# EXTENSION OF THE LONDON WEATHER RADAR LOCAL CALIBRATION PROCEDURE TO THE ENTIRE THAMES BASIN

by

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# Executive Summary

An extension of the London Weather Radar Local Calibration Procedure, originally developed for London and the Lee Valley, to the entire Thames Basin is considered in this report. The work stems from a recommendation in the original study for a further investigation if the radar recalibration method was in the future to be used over the entire Thames Basin. It was also motivated by observations from an NRA test program of adverse effects over the original study area when recalibration was applied using raingauges over the entire Thames Region.

Since completion of the original study in 1989 the number of telemetry gauges over London and the Lee Valley have increased from 30 to over 50. In addition, new telemetry links to raingauges in the rest of the Thames Basin now give access to a total of 98 raingauges for use with the recalibration procedure. This study has employed data from typically 65 to 70 of these raingauges for recalibration of the 2 km weather radar data over the period January 1990 to October 1994. A change in the at-site radar calibration on 16 August 1994 meant that two sets of analyses were undertaken, one based on 50 events prior to this date and the other using 10 events after the change. The results confirm the use of the existing recalibration method in operational use but with revised values for the incidental parameters employed in the multiquadric calibration surface fitting method. For the period prior to the change, the revised parameters provide an improvement of 3%. When compared with the uncalibrated radar the improvement is 32%, on average: significantly better than the 22% reported for the 23 events used in the original study. A different parameter set is recommended for the period after the change, and this gives an 8% improvement in performance compared with that obtained using the operational set. In this case the improvement over the uncalibrated radar is 28% on average. For the rainfall estimation method using raingauges only, again the results confirm the use of the existing method but with a modified parameter set, although the performance was little improved compared to the operational set. This rainfall estimation method was 16% worse than the radar recalibration with revised parameters, on average over the 50 events. For the 10 events the raingauge-only estimator gave similar performances to the uncalibrated radar, whilst the recalibration scheme provided an improvement of 28%.

The adverse effects of the recalibration method when applied over the entire Thames Basin, observed by the NRA, were explored and found to be associated largely with a problem with their test program and not with the method. This is now resolved. Other exploratory investigations looked at the effect on radar rainfall estimation of range and the beam infill area, demonstrating their importance to radar rainfall measurement. The pattern of time-averaged radar fields served to reveal anomalies caused principally by beam blocking and served to identify raingauges to be excluded from the recalibration procedure. An average calibration factor surface exposed a general tendency for the calibration factors to increase southwards with locally higher factor values on the southern boundary of the Thames catchment. The latter are thought to be possibly associated with orographic enhancement effects on radar rainfall measurement bias.

The main recommendation is to employ both the Local Radar Calibration method and raingauge-only rainfall estimation method, as implemented operationally, over the entire Thames Basin but with modified incidental parameters and excluding those raingauges in areas of radar anomaly. Also, in order to obtain complete recalibrated rainfall fields over the entire area, it is recommended that the radar data are first preprocessed to remove anomalies and clutter using the techniques developed for the London Weather Radar Local Rainfall Forecasting Study.

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# 1. Introduction

The London Weather Radar Local Calibration Study (Moore *et al.*, 1989a and b; 1991; 1994a) used a network of up to 30 raingauges over the Lee and London areas to develop a method of recalibrating the London Weather Radar to increase the accuracy of estimation of spatial rainfall. A 22% improvement in accuracy was achieved, relative to that obtained by the radar without calibration, over an area 60 km square. The recommended system for recalibration has operated at the NRA's London Flood Warning Centre since March 1989.

Between 1989 and 1994 the number of raingauges in the eastern part of the Thames region increased to over 50 and in 1994 telemetry raingauge data from the western part of the region were made available to the recalibration scheme. Initial tests by the NRA of the recalibration scheme using raingauges across the entire Thames Region highlighted problems. It appeared that the application of the scheme over the extended area had an adverse effect on the calibration over the original eastern area. IH were asked to "trouble-shoot" and also to provide a reoptimization of the radar recalibration scheme applicable to the extended region and based on more recent data.

# 2. Data and event selection

The original study employed 23 events over the period October 1987 to May 1989 for which data from up to 30 raingauges over the eastern area of the Thames basin were available. For the current study data for the period 1990 to 1994 have been used. Raingauge data from up to 98 raingauges over the Thames basin are available for this period. Within the 75 km radar circle, for which 2 km data are available, there are anomalous areas caused mainly by beam blockage and clutter. Figure 2.1 indicates that some of the raingauges lie in these areas of anomaly. These have been excluded from the recalibration process along with those raingauges which lie outside the radar circle. The number of raingauges with available data varies from event to event. Table 2.1 lists the raingauges available and highlights those excluded.

The original calibration study identified timing errors in the telemetry raingauge data due to the method of archiving. Therefore, for each raingauge in each event, correlation coefficients for various fifteen minute lags were found between the radar and raingauge data. The raingauge data were then automatically time shifted to the lag giving the maximum correlation coefficient. In practice more often than not a zero lag was found to give the best correlation due to an improvement in the archiving procedure and subsequent quality control since the time of the original study.

A feature of the London Weather Radar is that a factor of 2 is incorporated in the calibration as an empirical adjustment to correct for rainfall estimation bias. This factor was removed on 16 August 1994 following adjustments to the radar. As a result the event data selected for analysis have been treated as two sets, one set prior to 16 August 1994 and the other after this date. Tables 2.2 and 2.3 list the events chosen for analysis, there being 50 events in the first set from January 1990 to June 1994, and 10 events from 17 August to 31 October 1994.

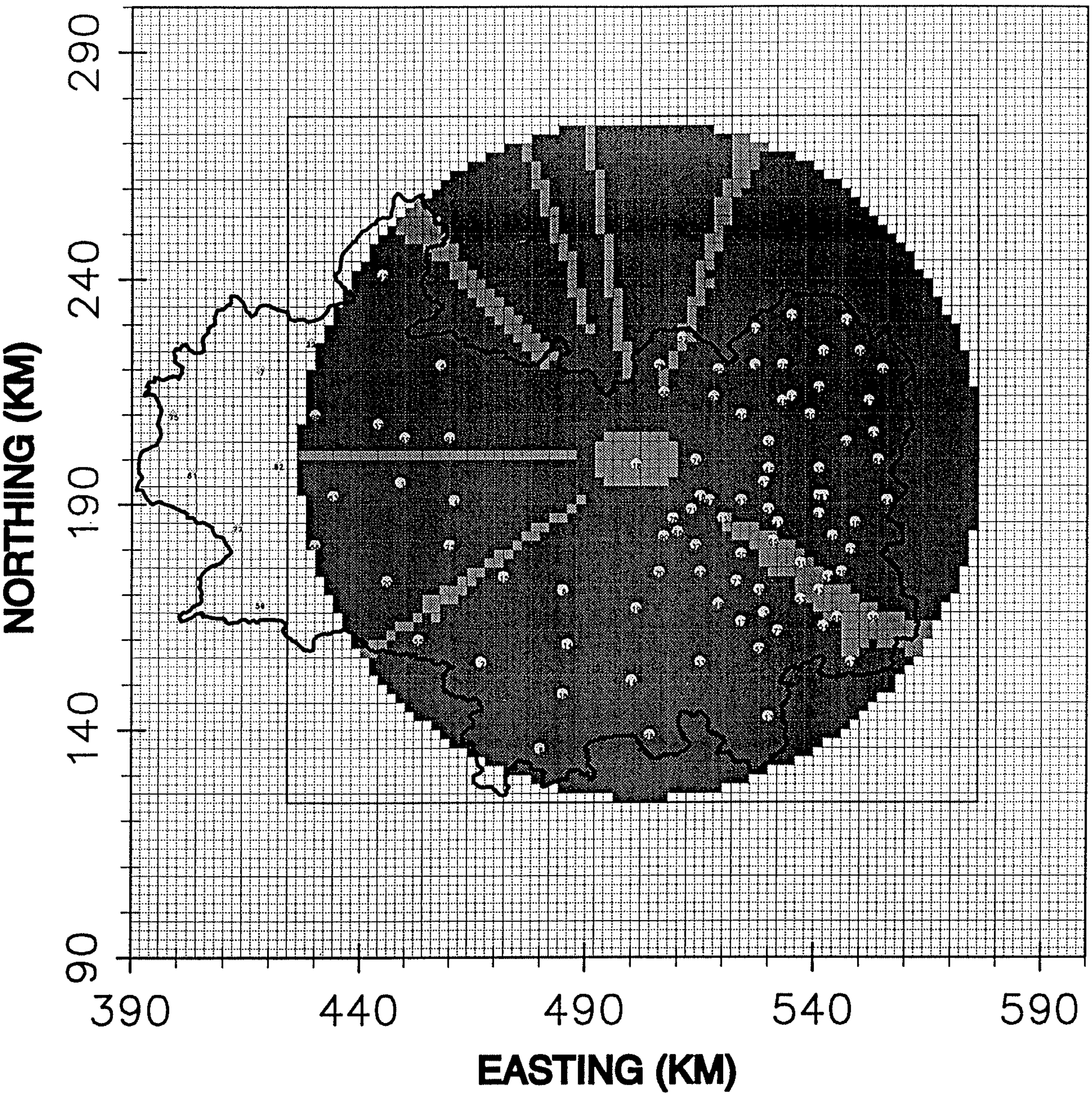


*Figure 2.1* *Raingauge locations and areas of radar anomaly*

*Table 2.1 Telemetry raingauges in the Thames Basin*

| Gauge No. | Gauge name | Grid ref. | Area | Error status | Height mAOD |
|---|---|---|---|---|---|
| 1 | Abingdon | 4493 1952 | W | | 50 |
| 2 | Basingstoke | 4676 1552 | W | | 67 |
| 3 | Beddington | 5299 1661 | E | | 39 |
| 4 | Benson | 4613 1913 | W | | 43 |
| 5 | Bicester | 4581 2212 | W | | 66 |
| 6 | Bordon | 4804 1362 | W | | 74 |
| 7 | Bourton | 4182 2203 | W | outside circle | 128 |
| 8 | Bracknell | 4858 1718 | W | | 49 |
| 9 | Bragbury Park | 5274 2211 | E | | 69 |
| 10 | Braughing Friars | 5420 2245 | E | | 116 |
| 11 | Brent Reservoir | 5208 1870 | E | anomaly | 42 |
| 12 | Broadmeads | 5354 2140 | E | | 35 |
| 13 | Burstow Rain | 5306 1437 | W | | 58 |
| 14 | Camberley | 4862 1598 | W | | 60 |
| 15 | Caversham | 4720 1740 | W | | 37 |
| 16 | Central Park | 5499 1863 | E | | 16 |
| 17 | Cheam | 5247 1641 | E | | 47 |
| 18 | Chenies | 5017 1999 | W | anomaly | 138 |
| 19 | Chertsey | 5016 1674 | W | | 16 |
| 20 | Chieveley | 4468 1739 | W | | 104 |
| 21 | Chigwell | 5423 1926 | E | | 15 |
| 22 | Chipping Norton | 4294 2268 | W | outside circle | 140 |
| 23 | Chipping | 5357 2323 | E | | 104 |
| 24 | Clavering STW | 5474 2318 | E | | 91 |
| 25 | Cleeve | 4601 1818 | W | | 45 |
| 26 | Cranleigh | 5041 1393 | W | | 47 |
| 27 | Crossness | 5486 1805 | E | | 8 |
| 28 | Dane End | 5334 2219 | E | | 91 |
| 29 | Danson Park | 5468 1754 | E | | 50 |
| 30 | Darnicle Hill | 5309 2048 | E | | 73 |
| 31 | Deptford | 5377 1771 | E | anomaly | 5 |
| 32 | Ealing | 5141 1815 | E | | 23 |
| 33 | Elmer | 5159 1557 | W | | 51 |
| 34 | Eltham | 5433 1745 | E | | 75 |
| 35 | Epping | 5412 1981 | E | | 110 |
| 36 | Eynsford | 5535 1655 | E | anomaly | 40 |
| 37 | Eynsham | 4445 2087 | W | | 65 |
| 38 | Farnham STW | 4856 1481 | W | | 75 |
| 39 | Furzedown | 5286 1712 | E | | 40 |
| 40 | Gascoigne Road | 5447 1830 | E | | 2 |
| 41 | Green Lanes | 5320 1868 | E | | 31 |
| 42 | Grimsbury | 4458 2418 | W | | 91 |
| 43 | Grove Park | 5415 1715 | E | anomaly | 70 |
| 44 | Guildford STW | 5002 1518 | W | | 30 |
| 45 | Hadley Road | 5302 1982 | E | | 49 |
| 46 | Harrow Weald | 5153 1922 | E | | 98 |
| 47 | Hatfield Heath | 5524 2131 | E | | 67 |
| 48 | Hertford | 5338 2134 | E | | 37 |
| 49 | Hogsmill | 5194 1682 | E | | 12 |
| 50 | Holland Park | 5246 1795 | E | | 21 |
| 51 | Hornsey | 5308 1894 | E | | 33 |
| 52 | How Green | 5283 1581 | E | | 161 |
| 53 | Kelsey Park | 5375 1692 | E | anomaly | 35 |
| 54 | Keston | 5422 1636 | E | | 172 |

