characteristic differences in the patterns of the radar and raingauge intensity time series. However, care must be taken to ensure that the radar rainfall intensity time series is not affected by clutter, bright band or any other significant anomalous factors. In addition, timing errors associated with the logging of raingauge data may be detected by comparing the raingauge and radar intensity time series data. Often, simple time lag may be corrected easily by adjusting the raingauge data timing to coincide with that of the radar data. Finally, the raingauge totals over the duration of the storm event are calculated and data from neighbouring raingauge sites are checked for consistency.

Any data affected by an uncorrectable error is rejected for the whole duration of the storm period. Thus, for the periods of study, the number of raingauges used is between 62 and 67 of the potential 80. Because of this rigorous quality control of the raingauge data, we are confident that the raingauge data represent the best available measurements of the true surface rainfall intensity at the sites used in the research.

3.3 Statistical Assessment

The method of *statistical* assessment of the accuracy of the calibrated radar rainfall estimates is based entirely on the quality controlled raingauge data. However, certain other properties of the radar images which cannot easily be assessed statistically are evaluated in a more subjective manner. An example of such a property is the extent and magnitude of any remaining anomalies in the calibrated radar images which do not affect the radar rainfall intensity estimates at the site of a validation raingauge.

Whilst it would be incorrect to consider that pixel values from the calibrated radar images should be *identical* to the corresponding raingauge estimates of rainfall intensity, the difference between the calibrated radar and raingauge should be of zero mean for ideal performance, assuming good quality raingauge data. Consequently, the rainfall storm totals, as estimated by calibrated radar and raingauge, should be virtually identical and the variance between these two intensity estimates should be minimised.

Rainfall intensity data from all the available raingauges *that were not used for calibration* (see Figure 2.4) are used for the statistical assessment (validation). This may be as many as 67 tipping bucket raingauges for some of the rainfall study periods (Appendix B). The two assessment criteria described below are used simultaneously to assess different properties of the ARC calibrated radar relative to the raingauge measurements and other calibration methods.

3.4 Radar Calibration Assessment Criteria

The performance of each calibration technique is assessed using the two criteria below.

- **Percentage of Total Storm Rainfall** (denoted by %TSR)

The ratio of the radar rainfall accumulation to the raingauge rainfall accumulation measured at the same pixel over the same period of time is expressed as a percentage; so that 100% is thus the optimum achievable performance, representing complete agreement between the calibrated radar and raingauge accumulations.

- **Percentage of Remaining Squared Errors** (denoted by %RSE)

The magnitude of the instantaneous mean squared errors between the raingauge and calibrated radar intensities is expressed as a percentage of the magnitude of the instantaneous mean squared errors between the raingauge and default calibrated radar intensities. Both comparisons are made over the same period of time, usually the whole duration of a rainfall event. This value should be as low as possible, since 100% indicates no improvement by the calibration procedure in terms of reduction in the mean squared errors.

The first of the criteria above has been designed to reflect the accuracy of the radar in terms of measurement of the *total rainfall* for the duration of the storm event. The second is designed to assess the mean *accuracy* of each quarter hourly radar rainfall intensity estimate, i.e. the confidence that can be placed in the accuracy of the rainfall intensity values from within each radar image. It is felt that these two contrasting assessment criteria provide a valid overall assessment of the ARC calibration performance.

4. RESULTS OF ASSESSMENT

The following results are generated using the two assessment criteria described above. A pair of values is calculated for each of the validation raingauge sites (all the raingauge sites except those used for calibration) and these are presented in the tables below for each event in turn. For details of the event meteorology, duration and the number of raingauges available for study, see Appendix B.

4.1 Comparison of ARC System and Collier-Larke Technique

Table 1 demonstrates a direct comparison between the performance of the ARC System and that of the operational, Collier-Larke, radar calibration technique. It should be emphasised that both systems use data from the *same* five calibration raingauge sites to perform the adjustment. The radar calibration performance is assessed according to the two assessment criteria described above, using data from all the tipping bucket raingauges that were *not* used for calibration. The assessment of both radar calibration techniques are presented alongside an assessment of the default calibrated radar data which undergoes no raingauge-based adjustment.

