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Investigation of Spatial and Temporal Aspects of Airborne Gamma Spectrometry

Final Report

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Abstract:

A study has been conducted which demonstrates the reproducibility of Airborne Gamma-ray Spectrometry (AGS) and the effects of changes in survey parameters, particularly line spacing. This has involved analysis of new data collected from estuarine salt marsh and upland areas in West Cumbria and SW Scotland during three phases of field work, in which over 150000 spectra were recorded with a 16 litre NaI(Tl) detector. The shapes and inventories of radiometric features have been examined. It has been shown that features with dimensions that are large relative to the survey line spacing are very well reproduced with all line spacings, whereas smaller features show more variability. The AGS technique has been applied to measuring changes in the radiation environment over a range of time scales from a few days to several years using data collected during this and previous surveys of the area. Changes due to sedimentation and erosion of salt marshes, and hydrological transportation of upland activity have been observed.

The results of this work will be used in the formulation of Government policy, but views expressed in this report do not necessarily represent Government policy.

Executive Summary

Airborne Gamma Spectrometry (AGS) is highly relevant to mapping deposited radioactivity as part of a nuclear emergency response capability. A project (RW 8/6/80, EPG 1/4/53), aimed at investigating spatial and temporal aspects of the AGS technique is reported here, that provides information which may be useful for definition of survey strategies for use both in emergency response and in collection of reference data for environmental purposes.

Three new airborne radiometric surveys were conducted in coastal and terrestrial areas between the Solway Firth and the Duddon Estuary, with over 150000 NaI(Tl) spectra recorded. The data gathered are of interest in their own right as well as serving as the basis for describing their contemporary radiation environments and assessing change relative to past surveys and the future. Taken together with the complete set of surveys conducted in the past by SURRC since 1988 there is now radiometric coverage of the majority of Scotland south of the Clyde and a substantial part of northwest England.

Within the Inner Solway, salt marshes and mud flats remain as repositories for significant inventories of environmental radioactivity, and these new data provide clear evidence for continuing areas of sedimentation and highlight areas where coastal erosion is both exposing and dispersing former sinks for environmental contamination. In the coastal environs of the Sellafield site the new data confirm the presence of Sellafield derived activity in estuarine and salt marsh environments and their flood plains, as well as activity on the beach between Sellafield and St Bees, together with direct radiation observed close to the site and signals from gaseous discharges from the Calder Hall reactors. A number of areas of enhanced activity associated with former industrial wastes containing low levels of uranium series activity were also noted. The third phase of survey provided extensive data from the area between the Solway and Duddon estuaries, including upland areas which had received deposition from the Chernobyl accident and Windscale fire. A repeat survey was conducted of Rockcliffe Marsh to permit evaluation of environmental changes over a 15 month period.

The spatial response and registration of these features in their known locations provides further verification of the ability of AGS to locate discrete sources of activity correctly, another feature highly relevant to emergency response. The juxtaposition of remote sensing data has provided a clear demonstration of the strong links between landscape compartment and environmental radioactivity, both in coastal environments and wetland areas. The strong correlations between the shapes of radiometric and landscape features provide a compelling confirmation of the effectiveness of AGS techniques in defining real areas with common radiation environments. In dynamic coastal environments some features were noted, for example in the lower reaches of the River Esk, where even relatively recent digital maps mispositioned environmental features relative to both satellite imagery and radiometrics. This underlines the importance of using contemporary land classification information in making detailed interpretation of high resolution AGS data, which may be relevant to some aspects of late stage emergency response.

AGS data are subject to uncertainties associated with the statistical limitations of short measurements, and corrections and calibration procedures used in quantification. The greatest systematic uncertainties in calibrated data being associated with variations in the depth distribution of environmental radioactivity. A mass depth of approximately 15 g cm^{-2} was observed at the Caerlaverock calibration site, producing a calibration which was within 20% of a

test in West Cumbria. For ^{137}Cs activities below 10 kBq m^{-2} the statistical counting errors on individual 2 s observations are the dominant source of uncertainty, whereas for higher activities these are less than 10%. The statistical limits on individual 2 s data are mitigated by averaging operations involved in both mapping and regridding. Moreover, in considering potential detection limits applicable to emergency response the greater sensitivity of superficially deposited activity (giving approximately 3.5 times greater count rates per unit activity per unit area) compounds these benefits. Therefore, short acquisition times capable of providing spatial location of strong radiation sources within 50-100 m dimensions are warranted.

The observed reproducibility of the method has been demonstrated by analysis of repeat survey flights of a line across the Drigg waste store and tie lines. It is evident that over longer time scales the results of airborne surveys are highly consistent once radioactive decay, differences in calibration methods and known processes for change in the radiation environment are taken into account; after correcting for these the total ^{137}Cs inventory measured in West Cumbria in 1988 and June 2000 differs by only 3%, even with significant improvements in equipment and methodology. The work presented here confirms therefore, that AGS is capable of recording external radiation fields in a reproducible manner providing adequate steps are taken to control detector operating conditions and account is taken of spatial and temporal effects in the environment.

The effect of survey line spacing has been studied by subsampling the survey data into sets which can be treated as contemporary independent survey subsets. ^{137}Cs inventory estimates of the Inner Solway and West Cumbrian survey areas have been evaluated and compared for such subsampled data sets. The shapes of radiometric features have been examined to assess the extent to which inventory and shape can be reproduced with increasingly sparse survey sets. In the Inner Solway, inventory estimates for the whole area and larger salt marshes were remarkably stable, with the 50 m line spacing set giving an inventory of 1.1 TBq for the entire area, compared with a range from 1.06-1.13 TBq for the 500 m line spacing subsets. Moving to larger dimensions the northern part of the Chernobyl deposited area of West Cumbria gives an inventory of 15.9 TBq for the 500 m spaced data subsets compared with a range from 15.4-16.8 TBq based on the 5 km spaced subsets. Visual observations of remapped data and quantitative parameterisation of the shapes of major features confirm that environmental features of large dimensions in comparison with line spacing are well estimated by AGS methods. By contrast, when the spatial dimensions of individual features are comparable with line spacing the shapes of features and their detection probabilities are adversely effected. Thus, Rockcliffe Marsh in the Inner Solway with dimensions of the order of 5 km is relatively well mapped with all permutations up to 500 m, whereas some of the smaller salt marsh areas of the Inner Solway are detected with decreasing edge detail in the sparser data sets. In the upland areas the overall outline of the general deposition areas is broadly delimited, even with 2.5 or 5 km line spacing. However, local variations are not clearly defined by such sparse surveys.

Both cost and speed of survey are critically linked to line spacing, with the appropriate choice of line spacing dependent on the purpose of the survey and the spatial dimensions of the features of interest. The work presented here has shown the influence of line spacing on data quality and information content. It is, perhaps, helpful to note that data with line spacings of several km would be expected to identify the majority of areas showing enhanced deposition following a major release of activity, which might be appropriate for initial rapid post-accident reconnaissance or collection of general baseline reference data on regional or national scales.

Where more detail is needed, for example in detailed deposition mapping of areas of interest revealed by first-pass survey or small scale studies of local environments or path ways associated with discharges from sites, line spacings of 100-500 m may be practical and adequate. It is only in cases where the highest possible sensitivity and density of information are required, for example detailed definition of activity distributions relative to individual field boundaries or searches for radioactive sources, where survey line spacings of 50 m or less might be required.

It has been demonstrated that AGS techniques can detect, quantify and map changes in the radiation environment by comparison of the results of repeated surveys over common areas, with both inventory analysis and spatial comparisons being undertaken. To account for differences in spatial location of individual measurements, such comparisons have been based on regridded estimates using a common spatial grid. Procedures to do this based on inverse distance weighted estimation have been developed and shown to be robust. In the Inner Solway, comparison between data collected in April 1999 and June 2000 has shown distinct areas of slightly reduced activity attributed to continuing accumulation of the less active estuarine sediments on salt marshes with buried activity maxima. At Rockcliffe Marsh this consistent with a sedimentation rate of 1.4 g cm^{-2} per year, well within the range of values inferred from analysis of soil cores. The eroding edges of Burgh Marsh and the southern limit of Rockcliffe Marsh are clearly identified as a result of the exposure of previously buried sediments of higher activity. Small positive increases were observed in an area of mud flats, which may be a temporary sink for recently eroded active sediments, and areas of low lying land near the Eden estuary possibly related to a combination of high tides and flooding in the winter of 1999. In West Cumbria, there is evidence of transfer of activity from upland to lowland contexts, with hydrological down wash or erosion likely to be the dominant processes responsible. It would be of interest to examine the geographical and geomorphological contexts of these changes in more detail in the future.

Overall, the new survey results, their relation to known landscape features, and the analysis conducted so far have both confirmed the utility of the AGS technique for environmental research, and illustrated many of the key features of the method which are fundamentally relevant to its use in emergency response. The comparative techniques developed and illustrated in this project are directly relevant to quantification, location and demarcation of contaminated areas following environmental deposition of radioactivity. The techniques used for measurement and identification of environmental change are relevant to demonstration of increased activity levels relative to baseline data even in areas with complex deposition histories. Moreover, the data sets produced during this study represent a valuable resource for future environmental research.

Acknowledgements

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The aircraft used for the field work was supplied by PDG Helicopters Ltd, and flown mostly by John Constable, with a few hours flown by Ivor Griffiths. True colour composite and classified satellite imagery were produced by Dr Andrew Tyler and Paula Atkin of the Department of Environmental Science, University of Stirling. Liquid nitrogen for cryogenic cooling of the Ge detectors was supplied by Dr Paul McDonald of the Westlakes Research Institute. Iona Anthony, Iain Houston and Anne Sommerville assisted with the field work.

Contents

Appendices

1. INTRODUCTION

This is the final report of a project (RW 8/6/80, EPG 1/4/53) aimed at investigating spatial and temporal aspects of the Airborne Gamma Spectrometry (AGS) technique. Three new airborne radiometric surveys were conducted during this project in coastal and terrestrial areas between the Solway Firth and the Duddon Estuary. The data collected have been analysed to quantify and map the distributions of natural and anthropogenic nuclides, and have also been used to define the reproducibility of the method, its sensitivity to survey line spacings, and to measure environmental changes taking place over the duration of the project and the previous decade. This report summarises the main findings of the surveys and presents the results of analyses of the data dealing with spatial and temporal matters. AGS is highly relevant to mapping deposited radioactivity as part of a nuclear emergency response capability. The work presented here provides information which may be useful for definition of survey strategies for use both in emergency response and in collection of reference data for environmental purposes.

1.1 Airborne Gamma Spectrometry

The AGS method depends on the relatively high penetration of γ-radiation, with, for example, the 662 keV γ-ray associated with ^{137}Cs having a half distance in air of approximately 70 m. Thus, by operating suitable spectrometers, typically high volume NaI(Tl) scintillators or Ge semiconductors, from low flying aircraft it is possible to map the distribution of γ-ray emitting radionuclides at ground level. This has a number of advantages when compared with conventional methods. High sensitivity γ-ray detectors installed in the aircraft are capable of making environmental radioactivity measurements every few seconds, thus providing a sampling rate some 10^2-10^3 times greater than other approaches. The radiation detector averages signals over fields of view of several hundred metre dimensions, resulting in area sampling rates some 10^6-10^7 times greater than ground based methods. Sequences of γ-ray spectra, geographic positioning information and ground clearance data are recorded, and are used to quantify levels of individual radionuclides and the general γ-dose rate.

The high mobility of the aircraft is also advantageous, as is its ability to operate over varied terrain, unimpeded by ground level obstacles or natural boundaries. Moreover, the remote sensing nature of the measurements minimises exposure of survey teams to contamination or radiation hazards. This results in a practical means of conducting surveys with total effective coverage, which can be used for rapid location of point sources or areas of radioactive contamination. This has important implications for environmental radioactivity studies, especially where there are time constraints, and is highly effective in emergency response situations.

The AGS method is particularly appropriate for large scale environmental surveys of areas of potentially contaminated ground. The methodology for aerial surveys is well established (Sanderson *et al*, 1994a, 1994b), and has been used by the SURRC team for a variety of purposes including environmental assessments of contamination (Sanderson *et al*, 1990a, 1990b); Chernobyl fallout mapping (Sanderson *et al*, 1989a, 1989b, 1990c, 1994c); baseline mapping around nuclear establishments (Sanderson *et al*, 1990d, 1992, 1993b, 1994d, 1994e); the effects of marine discharges on coastal environments (Sanderson *et al*, 1994c); epidemiological studies (Sanderson *et al*, 1993a); and radioactive source searches (Sanderson *et al*, 1988, 1991).

In addition to the series of application and developmental surveys conducted by SURRC in the UK, a number of other European groups have developed similar capabilities in the period following the Chernobyl accident. Work has been undertaken to define their capability and modes of operation (Sanderson and Ferguson, 1997d), and a comprehensive bibliography of European work has recently been published (Sanderson *et al*, 2001c), together with an appraisal of the state of development and needs for standardisation (Sanderson and McLeod, 1999). It is evident that at a European level there is widespread recognition of the need for and value of AGS systems as a component of national emergency response. A recent UK study commissioned by BNFL Magnox Generation on behalf of IMC (Darwin and McColl, 2000) confirmed the important role for the method in UK emergency response and examined a number of possible models for insuring the retention of a suitable capability. Internationally work is continuing to address outstanding issues of transnational comparability of AGS data, and to review ongoing technical developments. Information about the interaction between survey parameters and data quality are needed both to plan emergency strategies and to define practical needs for reference data for environmental and emergency use. This information is needed at national level in the UK. Moreover, it will be of interest to European teams, particularly once calibration issues have been resolved in providing a rational basis for definition of the requirements for representative background data at continental scale.

1.2 Project Aims

The project aims to investigate spatial and temporal influences on airborne gamma ray spectrometry (AGS), with particular reference to the effects of (i) line spacing, (ii) survey ground clearance, (iii) seasonality, and (iv) environmental change. AGS surveys of a series of areas in NW England and SW Scotland were conducted during the project, using a range of line spacings from 50 m to 2.5 km. To investigate seasonal effects the field work was divided into three phases, two of which included common areas surveyed under different seasonal conditions. The areas chosen for this study exhibit a range of radiation environments due to natural variations, Chernobyl fallout and Sellafield discharges; and encompass wide variations in landscape with mountainous terrain, moorland, forest, pasture, estuarine and coastal environments. The SURRC AGS team have previously conducted radiometric surveys of some of the areas covered in this project over a ten year period (Sanderson *et al*, 1989, 1990d, 1992) allowing evaluation of changes in the environment over a more extended period.

The location of the survey areas are given in Figure 1.1 and Table 1.1, which also gives the line spacing used for each area. Areas A and B covering the Inner Solway and Rockcliffe Marsh were surveyed in April 1999 (Sanderson *et al*, 2000) with a 250 m line spacing for the larger area B and 50 m line spacing for area A. Areas E to I were surveyed in March 2000 (Sanderson *et al* 2001) with a 100 m line spacing for the area around Sellafield and 50 m line spacing for the other areas, the coastline was surveyed at low tide with lines approximately 100 m apart ensuring one line was over the terrestrial environment and one over open water, with additional lines in between these. Areas C and D covering West Cumbria and area A covering Rockcliffe Marsh were surveyed in June 2000 (Sanderson *et al*, 2001), with a 500 m line spacing for area C, a 1 km line spacing for area D and a 250 m line spacing for the resurvey of area A.

Each survey included a tie line flown between Bassenthwaite Lake and Bowness Common at a range of heights. The data from these, along with some other repeat flights, have been used to explore the reproducibility of data collected by AGS.

To investigate the effect of line spacing on AGS results the data from area A recorded at 50 m line spacing in April 1999 and areas C (500 m line spacing) and D (2.5 km line spacing) have been used. These data sets were subsampled into a number of data sets containing data from lines with a spacing of 100 m, 250 m and 500 m for area A and 1 km, 2.5 km and 5 km for area C and 5 km and 10 km for area D. The data from each of these data sets were analysed to assess radionuclide inventory estimates following regridding of the data, and to describe the shapes of identified radiometric features and statistical measures of the similarity between permutations of the data sets.

The response of AGS to changes in the radiation environment have been assessed over a range of time scales, from short term changes during the course of a survey through changes as a result of seasonality to long term changes over several years. Any seasonal changes will be assessed by comparing tie line data recorded during each of the survey periods and analysis of inventory and spatial characteristics of area A measured in April 1999 and June 2000. Long term changes were assessed by comparing ^{137}Cs data recorded during this project with data collected during previous surveys in the same areas; specifically areas A and B were compared to data collected during the 1992 Chapelcross survey (Sanderson *et al*, 1992) and areas C and D were compared with data collected during the MAFF 1988 survey of West Cumbria (Sanderson *et al*, 1989a). The comparison between these data sets was based on both inventory analysis and consideration of the spatial characteristics of the data sets, taking account of technical differences in the measurements between these surveys, including calibration and radioactive decay.

The next section of the report provides a brief summary of the main findings of the surveys themselves. This is followed in turn by consideration of expected and observed reproducibility of AGS results covering a range of activities, by analysis of inventory estimates in the Inner Solway and West Cumbria as a function of line spacing, and the assessment of environmental change. The report concludes with a brief discussion of the use of high resolution detectors and remote sensing, and a summary of the main conclusions.

Area	Size (km)	OS bounds	Description	Line Spacing (m)
A	10×6	NY270590-NY370650	Rockcliffe, Burgh Marsh	50, 250
B	30×20	NY100500-NY400700	Inner Solway	250
C	40×40	NY000100-NY400500	NW Cumbria	500
D	50×50	SD000750- NY500250	NW England	2500
E	Coastline	Gretna-Duddon	4 lines at ~100 m spacing	n/a
F			Former RAF Carlisle site	50
G	25×5	St Bees-Eskmeals	Sellafield, extending 5 km inland	100
H			Workington Harbour	50
I			Rhodia Consumer Specialities Ltd, Whitehaven	50

Table 1.1: Survey areas for the project.