*Table 2.1 continued* *Telemetry raingauges in the Thames Basin*

| Gauge No. | Gauge name | Grid ref. | Area | Error status | Height mAOD |
|---|---|---|---|---|---|
| 55 | Kingsclere | 4531 1609 | W | | 79 |
| 56 | Lambourn | 4305 1817 | W | | 150 |
| 57 | Lilley Manor | 5112 2278 | E | anomaly | 152 |
| 58 | Markyate | 5071 2155 | W | anomaly | 119 |
| 59 | Marlborough Rain | 4184 1682 | W | outside circle | 160 |
| 60 | Mill Green | 5245 2100 | E | | 61 |
| 61 | Mill Hill | 5241 1919 | E | | 100 |
| 62 | Mogden | 5154 1753 | E | | 10 |
| 63 | Moreton | 5533 2068 | E | | 61 |
| 64 | Nags Head Lane | 5565 1914 | E | | 40 |
| 65 | New River Head | 5314 1828 | E | anomaly | 26 |
| 66 | Northolt | 5102 1845 | E | | 34 |
| 67 | Oakwood Park | 5299 1952 | E | | 67 |
| 68 | Orpington | 5459 1652 | E | anomaly | 67 |
| 69 | Osney | 4504 2058 | W | | 57 |
| 70 | Perry Oaks | 5060 1759 | E | | 23 |
| 71 | Pinner Cemetry | 5132 1894 | E | | 57 |
| 72 | Purley Oaks | 5321 1623 | E | | 58 |
| 73 | Putney Heath | 5234 1737 | E | | 56 |
| 74 | Radlett | 5148 2002 | W | | 79 |
| 75 | Rapsgate | 3996 2105 | W | outside circle | 236 |
| 76 | Ray Park | 5418 1923 | E | | 20 |
| 77 | Rodbourne | 4132 1855 | W | outside circle | 95 |
| 78 | Ruislip | 5090 1877 | E | | 45 |
| 79 | Runley Wood | 5064 2217 | E | | 137 |
| 80 | Rye Meads | 5392 2103 | E | | 30 |
| 81 | Shorncote | 4034 1971 | W | outside circle | 94 |
| 82 | St. Johns | 4222 1990 | W | outside circle | 72 |
| 83 | Stanford | 4343 1929 | W | | 68 |
| 84 | Stanford Rivers | 5545 2002 | E | | 38 |
| 85 | Stansted Argus | 5504 2243 | W | | 20 |
| 86 | Stansted | 5502 2243 | E | | 70 |
| 87 | Sundridge | 5489 1556 | E | | 82 |
| 88 | Takeley | 5550 2209 | E | | 94 |
| 89 | Thornwood | 5476 2048 | E | | 76 |
| 90 | Uxbridge | 5074 1839 | E | | 43 |
| 91 | Wanstead PS | 5415 1882 | E | | 18 |
| 92 | Weston | 5275 2297 | E | | 122 |
| 93 | Wheathampstead | 5181 2142 | E | | 91 |
| 94 | Wheatley STW | 4608 2052 | W | | 61 |
| 95 | Whitwell STW | 5194 2209 | E | | 91 |
| 96 | Widford | 5417 2164 | E | | 60 |
| 97 | Wolverton Road | 5170 1915 | E | | 67 |
| 98 | Worsham | 4301 2105 | W | | 99 |

*Table 2.2 Selected storm events for the period prior to 16 August 1994*

| | | | | | |
|---|---|---|---|---|---|
| **1990:** | | | | | |
| 1. | 00:00 | 30 January | - | 23:55 | 31 January |
| 2. | 12:00 | 1 February | - | 01:00 | 2 February |
| 3. | 00:00 | 7 February | - | 23:55 | 7 February |
| 4. | 06:00 | 13 April | - | 21:00 | 13 April |
| 5. | 06:00 | 10 May | - | 21:00 | 10 May |
| 6. | 12:00 | 20 June | - | 23:55 | 22 June |
| 7. | 08:00 | 29 September | - | 23:55 | 30 September |
| 8. | 00:00 | 26 October | - | 01:00 | 27 October |
| 9. | 19:00 | 25 November | - | 23:55 | 26 November |
| 10. | 07:00 | 25 December | - | 14:00 | 25 December |
| 11. | 07:00 | 26 December | - | 17:00 | 26 December |
| **1991:** | | | | | |
| 12. | 10:00 | 8 January | - | 23:55 | 10 January |
| 13. | 06:00 | 27 February | - | 01:00 | 28 February |
| 14. | 00:00 | 5 March | - | 11:00 | 6 March |
| 15. | 12:00 | 29 April | - | 13:00 | 30 April |
| 16. | 10:00 | 23 June | - | 19:00 | 23 June |
| 17. | 14:00 | 2 July | - | 08:00 | 3 July |
| 18. | 06:00 | 30 July | - | 05:00 | 31 July |
| 19. | 00:00 | 26 September | - | 23:55 | 29 September |
| 20. | 12:00 | 29 October | - | 09:00 | 30 October |
| 21. | 15:00 | 18 November | - | 13:00 | 19 November |
| **1992:** | | | | | |
| 22. | 00:00 | 8 January | - | 23:55 | 9 January |
| 23. | 17:00 | 10 February | - | 8:00 | 11 February |
| 24. | 00:00 | 26 April | - | 23:55 | 27 April |
| 25. | 01:00 | 29 May | - | 14:00 | 30 May |
| 26. | 12:00 | 9 June | - | 19:00 | 9 June |
| 27. | 10:00 | 20 July | - | 08:00 | 21 July |
| 28. | 07:00 | 13 August | - | 22:00 | 13 August |
| 29. | 01:00 | 22 September | - | 12:00 | 23 September |
| 30. | 15:00 | 19 October | - | 23:55 | 20 October |
| 31. | 12:00 | 24 November | - | 23:55 | 25 November |
| 32. | 04:00 | 18 December | - | 22:00 | 18 December |
| **1993:** | | | | | |
| 33. | 00:00 | 10 January | - | 17:00 | 10 January |
| 34. | 09:00 | 31 March | - | 23:55 | 1 April |
| 35. | 12:00 | 23 April | - | 15:00 | 25 April |
| 36. | 09:00 | 20 May | - | 23:55 | 20 May |
| 37. | 06:00 | 10 June | - | 23:55 | 12 June |
| 38. | 14:00 | 23 July | - | 23:55 | 23 July |
| 39. | 17:00 | 21 August | - | 11:00 | 22 August |
| 40. | 06:00 | 12 September | - | 23:55 | 13 September |
| 41. | 12:00 | 22 September | - | 22:00 | 22 September |
| 42. | 09:00 | 1 October | - | 18:00 | 2 October |
| 43. | 22:00 | 10 October | - | 23:55 | 13 October |
| 44. | 10:00 | 9 November | - | 21:00 | 10 November |
| 45. | 03:00 | 30 December | - | 20:00 | 30 December |

*Table 2.2 cont.* *Selected storm events for the period prior to 16 August 1994*

| | | | | | |
|---|---|---|---|---|---|
| **1994:** | | | | | |
| 46. | 00:00 | 3 January | - | 23:55 | 5 January |
| 47. | 05:00 | 3 February | - | 14:00 | 3 February |
| 48. | 00:00 | 31 March | - | 08:00 | 1 April |
| 49. | 00:00 | 21 May | - | 23:55 | 22 May |
| 50. | 12:00 | 3 June | - | 20:00 | 4 June |

*Table 2.3* *Selected storm events for the period after 16 August 1994*

| | | | | | |
|---|---|---|---|---|---|
| **1994:** | | | | | |
| 1. | 00:00 | 17 August | - | 13:00 | 17 August |
| 2. | 00:00 | 25 August | - | 15:00 | 25 August |
| 3. | 00:00 | 31 August | - | 21:00 | 1 September |
| 4. | 00:00 | 14 September | - | 23:55 | 15 September |
| 5. | 00:00 | 19 September | - | 23:55 | 19 September |
| 6. | 13:00 | 2 October | - | 23:55 | 3 October |
| 7. | 00:00 | 20 October | - | 15:00 | 20 October |
| 8. | 14:00 | 21 October | - | 17:00 | 22 October |
| 9. | 22:00 | 24 October | - | 14:00 | 25 October |
| 10. | 00:00 | 29 October | - | 23:55 | 31 October |

# 3. Review of the London Weather Radar Local Calibration Study methods of rainfall estimation

## 3.1 RADAR CALIBRATION METHOD

A number of possible approaches to merging radar and raingauge data to obtain a more accurate estimate of the rainfall field are available. The approach adopted in the London Weather Radar Local Calibration Study was based on the simple fitting of a mathematical surface to calibration factors, defined as a modified ratio of the rainfall at raingauge i, $R_g^i$, to the radar estimate, $R_r^i$, for the grid square coincident with the raingauge, such that

$$z_i = \frac{R_g^i + \epsilon_g}{R_r^i + \epsilon_r} \; ; \tag{3.1.1}$$

here $\epsilon_g$ and $\epsilon_r$ are positive constants chosen to ensure that $z_i$ is defined for all values of $R_r^i$ and $R_g^i$. Surface fitting as a calibration method was chosen because it was fast to execute; it also provided a simple and direct method of merging radar and raingauge data in which uncertainties are accommodated implicitly through the fitting method.

uncertainties are accommodated implicitly through the fitting method.

The particular form of mathematical surface adopted was an extension of the multiquadric surface introduced by Hardy (1971) and expressed as follows:

$$z_i = a_0 + a_1 d_{i1} + a_2 d_{i2} + \ldots + a_n d_{in}, \qquad i = 1,2,\ldots,n. \tag{3.1.2}$$

Here, $\{z_i,\ i = 1,2,\ldots,n\}$ are the calibration factor values at the n raingauge sites, $d_{ij}$ is the 'distance' between sites i and j, and $\{a_k,\ k = 0,1,2,\ldots,n\}$ are a set of weighting coefficients. The choice of 'distance' measure controls the form of surface fitted. Possible alternatives include:

**(i) the simple Euclidean distance**

$$d_{ij} = \sqrt{x_{ij}^2 + y_{ij}^2} \tag{3.1.3a}$$

where $x_{ij}$ and $y_{ij}$ are the distances in the x and y coordinate directions (this is equivalent to building up the surface from a number of cones);

**(ii) the smoothed Euclidean distance**

$$d_{ij} = \sqrt{x_{ij}^2 + y_{ij}^2 + c^2} - c \tag{3.1.3b}$$

where c is a smoothing parameter (in this case the surface is built up from a number of hyperboloids);

**(iii) the exponential form of the Euclidean distance**

$$d_{ij} = \exp\left[-\frac{\sqrt{x_{ij}^2 + y_{ij}^2}}{\ell}\right] \tag{3.1.3c}$$

where the parameter $\ell$ is a scaling length; and

**(iv) the inverse distance**

$$d_{ij} = \frac{1}{1 + \sqrt{x_{ij}^2 + y_{ij}^2}\,/\ell}\ . \tag{3.1.3d}$$

Constraints imposed when fitting the surface can be used to affect the characteristics of its behaviour. The classical method of fitting a multiquadric (Hardy, 1971) forces the surface to pass exactly through the calibration factor value and no additional constraint is imposed. The original calibration study developed other fitting methods which, whilst requiring the surface to pass through the factor values, either impose a roughness minimization on the surface or constrain the surface to flatten away from the raingauge sites. A special case of the latter can be used to achieve the effect of a tendency towards no calibration with increasing distance away from the raingauge network.