Rainfall Event	Assessment Criterion	Default Calibrated	Collier-Larke Calibrated	ARC Calibrated
December 3rd	%TSR	48	113	99
1986	%RSE	**100**	**133**	**60**
July 18th	%TSR	66	89	110
1987	%RSE	**100**	**126**	**79**
February 22nd	%TSR	51	114	60
1991	%RSE	**100**	**161**	**82**
December 20th	%TSR	48	113	88
1991	%RSE	**100**	**158**	**59**
January 5th	%TSR	52	108	96
1992	%RSE	**100**	**141**	**52**
Average	%TSR	53	107	91
(5 Events)	%RSE	**100**	**144**	**66**

%TSR %age of total storm rainfall estimated by radar compared with that measured by raingauges.
%RSE %age of instantaneous squared errors between radar and raingauge remaining after calibration, relative to the baseline case of default calibrated radar.

Table 1. Comparison of Collier-Larke and ARC performance using a five raingauge network.

From Table 1, it is clear that there is considerable underestimation of the true surface rainfall total by the default calibrated radar during all the five rainfall events. In particular, the default calibrated radar estimates only about one half of the rainfall recorded by the raingauges.

Both radar calibration methods greatly improve the estimation of the total storm rainfall: the Collier-Larke technique overestimates slightly, whilst the ARC System underestimates by a similar amount. On the other hand, the difference between the two calibration methods in terms of the mean square accuracy is obvious. Whilst the ARC System reduces the size of the remaining squared errors by 34%, the Collier-Larke technique *increases* the size of these errors by 44%, giving a total improvement of 78%. In practical terms, this indicates that the accuracy of the rainfall estimates made by the radar at any time are, on average, worse after Collier-Larke calibration than in the default calibrated data. This difference can be attributed in part to the image processing stages carried out by the ARC System, particularly the combined bright band and range processing; and in part because of the improvement introduced by the more sophisticated ARC adaptive calibration.

For example, if the image processing stages are removed from the ARC System, the performance of ARC adaptive raingauge calibration can be assessed alone. In this case the total storm rainfall is still estimated accurately, but the remaining squared errors are only reduced by about 5%, which is still an improvement of 49% over the Collier-Larke technique. This demonstrates that there is an improvement over the Collier-Larke technique achieved purely by using the more sophisticated adaptive calibration parameter estimation algorithm in the ARC System.

For both assessment criteria, the average results for the five events are presented graphically in Figure 4.1 below.