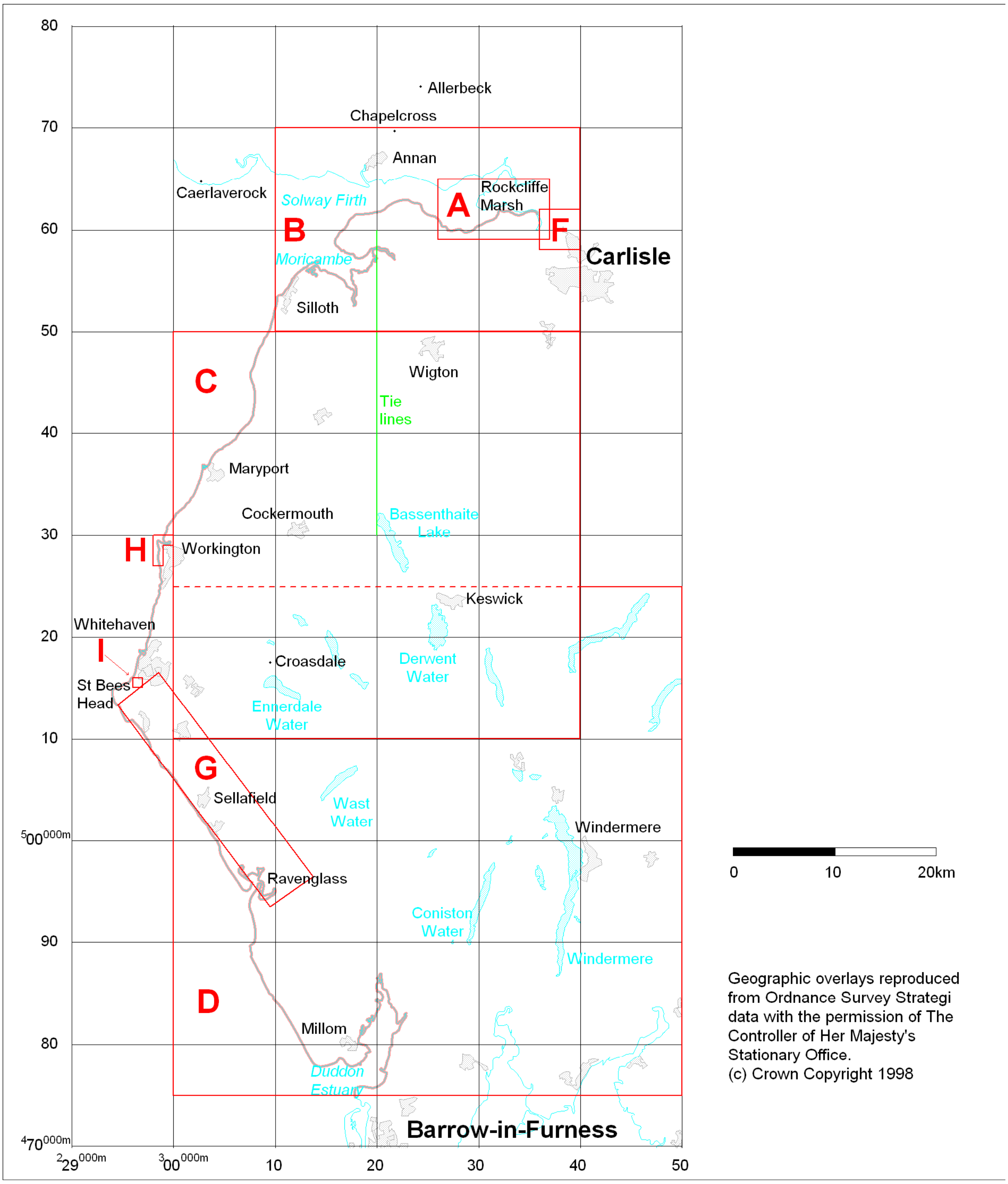

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Figure 1.1: Map of survey areas for the project. Note that areas C and D overlap.

2. SURVEY RESULTS

New airborne radiometric data were collected for this project during three phases of field work in April 1999 and March and June 2000. For these surveys a combined detector system, utilising both a 16 litre NaI(Tl) detector and one or two cryogenically cooled germanium (Ge) semiconductor detectors, was used. Whilst the use of high volume NaI(Tl) detectors is well established and used frequently in airborne surveys, the use of Ge detectors is relatively new. Ge detectors have a much higher energy resolution than the NaI(Tl) scintillator detector, and so are able to identify the nuclides contributing to the gamma ray spectrum, particularly where complex fission product sources are present. However, they are considerably less sensitive than NaI(Tl) requiring the use of longer integration times with a resulting loss of spatial resolution in all but the most active environments. A pair of LoAx detectors mounted outside the aircraft were used for the first survey tasks in April 1999, and a single 50% efficiency Ge (GMX) detector mounted inside the aircraft for the later survey tasks in March and June 2000.

2.1 Summary of April 1999 Survey

The first phase of survey within the project was conducted between 20th and 28th April 1999 and covered two of the survey areas in the Inner Solway. The combined spectrometer including external LoAx detectors was installed in an AS355 helicopter at Cumbernauld airport, North Lanarkshire, tested and deployed from a local field base near the survey area. At the start and end of survey measurements were taken at a calibration site on Caerlaverock Merse, Dumfries and Galloway, which had previously been used for 1992 survey of the environment of the Chapelcross nuclear power station. A series of 25 core samples was collected for laboratory gamma spectrometry to update knowledge of the activity per unit area and mean mass depth for the calibration site. The ^{137}Cs inventory for the top 30 cm of the merse was within measurement errors of the decay corrected 1992 value. The mean mass depth had increased by 20% since 1992. Both these findings were consistant with the known continuing accumulation of sediments on the site, which carry lower specific activities than those associated with the peak discharge periods from the Sellafield site.

Area A over Rockcliffe Marsh was surveyed at 50 m line spacing using a 2 s integration time for the NaI(Tl) spectrometer with some 18700 NaI(Tl) spectra recorded. Area B around the Solway was surveyed at 250 m line spacing using a 3 s integration time for the NaI(Tl) spectrometer with some 21300 NaI(Tl) spectra recorded. The data were used to quantify and map the distributions of ^{137}Cs, ^{40}K, ^{214}Bi, ^{208}Tl and the gamma dose rate. The results have been reported elsewhere (Sanderson *et al*, 2000a) and will only be summarised and illustrated briefly here. Figures 2.1 and 2.2 show the ^{137}Cs distribution determined for areas A and B during this survey. The highest ^{137}Cs activities were observed on salt marsh environments resulting from past marine discharges from Sellafield, the largest areas identified being Rockcliffe Marsh, Burgh Marsh and the system of salt marshes and mud flats of Moricambe Bay. Smaller features on both the Scottish and English sides of the Solway were also observed, the overall pattern being similar to that observed in the 1992 survey. The ^{40}K, ^{214}Bi and ^{208}Tl distribution largely reflects local geology and soils with relatively high levels of ^{40}K on estuarine mud and very low activity levels for all naturally occurring radionuclides on wet peatlands. A small ^{214}Bi anomaly was observed to the northwest of Carlisle, which was surveyed in further detail in the second survey phase. Gaseous discharges of ^{41}Ar and ^{16}N from the Chapelcross power station were observed to the north east of the station.

A contempory LandSat image was obtained during the first phase survey, and used to produce a thematic map depicting the different landcovers within the area. Further details are given in the first phase survey report and in section 6 of this report. It was noted however that the radiometric data showed a remarkable registration and correspondence of landscape features relating both to the coastal environment and to terrestrial wetlands. Both radiometric and remote sensing data showed common features in coastal areas which were not reproduced in digital maps obtained from the Ordnance Survey. These differences are attributed to the difficulties of keeping cartographic information up to date in a rapidly changing estuarine environment.

2.2 Summary of March 2000 Survey

The second phase of survey within this project was conducted between 14th and 22nd March 2000 and covered several areas within Cumbria. A 25×5 km region around Sellafield and the Cumbrian coastline were surveyed with 100 m line spacings. Small survey areas around the former RAF Carlisle site, the Rhodia Consumer Specialities (formerly Albright and Wilson) plant near Whitehaven and Workington Harbour were surveyed with 50 m line spacings. Some 47000 spectra were recorded using the NaI(Tl) spectrometer with a 2 s livetime. The data were used to quantify and map the distributions of ^{137}Cs, ^{60}Co, ^{40}K, ^{214}Bi, ^{208}Tl and the gamma dose rate. Calibration measurements were, again, recorded from the Caerlaverock Merse.

Signals in the immediate vicinity of the Sellafield and Drigg sites were observed which were associated with stored materials on the site and discharges of ^{16}N and ^{41}Ar from the Calder Hall reactors. ^{137}Cs activity was observed on the salt marshes of the rivers Irt, Mite and Esk as well as the Duddon Estuary, Moricambe Bay and the Solway Firth. Some of these salt marshes also showed low levels of ^{60}Co activity, which may be the result of incomplete stripping of spectral interferences from ^{40}K. There were further ^{137}Cs signals associated with contamination of the beach near Sellafield and St. Bees, the flood plains of the River Esk above the intertidal limit, and Chernobyl and Windscale fire fallout on the upland areas of Irton Pike and Muncaster Fell.

The RAF Carlisle site had been contaminated with radium, the survey of this site was commissioned to confirm that decontamination of the site had removed all activity above the detection limits of the airborne method. The only anthropogenic signals observed in the area were from slight ^{137}Cs contamination along the River Eden and enhanced ^{214}Bi signals associated with railway sidings to the west of the mainline, probably resulting from the use of industrial waste material as hard core for the construction of the line. The signal from the railway line identifies the anomaly observed in the April 1999 survey.

During the course of the survey a few sites with anomalous ^{214}Bi activity, associated with industrial waste material, were noted. There were two such features near Millom, from waste material in a disused quarry south of the town and a larger area to the east, an area of wastes near Askam pier and a few features near Cleator Moor and Frizington.

2.3 Summary of June 2000 Survey

The final phase of survey within this project was conducted between 13th and 26th June 2000. This covered a 40×40 km area in north west Cumbria (area C) at 500 m line spacing, a 50×50 km area in west Cumbria (area D) at 2.5 km line spacing and a repeat flight of area A over Rockliffe Marsh at 250 m line spacing. An additional 10×30 km area at 500 m line spacing was flown to the south of area C to cover an area flown in 1988, a small 10×10 km section within area C was flown at 500 m line spacing perpendicular to the lines flown in area C, some additional survey flights were also conducted around Sellafield. Calibration manouvres were conducted at the Caerlaverock site near the start and end of the survey. More than 70000 NaI(Tl) spectra were recorded with a 2 s integration time. The data were used to quantify and map the distributions of ^{137}Cs, ^{60}Co, ^{40}K, ^{214}Bi, ^{208}Tl and the gamma dose rate.

Figure 2.3 shows the ^{137}Cs distribution in West Cumbria determined from all the data recorded in this area during the survey. The upland areas show ^{137}Cs levels consistent with Chernobyl deposition, with a number of relatively small spatial features with levels in excess of 35 kBq m^{-2}. The distribution of activity in these areas is very similar to the distribution measured in the 1988 survey. The highest ^{137}Cs activities were observed on the salt marshes around Ravenglass, and the Duddon Estuary. There were also slight levels of ^{60}Co observed on the salt marshes around Ravenglass, although long integration time summed GMX spectra showed no evidence of ^{60}Co in these environments. The distribution of the naturally occuring activity is consistent with variations in local geology and soil cover.

The repeat survey of area A produced very similar results to the 1999 survey, with the salt marshes of Rockcliffe Marsh and Burgh Marsh contaminated with Sellafield derived ^{137}Cs activity in an almost identical pattern, although the river channels are less clearly defined possibly as a result of the wider line spacing. Very similar acitivity distributions were also observed in the natural channels.

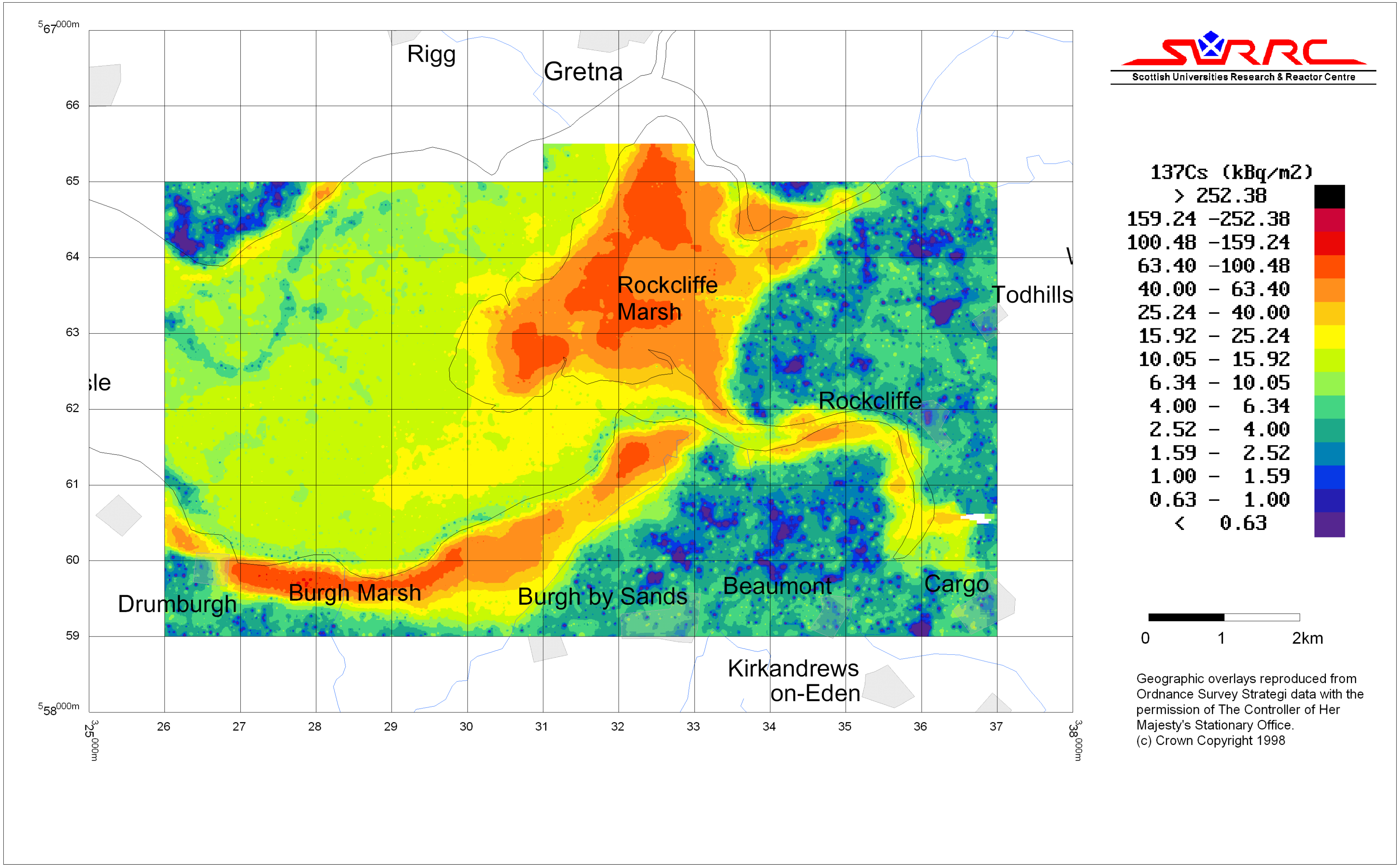

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Figure 2.1: ^{137}Cs distribution in the Inner Solway (area A) measured in April 1999.

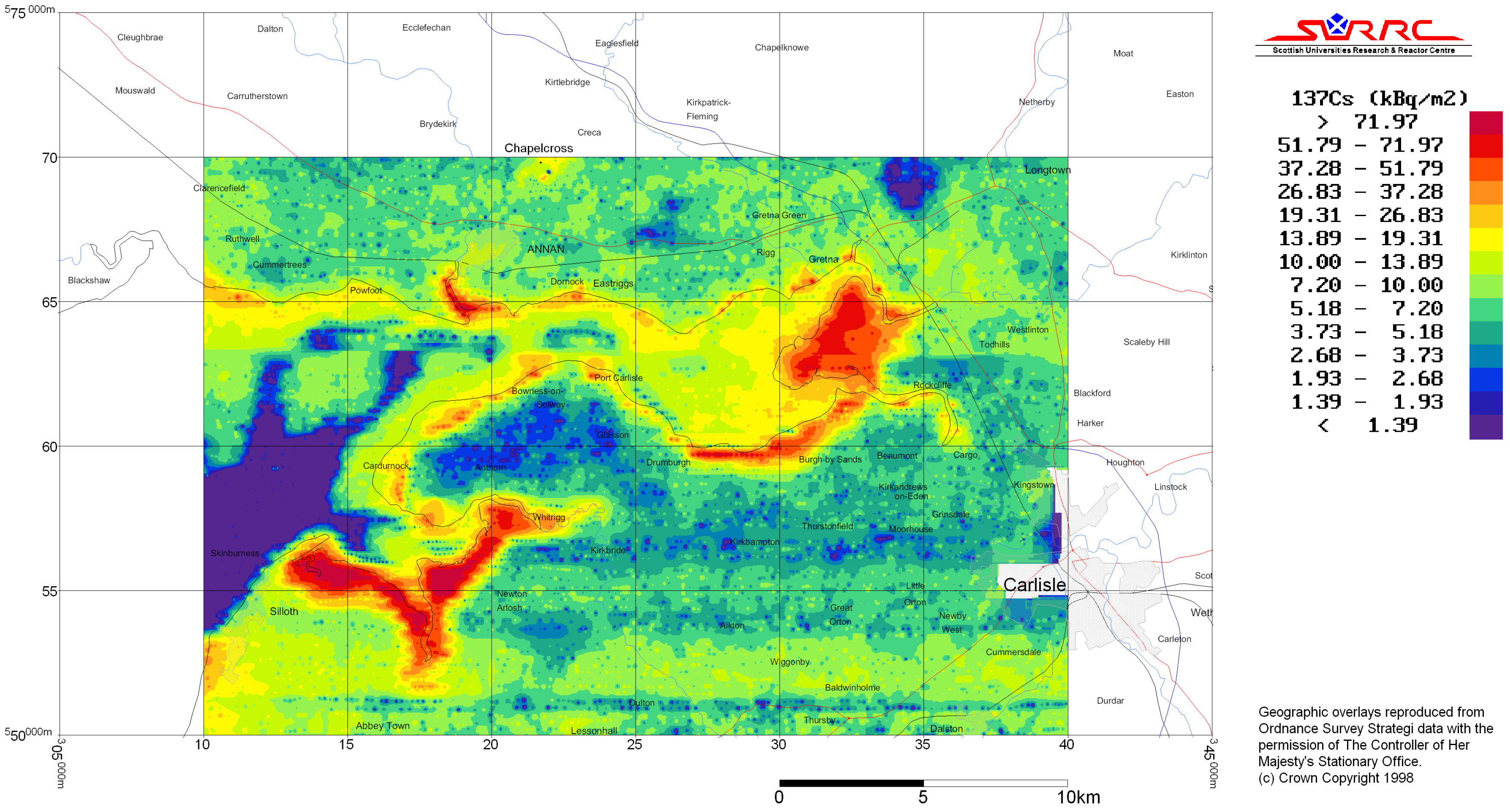

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Figure 2.2: ^{137}Cs distribution around the Inner Solway Estuary (area B) measured in April 1999.