In addition, variants of the above allow the surface to depart from the calibration factor values. This is achieved in cases (3.1.3a) and (3.1.3b) by replacing the distance measure $d_{ij}=0$ when $i=j$ by the offset parameter $-K$; for case (3.1.3c), $d_{ij}$ is changed from unity to $1+K$. The surface will then pass within a distance $a_iK$ of the calibration factor value at the ith gauge location. Both this and the roughness minimization fitting procedure allow multiquadric surfaces to be fitted to a field of calibration factor values to give a conservative calibration factor surface for use in adjusting the radar rainfall field.

The parameters $\epsilon_g$, $\epsilon_r$, c, $\ell$ and K of these variants of the surface fitting method will be referred to as the incidental parameters, and are optimised off-line using past records of radar and raingauge data. In contrast the parameters of the surface, the $\{a_j\}$ coefficients, are estimated in near real-time for each time frame for which a radar calibration is required (every 15 minutes in the present case). A more formal outline of the fitting methods and their associated solutions are given in the Appendix.

The recommended method for radar calibration, and that which is used operationally, has the following characteristics:

(i) a Euclidean distance function;
(ii) a flatness constraint;
(iii) a smoothing constant, $c=0$;
(iv) an offset parameter, $K=25$km; and
(v) a calibration factor with $\epsilon_g=3$ and $\epsilon_r=5$mm/hr i.e. $(R_g+3)/(R_r+5)$.

A second method which was slightly more accurate, but also more complex and time consuming was recommended if the above method caused raingauges to have too large an influence on the rainfall field away from the gauge location. This has the following characteristics:

(i) an inverse distance function with a scaling length parameter $\ell=30$km;
(ii) a flatness constraint;
(iii) a smoothing constant, $c=0$;
(iv) an offset parameter $K=0.35$;
(v) a calibration factor with $\epsilon_g=3$ and $\epsilon_r=5$mm/hr i.e. $(R_g+3)/(R_r+5)$.

## 3.2 RAINGAUGE-ONLY RAINFALL ESTIMATION METHOD

In order to complement the radar calibration method and to replace it if the radar is unavailable it was recommended that a rainfall estimator, based on raingauge values only, be implemented. The recommended raingauge surface fitting method has the following characteristics:

(i) an exponential form of the Euclidean distance, with a scaling length $\ell=20$km;
(ii) a flatness constraint;
(iii) a smoothing constant, $c=0$;
(iv) an offset parameter, $K=0.15$; and
(v) transformation of the raingauge values prior to surface fitting using the transform $\log(R_g)$ for $R_g>R_o$ and $(R_g/R_o)+\log(R_o)-1$ otherwise (any negative values resulting from back-transformation are replaced by zero). Here, $R_g$ is the rainfall rate as measured by the raingauge in mm $h^{-1}$, and $R_o$ is a constant equal to 4.5mm $h^{-1}$.

# 4. Reassessment of rainfall estimation methods over the entire Thames Basin

## 4.1 INTRODUCTION

This section contains the results of the major component of the study concerned with a reassessment of the methods for radar recalibration for use over the entire Thames Basin. The form of root mean square error criterion used to assess the performance of the methods is first introduced. Then results are presented for different methods, first using data prior to the change in the radar and then for data after the change. Initially the assessment focusses on application to the entire Thames Region and only later is the stability of the parameters for application to the original eastern (London and Lee Valley) area examined.

## 4.2 PERFORMANCE ASSESSMENT CRITERION

A root mean square quantised-adjusted log-error has been used as the measure of calibration accuracy in the present assessment. This form of root mean square error is given by

$$\text{rmse} = n^{-1} \Sigma e_g$$

where

$$e_g = \log\{1 + e'/(10 + r)\}$$

and

$$e' = \begin{cases} R_g - r - \delta_g & R_g - r > \delta_g \\ 0 & |R_g - r| \leq \delta_g \\ R_g - r + \delta_g & R_g - r < -\delta_g \end{cases} \quad . \tag{4.2.1}$$

Here, r is the recalibrated rainfall estimate, n is the number of estimates and $\delta_g$ is the rainfall intensity corresponding to one tip of the raingauge in the time-frame period. The n error estimates are obtained across all events and, for a given time-frame, relate to the set of errors obtained by "selected deletion". That is one gauge is omitted from the surface fitting procedure and used as the "truth" ($R_g$) and this is repeated for each gauge in the network.

## 4.3 ASSESSMENT BASED ON EVENTS PRIOR TO 16 AUGUST 1994

### 4.3.1 Comparison of operational rainfall estimation methods

A preliminary investigation, using the operational methods described in Section 3, compared the accuracy of rainfall estimation using decalibrated radar data and the recalibrated radar and the raingauge-only methods. The results are shown in the table below for the 50 events prior to 16 August 1994 across the entire Thames Region.

| **Rainfall estimation method** | **rmse** | **% improved** |
|---|---|---|
| Decalibrated radar | 0.0700 | 0 |
| Raingauge-only | 0.0568 | 19 |
| Recalibrated radar | 0.0488 | 30 |

It can be seen that there is a 30% improvement in using the recalibrated radar method over the decalibrated data and a 14% improvement using the recalibrated method over the raingauge-only estimate. The improvement obtained with the recalibrated method over the decalibrated radar data is consistent with the original calibration study.

### 4.3.2 Optimization of operational method

The operational recalibration method described in Section 3.1 was reoptimized over the 50 events. This involved 344,390 error estimates. It was found that the following incidental parameters gave the best results: $\epsilon_g=2.5$, $\epsilon_r=7$ and K=30km. There was a 3% improvement in using these parameters over the ones in operational use. Imposing the constraint $\epsilon_g = \epsilon_r$ and with K=30 km gave a general worsening in performance as indicated below.

| $\epsilon_g$, $\epsilon_r$ | **% increase in rmse** |
|---|---|
| 1 | 16.4 |
| 2 | 14.5 |
| 5 | 14.6 |
| 7 | 15.2 |

Use of $\epsilon_g=2$, $\epsilon_r=6$ and K=30km only reduced the accuracy by a trivial amount compared to the optimal set. Later it will be shown that other methods suggest the use of $\epsilon_g=2$ and $\epsilon_r=6$.

### 4.3.3 Explanatory variables for operational method

The optimal parameters found in Section 4.3.2 were used to explore whether any improvement in performance could be obtained through the use of explanatory variables. A description of the use of explanatory variables in an extended form of multiquadric surface fitting method is given in Section 3.5.3 of Moore *et al.* (1989) and is summarised here in the Appendix. The basic idea is the extension of the linear dependence function involving Euclidean distances to include explanatory variables thought to influence the radar calibration factors. The explanatory variables considered here are:

(i) height of raingauge above Ordance Datum;
(ii) Range of raingauge from radar; and
(iii) Height of radar beam above raingauge.

The following root mean square log-errors were obtained:

| Explanatory variable | Root mean square log-error |
|---|---|
| None | 0.04750 |
| Height of raingauge AOD | 0.04760 |
| Range of raingauge from radar | 0.04757 |
| Height of radar beam above raingauge | 0.04745 |

As can be seen there is little improvement in accuracy arising from the inclusion of explanatory variables. These results serve to confirm those in the original study which also concluded that the addition of explanatory variables was not worthwhile.

### 4.3.4 Optimization of reciprocal distance method

The reciprocal distance method described in Section 3.1 was reoptimized over the 50 events. It was found that the following parameters gave the best results: $\epsilon_g=2$, $\epsilon_r=6$, $\ell=16$km and K=0.39. This parameter set gives a 2.5% improvement over the results obtained using the originally recommended set. There is only a 0.5% improvement in accuracy of this reciprocal distance method over the Euclidean distance scheme described in Section 4.3.2. As in the original study this improvement may be considered too small to merit the use of this method, given its greater complexity.

### 4.3.5 Explanatory variables for reciprocal distance method

Inclusion of explanatory variables in the reciprocal distance method gave the incidental parameters $\epsilon_g=2$, $\epsilon_r=6$, $\ell=16$km and K=0.39; the assessment of accuracy is summarised in the table below:

| Explanatory variable | Root mean square log-error |
|---|---|
| None | 0.04726 |
| Height of raingauge AOD | 0.04740 |
| Range of raingauge from radar | 0.04733 |
| Height of radar beam above raingauge | 0.04723 |

Again there is little difference in the errors and the inclusion of explanatory variables does not seem justified.

### 4.3.6 Optimization of raingauge-only rainfall estimation method

The operational method described in Section 3.2 was reoptimized over all 50 events giving the following parameter values: K=0.25, $\ell=25$km and $R_0=4.5$mm $h^{-1}$.

### 4.3.7 Optimization of operational method over eastern area

The analysis of Sections 4.3.2 to 4.3.5 carried out for the entire Thames Region were repeated using only the raingauges in the eastern part of the Thames Region to investigate differences in optimized parameters. The accuracy statistics obtained for the eastern area relates to the 50 events and involve 235,467 error estimates.

The optimized parameters found for the standard operational method are: $\epsilon_g=2$, $\epsilon_r=6$ and K=20km. Using a value of K=30km gives a reduction in accuracy of only about 0.1%. It was noted at the end of Section 4.3.2 that using parameter values $\epsilon_g=2$, $\epsilon_r=6$ and K=30km for calibration over the entire Thames Region very nearly gives the best results (they were only about 0.01% worse than those optimized). This together with the results presented here lead to the conclusion that these are the best parameters to use on average for both combinations of gauges over the Thames area.

### 4.3.8 Explanatory variables for operational method over eastern area

Using explanatory variables and the incidental parameters $\epsilon_g=2$, $\epsilon_r=6$ and K=20 km, the following root mean square log-errors were obtained:

| Explanatory variable | Root mean square log-error |
|---|---|
| None | 0.04341 |
| Height of raingauge AOD | 0.04362 |
| Range of raingauge from radar | 0.04354 |
| Height of radar beam above raingauge | 0.04331 |

There is little difference in the errors and use of explanatory variables appears not to be worthwhile.

### 4.3.9 Optimization of reciprocal distance method over eastern area

In a strict sense the optimized parameters are as follows: $\epsilon_g=2$, $\epsilon_r=6$, $\ell=19$km and K=0.36. However, use of $\epsilon_g=2$, $\epsilon_r=6$, $\ell=20$km and K=0.35 only gives a worsening error of about 0.01% and provides a good compromise to the optimal set obtained for the entire region. Therefore, it is recommended that these parameters be used in the reciprocal method to give a consistent set of parameters across both networks of raingauges.

### 4.3.10 Explanatory variables for reciprocal distance method over eastern area

Using explanatory variables in the reciprocal distance method with parameters $\epsilon_g=2$, $\epsilon_r=6$, $\ell=19$ and K=0.36, gave the following root mean square log-errors

| Explanatory variable | Root mean square log-error |
|---|---|
| None | 0.04324 |
| Height of raingauge AOD | 0.04349 |
| Range of raingauge from radar | 0.04336 |
| Height of radar beam above raingauge | 0.04314 |

There is little difference in the errors indicating that the use of explanatory variables is not justified.

### 4.3.11 Optimization of raingauge-only rainfall estimation method over eastern area

The operational method described in Section 3.2 was reoptimized over all 50 events for the eastern area raingauges giving the following parameters: K=0.17, $\ell$=25km and $R_0$=4.5mm/h. It is desirable to find a common set of parameters which suit both eastern and western area raingauge networks. Using parameter values of K=0.2, $\ell$=25km and $R_0$=4.5mm/h only worsens the results in the eastern and western network by only 0.001% and worsens those in the eastern network by 0.01%.