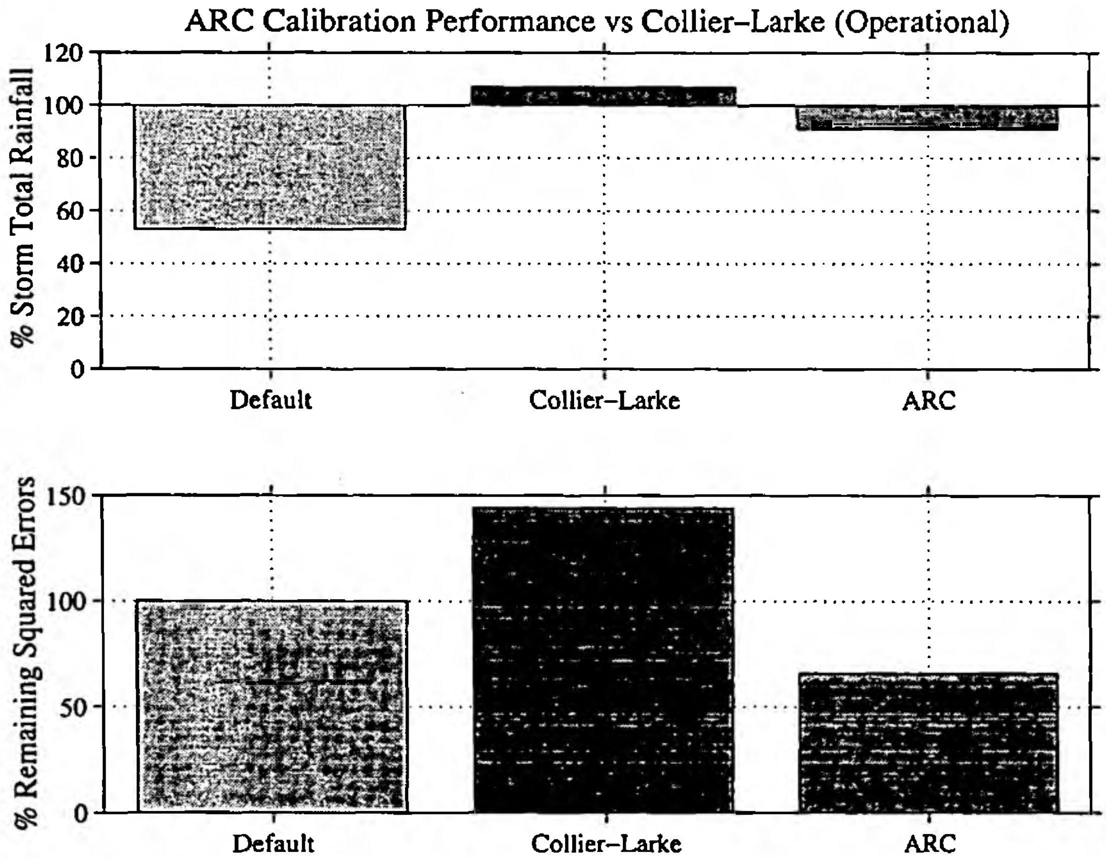

Figure 4.1 Graphical representation of the average calibration performance shown in Table 1.

One of the main reasons for the relatively poor ARC System performance in the February 1991 event (see Table 1) is the fact that the vast majority of the surface rainfall fell in an upland region of North Yorkshire, between 30 and 60 km away from the nearest calibration raingauge. During the event, this region experienced pronounced low level growth in rainfall intensity (orographic enhancement) which was unobserved by the radar. For the five gauge network, the calibration of data in this upland region relies largely upon measurement of the surface rainfall by a calibration raingauge over 30km away to allow for adjustment. This kind of shortfall in the coverage provided by an irregular raingauge network will always be present when heterogeneities in rainfall are experienced, but for the current five calibration raingauge network (Figure 2.4) almost half of the radar area is 30 km or more from the nearest calibration raingauge (Figure 4.3). Later results utilising six or more calibration raingauges in extended networks designed for research purposes (see Figure 2.4) show that improvements in performance are possible with better network design.

4.2 Performance of ARC System using extended raingauge networks

The potential benefits to be obtained by extending the calibration raingauge network have been studied in detail, and the results are presented below. These network extensions assume that the existing five calibration raingauge sites will be retained, with additional sites being added into the raingauge network. The additional sites we have used (see Figure 2.4) are presently NRA tipping bucket raingauge sites and would only require upgrading so that their data could be used in real-time.

The assessment shown in Table 2 has been performed using the three longest and most recent rainfall events for which the most extensive raingauge networks are available for validation. The results are also illustrated graphically in Figure 4.2.

Rainfall Event	Assessment Criteria	Default Calibrated	ARC System performance using given network size				
			5 Gauges	6 Gauges	8 Gauges	10 Gauges	12 Gauges
February 22nd 1991	%TSR	51	60	98	96	92	92
	%RSE	**100**	**82**	**54**	**53**	**53**	**53**
December 20th 1991	%TSR	48	88	96	111	104	106
	%RSE	**100**	**59**	**60**	**64**	**57**	**58**
January 5th 1992	%TSR	52	96	97	101	96	94
	%RSE	**100**	**52**	**51**	**48**	**45**	**43**
Average (3 Events)	%TSR	50	81	97	103	97	97
	%RSE	**100**	**64**	55	55	**52**	**51**

%TSR %age of total storm rainfall estimated by radar compared with that measured by raingauges.
%RSE %age of instantaneous squared errors between radar and raingauge remaining after calibration.

Table 2 Potential improvements in ARC calibration using extended calibration networks.

As might be expected, the percentage of remaining mean squared errors reduces as the number of raingauges in the calibration network increases. However, there appear to be diminishing returns: according to Table 2, the performance using six calibration raingauges is much the same as that using more than six raingauges. It must be emphasised however, that the sixth gauge was deliberately selected to provide adjustment in the area of worst raingauge coverage, both in terms of geography and meteorology. Based on the average over the three events, we see that the calibrated rainfall from the twelve raingauge network estimates the storm total rainfall to within 3% of the raingauge total, and reduces the average squared errors by almost one half.