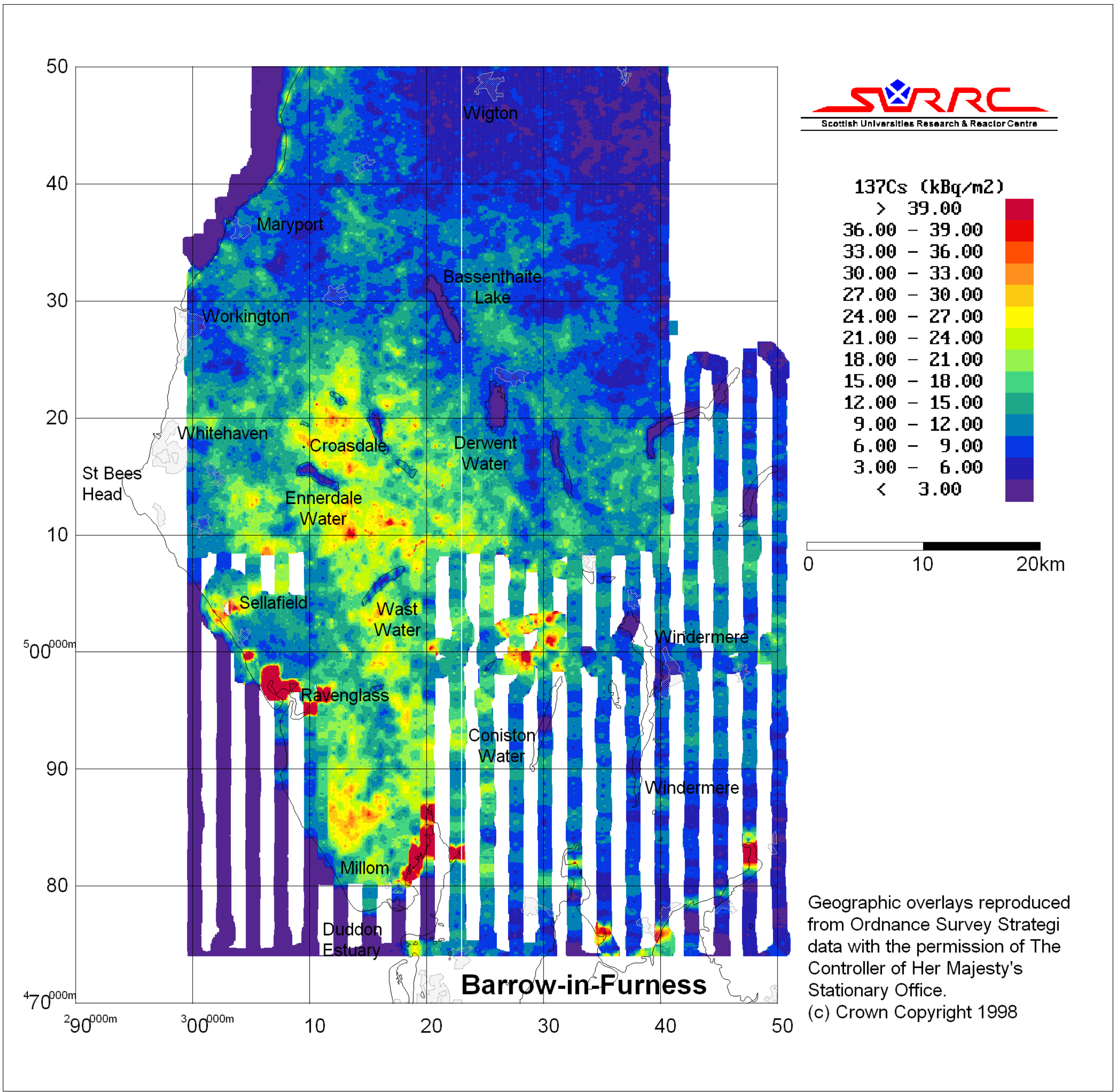


Figure 2.3: ^{137}Cs distribution over west Cumbria (areas C and D) measured in June 2000.

2.4 Summary of Surveys Conducted Prior to this Project

The areas surveyed in this project include some areas that have previously been surveyed in earlier work. The results of these earlier data and current data are compared to determine any long term changes in the radiation environment of these common areas. Three of these surveys are of particular relevance; a 1988 survey of West Cumbria (Sanderson *et al*, 1989), a 1990 baseline survey of the Sellafield site (Sanderson *et al*, 1990d) and a 1992 survey of the Chapelcross power plant and surrounding areas (Sanderson *et al*, 1992).

1988 MAFF Survey of West Cumbria

This survey, conducted between 22nd August and 3rd September 1988, covered an irregularly shaped area of approximately 20×40 km including the areas that, at the time, were subject to livestock movement restrictions. The survey was flown at 500 m line spacing using a prototype detector system consisting of a 11.5"×4" (7 litre) NaI(Tl) crystal with a 1024 channel 8k multichannel analyser and laptop computer. The spectrometry system had a resolution of 13-15% FWHM at 662 keV. Integrated counts from 6 spectral windows were recorded every 30 s, with the complete spectrum saved at the end of each 10 km survey line. A radar altimeter was constantly monitored by computer, but position was manually entered at the start of each 30 s reading from a Decca navigation aid.

The analysis used a stripping matrix derived from measurements of point sources and solutions and a working calibration based on overflights of 10 sites in SW Scotland in March 1988 was used. Ground level measurements and samples were taken from these sites which had ^{137}Cs activity levels ranging from below 5 kBq m^{-2} to over 30 kBq m^{-2}.

1990 Sellafield Baseline Survey

This survey, conducted on the 25th and 26th September 1990, produced a baseline of radionuclide levels in the immediate vicinity of Sellafield and covered an approximately triangular area from St Bees Head to the Ravenglass Estuary and inland to the eastern end of Ennerdale Water in the north and about 5 km inland from Ravenglass in the south. The survey was flown at 1 km line spacing using an 8 litre NaI(Tl) crystal interfaced to a multichannel analyser in the logging computer. The spectrometry system had a resolution of 8.5-9.0% FWHM at 662 keV. Spectra with 10 s integration time were recorded by the logging computer, with position entered manually every second reading from a Decca navigation aid.

The analysis used a stripping matrix derived from measurements of point sources and solutions, with a sensitivity calibration based on a set of sites in Ayrshire, each of which was sampled in the summer of 1990 (Sanderson *et al*, 1990c) with a pattern of 17 soil cores laid out in three concentric arcs, with measurements made while hovering at various heights above the centre marker. The values of these calibration constants were not significantly different from earlier values.

Figure 2.4 shows the ^{137}Cs distribution determined from the data collected in the 1988 MAFF survey and the 1990 Sellafield baseline. The main features of the survey results are that the upland areas in the centre of the survey area show a fairly broad north-south line of enhanced ^{137}Cs activity, exceeding 30 kBq m^{-2}. The distribution of ^{134}Cs in the central areas suggests that these are most likely to be dominated by Chernobyl derived Cs, with other areas receiving a larger proportion of Windscale derived Cs. It was clear that the enhanced ^{137}Cs distribution extended beyond the survey area.

1992 Chapelcross Baseline Survey

This survey, conducted between the 4th and 7th February 1992, covered an area of 21×25 km around the site, with extensions along the coast up to 25 km further west, with a line spacing of 500 m. The spectrometry system consisted of a 16 litre NaI(Tl) detector with an electronics rack containing a computer and power supplies, and maintained a resolution of better than 11% FWHM at 662 keV throughout the survey. Positional information was automatically logged from a Navstar XR-4 GPS system, with spectra recorded with integration times of 10 s.

The analysis used a stripping matrix determined from measurements of 1 m^2 calibration pads doped with K, U and Th series activity, which generate more scattering than smaller scale sources. Initial calibration was based on working values derived from the 1990 17 point calibration patterns (Sanderson *et al*, 1990c). A calibration pattern at Caerlaverock consisting of 31 cores in an expanding hexagonal pattern was also sampled, but it was found that the pronounced sub-surface maximum in the ^{137}Cs distribution on the merse resulted in a systematic under-response of some 20-30% in activity estimation compared to the earlier calibration. The earlier calibration was used for consistency with previous surveys.

Figure 2.5 shows the ^{137}Cs distribution determined from this data for the Inner Solway area, which shows activity on the salt marshes along the Solway Firth, especially Rockcliffe and Burgh Marshes in the Inner Solway, as well as activity associated with the Chapelcross site. Low natural series activity was observed associated with wet peat areas.

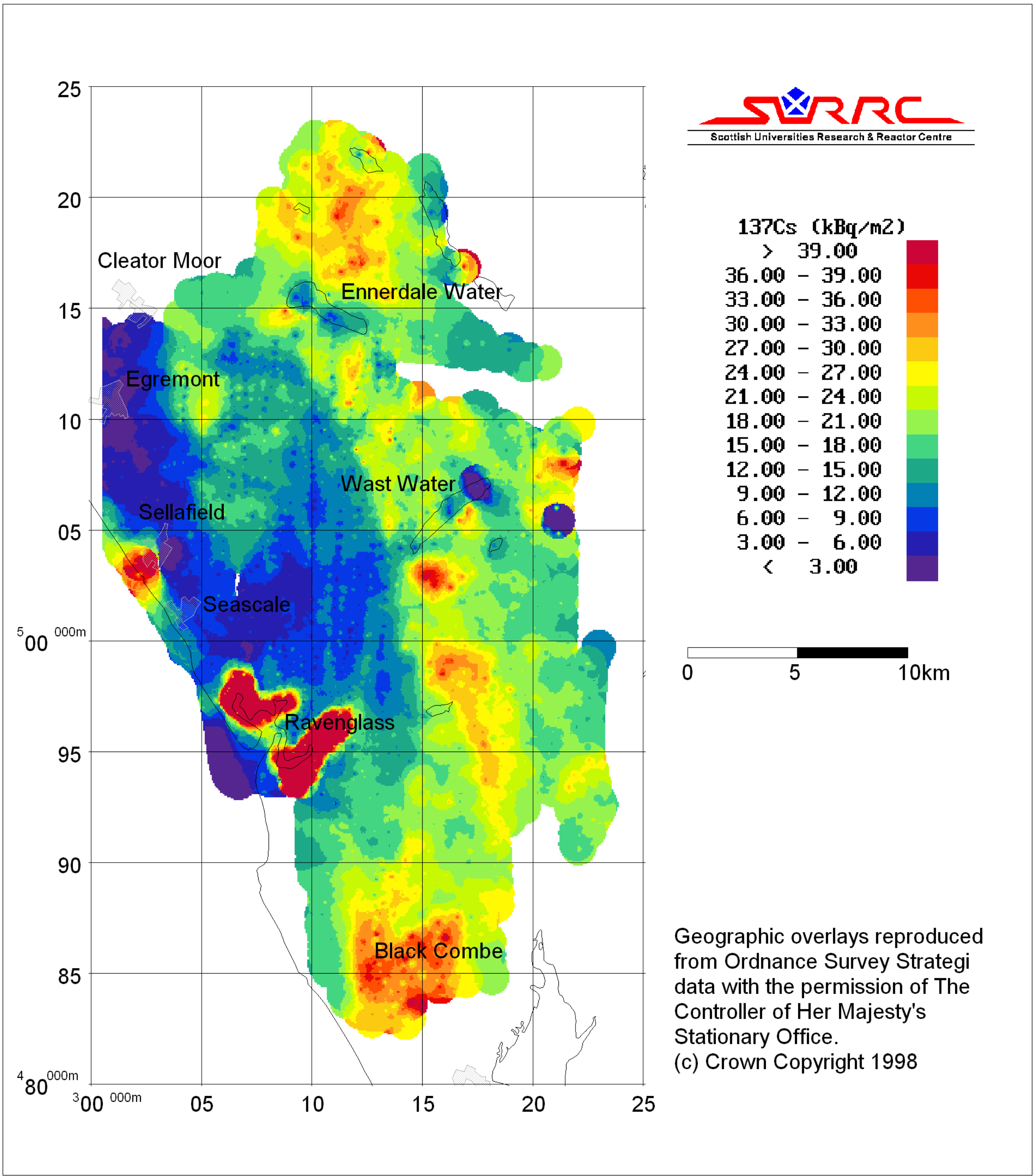
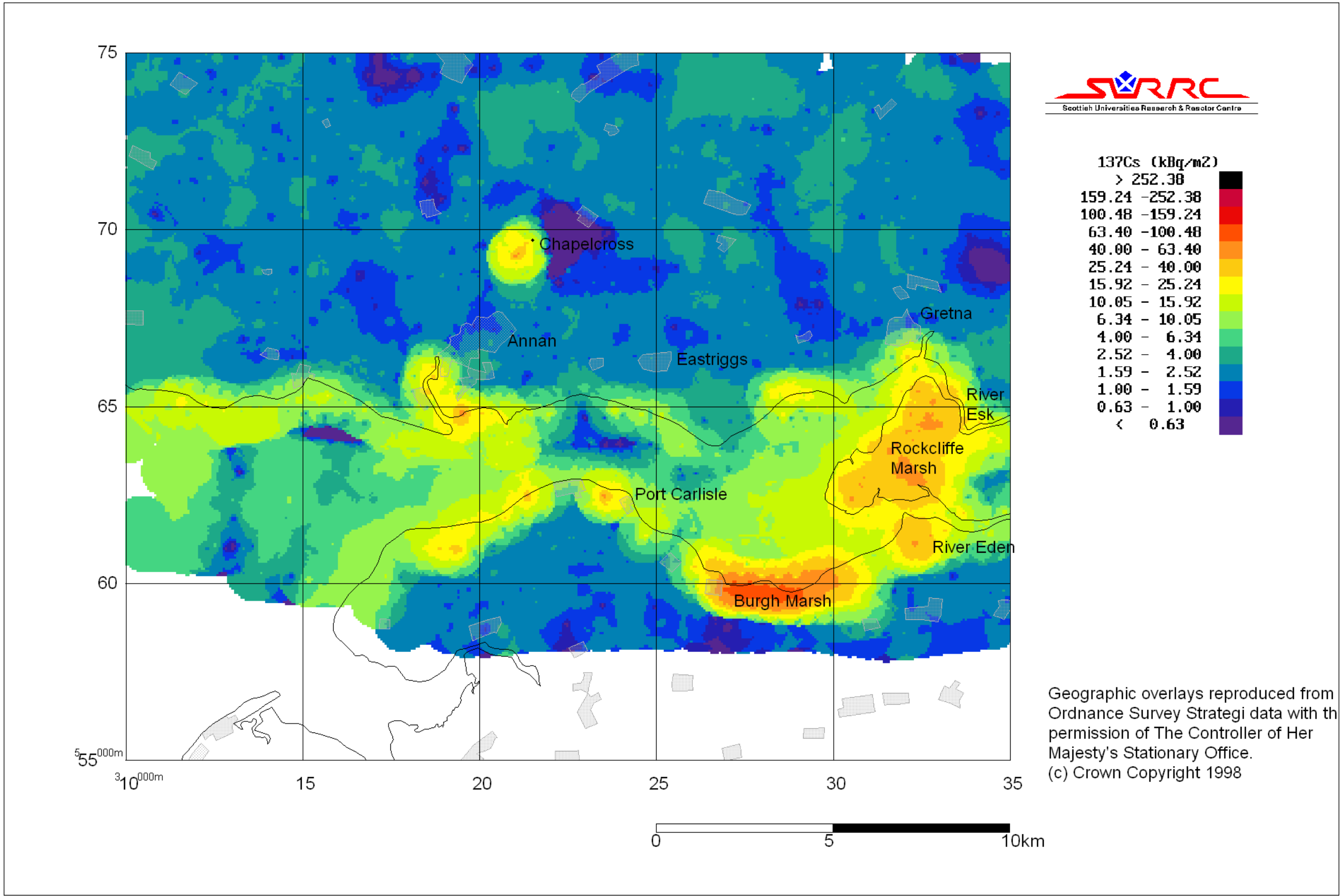


Figure 2.4: ^{137}Cs distribution over west Cumbria measured in 1988 and 1990. The original calibrated data from 1988 and 1990 are used, with current mapping methods.



Geographic overlays reproduced from Ordnance Survey Strategi data with th permission of The Controller of Her Majesty's Stationary Office.
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Figure 2.5: ^{137}Cs distribution over the Inner Solway measured in 1992. The original calibrated data from 1992 are used, with current mapping methods.

3. ASSESSMENT OF SHORT TERM REPRODUCIBILITY

3.1 Measurement Precision and Sources of Uncertainty

Under laboratory conditions it has been demonstrated that the NaI(Tl) detector used by the SURRC team is a highly stable instrument, with only slight gain drifts of a few percent over several days (Sanderson *et al*, 1997b). A gain monitor, based on the position of the 1.46 MeV ^{40}K peak, is used during acquisition to monitor any gain drift and allow correction by very small changes in the high voltage supply. During surveys the detector resolution is checked at least once a day, and can be improved by trimming the gain of individual detectors.

The system is constantly kept in a state ready for deployment, with the detector powered up and regularly checked, thus minimising any instabilities created by moving the detectors. When used in the field some additional factors, including variations in power supply from aircraft or batteries and the effects of vibration, may reduce detector performance. These can be minimised by daily performance checks, quality control monitoring of detector performance during data acquisition and initial processing infield and equipment maintenance. Detector performance should not seriously affect data quality.

The data processing algorithm used converts the number of counts in a given window, N_i, to calibrated activity concentration, A_i, by a number of steps. The number of counts in a window i is converted to a gross count rate, C_{gi}, by dividing by the integration time. A net count rate, C_{ni}, is then produced by subtraction of a background count rate, C_{bi}, recorded over water.

$$C_{ni} = C_{gi} - C_{bi} \qquad 3.1$$

Spectral interferences between channels are then stripped from the net count rate data. A stripping matrix, ***S***, giving the fractional interference for each nuclide window in the other nuclide windows, is formed from data collected from a series of calibration pads with perspex absorber sheets to simulate an air path of several 10 s of metres. The inverse of the stripping matrix is applied to a vector containing the net count rates in each of the five radionuclide channels, $\boldsymbol{c_n}$, producing a vector containing the stripped counts in these channels, $\boldsymbol{c_s}$.

$$\mathrm{c_s} = \mathrm{S}^{-1}\,\mathrm{c_n} \qquad 3.2$$

This is coded simply as a series of linear equations in which the elements of $\boldsymbol{c_s}$, C_{si}, are the sum over all five radionuclide channels of the product of the elements of $\boldsymbol{c_n}$ and the elements s_{ij}^{-1} of the inverted stripping matrix.

$$C_{si} = \textstyle\sum_j C_{nj}\, s_{ij}^{-1} \qquad 3.3$$

Differences between the laboratory geometry and field geometries, as well as possible differences in detector performance in the laboratory and field, may introduce small systematic errors in the stripping. These can be corrected for by using a small intercept in the sensitivity calibration coefficients, although this requires the use of at least two calibration sites with different activity levels.

The altitude correction coefficients normalize the stripped data to a ground clearance of 100 m, using an exponential altitude dependence. The altitude corrected count rates, C_{ai}, are determined from the stripped count rates, C_{si}, by

$$C_{ai} = C_{si}\, e^{(A-100)*a_{ci}} \qquad 3.4$$

where A is the ground clearance and a_{ci} the altitude correction coefficient. The altitude correction coefficient is determined from the gradient of a plot of the logarithm of stripped count rates against altitude at the calibration site.

The sensitivity calibration constants, s_i and $s_{i'}$, convert the altitude corrected stripped count rates to calibrated activity concentration units (kBq m^{-2} or Bq kg^{-1}). They are determined from the slope (s_i) and intercept ($s_{i'}$) of a plot of stripped count rate against activity concentration on the calibration sites for calibration manoeuvre data. To determine the intercept at least two calibration sites are required, so in the current work in which a single calibration site at Caerlaverock has been used a zero intercept is used. The calibrated activity is simply:

$$A_i = s_i C_{ai} + s_{i'} \qquad 3.5$$

The principal source of uncertainties for open field geometries is the statistical counting error in the gross count rate, ΔC_{gi}.

$$\Delta C_{gi} = \frac{\sqrt{N_i}}{T} \qquad 3.6$$

where T is the integration time and N_i is the number of counts in channel i, which is simply $C_{gi}T$. This could be reduced by using a longer integration time, but at the expense of the spatial precision of the reading. The uncertainty in net count rates, ΔC_{ni}, includes the error in the background count rate, ΔC_{bi}.

$$\Delta C_{ni} = \sqrt{\Delta C_{gi}^2 + \Delta C_{bi}^2} \qquad 3.7$$

In practice, C_{bi} is determined from a large number of readings and has a negligible uncertainty in comparison to the uncertainty of a single measurement.