### 4.3.12 Event-to-event changes in performance

Performance measures calculated for each of the 50 events using the optimized parameters (set 2: $\epsilon_g$=2.5, $\epsilon_r$=7 and K=30km) and those obtained from the original operational parameters (set 1: $\epsilon_g$=3, $\epsilon_r$=5 and K=25km) were compared. For 26 of the events the set 1 parameters gave more accurate rainfall estimates whilst for the other 24 events the set 2 parameters were best (Table 4.3.2). Closer analysis revealed that 19 out of the 26 events where set 1 was better occurred between June and November and that 18 out of the 24 events where set 2 was better occurred between December and May. In the original calibration study where the set 1 parameters were derived, 14 out of the 23 events occurred between June and November. Naturally this raised the question of whether there is some kind of seasonal variation in the optimum parameters possibly reflecting the behaviour of radar measurement of rainfall under different weather conditions. In order to test this conjecture the calibration scheme was reoptimized over both networks on a seasonal basis. The results are given below.

Optimization of the operational radar calibration method using events between December and May involved 24 events and 176,731 error estimates. Comparison of results obtained using set 1 parameters with those from set 2 show that for these months set 2 is 8.8% better than set 1, on average. When optimisation was carried out over all 50 events the parameters obtained were of an unacceptable order. The parameters in set 2 give estimation errors which are around 3.5% worse than the optimal set but are perhaps more intuitively acceptable. The same can be said when using $\epsilon_g$=2, $\epsilon_r$=6 and K=30km, which will be referred to as set 3.

Optimization of the operational radar calibration method using events between June to November involved 26 events and 167,659 error estimates. It was found that the set 1 parameters gave the best performance and comparison with the performance obtained using set 2 showed that for these months set 2 is 1.3% worse than set 1, on average.

***Table 4.3.2*** *Event-to-event changes in performance using set 1 and set 2 parameters across the entire Thames Region for events prior to 16 August 1994*

| **Event number** | **Season** | **Set 1 parameters** $\epsilon_g=3$, $\epsilon_r=5$, $K=25$ | **Set 2 parameters** $\epsilon_g=2.5$, $\epsilon_r=7$, $K=30$ |
|---|---|---|---|
| 1 | Dec-May | 0.0421 | 0.0416 |
| 2 | Dec-May | 0.0410 | 0.0399 |
| 3 | Dec-May | 0.0366 | 0.0396 |
| 4 | Dec-May | 0.0441 | 0.0411 |
| 5 | Dec-May | 0.0483 | 0.0485 |
| 6 | Jun-Nov | 0.0311 | 0.0314 |
| 7 | Jun-Nov | 0.0499 | 0.0540 |
| 8 | Jun-Nov | 0.0545 | 0.0543 |
| 9 | Jun-Nov | 0.0048 | 0.0051 |
| 10 | Dec-May | 0.0689 | 0.0671 |
| 11 | Dec-May | 0.0424 | 0.0418 |
| 12 | Dec-May | 0.0436 | 0.0430 |
| 13 | Dec-May | 0.0568 | 0.0434 |
| 14 | Dec-May | 0.0206 | 0.0185 |
| 15 | Dec-May | 0.0394 | 0.0381 |
| 16 | Jun-Nov | 0.0492 | 0.0504 |
| 17 | Jun-Nov | 0.0520 | 0.0578 |
| 18 | Jun-Nov | 0.0586 | 0.0601 |
| 19 | Jun-Nov | 0.0493 | 0.0519 |
| 20 | Jun-Nov | 0.0280 | 0.0294 |
| 21 | Jun-Nov | 0.1433 | 0.1159 |
| 22 | Dec-May | 0.0248 | 0.0212 |
| 23 | Dec-May | 0.0159 | 0.0133 |
| 24 | Dec-May | 0.0154 | 0.0146 |
| 25 | Dec-May | 0.1175 | 0.1006 |
| 26 | Jun-Nov | 0.1195 | 0.0849 |
| 27 | Jun-Nov | 0.0651 | 0.0657 |
| 28 | Jun-Nov | 0.0479 | 0.0512 |
| 29 | Jun-Nov | 0.0641 | 0.0663 |
| 30 | Jun-Nov | 0.0660 | 0.0651 |
| 31 | Jun-Nov | 0.0390 | 0.0408 |
| 32 | Dec-May | 0.0225 | 0.0231 |
| 33 | Dec-May | 0.0346 | 0.0371 |
| 34 | Dec-May | 0.0614 | 0.0526 |
| 35 | Dec-May | 0.0225 | 0.0232 |
| 36 | Dec-May | 0.0428 | 0.0408 |
| 37 | Dec-May | 0.0619 | 0.0679 |
| 38 | Jun-Nov | 0.0546 | 0.0608 |
| 39 | Jun-Nov | 0.0290 | 0.0315 |
| 40 | Jun-Nov | 0.0530 | 0.0583 |
| 41 | Jun-Nov | 0.0582 | 0.0651 |
| 42 | Jun-Nov | 0.0004 | 0.0018 |
| 43 | Jun-Nov | 0.0521 | 0.0554 |
| 44 | Jun-Nov | 0.0159 | 0.0158 |
| 45 | Dec-May | 0.0344 | 0.0297 |
| 46 | Dec-May | 0.0215 | 0.0198 |
| 47 | Dec-May | 0.0309 | 0.0294 |
| 48 | Dec-May | 0.0226 | 0.0227 |
| 49 | Dec-May | 0.0323 | 0.0348 |
| 50 | Jun-Nov | 0.0235 | 0.0234 |
| Over all events | | 0.0488 | 0.0475 |

In conclusion, there is some indication of seasonal dependence in the parameters based on the events before August 1994. The use of the original (set 1) parameters produces a far larger worsening in performance, over the optimal (set 2) or modified optimal (set 3) parameters, between December and May than the improvement in performance between June and November over set 2 or set 3. It is recommended that the parameter set 2 or set 3 is used on the pre-August 1994 data for operational purposes if no seasonal dependance is introduced. Overall set 3 is preferred.

## 4.4 ASSESSMENT BASED ON EVENTS AFTER 16 AUGUST 1994

Optimization of the incidental parameters was carried out for the ten events after 16 August 1994 to investigate the effect of the adjustment to the radar and removal of the factor of 2 from the at-site calibration on the parameters. A total of 73,586 errors were involved in the rmse performance criteria using raingauges across the entire Thames Region and 40,769 errors when only raingauges for the eastern area were used.

### 4.4.1 Optimization of operational method

Optimization of the operational method using raingauges over the entire Thames Region produced dramatic changes in the parameters compared to those derived from the pre-August 1994 data. The best parameters were $\epsilon_g=7$, $\epsilon_r=5$ and K=49km. However, there was only a 0.6% worsening using $\epsilon_g=\epsilon_r=1$ and K=55km, here designated as set 4, and a 1% worsening using $\epsilon_g=\epsilon_r=1$ and K=25km. Comparison of the performance obtained using the set 4 parameters with those using the original operational (set 1) parameters (Section 4.3.11 above) on an event basis is shown in Table 4.4.1. Set 4 is best for all events giving an 8% improvement overall.

### 4.4.2 Explanatory variables for operational method

The parameters used in this case were $\epsilon_g=\epsilon_r=1$ and K=55km and the performance of the different explanatory variables is summarised below:

| Explanatory variable | Root mean square log-error |
|---|---|
| None | 0.03169 |
| Height of raingauge AOD | 0.03183 |
| Range of raingauge from radar | 0.03170 |
| Height of radar beam above raingauge | 0.03186 |

It can be seen that using no explanatory variables gives the best calibration, on average.

### 4.4.3 Optimization of reciprocal distance method

The best parameters were $\epsilon_g=10$, $\epsilon_r=7$, $\ell=52$km and K=0.74. However, there was only a 0.5% worsening using $\epsilon_g=\epsilon_r=1$, $\ell=30$km and K=0.6. Note that the best set of parameters in the operational method gave a rmse performance statistic of 0.0315 compared to 0.0316

***Table 4.4.1*** *Event-to-event changes in performance using set 1 and set 4 parameters across the entire Thames Region for the events after 16 August 1994.*

| **Event number** | **Set 1 parameters** $\epsilon_g=3$, $\epsilon_r=5$, K=25 | **Set 4 parameters** $\epsilon_g=\epsilon_r=1$, K=55 |
|---|---|---|
| 1 | 0.0381 | 0.0338 |
| 2 | 0.0262 | 0.0230 |
| 3 | 0.0301 | 0.0275 |
| 4 | 0.0417 | 0.0374 |
| 5 | 0.0188 | 0.0174 |
| 6 | 0.0158 | 0.0149 |
| 7 | 0.0239 | 0.0198 |
| 8 | 0.0546 | 0.0499 |
| 9 | 0.0374 | 0.0366 |
| 10 | 0.0327 | 0.0315 |
| Over all events | 0.0344 | 0.0317 |

with the best parameters here. So, for these ten events at least, the reciprocal distance method is no longer out-performing the operational method.

### 4.4.4 Explanatory variables for reciprocal distance method

The parameters used were $\epsilon_g=\epsilon_r=1$, $\ell=30$km and K=0.6 and the performances obtained using the different explanatory variables is summarised below:

| **Explanatory variable** | **Root mean square log-error** |
|---|---|
| None | 0.03180 |
| Height of raingauge AOD | 0.03194 |
| Range of raingauge from radar | 0.03181 |
| Height of radar beam above raingauge | 0.03120 |

In this case using the height of the radar beam above a raingauge as an explanatory variable improves the accuracy by about 2%. It is also 1.5% more accurate than using no explanatory variables in the standard method. However, this small increase in accuracy is at the cost of the greater computing power demanded of the reciprocal distance with explanatory variables method.

### 4.4.5 Optimization of operational method over eastern area

Whilst the best parameters were $\epsilon_g=6$, $\epsilon_r=4$ and K=69km, there was only a 1.1% worsening using $\epsilon_g=\epsilon_r=1$ and K=55km and a 2.1% worsening using $\epsilon_g=\epsilon_r=1$ and K=25km.

### 4.4.6 Explanatory variables for operational method over eastern area

Using the parameter set $\epsilon_g=\epsilon_r=1$ and K=55km the following performance statistics were obtained:

| Explanatory variable | Root mean square log-error |
|---|---|
| None | 0.03023 |
| Height of raingauge AOD | 0.03048 |
| Range of raingauge from radar | 0.03029 |
| Height of radar beam above raingauge | 0.03048 |

It can be seen that using no explanatory variables gives the best calibration, on average.

### 4.4.7 Optimization of reciprocal distance method over eastern area

Whilst the best parameters were $\epsilon_g=11$, $\epsilon_r=8$, $\ell=41$km and K=1.05 there was only a 1.1% worsening using $\epsilon_g=\epsilon_r=1$, $\ell=30$km and K=0.6. Note that the best set of parameters in the operational method gave a performance statistic of 0.0299 compared to 0.0300 obtained using the best parameters here. So, again for these ten events, the reciprocal distance method is no longer out-performing the operational method.

### 4.4.8 Explanatory variables for reciprocal distance method over eastern area

The parameters used were $\epsilon_g=\epsilon_r=1$, $\ell=30$km and K=0.6 and the following performance statistics were obtained:

| Explanatory variable | Root mean square log-error |
|---|---|
| None | 0.03039 |
| Height of raingauge AOD | 0.03060 |
| Range of raingauge from radar | 0.03044 |
| Height of radar beam above raingauge | 0.03062 |

It can be seen that using no explanatory variables gives the best calibration, on average.