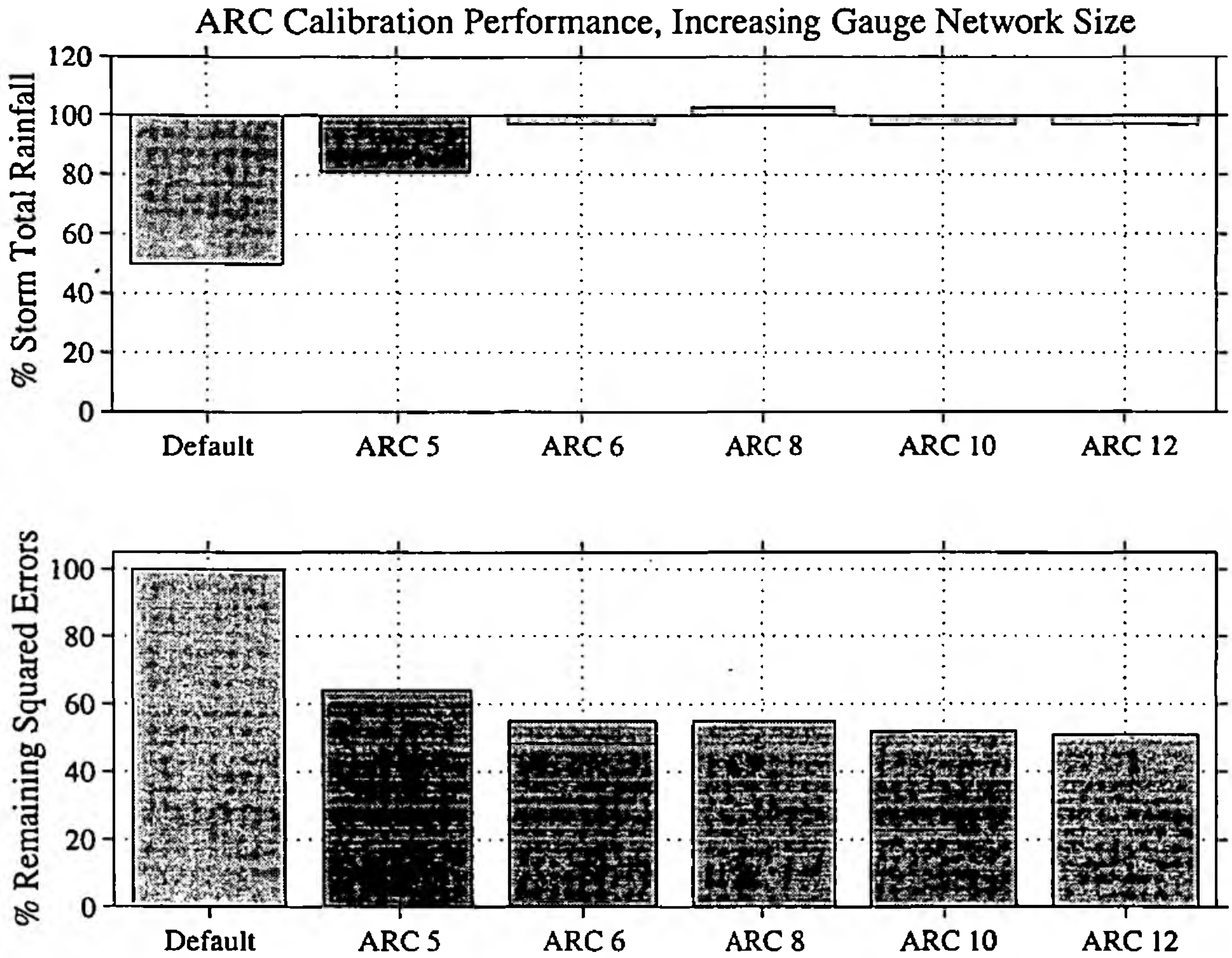

Figure 4.2 Graphical representation of the average calibration performances in Table 2.

With the ARC System, the accuracy with which the storm total is estimated is clearly limited by the present inadequate raingauge network. The System should be relatively unaffected by bright band effects, provided the image pre-processing is performed; or by orographic enhancement, provided the calibration raingauge coverage is sufficient.

The degree of coverage of the radar area provided by the networks shown in Figure 2.4, is shown in Figure 4.3. This presents the percentage of the radar area within given distances of the nearest calibration raingauge in relation to these networks. For the current five gauge network, one quarter of the radar area is more than 40 km away from the nearest calibration raingauge. This obviously limits the potential benefits which could be achieved by the ARC System. For example, we can note from Figure 4.3 that, by simply extending this network from five to ten gauges, less than one percent of the image would lie more than 40 km from the nearest calibration raingauge site.