The stripping procedure introduces an uncertainty in each radionuclide channel that is dependent on the uncertainties on the net count rates of other radionuclides in the environment. Due to the relatively large number of spectra recorded with long (30 s) integration times used to determine the stripping matrix, the statistical uncertainties of the elements of the stripping matrix are negligible and are not considered in this analysis. The uncertainty in the net count rate is propagated through the stripping matrix using the linear equation 3.3

$$\Delta C_{si}^2 = \sum_j (\Delta C_{ni}\, s_{ij}^{-1})^2 \qquad 3.8$$

As a result of stripping a significant uncertainty in the ^{137}Cs stripped count rate is due to the effect of the uncertainties on the uranium and thorium series channels which interfere strongly with the ^{137}Cs channel. At present, relatively wide windows are used to define the radionuclide spectral channels. The use of narrower windows, which can be achieved given the improved spectral resolution of the detectors currently used compared to earlier generations of detector systems, would reduce the interferences between channels and hence the uncertainties propagated between channels.

Most of the data recorded for this project has used an integration time of 2 s for the NaI(Tl) spectrometer. By taking the mean gross count rate of pairs of consecutive readings data with an effective integration time of 4 s can be generated; repeating this doubles the effective integration time again. The uncertainties in the ^{137}Cs stripped count rate were determined for a section of the data set from area A (Inner Solway and Rockcliffe Marsh) surveyed with 50 m line spacing.

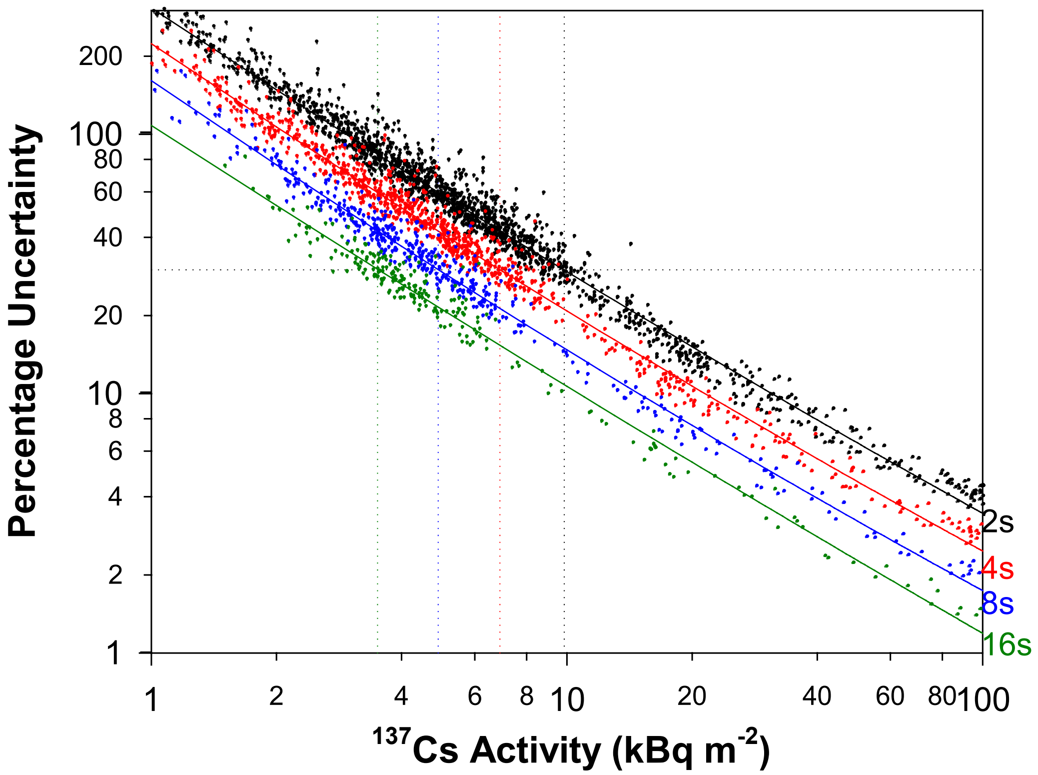

Figure 3.1: Percentage uncertainty on ^{137}Cs stripped count rate for 2, 4, 8 and 16 s integration times

Figure 3.1 shows a plot of the fractional uncertainty in the ^{137}Cs stripped count rate as a function of ^{137}Cs activity for this data with 2, 4, 8 and 16 s integration times.

A fractional uncertainty of approximately 30% would correspond to the limit of detection for a single reading; note that the smoothing algorithm employed when mapping or regridding data will combine several data points which would reduce the fractional uncertainty below this by a factor of $\sqrt{W}/W$, where W is the sum of the weighting for the contributing data points. Table 3.1 shows the limit of detection for single measurements and 10 measurements with similar weighting combined for each of the integration times given in Figure 3.1. The number of measurements contributing to each position as a result of the smoothing algorithm will be dependent on line spacing, flight speed and integration time; closer line spacing and lower flight speeds would result in a greater density of measurements.

Integration time (s)	LoD on single measurement (kBq m^{-2})	LoD on ten measurements (kBq m^{-2})
2	9.9	3.1
4	6.9	2.2
8	4.9	1.5
16	3.5	1.1

Table 3.1: Limits of detection for a single measurement and the equivalent of 10 weighted measurements.

The data set used for this analysis was measured over an area of salt marsh with buried ^{137}Cs activity, generating a stripped ^{137}Cs count rate of approximately 3 cps per kBq m^{-2} of activity. A more superficial activity distribution would result in a higher net count rate per unit activity, for example the activity measured in Finland for the Resume95 Exercise (Sanderson *et al*, 1997a) gave a ^{137}Cs stripped count rate of approximately 10 cps per kBq m^{-2}. The effect of this difference in sensitivity calibration would be to leave the shape of the plots in Figure 3.1 unaltered, but would shift the activity axis reducing the limit of detection by a factor of approximately 3. In the event of a nuclear accident with fresh deposition the activity would generate an even greater count rate per unit activity, reducing uncertainties yet further.

Since the uncertainties propagate through the stripping algorithm the concentrations of other radioisotopes in the environment will also affect the limit of detection. The data used to derive the uncertainties presented here was collected in an area with ^{40}K, ^{214}Bi and ^{208}Tl mean activity levels and standard deviations of 263±68, 9.9±6.8 and 5.6±1.6 Bq kg^{-1} respectively. Areas with lower natural background levels, particularly in the uranium and thorium series, would result in reduced detection limits for ^{137}Cs, whereas higher background levels would increase the limit of detection. Variations in the natural activity levels are a significant source of the scatter observed in Figure 3.1. The presence of other radioisotopes would introduce additional errors in the spectral stripping, and may require the use of a different set of windows and stripping matrix.

In situations where the source geometry and isotopic contribution differs significantly from the open-field conditions assumed in the standard analysis, significant uncertainties and systematic errors may be introduced to the spectral stripping and calibration. For example, highly localised sources and local shielding would introduce errors in the sensitivity calibration.

3.2 Repeat Flight over Drigg and River Irt

To assess the reproducibility of the AGS technique in measuring the location and activity of sources of activity a flight was conducted across the Drigg site on the morning of 15th March 2000. This followed the railway line from saltmarshes on the River Irt (near grid reference SD069984) then northwest over ISO containers on the railway line then across the site. Having passed the site, the same route was then flown in the reverse direction. A schematic map showing the route flown is given in Figure 3.2.

Figure 3.3 shows plots of activity for ^{137}Cs, ^{60}Co, ^{214}Bi and ^{208}Tl along this flight path. These clearly show the strong ^{137}Cs signals from the salt marsh, ISO containers and the Drigg site along with ^{60}Co and uranium and thorium activity on the site itself. The plots for the outward (northwesterly) and return (southeasterly) flights show substantial agreement with only very minor differences in the anthropogenic activity, although the natural series activities show greater variability. Some of this variability would be the result of the highly localised nature of the sources, local shielding effects and their comparatively high levels resulting in some spectral distortion over the higher activity areas. Relatively small changes in flight parameters may result in significant differences in the measured activity. Greater ground clearance would produce reduced spectral distortion, highly localised sources may be averaged over different numbers of spectra and slight differences in flight path may present different radiation fields due to shielding effects. A regular grid survey pattern of the site would average out many of these effects producing a fairly accurate representation of the radiation field from the averages of individual readings.

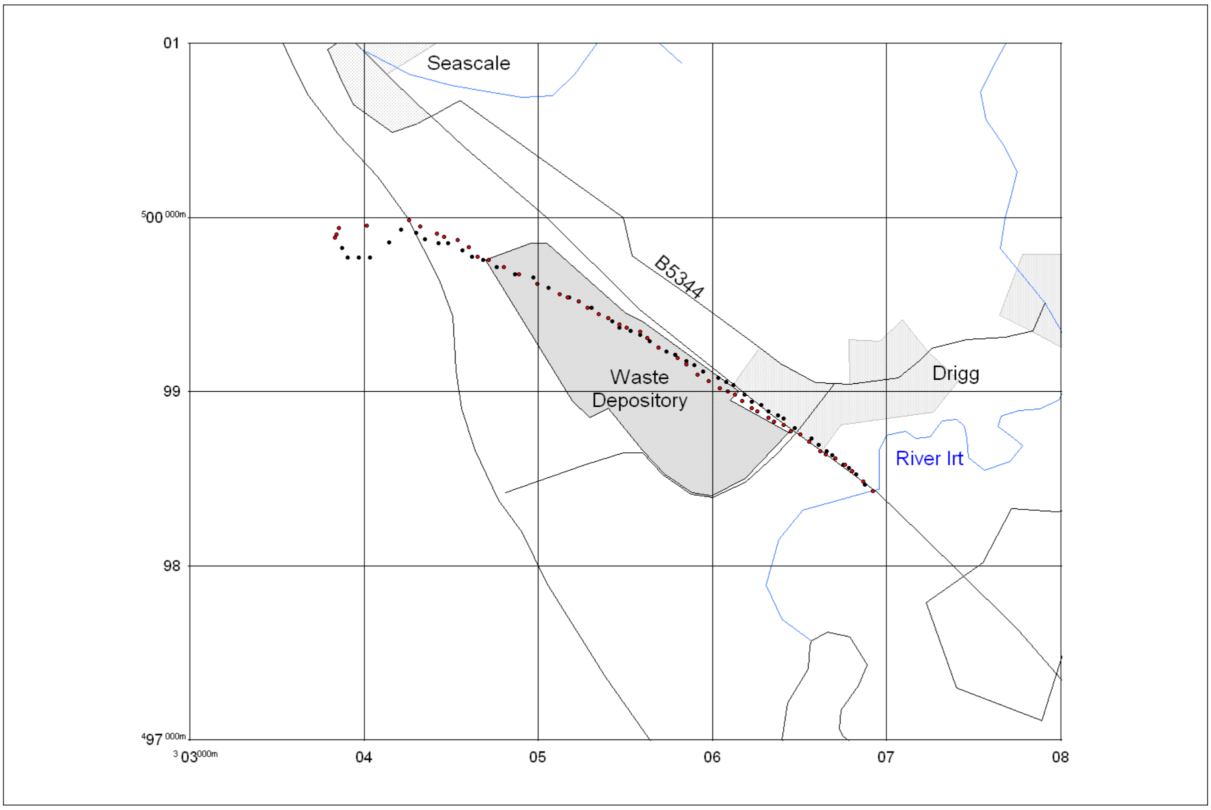

Figure 3.2: Schematic map of the area around the Drigg waste depository site showing the centre of each measurement on the outward (black) and return (red) flights on the 15th March 2000.

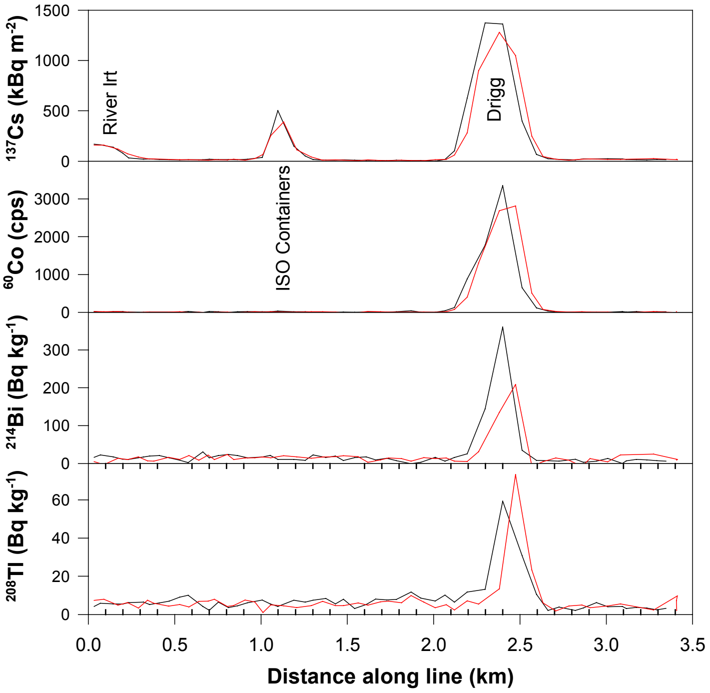

Figure 3.3: Activity measured from the outward (black) and return (red) flights over Drigg and the River Irt, 15th March 2000.

3.3 Tie Line Flights

During all three survey phases a series of tie lines at different altitudes were flown along a north-south line between grid references NY200600 (Bowness Common) and NY200300 (Bassenthwaite Lake). In April 1999 five different altitudes were flown; 70 m and 100 m over the full 30 km and 30 m, 50 m and 215 m over the northern 10 km of the line. In March 2000 three lines were flown at 40 m, 70 m and 100 m, and in June 2000 at 45 m, 65 m and 80 m over the full 30 km length. The tie lines cross a number of features that contribute to the observed radiometric data, including Newton Marsh (^{137}Cs contaminated intertidal salt marsh), Wedholme Flow (very wet peat land) and Bassenthwaite Lake with near background activity levels.

Figures 3.4, 3.5 and 3.6 show calibrated activity levels for ^{137}Cs, ^{40}K and ^{214}Bi for the April 1999, March 2000 and June 2000 flights respectively. Within each survey the data from each of the lines is very similar with the only major exception being for the 215 m flight in April 1999 which shows significant differences in the ^{137}Cs activity with higher levels over Newton Marsh and on either side of Wedholme Flow. It is probable that these are due to the larger field of view resulting from the increased ground clearance, which result in a larger area of salt marsh being included in the measurement. The activity on Newton Marsh to the west of the survey line would be the principle area now included within the field of view, and since this is not immediately below the aircraft the altitude correction coefficient results in an over estimation of the activity.

The other difference between tie lines recorded within each survey is the position of the southern edge of the Newton Marsh feature in the March and June 2000 data. For most of the tie lines this is placed 26 km north of Bassenthwaite, however for one line in each survey it is placed a few hundred metres further north. Examination of the position of each reading indicates that on these occasions the aircraft was a couple of hundred metres further east than for the other lines, as a consequence of avoiding directly overflying the small village of Newton Arlosh. The southern edge of the merse forms a line running north-east to south-west, so the line further east crosses this edge further to the north. The northern edge of the merse is formed by the east to west flowing River Wampool, so the positioning of this edge is unaffected.

There are low levels of ^{137}Cs activity further south with a scatter consistent with the uncertainties predicted in section 3.1 for such activity levels. It is possible to identify some trends within these lower ^{137}Cs activity parts of the tie line data, although the individual measurements are not significant compared to the scatter. For example, there is a slight increase in activity from about 5 kBq m^{-2} to about 10 kBq m^{-2} approximately 7 km north of Bassenthwaite where there is also a large increase in ^{214}Bi activity, this corresponds to the east side of a small hill near the village of Bothel. This demonstrates that by combining data points the uncertainties and limits of detection are reduced compared to single measurements.

The tie line data from March and June 2000 are very similar, however the April 1999 data are significantly different. The Newton Marsh feature is narrower and less active in April 1999, and the feature at Wedholm Flow is much less pronounced in the later data sets. Examination of the position of the each reading indicates that the April 1999 tie lines were at a slight angle to the later lines, with the northern waypoint approximately 1 km to the east. This resulted in the earlier tie lines crossing a narrower section of saltmarsh further upstream and closer to the centre of Wedholme Flow.

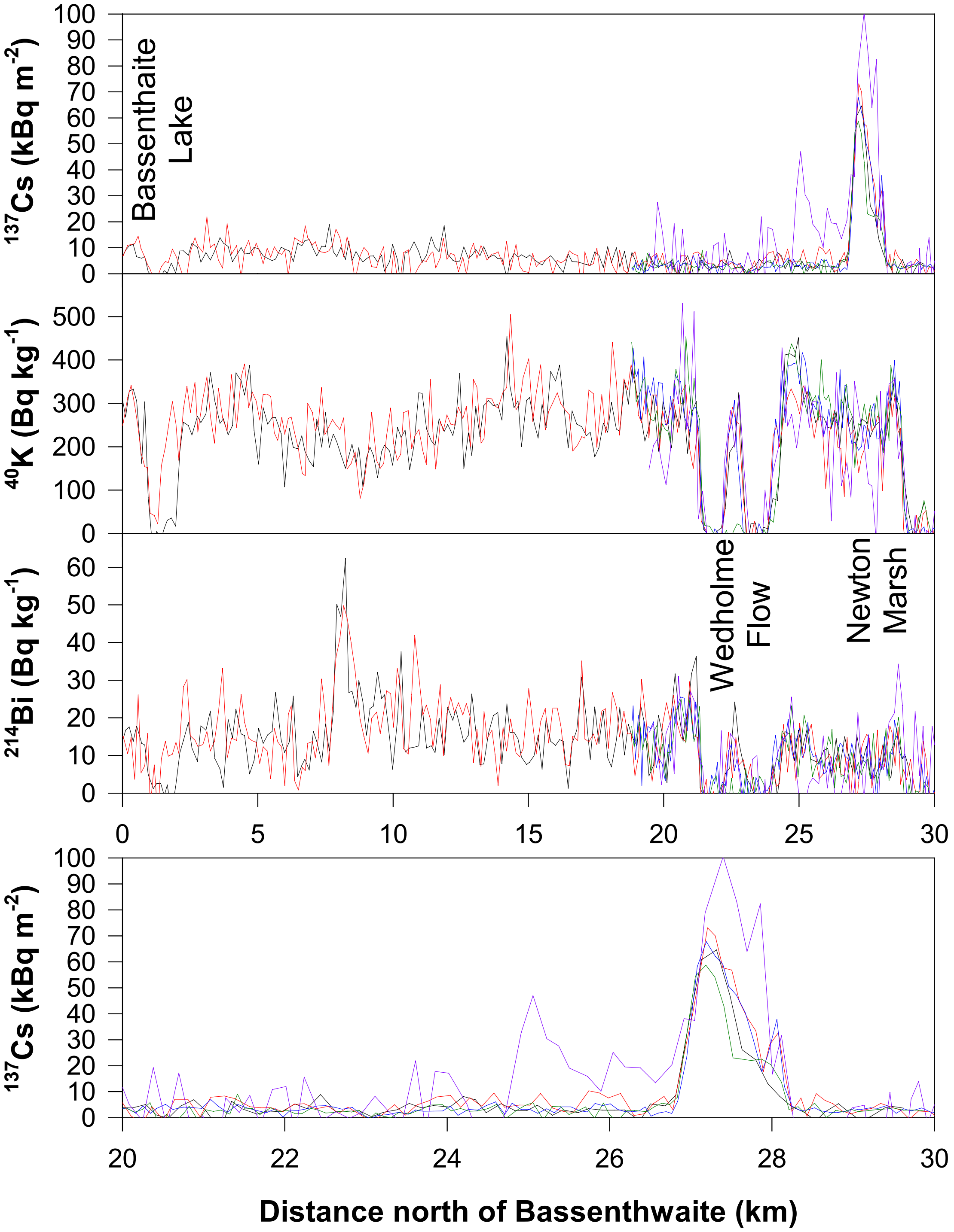

Figure 3.4: ^{137}Cs, ^{40}K and ^{214}Bi activity levels recorded from the tie lines flown on the 27th April 1999 at 30 m (blue), 50 m (green), 70 m (black), 100 m (red) and 215 m (purple) ground clearances. Note that the Newton Marsh feature is shown in greater detail at the bottom of the page.