## 4.5 ACCURACY USING WESTERN AREA GAUGES ONLY

A feature of the telemetry system operated at the Flood Warning Centre at Waltham Cross is that the situation can arise where data from the raingauges in the western area only are available. This raises the question as to how accurate the recalibrated radar data are over the eastern area in such circumstances; typically only about 20 of the 65 to 70 raingauges are available. The change in accuracy has been investigated by excluding the eastern area gauges in the calibration step but using these to assess accuracy of rainfall estimation over the eastern area. The results are summarised in the table below; 235,467 error estimates are involved in the 50 event assessment and 53,638 in the 10 event assessment.

| **Rainfall estimation method** | **rmse for 50 events** | **% improvement** | **rmse for 10 events** | **% improvement** |
|---|---|---|---|---|
| Decalibrated radar | 0.0674 | 0 | 0.0417 | 0 |
| Recalibrated radar: all gauges | 0.0434 | 36 | 0.0286 | 31 |
| Recalibrated radar: western gauges | 0.0582 | 14 | 0.0327 | 22 |

These results demonstrate that, whilst there is a reduction in rainfall estimation accuracy over the eastern area due to the use of only western gauges for calibration, the improvement over the use of the uncalibrated radar is still substantial (14 and 22% for the 50 and 10 event cases). Thus we can conclude that recalibration is still worthwhile when only raingauges over the western area are available.

# 5. Exploratory Investigations

## 5.1 INTRODUCTION

In this section a number of exploratory investigations are reported which provided background to the main work reported in Section 4. The first involves resolving the problem of the reported poor performance of the recalibration method when applied to the extended Thames Region. This investigation is considered in the next sub-section. Other issues investigated, in the light of the more recent data, include areas of radar anomaly and the effect of range and the beam infill area on the radar calibration. The average form of the calibration surface is also considered.

## 5.2 OPERATIONAL PROBLEMS WITH RADAR RECALIBRATION

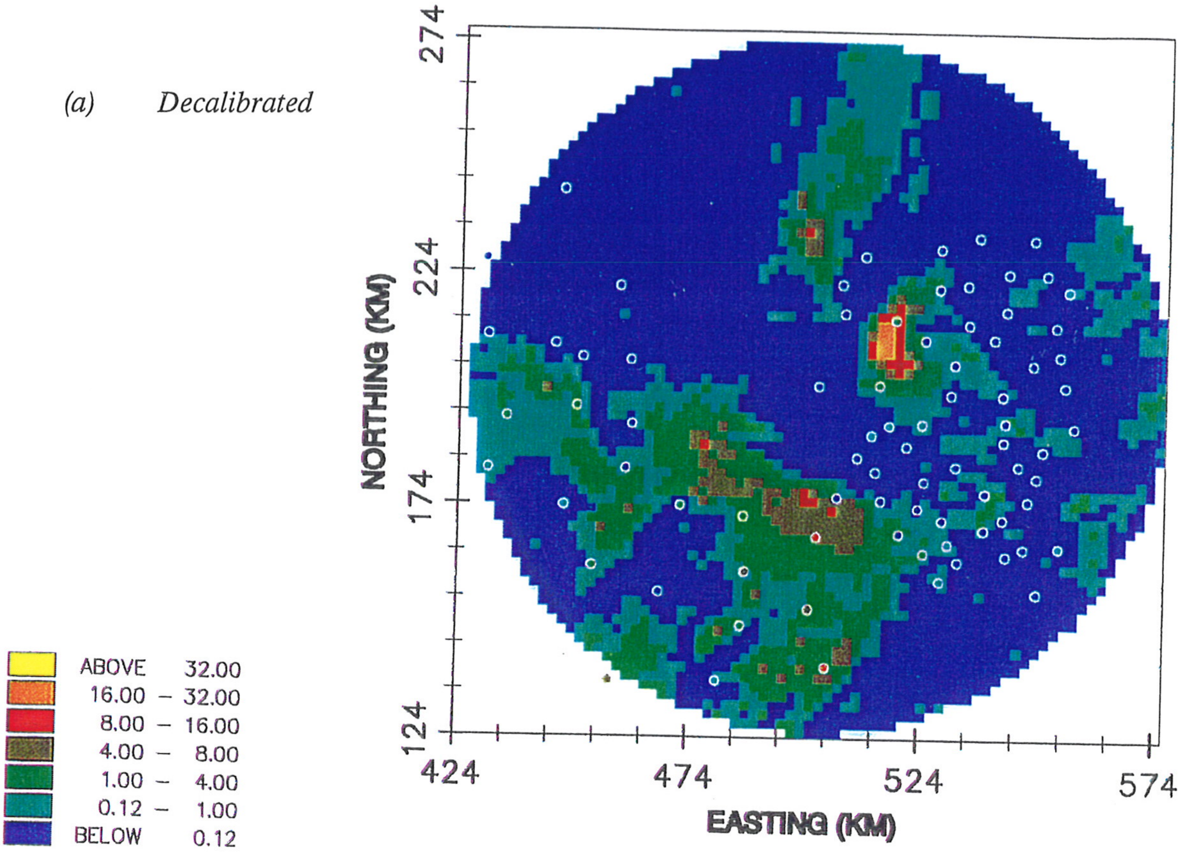
At the inception of the study, the NRA reported observing overestimation of rainfall over the original London and Lee Valley calibration area when the recalibration method was applied over the entire Thames Region, incorporating raingauges over the extended area. Recalibrations for the same period obtained using recalibration software at IH showed no evidence of this effect, suggesting that the problem stemmed from the software and data in use by the NRA and not from a failing of the recalibration method.

Close inspection revealed that the problem arose primarily through incorrect calculation of the Euclidean distances in test code developed by the NRA to investigate the validity of extending the recalibration method to apply over the entire Thames Region. Two other problems were exposed, affecting both the operational and test code, but having a lesser impact on the recalibration performance. These related to a shift of 2 km in the northing position of the radar data and, for five of the raingauges, a mis-specification of the associated 2 km radar cell. These problems have now been fully resolved, with the NRA and IH codes now giving consistent results. As an example, Figure 5.2.1 shows the radar field at 10:00 4 January 1994 in decalibration form, in recalibrated form from the faulty NRA test code, from the corrected NRA code and from the IH code. The latter two fields are marginally different on account of a slightly different set of raingauges being used.

## 5.3 AREAS OF ANOMALY

The rainfall intensity for each radar pixel, averaged over the 50 and 10 events used in assessment, are shown in Figure 5.3.1. These are obtained using the decalibrated data and serve to expose the areas of anomaly used to identify coincident raingauges which have been excluded from the recalibration method (see Section 2.1). The areas of anomaly are broadly consistent with those identified in the original calibration study and correspond to blockages, such as masts, pylons and towers in the radar field of view, and poor estimation at close range. A clear difference exists in the average rainfall intensities before and after the adjustment to the radar and removal of the factor of two, with 0.6 compared to 0.2 mm $h^{-1}$ dominating in the period prior to adjustment. The beam infill area, where the 1.5° beam replaces the 0.5° beam rainfall estimate, is delineated as a rectangular feature to the south, particularly in the 50 event average field.

*(a)* *Decalibrated*



*(b)* *Recalibrated using faulty NRA test code*

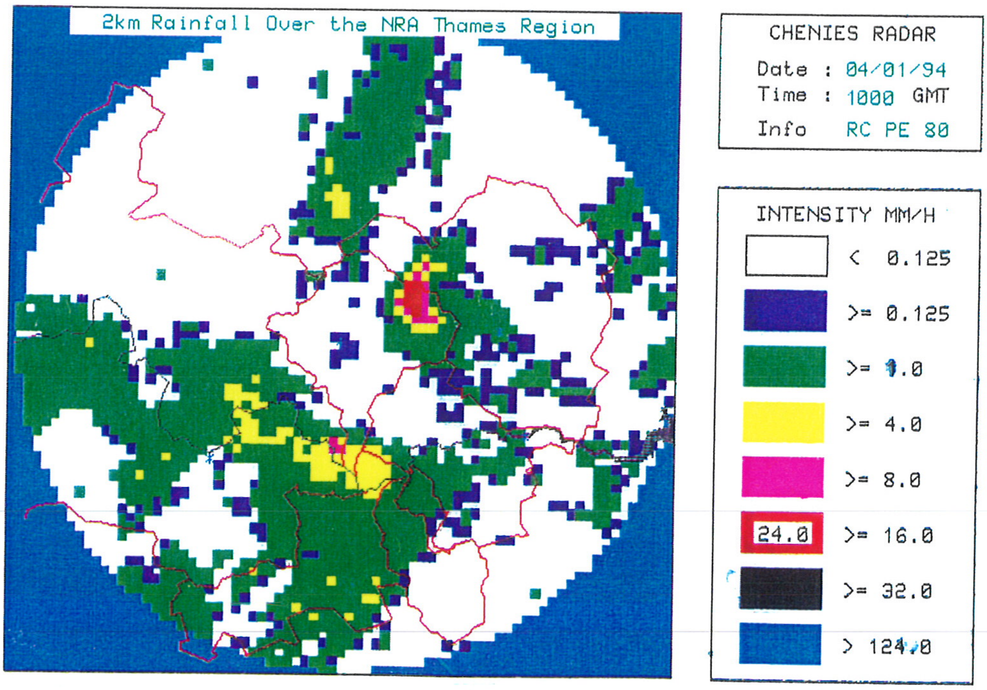
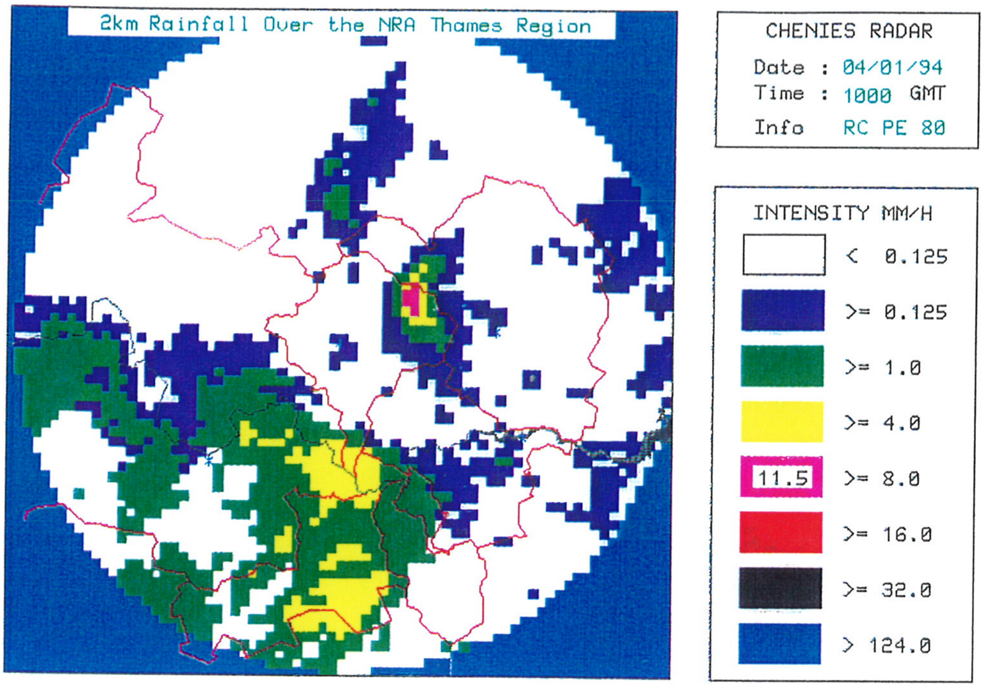