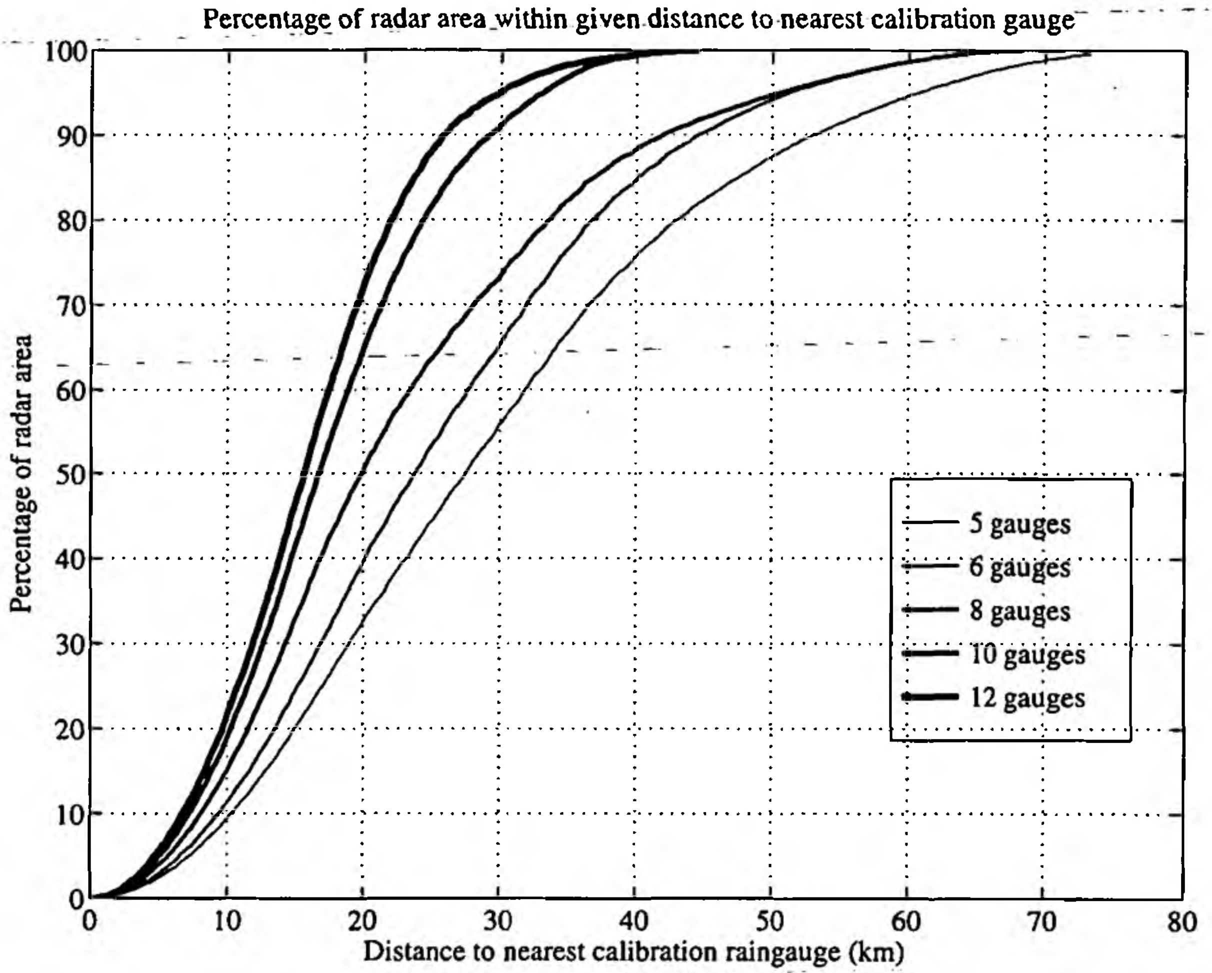

Figure 4.3 Analysis of the coverage provided by the various experimental calibration raingauge networks shown in figure 2.4. This demonstrates that with the twelve gauge network, the entire radar area is within 45km from the nearest calibration raingauge.