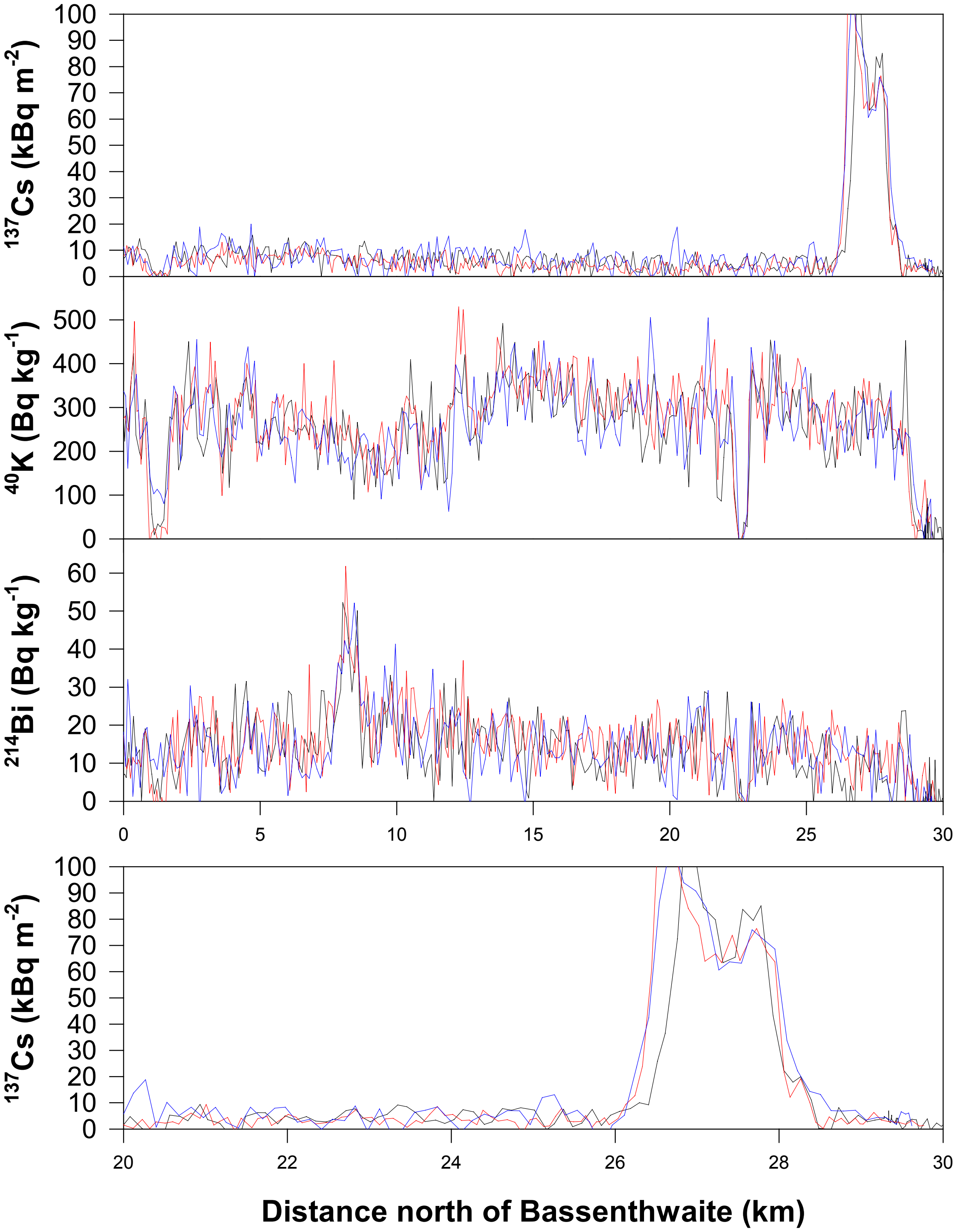

Figure 3.5: ^{137}Cs, ^{40}K and ^{214}Bi activity levels recorded from the tie lines flown on the 22nd March 2000 at 40 m (red), 70 m (black), and 100 m (blue) ground clearances. Note that the Newton Marsh feature is shown in greater detail at the bottom of the page.

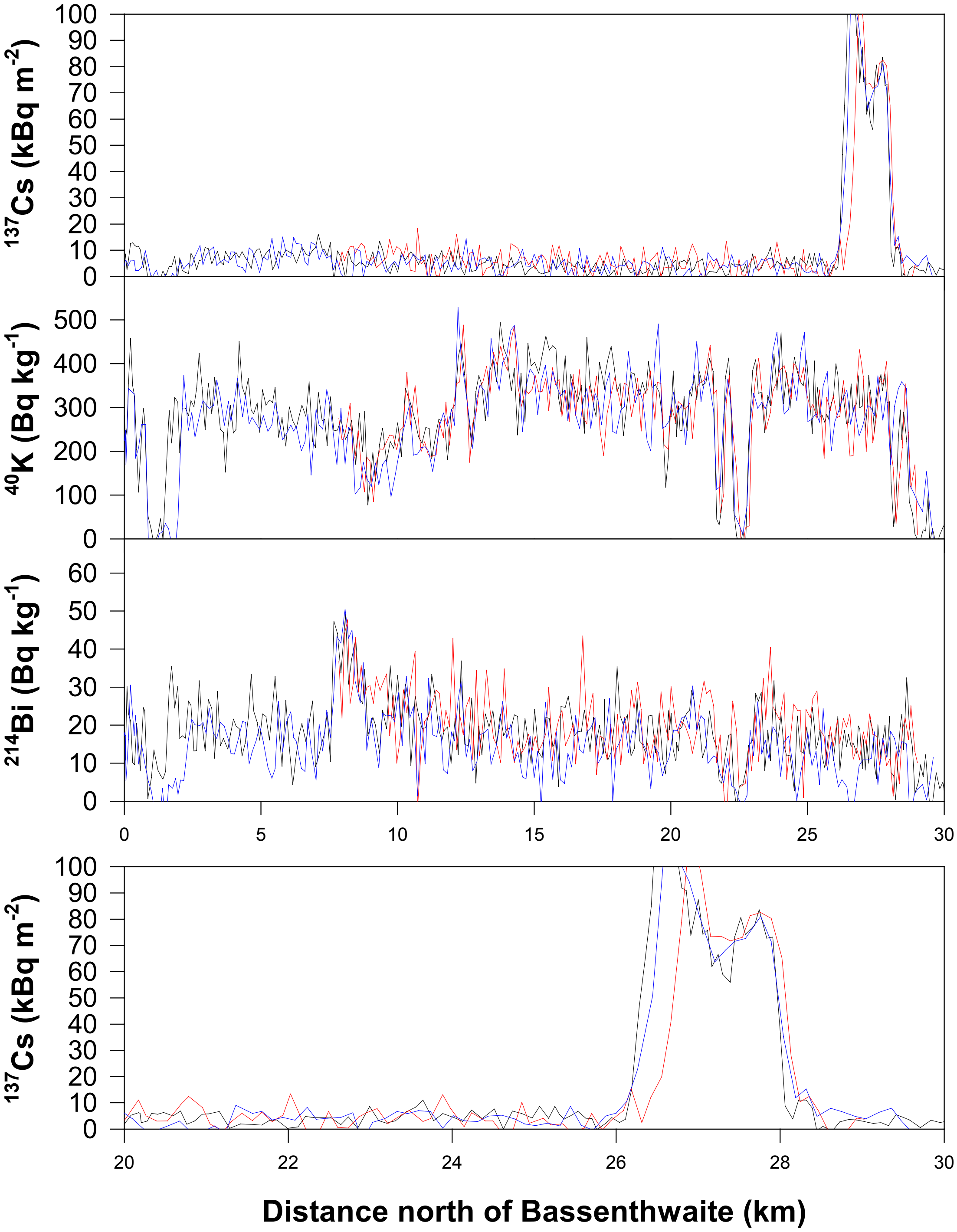

Figure 3.6: ^{137}Cs, ^{40}K and ^{214}Bi activity levels recorded from the tie lines flown on the 20th and 22nd June 2000 at 45 m (black), 65 m (blue) and 80 m (red) ground clearances. Note that the Newton Marsh feature is shown in greater detail at the bottom of the page.

3.4 Summary

An assessment of the sources of uncertainty in measurements, and the resulting precision in the calibrated data, has shown that the gross count propagated through the data analysis algorithm is the primary source of uncertainty in individual measurements in open field conditions. Although the uncertainties on single measurements in the data collected over Rockcliffe Marsh result in a limit of detection for ^{137}Cs of approximately 10 kBq m^{-2} on a single reading, combining measurements through the smoothing algorithm significantly reduces this limit of detection. The limit of detection would be lower still in situations with superficial activity deposition or lower background levels. The use of longer integration times would reduce the limit of detection for a single measurement, at the expense of spatial resolution, but this will be partially offset by a reduction in the number of readings being combined in the smoothing algorithm. It may be possible to use narrower spectral windows which would result in reduced interference between channels, and hence reduced uncertainties as a result of the stripping process.

Analysis of data recorded over the Drigg storage facility and the salt marshes on the River Irt has shown that the radiometric features observed during flights in two directions along a single route are very similar. This is despite a number of factors relating to the highly localised nature of the sources that might be expected to influence the reproducibility of the data. This has shown that the AGS method is highly stable in the short term, with the characteristics of such features being reproduced in two sections of data.

During each of the three phases of field work tie lines between Bowness Common and Bassenthwaite Lake were flown at a range of ground clearances. With the exception of one tie line flown in excess of 200 m ground clearance in April 1999, the data recorded within each survey show considerable agreement. Once again this demonstrates the levels of reproducibility achievable from the AGS technique.

Comparison between the tie line data recorded in March and June 2000 also shows definite similarities, demonstrating that the AGS technique can be reproducible over extended periods between surveys. It may be expected that some differences between these data sets would exist due to seasonal differences in the environment such as soil water content or the amount of vegetation. Such differences will be examined in detail in section 5.3.

To maintain a high quality, reproducible, AGS capability it is essential that the detector systems are well maintained between surveys, and that during field work the performance is regularly checked to ensure the detector performance is maintained.

4. INFLUENCE OF SURVEY LINE SPACING ON AGS RESULTS

4.1 Analytical Approaches

The survey areas studied in this project cover two different types of environment with enhanced anthropogenic activity; estuarine salt marshes with activity deposited through marine pathways following historic discharges from Sellafield, and Cumbrian upland areas with activity deposited through atmospheric pathways from the Windscale fire, Chernobyl accident and nuclear weapons fallout. For the purposes of studying the effect of line spacing data recorded from area A surveyed in April 1999 and areas C and D surveyed in June 2000 will be considered. The data corresponding to each flight line within the survey areas were identified, and sub-sets of these lines selected to produce survey data sets with increasing line spacing.

Area A, covering the Inner Solway around Rockliffe and Burgh Marshes, flown at 50 m and 250 m line spacing in April 1999 and at 250 m line spacing in June 2000 is fairly representative of the estuarine salt marsh environments. The 50 m data set recorded in April 1999 was subsampled to produce two 100 m, five 250 m and ten 500 m line spacing data sets.

Areas C and D, in West Cumbria, flown at 500 m (area C) and 2.5 km (area D) line spacing in June 2000 provide a data set covering the upland radiation environment, although parts of area D do include some salt marshes. The 500 m data set from area C was subsampled to produce two 1 km, five 2.5 km and ten 5 km line spacing data sets. Some of the survey lines in area C correspond to the continuation of the 2.5 km lines in area D, a composite data set was produced by combining these lines with the area D data. This composite data was then used as a 2.5 km line spacing data set, and subsampled to produce two 5 km and four 10 km line spacing data sets.

Two types of characteristics relating to different line spacing data sets will be considered. The first will be inventory estimates, which will assess the effect of line spacing on measurements of the amount of activity present within a given area, as well as measurements of the amount of a given area which has activity within particular activity density ranges. The second, spatial characterisation will assess the overall characteristics of the areas using semi-variograms, the effect of line spacing on the size and shape of radiometric features within the areas, and determine the statistical similarity between various line spacings utilizing the Kappa Index of Agreement (KIA). For the saltmarsh environments the shape of radiometric features closely reflect the shape of the saltmarshes determined from satellite imagery, and for this reason are used for the comparisons of the shapes of radiometric features.

These analyses have been used to assess how accurately data from different line spacings reproduce the activity distribution in a given area. It has been possible to determine the data quality, such as accuracy of inventory estimation and definition of spatial extents, for features of given dimensions and activities for different line spacings. Some recommendations for minimum line spacings for different survey requirements have been made from the assessment of such effects.

4.2 Inventory Estimates

4.2.1 Regridding of Data

In order to account for variations in sample density and imprecision within different data sets, the data were regridded into a regular array of cells of known area. An inverse weighting algorithm was applied to each measured data point to determine the contribution that data point would make to cells surrounding it, up to a user defined maximum range. This is the same algorithm used to interpolate between data points to produce smoothed maps. The mean activity density (in kBq m^{-2}) in each cell ($\overline{A_j}$) is then simply the weighted mean activity densities of the data points that contribute to that cell.

$$\overline{A_j} = \frac{\sum_i A_i r_i^p}{\sum_i r_i^p} \qquad 4.1$$

Where A_i is the measured activity of each data point, r_i the distance between each point and the centre of cell j, and p (which is a negative number) the power of the weighting function.

There are two sources of uncertainty relating to the activity density of each cell; systematic uncertainties on each measurement and variation between measurements.

The systematic uncertainty on the mean activity density of each cell ($\Delta\overline{A_j}$) is given by

$$\Delta\overline{A_j} = \frac{\sqrt{\sum_i (\Delta A_i r_i^p)^2}}{\sum_i r_i^p} \qquad 4.2$$

where ΔA_i is the uncertainty on A_i as a result of counting errors, spectral stripping and calibration. It is determined from the uncertainty on stripped count rate (equation 3.8). In practice, given the additional programming task required to determine this uncertainty from the raw data for each measurement, this was determined from the fractional error given by the equation used to fit the points for 2 s integration time in Figure 3.1.

The standard deviation between measurements (σ_j) is given by (Lyons 1986)

$$\sigma_j = \sqrt{\frac{1}{(n_{eff} - 1)} \frac{\sum_i (A_i - \overline{A_j})^2 r_i^p}{\sum_i r_i^p}} \qquad 4.3$$

where the effective number of measurements (n_{eff}) is

$$n_{eff} = \frac{(\sum_i r_i^p)^2}{\sum_i (r_i^p)^2} \qquad 4.4$$

These terms were calculated independently, and the larger of the two used as the uncertainty on $\overline{A_j}$.

4.2.2 Inventory Analysis

The regridded XYZ data are used to calculate the activity inventory of an area within the survey. The inventory is divided into a number of activity strata giving the area containing an activity density within that stratum, the total activity contained within that area and the resulting average activity density. The total activity and average activity density for the total area are also given.

The activity within each stratum is the sum of the product of the activity density of each contributing cell and the area of each cell. The uncertainty on the activity within each stratum is simply the product of the uncertainty on the activity density of each cell (the larger of $\Delta\overline{A_j}$ or σ_j) and the area of each cell added in quadrature.

4.2.3 Inventory Estimates for Area A

A total ^{137}Cs inventory of 1.1 TBq has been calculated for area A, corresponding to a mean activity density of 16.7 kBq m^{-2} averaged over the 66 km^2 area. The variation in total inventory for the different line spacing sets is given in Table 4.1, and shown in Figure 4.1. The spread in estimates increases slightly for increasing line spacing, to about 7% for the 500 m line spacing data sets, compared to the 1-2% uncertainty on the individual estimates for the total inventory.

The bulk of the ^{137}Cs activity in area A is on Rockcliffe Marsh, with the majority of the rest on Burgh Marsh. The ^{137}Cs inventories for each of these features for each line spacing are also given in Table 4.1, and shown in Figure 4.2. It can be seen that there is very little variation in inventory for Rockcliffe Marsh, as would be expected considering the lack of variation in the total area. However, for Burgh Marsh some of the inventory estimates for the 500 m line spacing data sets are up to 20% less than the inventory estimate for the 50 m line spacing data set. The difference between these reflects the different spatial dimensions of the two features. Rockcliffe Marsh is the larger feature, covering an area that extends some 3-4 km north to south and 3 km east to west. However, Burgh Marsh is smaller, about 6 km long east to west, but less than 1 km wide for much of the length. The flight lines are parallel to the long axis of the marsh, so at 500 m line spacing a very small number of flight lines actually cross the marsh.

Line spacing and permutation	Total Inventory (GBq)	Rockcliffe Marsh Inventory (GBq)	Burgh Marsh Inventory (GBq)
50 m	1100±5	468±3	381±7
100 m P1	1070±5	462±3	369±8
100 m P2	1100±5	466±3	378±10
250 m P1	1100±6	476±4	377±5
250 m P2	1130±8	472±4	405±22
250 m P3	1100±8	468±4	382±13
250 m P4	1090±7	461±5	376±7
250 m P5	1110±5	473±3	388±6
500 m P1	1120±7	483±4	369±12
500 m P2	1090±7	485±4	373±11
500 m P3	1100±7	485±4	388±11
500 m P4	1120±8	489±4	400±9
500 m P5	1130±7	488±4	392±8
500 m P6	1090±7	475±4	400±8
500 m P7	1120±7	488±4	386±43
500 m P8	1060±7	467±4	357±8
500 m P9	1080±6	456±4	350±44
500 m P10	1070±6	457±4	331±6

Table 4.1: ^{137}Cs inventory estimates for area A and Rockcliffe and Burgh Marshes for various line spacing data sets.