***Figure 5.2.1*** *Radar fields for 10:00 4 January 1994 illustrating the operational problem and its correction*

(c) *Recalibrated using corrected NRA code*



(d) *Recalibrated using IH code*

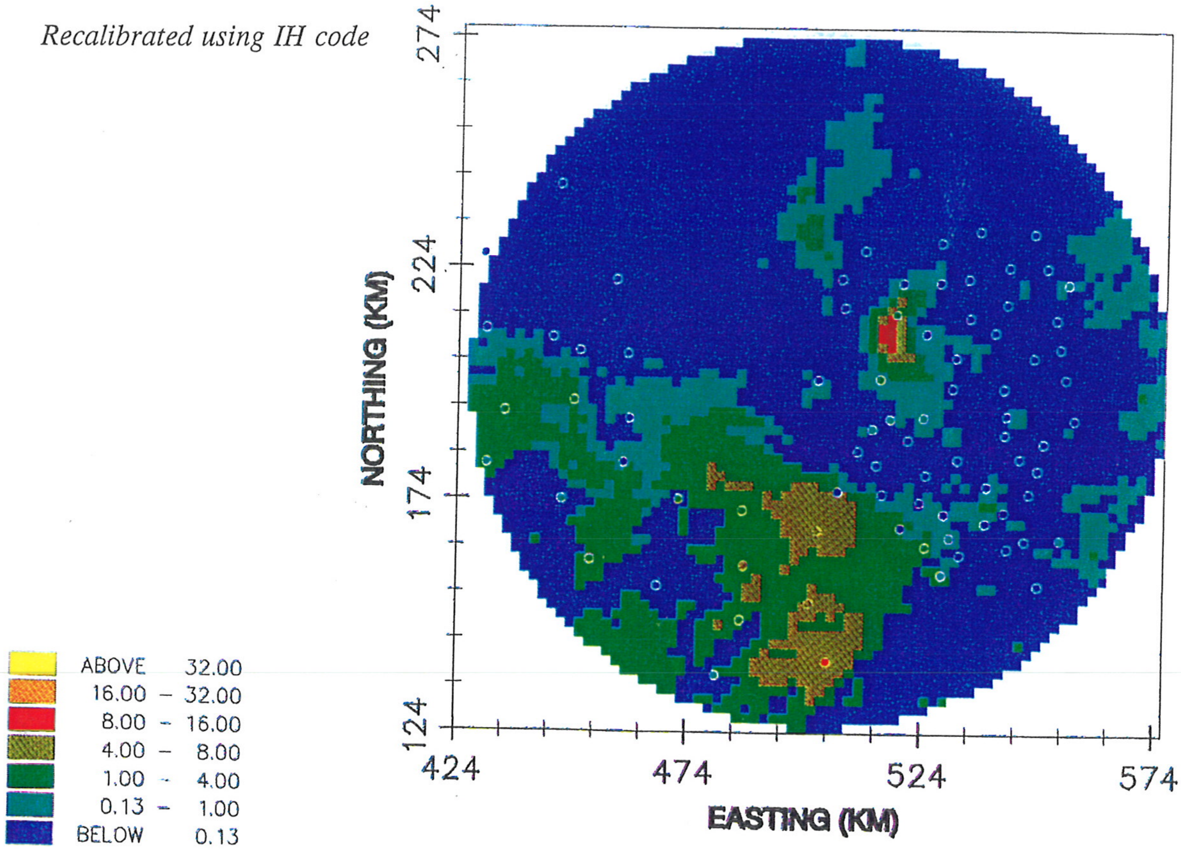
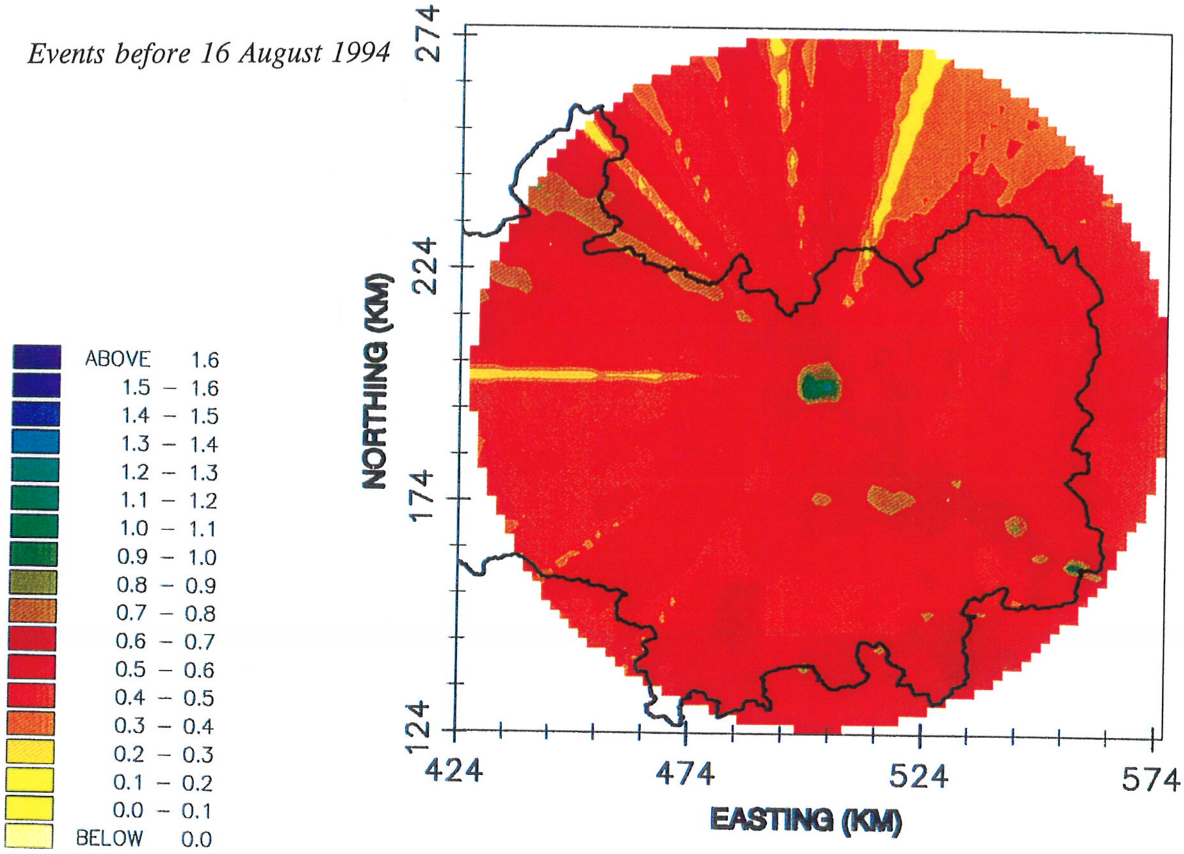


***Figure 5.2.1 cont.*** *Radar fields for 10:00 4 January 1994 illustrating the operational problem and its correction*

*(a)* *Events before 16 August 1994*



*(b)* *Events after 16 August 1994*

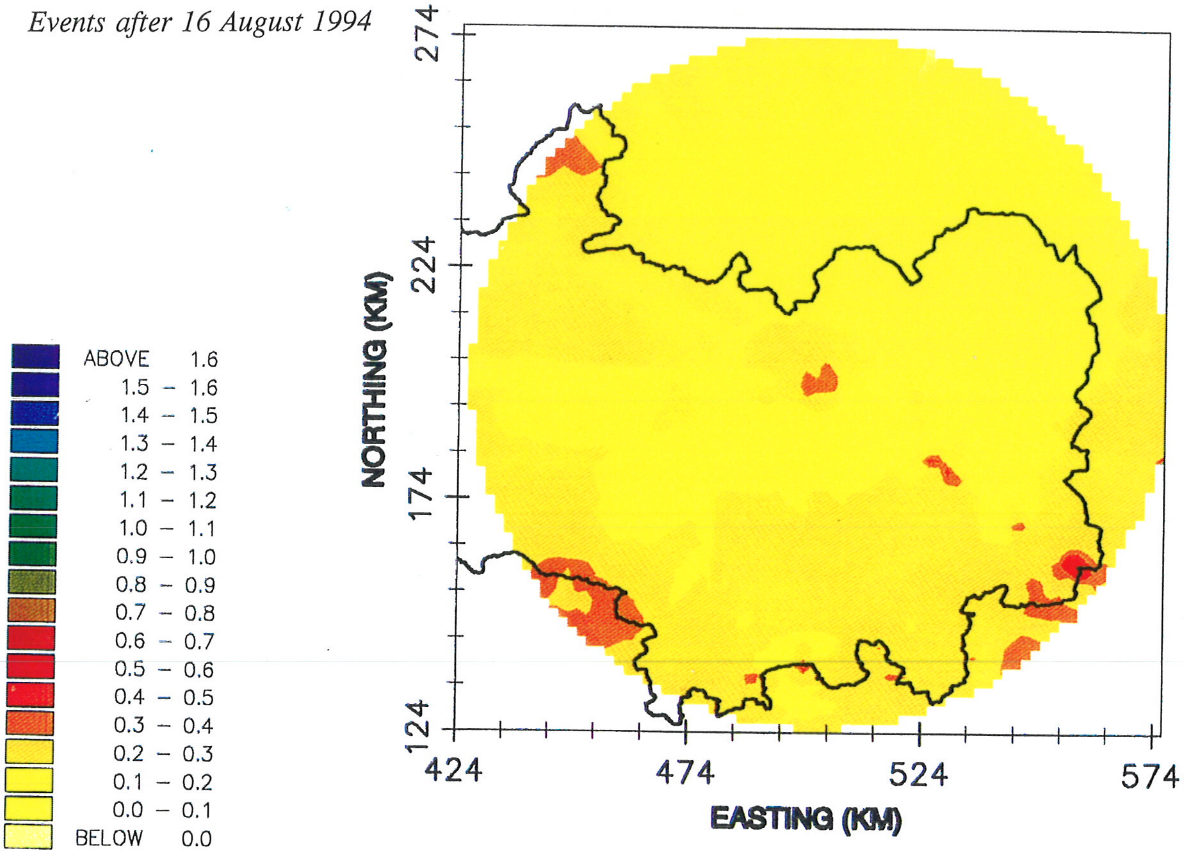


***Figure 5.3.1*** *Radar rainfall anomaly maps, calculated as average rainfall intensity in mm $h^{-1}$ over the set of events indicated*

## 5.4 RANGE-DISTANCE EFFECTS ON RADAR RAINFALL INTENSITY

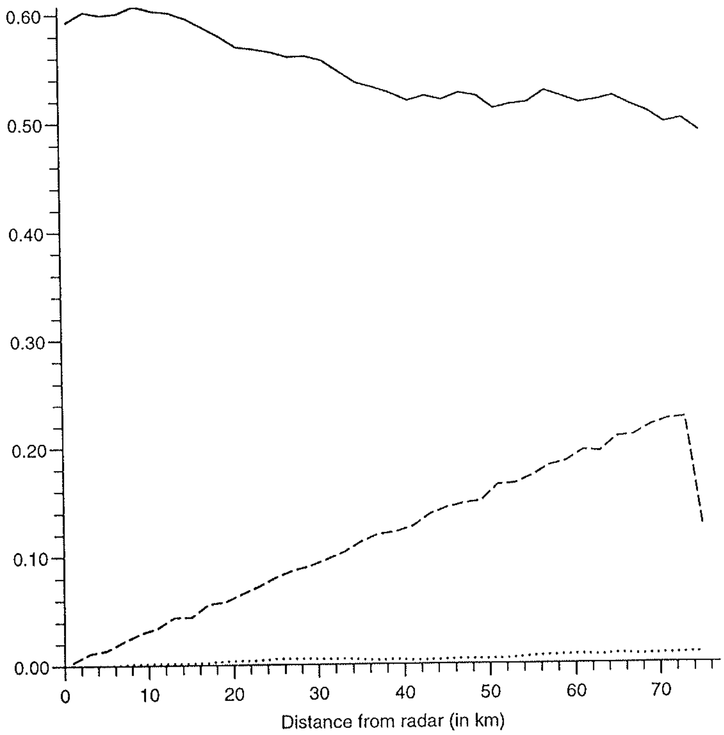
The general reduction in rainfall intensity with range observed in the original study was investigated here in the light of the more recent data. Figure 5.4.1 shows the average rainfall intensity at different ranges, averaged over the selected events. All results are obtained using data with anomalies removed by spatial interpolation. The result for the 50 events prior to radar adjustment confirm the earlier findings. However, an overall increase with range is seen in the average for the 10 most recent events. This may be a sampling artifact as the original study exposed the event-to-event variation of the range effect. Figure 5.4.2 provides similar results but with pixels in the beam infill area (using the 1.5° beam rainfall estimate instead of that from the 0.5° beam) treated separately. This exposes a higher rainfall intensity from pixels within the beam infill area out to a range of 46 km for the 50 event average. Beyond this the rainfall intensity in the beam infill area reduces markedly, presumably on account of the beam overshooting the rain-bearing clouds at longer range. A similar increase in rainfall intensity over the beam infill area is exposed by the 10 event average but in this case rainfall calculated from both beams continue to increase in intensity with increasing range. This may again be an artifact of sampling but warrants further investigation.