5. CONCLUSIONS

This report has outlined the main aspects of the Adaptive Radar Calibration (ARC) System developed at Lancaster over the past three years, and has provided a thorough statistical evaluation of its performance in relation to both the default calibrated radar and the currently operational Collier-Larke calibration technique. In relation to the latter, the ARC System produces comparable estimates of total storm rainfall but greatly reduced error variances, with some 78% improvement in the mean squared errors over the experimental periods.

One important aspect of the ARC System not anticipated in the original proposal is the use of image pre-processing, which was necessitated because of the large number of correctable anomalies detected in the default calibrated radar images. We have found that such image pre-processing considerably improves the subsequent adaptive calibration stage. For example if the image pre-processing is removed from the ARC System, the calibration produces very good estimation of the storm totals but there is no significant reduction in the error variances.

We are confident that the ARC System should always estimate the total storm rainfall accurately due to the nature of the adaptive raingauge calibration and the subsequent bias adjustment. This correct estimation of the storm total rainfall will be achieved most reliably using a suitably extended calibration raingauge network, which provides coverage throughout the radar area and is representative of the different topographical areas. It is also clear that removal of many of the geometrical radar errors by image processing will allow the subsequent adaptive raingauge calibration to perform at its best.

5.1 Conclusions for Implementation

On the basis of the research carried out in this project, we conclude that the current siting of the five calibration raingauges is not suitable for reliable calibration and that an enlarged set of calibration gauges is required if the ARC System (or any other system) is to perform at its best. This is partially because the current calibration raingauge network was installed for the operational domain-based (Collier-Larke) calibration technique which was originally designed to provide calibrated radar rainfall estimates mainly to the west of the Pennines. Improvements in the Collier-Larke technique have since been made, but the original calibration raingauge network remains basically unchanged and the network is clearly not optimal for ARC calibration over the whole radar region.

Also, we believe that five raingauges cannot possibly provide a representative coverage of a radar measurement area of some 16,400 km^2. This is confirmed by the research, which demonstrates how, by adding only a few well located additional raingauges to the calibration network, suitable coverage of the whole area can be achieved (Figure 4.3) and the ARC System performance greatly enhanced (Figure 4.2). In particular, twelve raingauges would provide a reduction of one half in the mean squared errors and correct estimation of the total storm rainfall.

The seven additional calibration sites, used to create the twelve raingauge network, have been chosen both to improve the calibration in some of the gaps in the network and provide calibration in currently ungauged upland areas. Such calibration network improvements would only require upgrading the current NRA tipping bucket raingauges at these seven additional sites to allow usage of the rainfall data in real-time by the calibration software. We strongly believe that such an extension of the calibration network, coupled with adoption of the ARC System, would provide a cost efficient and easily implementable improvement of the current Hameldon Hill calibration System.

REFERENCES

COLLIER, C.G. AND LARKE, P.R. (1981). A procedure for the adjustment in real time of radar measurements of rainfall. Met. Office Research Report No. 25, Met. Office RRL.

LEES, M.J., YOUNG, P.C., FERGUSON, S., BEVEN, KJ., BURNS, J. (1994). An Adaptive Flood Warning Scheme for the River Nith at Dumfries, Proc. 2nd International Conference on River Flood Hydraulics, Ed. WHITE, W.R., AND WATTS, J., John Wiley & Sons Ltd.

MANN, J.E. (1993). In Weather Radar and Storm and Flood Hazards. Final Report on EPOCH Project No. EPOC-CT90-0026, NERC, 25-26.

YOUNG, P.C. (1984). Recursive Estimation and Time Series Analysis., Springer-Verlag: Berlin.

YOUNG, P.C., LORD, M.E., GOODHEW, R.C. (1993). An Improved Adaptive Calibration Technique for Weather Radar. First Interim Report, NRA R&D 315 / 7 / ST.

YOUNG, P.C., LORD, M.E., GOODHEW, R.C. (1993). An Improved Adaptive Calibration Technique for Weather Radar. Second Interim Report, NRA R&D 315 / 11 / ST.

APPENDIX A The Collier-Larke Technique (Operational)

The current system providing final stage raingauge adjustment of the radar was developed by Collier and Larke (1981). This system also uses raingauge data from a set of calibration raingauge sites but does not perform any additional radar image processing and due to the nature of the errors in the radar data, does not currently provide a satisfactory calibration.