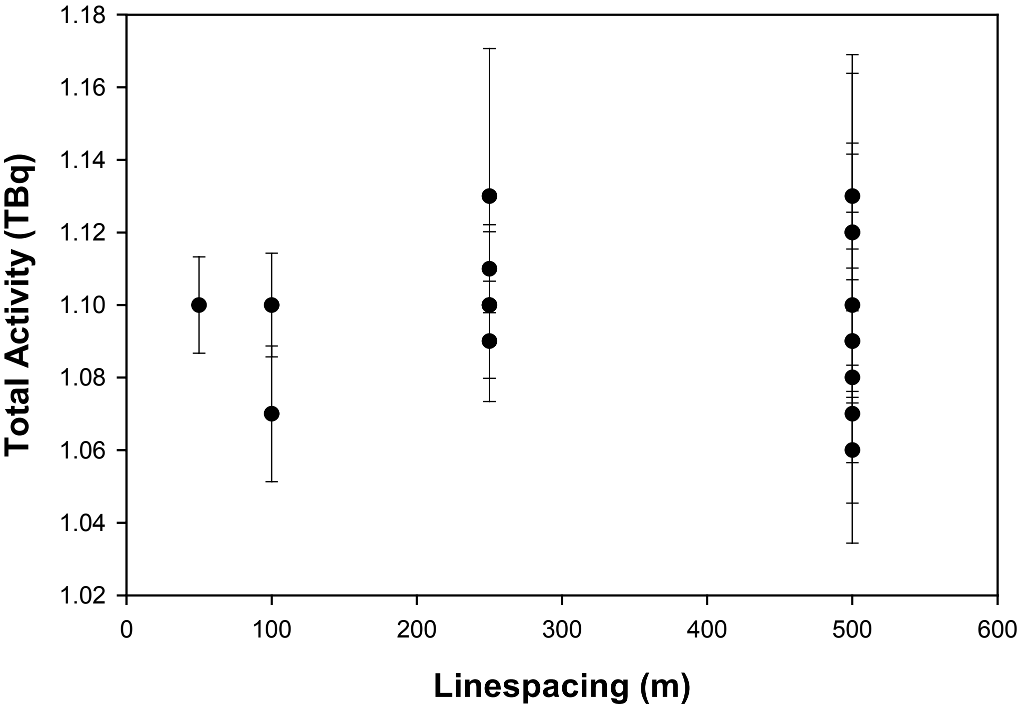

Figure 4.1: Total ^{137}Cs inventory estimates for area A (Rockcliffe Marsh and the Inner Solway) for 50 m, two 100 m, five 250 m and ten 500 m line spacing data sets

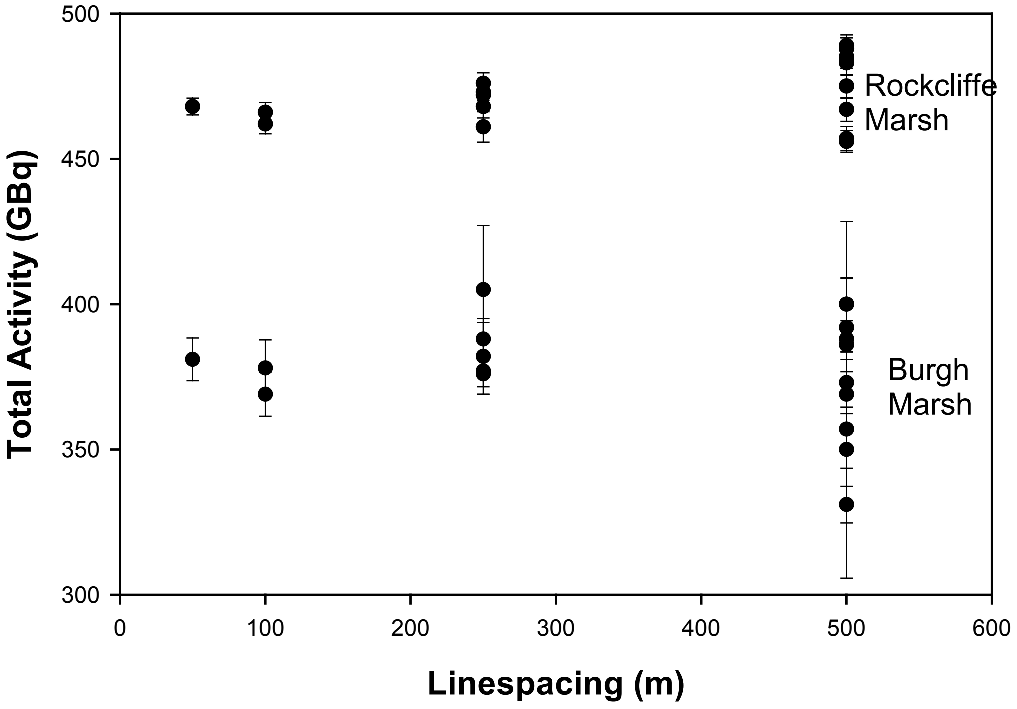

Figure 4.2: ^{137}Cs inventory estimates Rockcliffe Marsh and Burgh Marsh for the 50 m, two 100 m, five 250 m and ten 500 m line spacing data sets

4.2.4 Inventory Estimates for Areas C and D

A total ^{137}Cs inventory of 15.8 TBq has been calculated for area C, corresponding to a mean activity density of 9.9 kBq m^{-2} averaged over the 1600 km^{2} area. The variation in total inventory for the different line spacing sets is given in Table 4.2, and shown in Figure 4.3. The spread of estimates increases slightly for increasing line spacing, to about 9% for the 5 km line spacing data sets, with a 2-3% uncertainty on individual estimates for the total inventory.

For the combined 2.5 km line spacing data sets for areas C and D a total ^{137}Cs inventory of 37.8 TBq has been calculated, corresponding to a mean activity density of 10.8 kBq m^{-2} averaged over the 3500 km^{2} area. The variation in total inventory for the different line spacing sets is given in table 4.3, and shown in figure 4.4. There is still a slight increase in the spread of the estimates with increased line spacing, but it is much smaller at about 3% than in the other data sets, and much smaller than the 7-12% uncertainty on individual estimates for the total inventory.

Line spacing and permutation	Inventory (TBq)	Line spacing and permutation	Inventory (TBq)
500m	15.90±0.02	5km P1	15.90±0.03
1km P1	16.10±0.01	5km P2	15.50±0.03
1km P2	15.80±0.03	5km P3	15.40±0.02
2.5km P1	16.10±0.03	5km P4	15.80±0.04
2.5km P2	16.00±0.03	5km P5	16.40±0.03
2.5km P3	15.60±0.03	5km P6	16.40±0.04
2.5km P4	16.00±0.03	5km P7	16.80±0.02
2.5km P5	16.00±0.03	5km P8	16.10±0.03
		5km P9	16.30±0.02
		5km P10	16.00±0.03

Table 4.2: ^{137}Cs inventory estimates for area C (northwest Cumbria) for various line spacings

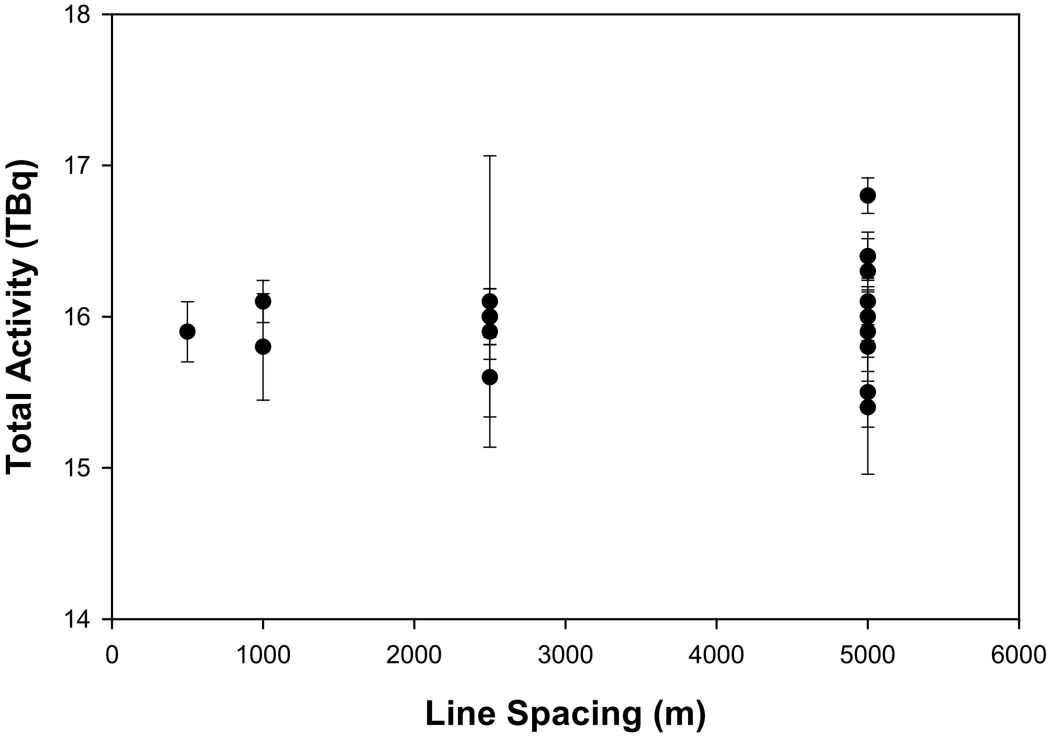

Figure 4.3: Total ^{137}Cs inventory estimates for area C (north west Cumbria) for the 500 m, two 1 km, five 2.5 km and ten 5 km line spacing data sets

Line spacing and permutation	Inventory (TBq)
5km P1	37.80±0.10
5km P2	37.80±0.09
10km P1	37.70±0.15
10km P2	38.30±0.09
10km P3	37.80±0.09
10km P4	37.50±0.11

Table 4.3: ^{137}Cs inventories for the combined areas C and D (West Cumbria) for various line spacings

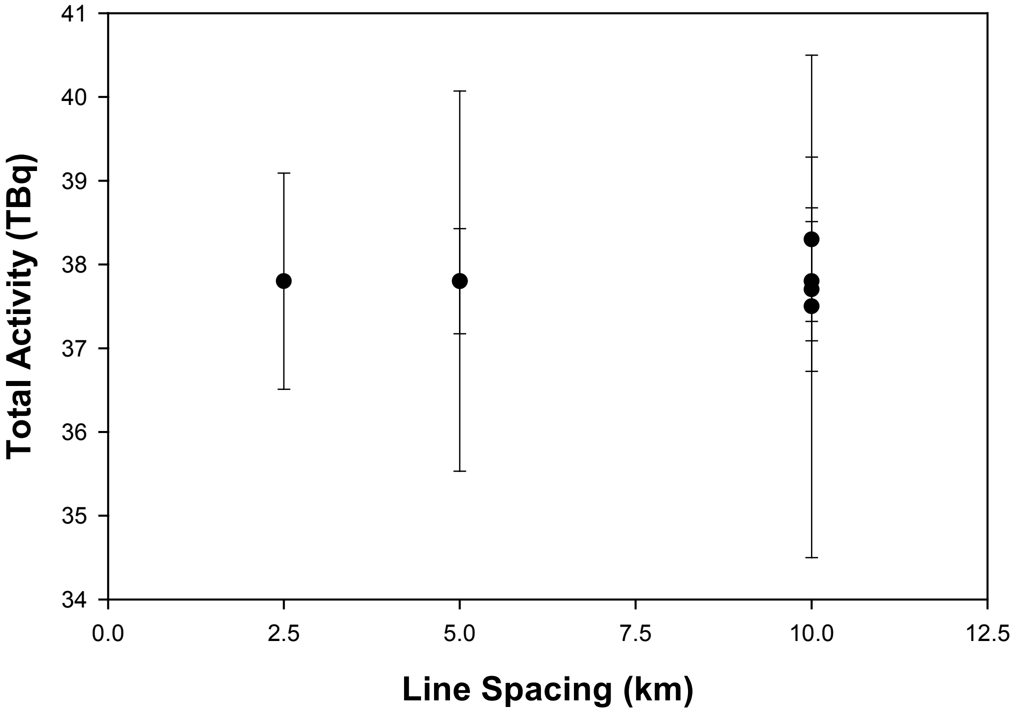

Figure 4.4: Total ^{137}Cs inventory estimates for area D and the corresponding 2.5 km line spacing data from area C (west Cumbria) for the 2.5 km, two 5 km and four 10 km line spacing data sets

4.3 Spatial Characterisation

It is clear from the inventory analysis that the technique is extremely robust, even at considerable line spacing intervals. However, the identification of radiometric features and their spatial characteristics, in terms of their general spatial locations within survey areas, their radiometric shapes and how much radiometric feature shapes vary at increasing line spacing intervals are likely to break down as line spacing interval increases. The ability of the AGS technique to detect radiometric features reflected in the environment at various line spacing intervals will be explored in this section.

4.3.1 Underlying Characteristics of Areas A, C and D

To obtain a general description of radiometric features identified in areas A and C+D semi-variogram analysis was employed. Semi-variogram analysis forms a stage in the geostatistical technique known as Kriging developed by Matheron, Krige and their co-workers. The semi-variogram is a useful geostatistical technique for establishing the spatial structure of geospatial data (Burrough and McDonnell, 1998). The semi-variogram is a graph, which expresses half the mean of squared differences between samples as a function of distance between them, termed the semi-variance (Figure 4.5). The variance and semi-variance are computed as follows as stated by Krejčíř (1999):

Let Z(.) be a spatial process and let a function $\gamma: D \rightarrow R$ exist so that

$$\text{var}\ \{Z(\mathbf{s})-Z(\mathbf{t})\} = 2\gamma(\mathbf{s}-\mathbf{t}) \text{ for all } \mathbf{s},\mathbf{t} \in D. \tag{4.5}$$

Then the function $2\gamma(.)$ is called the variogram and the function $\gamma(.)$ is called the semi-variogram. The vector **s-t** is then called the lag.

Omnidirectional and directional semi-variograms (at 90^{o} intervals with 45^{o} angular tolerance) were produced, using S-Plus and S+Spatial Stats software, for areas A and C+D from the survey data to identify the spatial structure of the data sets statistically (Figure 4.6). Area A has an increase in semi-variance up to a range of 5.5 km with a corresponding sill of 475, values decrease dramatically after this distance back to the nugget value of 25 at 14 km. This dramatically inclining and declining semi-variogram is explained by the extreme range in data variability across the area. Rockcliffe and Burgh marshes (with correspondingly high ^{137}Cs values) within the centre of the area, are surrounded by sea and farmland with low level activity in conjunction with a sharp decline in ^{137}Cs on the marsh peripheries. Directional semi-variograms for area A also display the same distinctive changes in variability with distance. There is a notable change in the structure of semi-variograms in the NE and SW direction compared to those in the NW and SE direction, indicating zonal anisotropy, which reflects the spatial extent of Rockcliffe and Burgh marshes (which predominate along the NE and SW of area A).

The omnidirectional semi-variogram for area C+D contrasts markedly to area A. Variability with distance is much lower, increasing to a sill of 350 at a corresponding range of 55 km. The nugget is also significantly higher at 150, compared to 25 for area A, which is likely to be the result of the spatial characteristics of the radiometric features identified for area C+D which are much more convoluted than for area A at the spatial scale and sample intervals used. Lower semi-variance between sample pairs for area C+D demonstrates the dispersed nature of ^{137}Cs activity over the Cumbrian mountains. The directional variograms reveal a situation of no variability in a

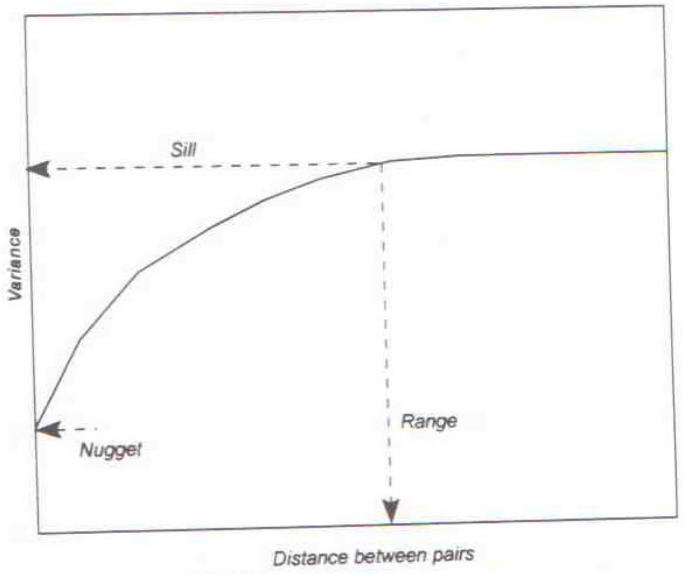

Figure 4.5: An ideal semi-variogram, from Eastman 1999

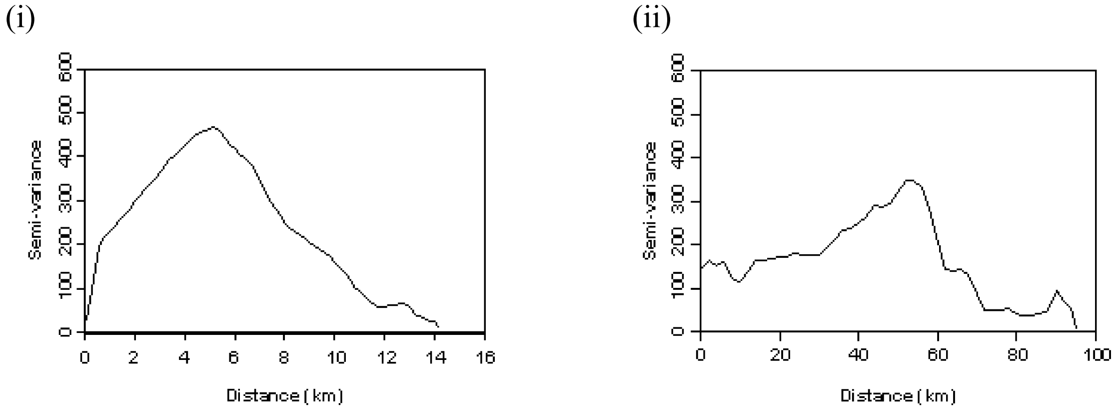

Figure 4.6: Omnidirectional semi-variograms for (i) Area A and (ii) Area C+D

SE and NW direction, i.e., a pure nugget effect, and falling and rising variogram limbs in a NE, SW direction. These directional differences reflect low activity values in the NE of area C+D contrasting with localised high ^{137}Cs to the SW due to coastal salt marshes, NW and SE ^{137}Cs variability is almost non-existent.

4.3.2 Shape of Identified Radiometric Features

The activity distribution from the regridded data sets for the various line spacings can be mapped simply by setting the pixel size to the size of the cells used in the regridding. The resulting images are slightly coarser quality than what would be produced by smoothing the raw data, but still show the major features that would be observed for each data set and allow direct comparison between different line spacings within each area.

Figure 4.7 shows the regridded data from area A for the 50 m, two 100 m, five 250 m and ten 500 m line spacing data sets, with a 250 m cell size. The 50 m regridded data reproduce the features observed from the raw data given in figure 2.1, although the finer detail has been lost through regridding into a relatively large cell size. The 100 m and 250 m regridded data sets also reproduce these features, although some of the activity along the River Eden has not been recorded in some of these. The 500 m data sets start to lose some significant information; some of the data sets significantly underestimate the size of the Burgh Marsh feature, others detect very little activity along the River Eden, and the small feature on a small saltmarsh on the northern side of the Solway is also not observed in some of these data sets. In all the data sets there are only small changes in the Rockcliffe Marsh feature.