## 5.5 CALIBRATION FACTOR SURFACES

It is of interest to look at the event average calibration factor surfaces to gain an insight into the general behaviour of the surface fitting method. Figure 5.5.1 shows the calibration factor surfaces averaged for the 50 and 10 events, using the set 2 and set 4 parameters respectively. The calibration factors are slightly lower for the events prior to the adjustment of the radar and removal of the factor of 2, with values of 1.04 dominating compared to 1.1. There is a tendency in the 10 event average surface for calibration factors to increase southwards. The effect is more localised on the southern boundary of the Thames Region for the 10 event average surface. This seems to be related to orographic enhancement effects on rainfall associated with the North Downs.

Note that the effect of the anomalies persist in the field because these are not presently removed in the calibration procedure and because of how zero radar rainfall values are handled. If a radar pixel takes a zero value then the calibration factor also takes a zero value; at other times the calibration factors are independent of the radar values not coincident with raingauges. This has the effect of exposing the anomalous areas which are clearly absent from the fitted calibration factor surface.

(a) *Average over 50 events*



(b) *Average over 10 events*

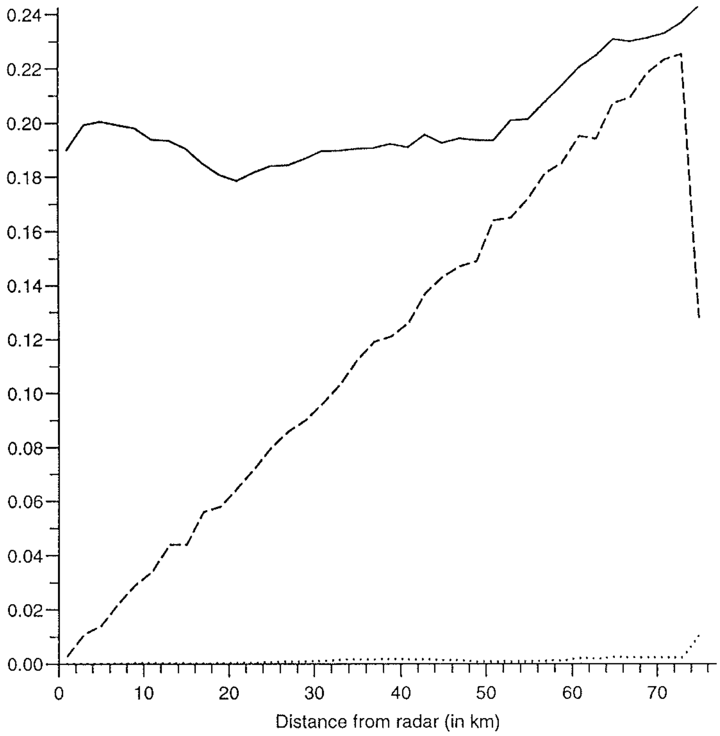
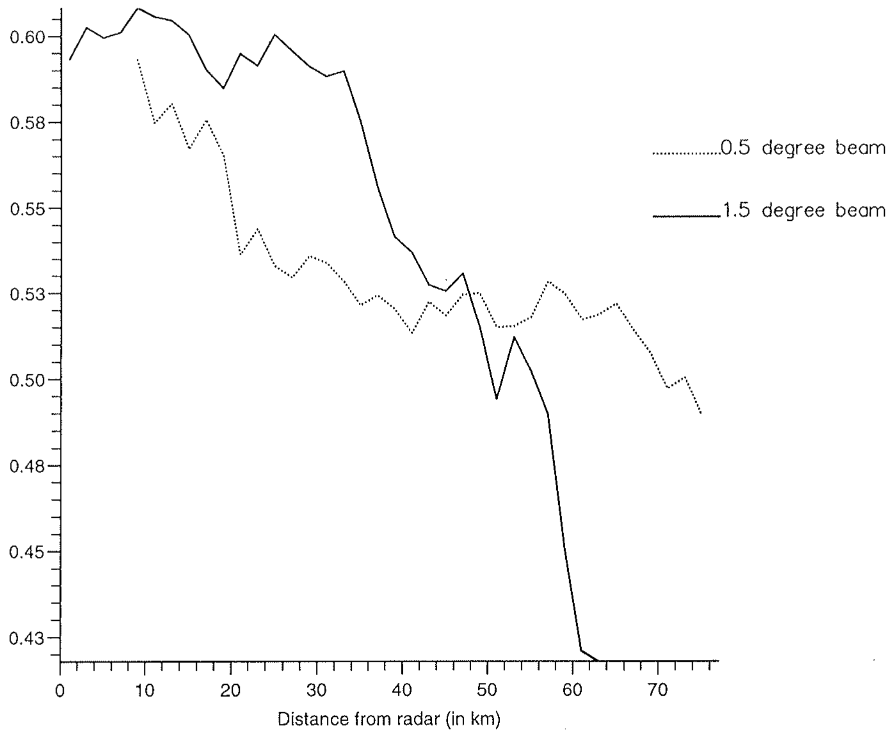


***Figure 5.4.1*** *Variation of average rainfall intensity with range from radar (Dots: standard deviation between cells at same distance; Dashes: number of contributing cells divided by 1000)*

*(a)* *Average over 50 events*



*(b)* *Average over 10 events*

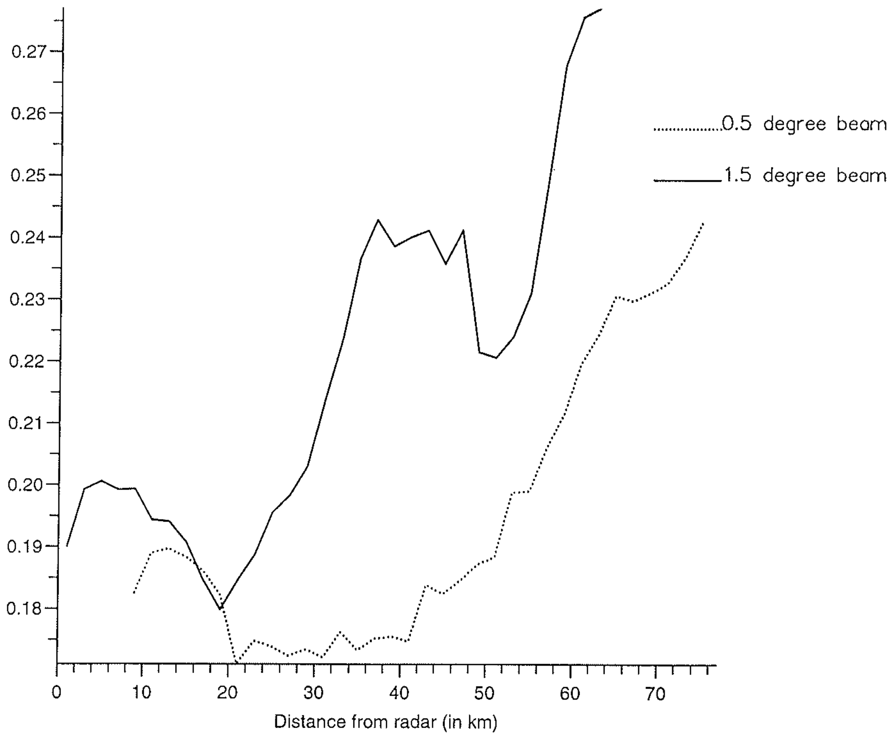
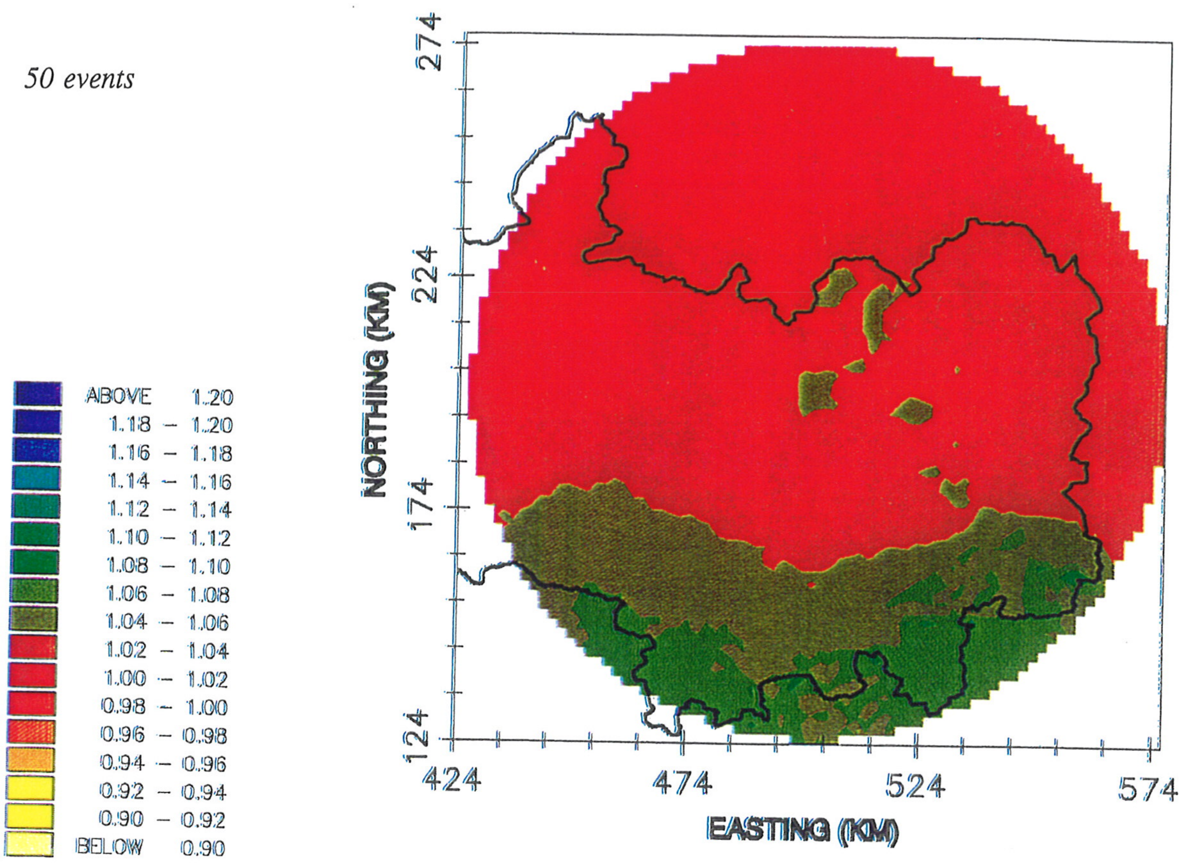


***Figure 5.4.2*** *Variation of average rainfall intensity with range from radar, with radar pixels in the beam infill area (using the 1.5° beam) treated separately.*