The default calibrated radar images are used as the input to this system, together with data from five calibration raingauge sites. Using the raingauge rainfall intensity estimates and the radar intensity estimates, taken as the mean of the four pixels closest to each raingauge site, assessment factors are calculated every fifteen minutes from the simple division of the radar intensity by the raingauge intensity. If either the raingauge or radar intensity is zero, a value of 1 is assumed. The average of the last four assessment factors is calculated (one hour of data) for each site. The reciprocal of these values, termed calibration factors, are used to adjust the default calibrated radar image data in the following manner.

It is assumed that the relationship between the raingauge rainfall estimates and the default calibrated radar rainfall estimates can be explained by a multiplicative correction factor. Further, it is assumed (incorrectly) that the variation in this relationship throughout the radar area is entirely of a geographical and meteorological nature. A set of calibration domains are defined within the radar area, with each domain defined to encompass a region of assumed similar geographical and meteorological conditions. A set of tessellating domains form the domain map which is suitable for use during specific meteorological conditions described by a 'synoptic type' of weather. For example in the domain map used during 'Welsh rain-shadow' conditions, all low lying areas to the south and west of Manchester and Preston are included in one domain. Because the meteorological conditions obviously vary, an automatic assessment of the synoptic type is made from a frequency analysis of the rainfall intensity variations at the calibration raingauge sites. Based on the results of the frequency analysis, which utilises a very small data set, a synoptic type is determined and this is then used to select a suitable domain map. The calibration factors are then applied throughout the defined domains within the chosen domain map as multiplicative corrections to the radar rainfall intensity values. It is assumed that, throughout each domain, a simple multiplicative calibration factor represents the complete relationship between the radar and raingauge intensity estimates.

For a more full description of the Collier Larke Calibration Technique the reader is referred to Collier and Larke (1981), or to the First Interim Report on this project, 315 / 7 / ST.

APPENDIX B Meteorology of Rainfall Events

December 3rd 1986. (1300 GMT, 3rd to 1600 GMT, 4th) (27 Hrs, 26 Gauges)

A deep depression centred to the south of Ireland brought a strong south westerly airflow over Britain. A cold front extending from this depression lay south west, north east across Britain and moved gradually southwards from the Scottish Borders at 1200 GMT on the 3rd, to North Wales at 2400 GMT on the 3rd. The same frontal system then pushed back North as a warm front to lie over the Scottish Borders again at 1800 on the 4th.

Rainfall in the 36 hour period from 0900 GMT on the 3rd, was very heavy over North West England with up to 50 mm falling throughout Lancashire, Cumbria and North Wales. Only 10 mm or less fell over the midlands, Eastern and Southern England. Scotland received two periods of heavy rainfall, the first between 0900 GMT on the 2nd and 0900 GMT on the 3rd, and the second between 2100 GMT on the 4th and 0900 GMT on the 5th. These two periods being before and after the period of heavy rainfall in north west England.

Surface temperatures were between 8 and 10°C to the North of the frontal system and between 12 and 14°C to the south.

Winds at Lancaster remained mainly south westerly throughout, with a strength of 25 knots decreasing to 5 knots by the morning of the 4th December. These conditions, together with the high relative humidity caused conditions of orographic enhancement over the upland areas of Northern England.

July 18th 1987. (0500 GMT to 2400 GMT) (18 Hrs, 29 Gauges)

An occluded depression with a central pressure of 987 millibars lay off the coast of north-east England at 0600 GMT, and moved very slowly *Westwards* to lie over the western Irish Sea with a central pressure of 994 millibars at 2400 GMT on the 18th July. Rainfall for the 24 hours ending 2100 GMT on the 18th was highest over northern England and southern Scotland in association with the depression centre and an occluded front, these areas having between 25 and 50 millimetres of rainfall.

Periods of heavier rainfall were embedded within the widespread rainfall associated with the occluded front. The occluded front crossed the Hameldon Hill radar area between about 0700 and 1100 on the 18th.

Temperatures were about normal for the time of year overnight, but the maximum temperature was low on the 18th due to the thick cloud cover.

Winds at Lancaster were initially 11 knots westerly, increasing to 17 knots then backing south easterly and dropping to about 5 knots by 2400 GMT.