Figure 4.8 shows the regridded data for area C for the 500 m, two 1 km, five 2.5 km and ten 5 km line spacing data sets, with a 1 km cell size. The 500 m regridded data reproduce the features observed from the raw data sets given in figure 2.3, although again the finer detail of the activity distribution in the upland areas and the definition of the lakes has been lost through regridding into the relatively large cell size. The 1 km line spacing data set also largely reproduces these features. In the 2.5 km line spacing data set there is a noticeable loss of information, particularly the extent of the lower activity extension of the Chernobyl deposition to the north of the upland areas, some artificial north-south lines are evident along the data lines. The 5 km line spacing

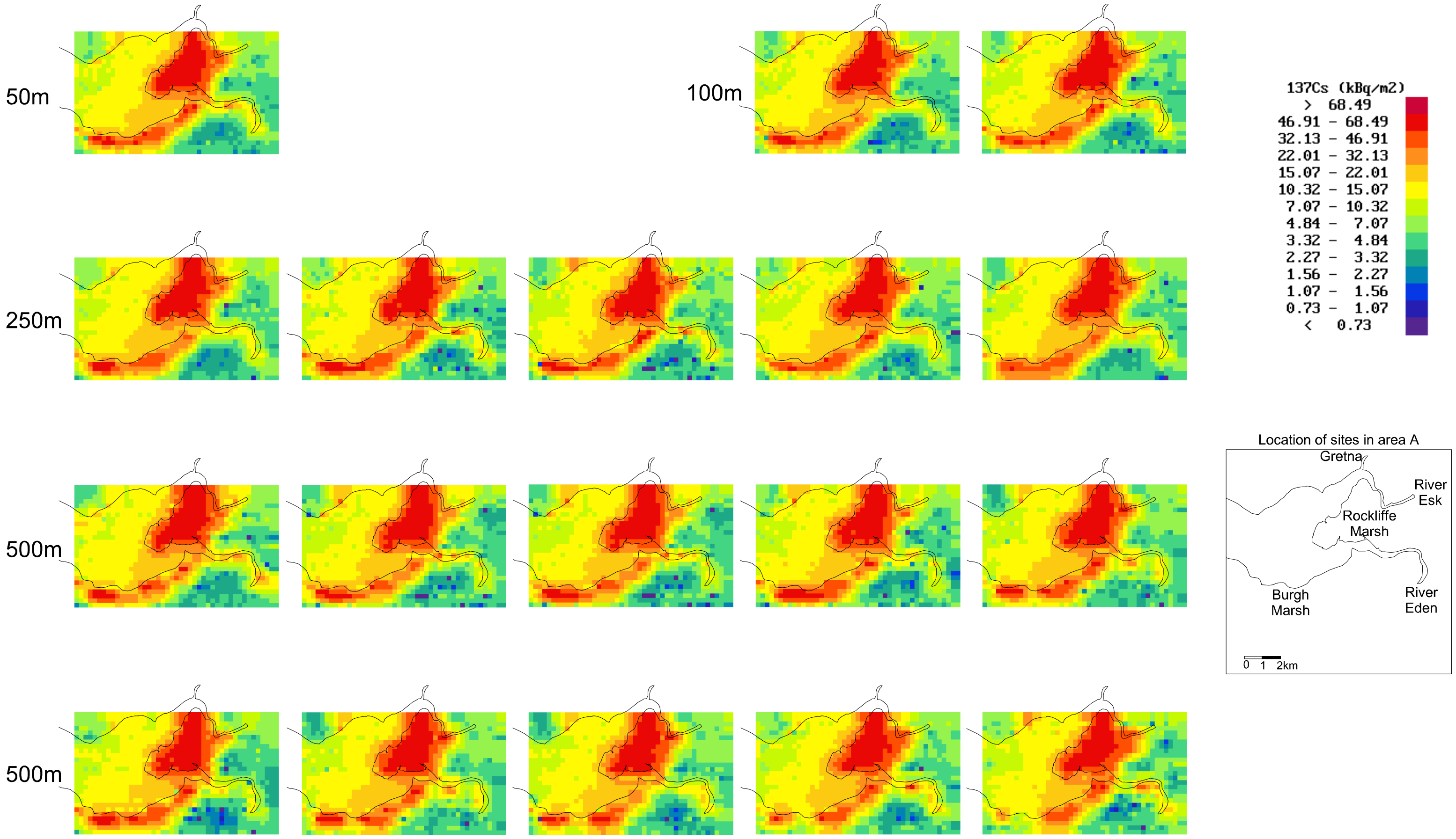

Figure 4.7: Regridded ^{137}Cs activity for area A (Rockcliffe Marsh and Inner Solway) for the 50 m, two 100 m, five 250 m and ten 500 m line spacing data sets

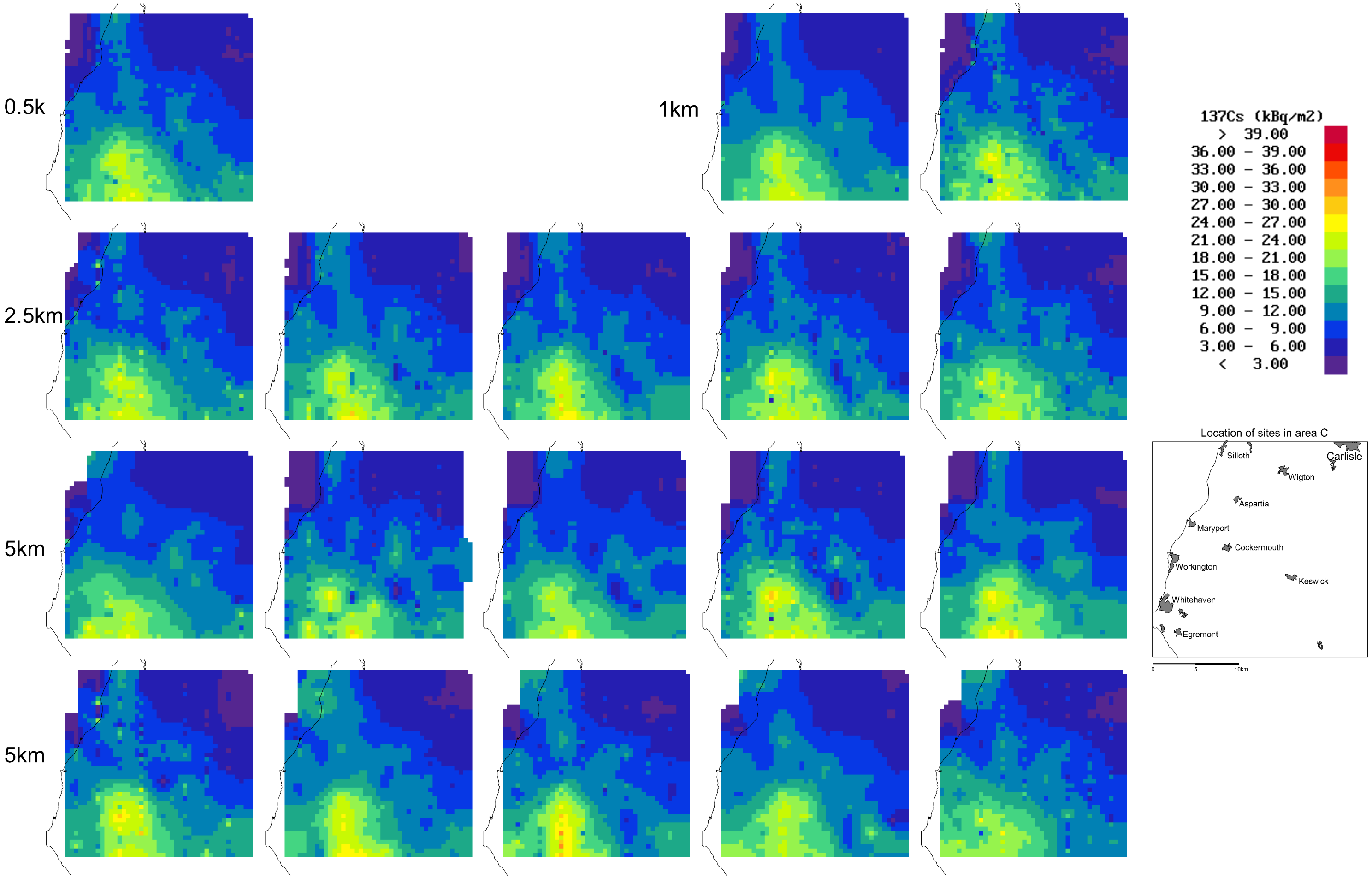

Figure 4.8: Regridded ^{137}Cs activity distributions for area C (north west Cumbria) for the 500 m, two 1 km, five 2.5 km and ten 5 km line spacing data sets

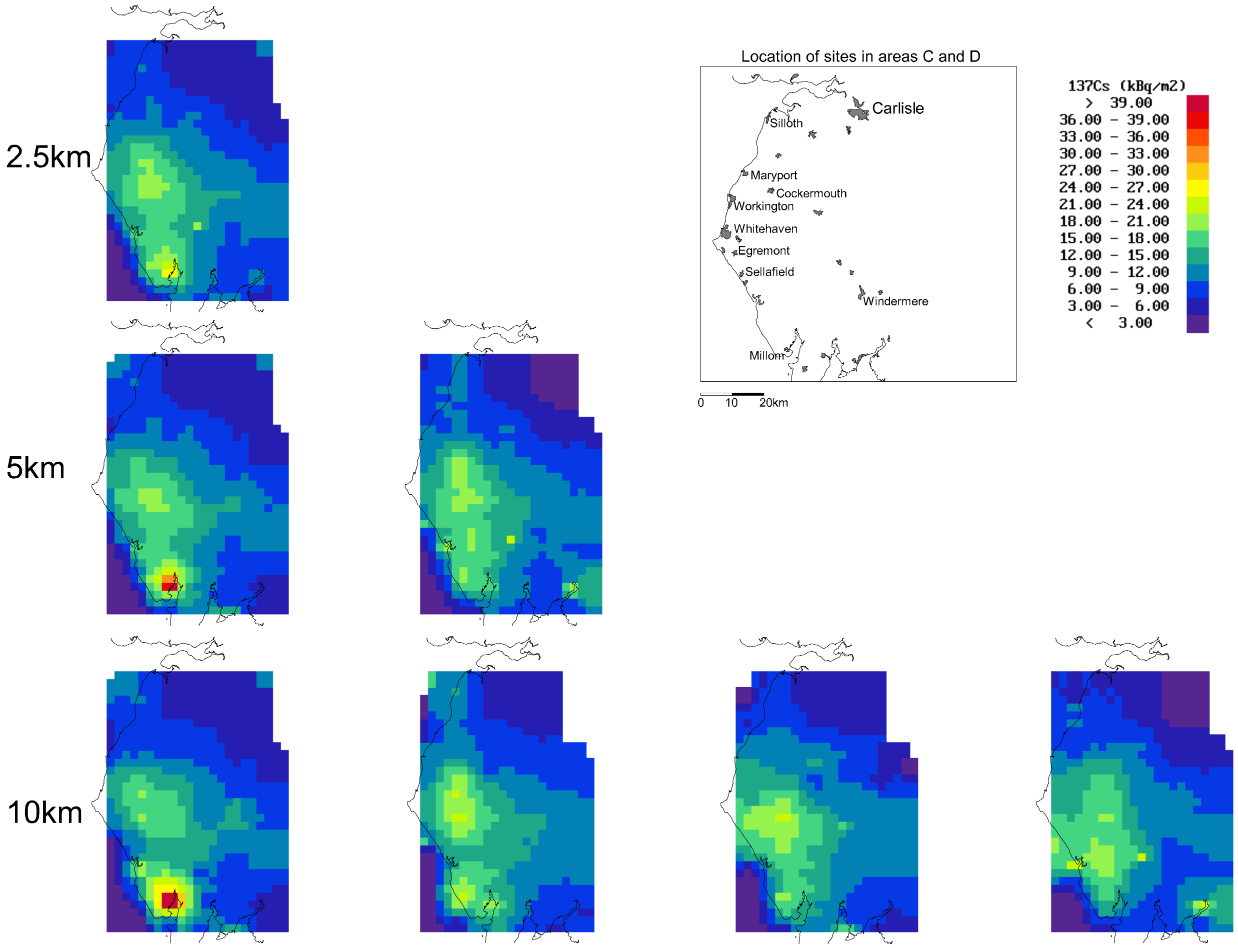

Figure 4.9: Regridded ^{137}Cs activity distributions for area D and the corresponding 2.5 km line spacing data from area C (West Cumbria) for the 2.5 km, two 5 km and four 10 km line spacing data sets

data still shows the larger features in the area, the higher activity on the uplands to the south and lower activity to the north east, but in some of these data sets many of the smaller features are almost completely absent.

Figure 4.9 shows the regridded data for area D and the corresponding 2.5 km line spacing data from area C for the 2.5 km, two 5 km and four 10 km line spacing data sets with a 2.5 km cell size. Although, as would be expected from the 2.5 km line spacing data for area C, the finer details of the distribution of ^{137}Cs activity in this area are not evident the broad features of increased activity in the upland areas north east of Sellafield and Black Coombe, the low levels of activity to the north east of the area and the activity on salt marshes in the Duddon Estuary, are clear in the 2.5 km line spacing data set. At 5 and 10 km line spacing only one of the data sets detects the salt marsh feature on the Duddon Estuary.

To provide a more detailed investigation of radiometric feature shape changes with line spacing, specific geometric attributes (area, perimeter, and an area/perimeter ratio) of identified features above a given threshold have been computed, using Idrisi32 GIS (Geographical Information Systems) software.

A threshold of 32.13 kBq m^{-2} was selected as an appropriate value, to enable the radiometric features of Rockcliffe and Burgh marshes to be clearly identified. Data for each permutation relating to the 50, 100, 250 and 500 m line spacings, from the inventory analysis were imported into Idrisi32 and a linear inverse distance weighting function was applied to them. The resulting images were reclassified to ensure only the identified radiometric features of Rockcliffe and Burgh marshes were present. Figure 4.10 shows one of these reclassified images for Rockcliffe and Burgh Marshes to illustrate the process. It is notable that this operation, which demarcates areas above the selected activity threshold, is extremely easily and rapidly achieved using GIS techniques, and illustrates precisely the processes which might be needed in using AGS data to delimit areas requiring consideration of counter measures in emergency response. For this study, however, the reclassified images were generated to examine the extent to which spatial characteristics are reproduced in resampled permutations of the original data sets. Area and perimeter computations were then executed on the reclassified images for each of the line spacing permutations for each marsh individually. Results were then exported into tables in sigma plot and scatter plots produced to provide comparative output. Saltmarsh boundaries identified on a Landsat Thematic Mapper image recorded at 12:00 hours on 27th April 1999 were imported into Idrisi32 and rasterised, area and perimeter calculations were then computed using the same procedure as discussed earlier, these were added to the tabulated results for comparative purposes.

Tabulated results from shape geometry calculations summarised in Tables 4.4 and 4.5 indicate a trend of increased variability of geometric feature shape characteristics between permutations with increasing line spacing for both Rockcliffe and Burgh marshes. Landsat TM image marsh features are slightly lower for Rockcliffe marsh and slightly higher for Burgh marsh. These differences could be explained by: (i) the Rockcliffe marsh boundary is more clearly defined in the satellite image (30 m cell size resolution) than from the inventory images (50 m cell resolution); and (ii) the Burgh marsh boundary covering a larger area on the satellite image than when identified at the threshold of 32.13 kBq m^{-2}.

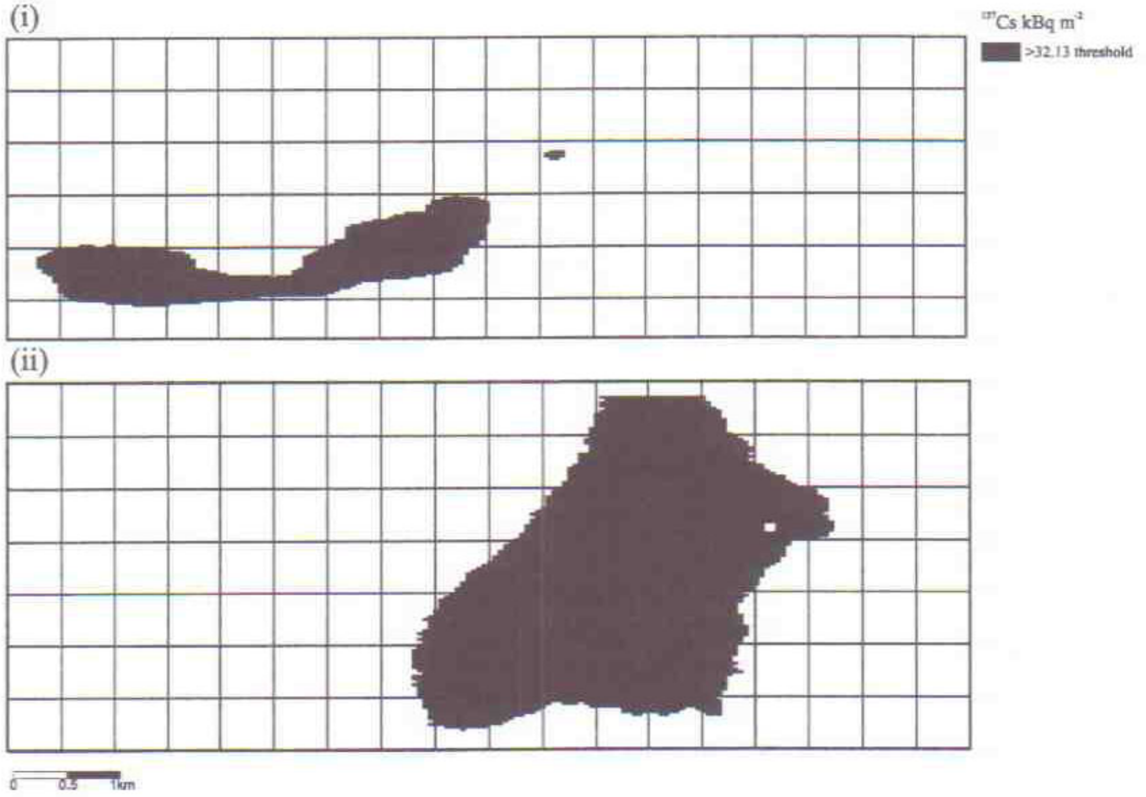

Figure 4.10: Threshold classified images for (i) Burgh Marsh and (ii) Rockcliffe Marsh for one of the line spacing data sets

A clearer picture of the trend of increased variability of geometric feature shape characteristics between permutations with increasing line spacing for both marshes is provided in Figure 4.11. For all the geometric properties of both Rockcliffe and Burgh marshes this trend is apparent. Another aspect which also becomes more striking on the plots is the elevated variability between increased line spacing permutations for Burgh marsh, variability is much higher, generally double and in the case of the P/A ratio an order of magnitude higher, than those for Rockcliffe marsh. A possible explanation for greater variability in the geometric properties of Burgh marsh than for Rockcliffe marsh is the shape, size and geospatial positioning of these two radiometric features relative to flight lines. Rockcliffe marsh is a fairly symmetrical large rectangular feature, covering a larger area NS than EW, the feature is more prominent in the direction of flight lines which have a NS orientation. Whereas Burgh marsh is a much smaller linear feature, orientated in a EW direction opposite to flight line orientation. Burgh marsh often breaks down into several small features due to flight line direction and the geometric properties of the feature, whereas the size, shape and orientation of Rockcliffe marsh ensure a more consistent identification by the survey technique.