*(a)* *50 events*



*(b)* *10 events*

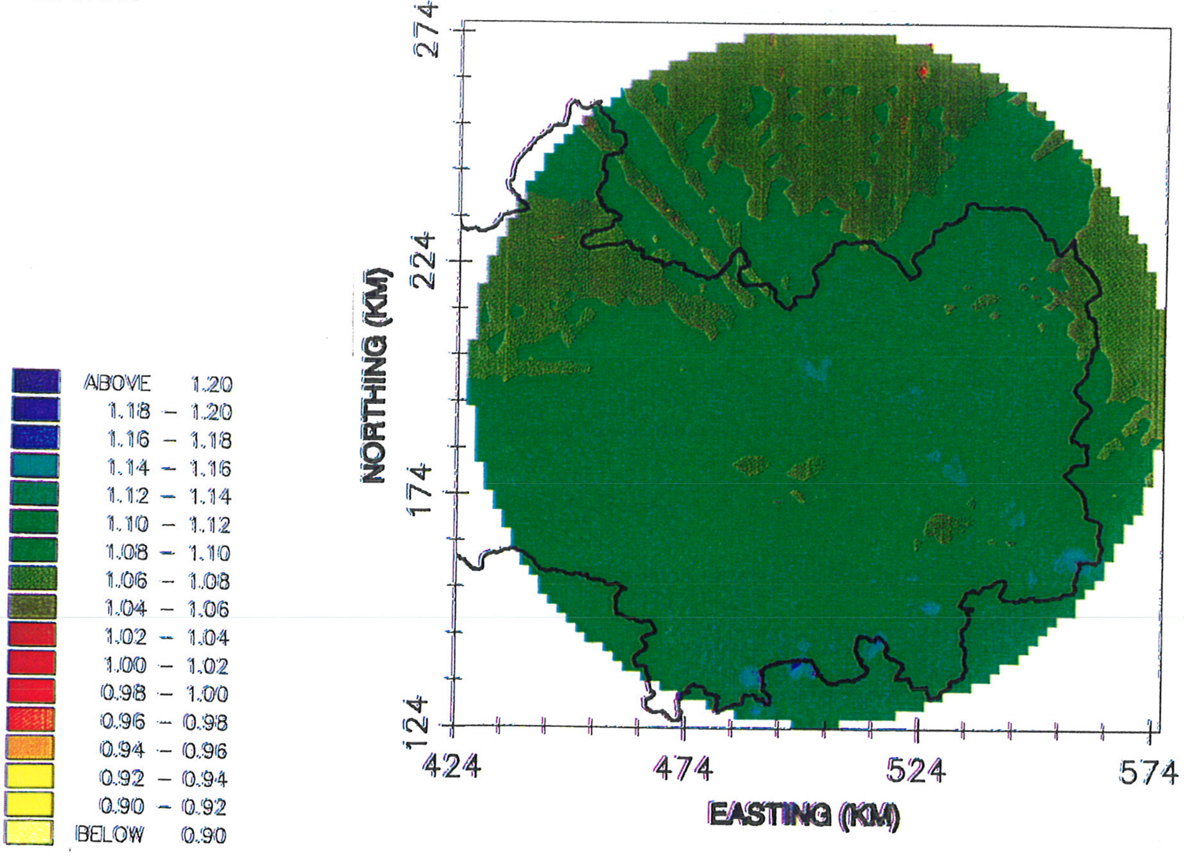


***Figure 5.5.1*** *Average calibration factor surface.*

# 6. Conclusions and Recommendations

## 6.1 CONCLUSIONS

*January 1990 to 16 August 1994 assessment*

(i) For 50 rainfall events between January 1990 and 16 August 1994 the operational method of recalibration gives a 30% improvement over the use of uncalibrated radar data and a 14% improvement over a raingauge-only estimate, when judged over the entire Thames Basin.

(ii) A further 3% improvement in accuracy, on average, can be achieved using the incidental parameters $\epsilon_g=2.5$, $\epsilon_r=7$ and K=30km instead of the operational set $\epsilon_g=3$, $\epsilon_r=5$ and K=25km. Almost as good accuracy (0.017 worse) can be obtained using $\epsilon_g=2$, $\epsilon_r=6$ and K=30km and this set is preferred overall for use with the pre 16 August 1994 data, based on separate assessments over the Thames Basin and the eastern area only and a seasonal analysis. The optimal eastern area set was only 0.1% better.

(iii) Use of explanatory variables, such as the height of the radar beam above the raingauge, in an extended form of the calibration factor surface fitting method failed to improve the accuracy of rainfall estimates.

(iv) Whilst the use of reciprocal distance in place of Euclidean distance gave some improvement (0.5%) the advantage was not judged sufficient to recommend this more complex scheme for operational use. The preferred parameter set, taking into account results from the entire Thames Basin and the eastern area, are $\epsilon_g=2$, $\epsilon_r=6$, $\ell=20$km and K=0.35.

(v) A new optimal parameter set for the raingauge-only rainfall estimation method is K=0.2, $\ell=25$km and $R_o=4.5$ mm $h^{-1}$. This gave negligible improvement in performance over the operational set but is generally preferred. The value for K is a compromise, with .25 and .17 being optimal for the entire and eastern areas respectively, but with no worse than a 0.01% worsening of performance, on average.

(vi) An event analysis revealed seasonal differences in performance obtained from different sets of incidental parameters with the new parameters improving performance for events in the months between December and May, but with a slight worsening (1.3%) in the other months. These results failed to provide sufficient justification for the use of seasonally varying parameters. If there is a wish to do so then $\epsilon_g=3$, $\epsilon_r=5$ and K=25km could be used in place of the recommended set for the months June through to November.

*Post 16 August 1994 assessment*

(vii) For 10 events between 16 August 1994 and 31 October 1994, following adjustment of the London Weather Radar and removal of the factor of 2 from the at-site calibration, the optimal parameter set for recalibration changed markedly. The preferred set is $\epsilon_g=\epsilon_r=1$ and K=55km giving an 8% improvement, on average, compared with the operational set. This set only gave a 1.1% worsening in performance for the eastern area when compared to the best set.

(viii) Use of variants, such as explanatory variables and reciprocal distance based calibration surface fitting, again are not justified.

Finally, Table 6.1.1 summarises the performance of the rainfall estimators, using the revised parameter sets for the pre- and post- 16 August 1994 events.

*Table 6.1.1 Comparison of rainfall estimators using revised parameter sets*

| Rainfall estimation method | rmse | % improved |
|---|---|---|
| **(a) 50 events** | | |
| Decalibrated radar | 0.0700 | 0 |
| Raingauge-only | 0.0567 | 19 |
| Recalibrated radar | 0.0475 | 32 |
| **(b) 10 events** | | |
| Decalibrated radar | 0.0439 | 0 |
| Raingauge-only | 0.0440 | 0 |
| Recalibrated radar | 0.0317 | 28 |

## 6.2 RECOMMENDATIONS

(i) The form of the operational Local Radar Calibration method is satisfactory but it is recommended that the incidental parameters be modified as follows:

(a) January 1990 to 16 August 1994

$\epsilon_g=2$, $\epsilon_r=6$ mm $h^{-1}$ and K=30km

(b) Post 16 August 1994

$\epsilon_g=\epsilon_r=1$ mm $h^{-1}$ and K=55km.

(ii) Whilst the change in incidental parameters since 16 August 1994 is thought to reflect the adjustment to the radar, it may also in part be associated with sampling effects related to the 10 events used for estimation. It is recommended that further events, spanning over a range of seasons, be used to check the stability of the new parameter set at some later date.

(iii) The original study area 60 km square was not affected by areas of radar anomaly and consequently there was no need to remove their effect. Extension of the method to the entire Thames Region now makes incorporation of a correction for radar anomalies necessary to meet the requirement for complete rainfall fields over the area. It is recommended that the anomaly correction and clutter suppression procedures developed for the London Weather Radar Local Rainfall Forecasting Study (Moore *et al.*, 1992; 1994a) be implemented as a preprocessing step to the radar calibration and rainfall forecasting procedures. This approach has already been adopted for IH's HYRAD system for radar preprocessing, calibration, rainfall forecasting and image display (Moore *et al.*, 1994c).

(iv) Raingauges used for region-wide recalibration should omit those identified in Table 2.1 as being in areas of anomaly or outside the 76 km radar range circle.

(v) The form of the operational raingauge-only rainfall estimation method is satisfactory but should be modified to have the following incidental parameters:

$K=0.2$, $\ell=25$km and $R_0=4.5$ mm $h^{-1}$.

(vi) When only raingauge data are available for the western area gauges for calibration it is recommended that the radar is still recalibrated over the entire Thames area, since the recalibrated data will still be more accurate than the uncalibrated radar, on average.

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# Appendix  Multiquadric Surface Fitting

The surface fitting method employed by the Local Calibration procedure is based on an extended form of the multiquadric presented by Hardy (1971). First, let $z_i$ be the calibration factor values defined at the n raingauge locations, having grid coordinates $\underline{x}_i = (u_i, v_i)$. The multiquadric calibration surface is defined as the weighted sum of n distance, or basis functions centred on each gauge; that is

$$s(\underline{x}) = \sum_{j=1}^{n} a_j \, g(\underline{x}-\underline{x}_j) + a_0 \tag{A.1}$$

where $\{a_j, j=0,1,2,\ldots,n)$ are parameters of the surface. The distance function used is the simple Euclidean distance

$$g(\underline{x}) = \|\underline{x}\| = \sqrt{(u^2+v^2)} \tag{A.2}$$

which corresponds to building up the surface from a set of n right-sided cones, each centred on one of the n raingauge locations.

Formally, estimation of the $a_j$ weights is achieved as follows. Equation (A.1) for

$$s(\underline{x}_i) = \sum_{j=1}^{n} a_j \, g(\underline{x}_i-\underline{x}_j) + a_0 = z_i \qquad (i=1,2,\ldots,n) \tag{A.3}$$

expressed in matrix form is

$$\underline{G}\,\underline{a} + a_0\underline{1} = \underline{z} \tag{A.4}$$

where $\underline{G}$ is an n by n matrix with the (i,j)'th element given by $G_{ij} = g(\underline{x}_i - \underline{x}_j)$, $\underline{1}$ is a unit vector of order n, and $\underline{z}$ is the vector containing the n calibration factor values. To avoid anomalies in the surface form away from n raingauge locations, a requirement for flatness at large distances is imposed through the constraint

$$\underline{a}^T\underline{1} = 0. \tag{A.5}$$

For the Euclidean distance function of cone type this constraint corresponds to a requirement of zero-slope with increasing distance from the raingauge network. Solution of equation (A.4) subject to constraint (A.5) for the weighting coefficients gives

$$\begin{aligned} a_0 &= (\underline{1}^T\underline{G}^{-1}\underline{z})/(\underline{1}^T\underline{G}^{-1}\underline{1}) \\ \underline{a} &= \underline{G}^{-1}(\underline{z} - a_0\underline{1}) \end{aligned} \tag{A.6}$$

An important feature of the Local Calibration procedure is the forming of a conservative calibration factor surface by adopting a fitting method which allows the surface to depart from the actual calibration factor values. This is achieved by allowing the Euclidean distance $g(\underline{x}_i - \underline{x}_i) = g(\underline{0})$, normally zero, to take a value -K. The result is a surface which passes within a distance $a_i$ K of the calibration factor value for the i'th raingauge; K is referred to as the offset parameter. The problem of discontinuities is avoided by using this form in the estimation of the weights, $a_j$, and using the normal form in calculating the surface values for radar calibration of the full field. The constraint of equation (A.5) ensures that the "errors", introduced by using $g(\underline{0}) = 0$ in equation (A.1) (and not -K) when forming the surface for calibration, add up to zero.

The surface fitting method employed operationally for raingauge-only rainfall estimation differs functionally only in the use of the exponential distance function

$$g(\underline{x}) = \exp(- \| (\underline{x}) \| / \ell \qquad \text{(A.7)}$$

where $\ell$ is the scaling length parameter. In this case, allowing the surface to depart from the raingauge values is achieved by setting $g(\underline{0}) = 1+K$. Of course, $z_i$ now refers to the raingauge value at gauge i of n raingauges.

Methods based on the reciprocal distance function

$$g(\underline{x}) = \frac{1}{1+\| (\underline{x}) \| / \ell} \qquad \text{(A.8)}$$

and which employ an offset parameter also use $g(\underline{0}) = 1+K$ in fitting.

Extension to include explanatory variables is simply achieved by incorporating these variables along with the distance measures in the linear dependence function. Thus, if $h_i$ is some height measure thought to be related to the radar calibration factor (e.g. the height of the beam above the raingauge) then

$$z_i = \sum_{j=2}^{n+1} a_j \, g(\underline{x}_i - \underline{x}_j) + a_1 h_i + a_0 \qquad \text{(A.9)}$$

provides the basis of the method. Estimation of $a_0$ and $a_1$ is first achieved by least squares regression on the calibration factors and the residuals used as the $z_i$ values for multiquadric surface fitting.