February 22nd 1991 (1845 GMT, 22nd to 1800 GMT, 24th) (50 Hrs, 57 Gauges)

An Atlantic depression rapidly crossed from western Ireland, over Scotland then over the northern North Sea between 1200 GMT on the 22nd to 0600 GMT on the 23rd. To the south, the warm front passed over North West England during the late evening of the 22nd replacing cool air (6°C) with much milder (12°C), moister air on a south westerly wind. The movement southwards of the associated cold front slowed and became quasi-stationary, meandering over the Scottish borders and northern England for almost the whole of the 23rd February. At this time, south westerly winds of 15 to 20 knots fetching warm moist air created ideal orographic enhancement conditions over the hills of northern England. Parts of North Yorkshire had moderate or heavy rain all day with over 100 mm being recorded in some places. To the east of the Pennines and on the west coast of Lancashire, rainfall totals of less than 10 mm were generally recorded.

A developing wave depression formed on the front off south west Ireland by 1800 on the 23rd and moved along the length of this front, crossing the Irish Sea and passing over the Scottish borders to clear the east coast of England by about 0600 GMT. This brought a renewed period of rainfall to most areas of northern England. The cold front from this depression moved south over the radar area between about 0900 and 1200 on the 24th. Behind the cold front a few showers from off the Irish Sea brought rain to some parts.

December 20th 1991 (0000 GMT, 20th to 1500 GMT, 22nd) (64 Hrs, 62 Gauges)

Cold air (2°C) in a west north westerly wind of about 20 knots brought a continuous stream of showers off the Irish Sea between 0000 GMT and about 1800 GMT on the 20th. The showers then began to die out as a warm front approached from the west. This brought rainfall to the north of England from about 1900 GMT on the 20th. For the next five hours the radar rainfall estimates were seriously affected by bright band effects (Figure 2.2). During the early morning the warm air swept across the whole radar area and the temperature rose to about 10°C. The arrival of the warmer air brought about the end of the worst bright band effects, but behind the warm front heavy orographically enhanced rain fell over the Peak District and North Wales.

The depression associated with the warm front moved eastwards over central Scotland from 1200 on the 21st leaving a trailing cold front over the Scottish borders. This gave heavy rain in Southern Scotland until 0000 GMT on the 23rd when the cold front swept rapidly southwards across the whole of England.

The storm totals in this 63 hour event were highest in the Pennines and Peak District with over 75 mm falling at sixteen of the raingauge sites within the radar area.

January 5th 1992 (0000 GMT, 5th to 0300 GMT, 6th) (27 Hrs, 60 Gauges)

Cool air (5°C) lay over the country in a slack pressure system with only light winds during the evening of the 4th. A weak warm front which lay east-west along the English channel at this time began to move northwards as a weak depression formed on it. The warm front associated with the depression began pushing across the radar area by about 0100 on the 5th. The radar rainfall estimation was affected by bright band until about 1200 GMT by which time warmer air (12°C) lay across the whole radar area. In this time, the depression moved across the Irish Sea and across Northern England to clear the east coast by about 1800 GMT on the 5th.

A second depression which formed over Ireland on the weather front behind the first moved up the west coast of Scotland between 0000 GMT and 1200 GMT on the 6th, with the warm front crossing the region at about 0100 but only producing generally light rainfall.

Storm totals of up to 40 mm were measured in some parts of the north of England, with almost all areas receiving over 10 mm.

GLOSSARY

Attenuation	Reduction in power of the radar beam as it propagates through the atmosphere.
ARC System	The Adaptive Radar Calibration (ARC) System designed under NRA research project 315 ST.
Bright Band	The artificially high radar rainfall estimates caused by variations in the relationship between echo strength and rainfall intensity.
Clutter	Spurious radar echoes received from non-precipitation sources.
Collier-Larke	The current operational raingauge based calibration technique (Collier and Larke, 1981).
Default Calibrated Radar	8-bit C-band conventional radar data, processed for occultation, clutter, transformed from Z (reflectivity) to R (rainfall intensity), range and attenuation corrected, then transformed from a Polar to a 2km by 2km Cartesian grid.
Occultation	Obstruction of the emitted radar beam by hills, or objects such as transmitter masts or pylons.
Pixel	A 2km by 2km radar rainfall intensity estimate within the radar image (picture element).
Radar area	An approximately circular area of 75 km radius centred on Hameldon Hill Radar (Grid Ref. 381.1, 428.7).
Range	The horizontal distance from the radar antenna to any given point in the radar area.