The results indicate that the thresholding technique is a quick and effective means of identifying major radiometric features. Thresholding could thus be a valuable technique for rapidly identifying radiometric features in an emergency response situation.

Line Spacing and Permutation	Area (km^2)	Perimeter (km)	P/A Ratio
50 m	7.463	17.440	2.337
100 m P1	7.453	17.270	2.317
100 m P2	7.398	17.078	2.308
250 m P1	7.511	17.616	2.345
250 m P2	7.173	16.578	2.311
250 m P3	7.232	17.056	2.358
250 m P4	7.503	15.992	2.131
250 m P5	7.619	16.600	2.179
500 m P1	7.967	19.772	2.482
500 m P2	7.545	16.594	2.199
500 m P3	7.545	16.594	2.199
500 m P4	7.595	15.531	2.045
500 m P5	7.619	16.600	2.179
500 m P6	7.394	16.954	2.135
500 m P7	7.904	15.884	2.010
500 m P8	7.568	16.346	2.160
500 m P9	7.650	16.469	2.153
500 m P10	7.804	18.024	2.310
Landsat Image	6.087	15.742	2.586

Table 4.4: Summary of Rockcliffe Marsh Radiometric Feature Shape Characteristics

Line Spacing and Permutation	Area (km^2)	Perimeter (km)	P/A Ratio
50 m	2.432	15.467	6.360
100 m P1	1.981	11.894	6.004
100 m P2	2.360	15.375	6.515
250 m P1	1.817	11.916	6.558
250 m P2	2.771	16.578	5.983
250 m P3	2.526	17.274	6.838
250 m P4	2.341	15.421	6.587
250 m P5	1.962	13.346	6.802
500 m P1	1.642	19.772	12.041
500 m P2	1.862	12.808	6.879
500 m P3	2.169	13.231	6.100
500 m P4	2.892	14.615	5.054
500 m P5	1.962	13.346	6.802
500 m P6	2.699	18.927	7.013
500 m P7	2.185	16.296	7.458
500 m P8	1.601	16.346	10.210
500 m P9	1.531	15.052	9.831
500 m P10	1.536	11.929	7.766
Landsat Image	3.517	16.919	4.811

Table 4.5: Summary of Burgh Marsh Radiometric Feature Shape Characteristics

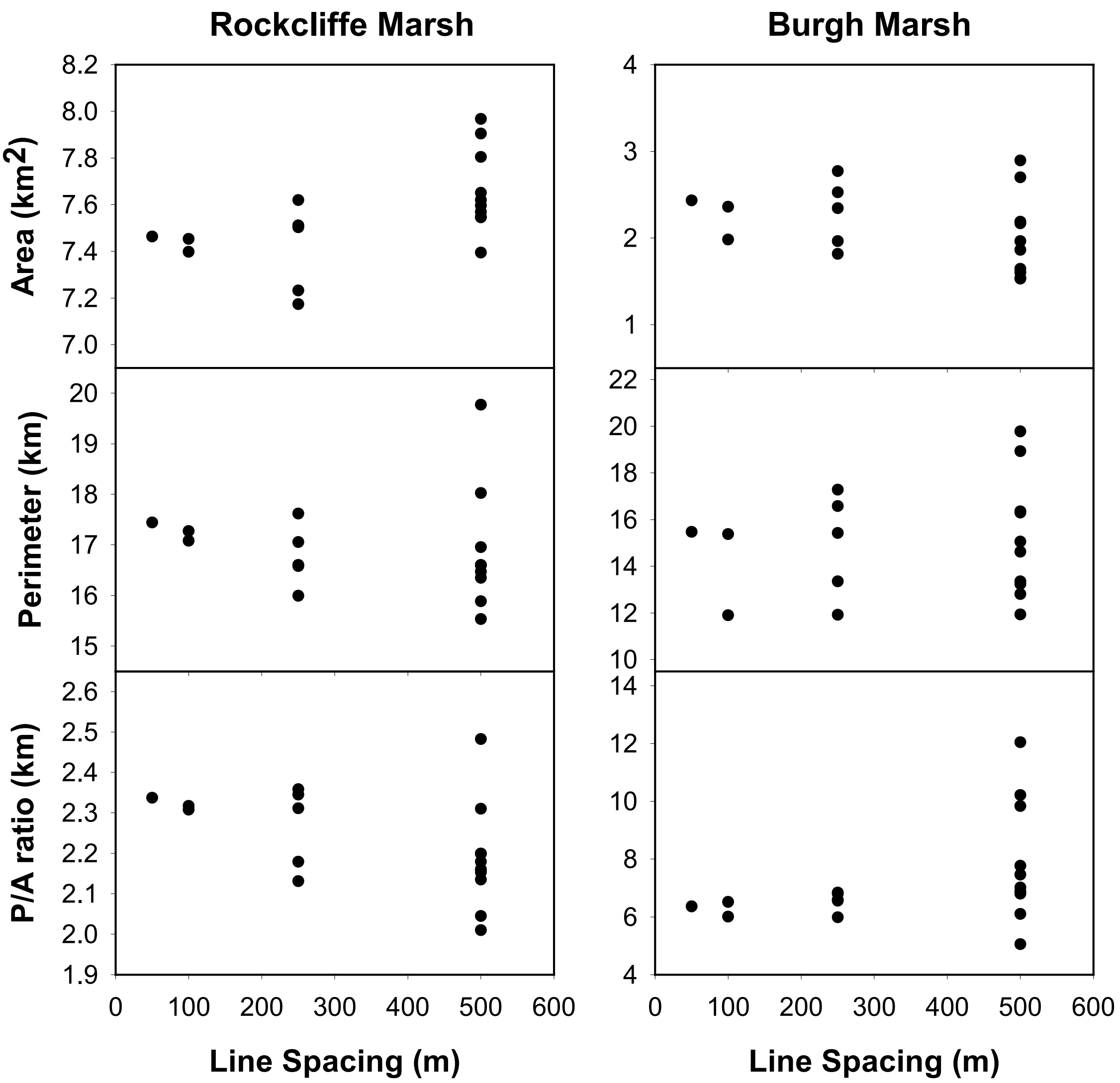

Figure 4.11: Comparative Plots of Radiometric Feature Shape Changes with Line Spacing for Rockcliffe and Burgh Marshes showing (i) Changes in area with line spacing, (ii) Changes in perimeter with line spacing and (iii) Changes in P/A ratio with line spacing

4.3.3 Statistical Measures of Similarity

The previous spatial characterisation sections have focused upon establishing the underlying characteristics of areas A and C+D and identifying the geometric shape of radiometric features in relation to various line spacing permutations. This section will take the spatial analysis further by quantifying, using statistical techniques, how radiometric images produced for the entire extent of areas A and C+D vary with various line spacings and permutations. Thus, enabling a quantitative evaluation to establish which line spacing and permutation combination for each area most accurately reflects the entire range of the data for the highest radiometric image resolution recorded, i.e. 2.5 km for area C+D and 50 m for area A.

There is a wide range of bi-variate statistical techniques which have been proposed and adopted in the statistical and geographic literature for establishing quantitatively the similarity between two sets of geospatial images/data. Techniques currently advocated include: (i) Cross-tabulation/chi-square (Ott *et al*, 1992); (ii) cross validation (used in conjunction with kriging) (Burrough and McDonnell, 1998); (iii) Cramer's V (Ott *et al*, 1992; Eastman, 1999); (iv) KIA (Kappa Index of Agreement) sometimes termed Khat (Carstensen, 1987; Cohen, 1960); (v) simple differencing (Eastman, 1994); (vi) image regression (Eastman, 1994); (vii) autocorrelation (Eastman 1999; Jones, 1999); and (viii) geographically weighted regression (Brunsdon *et al*, 1996; Fotheringham, 1999).

The KIA statistic is the preferred statistical technique to be employed for a number of reasons: (i) KIA considers relative areas because it samples the map patterns themselves to generate its strength agreement value (Cartensen, 1987) which is important when values are consistent over larger spatial areas than others (White, 2000); (ii) the previous statement has also been proven in a comparative study of a number of bi-variate statistical techniques using radiometric data conducted by White (2000); and (iii) the values are relatively easy to interpret and compute (in Idrisi or S-Plus SpatialStats) compared to some of the other techniques, such as geographically weighted regression.

The KIA statistic proposed by Cohen (1960), describes the degree of agreement between two sets of categorical data. KIA is calculated through the development of an error matrix (Figure 4.12). The columns on the matrix depict the categories for map one, the rows are the same categories for map two. Individual sample points are represented in the matrix according to the categories found at its location on the two maps. The error matrix displays the number of samples that have the same category on both maps along the diagonal, with all other positions filled by those samples where the categories disagree (White, 2000).

KIA compares two measures, the observed agreement found in the diagonal (P_o) and the expected agreement in the diagonal (P_e). Therefore, for a 3×3 matrix (Figure 4.12) the following equations are formulated:

Where $(P_o - P_e)$ represents the relationship between observed and expected values for agreement

$$P_e = ((p/sxd/s) + (q/sxh/s) + (r/sxn/s)) \qquad 4.7$$

$$P_0 = (a/s + f/s + m/s) \qquad 4.6$$

$$KIA = \frac{P_0 - P_e}{1 - P_e} \qquad 4.8$$

and $(1 - P_e)$ represents potential for agreement beyond that expected by chance (Carstensen, 1987).

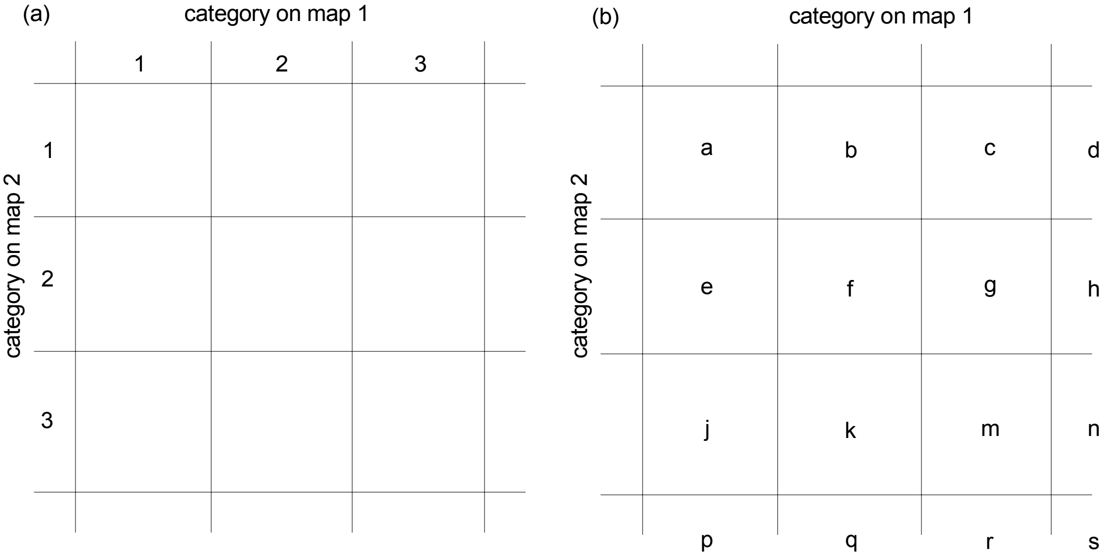

Figure 4.12: Construction of cross-tabulation tables for KIA, from Cartensen 1987

The KIA statistic can be interpreted as follows: (i) +1.0 - prefect agreement, all frequencies lie in the diagonal; (ii) 0.0 - agreement is equal only to the chance level; and (iii) <0.0 - agreement is less than chance, -1.0 is the absolute minimum value, but the actual minimum varies case by case (Cohen, 1960).

The KIA statistic was computed for area A and area C+D, respectively, map one being the highest resolution image (2.5 km for area C+D and 50 m for area A), map two being all other images for the various line spacings and permutations. The results of the KIA agreement values are summarised in Tables 4.3 and 4.4 and visualised in scatter plots in Figure 4.13.

Area C+D shows a dramatic decline in agreement with increasing line spacing, ranging between 0.7742 and 0.6858 for 5 km spacings and 0.3453 to 0.0087 for 10 km spacings (refer to Table 4.6). Area A represents a similar outcome to that found for area C+D, although less marked. KIA values range from 0.5949 to 0.4430 for 100 m line spacings, 0.3721 to 0.2553 for 250 m line spacings, and 0.3721 to 0.2221 for 500 m line spacings (see Table 4.7). KIA values for both areas are above the chance level, with the closest line spacings having the highest agreements, although all values are below perfect agreement.

A clearer pattern can be seen to emerge in Figure 4.13 (i) and (ii) where the difference between permutations for each of the line spacings is more apparent. Area C+D displays much greater differences in agreement for permutations for the 10 km line spacing than the 5 km line spacing. Area A shows a slight increase in the difference in KIA values for permutations at 500 m than for 250 and 100 m, although there is more consistency in differences between permutations than for area C+D.

Statistical testing of the differences in radiometric images produced for various line spacings and permutations clearly indicate that the stagger or alignment of line spacing permutations can

Line spacing permutation	KIA statistic
5 km P1	0.7742
5 km P2	0.6858
10 km P1	0.3453
10 km P2	0.2238
10 km P3	0.0087
10 km P4	0.2492

Table 4.6: Statistical similarity of area C+D with various line spacings and permutations

Line spacing permutation	KIA statistic
100 m P1	0.4430
100 m P2	0.5949
250 m P1	0.3343
250 m P2	0.3641
250 m P3	0.2553
250 m P4	0.3664
250 m P5	0.3721
500 m P1	0.2389
500 m P2	0.2575
500 m P3	0.2553
500 m P4	0.3664
500 m P5	0.3721
500 m P6	0.2491
500 m P7	0.2221
500 m P8	0.2429
500 m P9	0.2360
500 m P10	0.2374

Table 4.7: Statistical similarity of area A with various line spacings and permutations

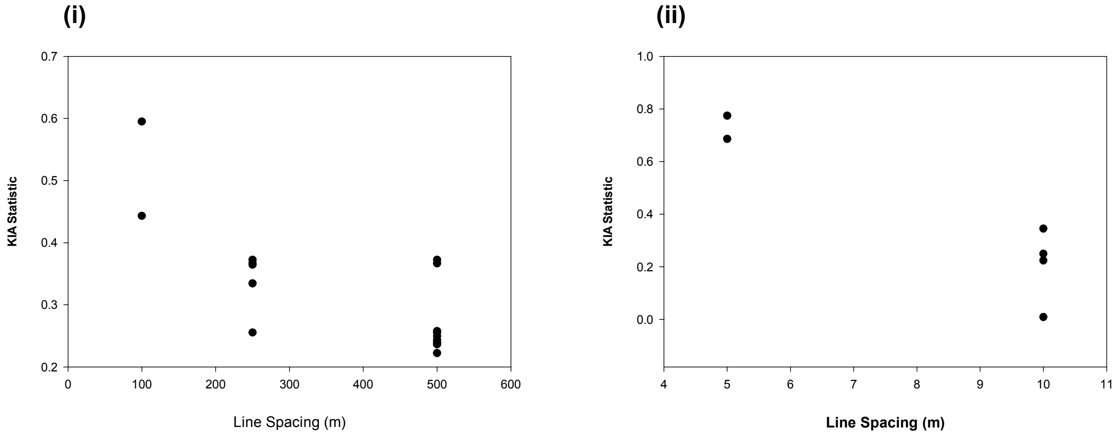

Figure 4.13: Changes in KIA with line spacing for (i) Area A, and (ii) Area C+D

greatly affect how features are detected and reproduced in radiometric imagery, particularly as line spacing becomes more sparse. There is obviously scope for further research into the range of statistical techniques outlined earlier in section for exploring further the quantification of imagery produced at different line spacing arrays.

4.4 Influence of Line spacing on Limits of Detection

It has been shown (section 3.1) that for a single 2 s measurement the limit of detection for ^{137}Cs in the saltmarsh environment is 10 kBq m^{-2}, decreasing to 3.5 kBq m^{-2} for a 16 s measurement. For environments where the activity is more superficial these detection limits would be lower, by a factor of about 3.5 for surface deposition. The data analysis utilizes an inverse distance weighting algorithm to interpolate between data points, with the result that the activity of each pixel in the smoothed maps or cell in regridded data is determined from a number of data points which will lower the limit of detection. The number of measurements contributing to each point will depend on the measurement density, and hence be influenced by line spacing.

Plots of percentage uncertainty against activity level, similar to Figure 3.1, were produced for one of each of the 50, 100, 250 and 500 m line spacing regridded data sets from area A, with the limit of detection being the 30% uncertainty level. Also, consecutive measurements in the calibrated data were averaged to simulate data sets with 4, 8 and 16 s integration times and the limits of detection determined for these combinations. Table 4.8 shows the limits of detection determined for each of these combinations of line spacing and integration time.

For each of the line spacings, the limit of detection decreases with increasing integration time as would be expected from the reduction in the limit of detection for a single measurement. Although the detection limits for individual measurements decrease by a factor $\sqrt{2}$ for each doubling of the integration time, for the regridded data the limit of detection is reduced by less than this because of the reduction in measurement density that accompanies the increase in integration time. It would be expected that increasing line spacing would increase the limit of

Line spacing(m)	Integration Time (s)			
	2	4	8	16
50	5.35	4.60	3.70	1.75
100	5.55	4.75	3.90	2.60
250	5.85	4.85	3.35	2.10
500	6.40	4.10	2.55	1.55

Table 4.8: ^{137}Cs detection limits (kBq m^{-2}) for different line spacings and integration times. For superficial activity the limits of detection would be reduced by a factor of approximately 3.5

detection as a result of the reduced measurement density. This is observed for the 2 s integration time and the first couple of line spacings for the longer integration times; it is unclear why the increase in detection limit with line spacing does not continue for the longer integration times.

The detection limits given here have been determined from data collected over salt marsh environments with buried activity. It is known (ICRU 1994) that the photon fluence above the ground decreases with burial depth. At 50 m ground clearance surface ^{137}Cs activity would result in a 662 keV photon fluence of 0.303 per source photon, whereas for an exponentially distributed source with a relaxation depth of 10 g cm^{-2} the photon fluence would be 0.123. The salt marsh environments considered in this analysis have mass depths of approximately 15 g cm^{-2}, but with a non-exponential depth profile, corresponding to a factor of approximately 3. Given the difference between the observed depth profile and the modelled exponential distribution the factor of approximately 3.5 observed between current calibration and the calibration used at Resume95 is not unreasonable. Thus, for a 250 m line spacing survey with 8 s integration times detection limits for superficial ^{137}Cs activity would be approximately 1 kBq m^{-2}, or a few hundred Bq m^{-2} for integration times greater than 10 s. Slower survey speeds would enable greater sample densities for the same integration times, which would also reduce detection limits as well as maintain spatial resolution.

The detection limits determined here were calculated for data regridded into 250 m cells. Larger cells would incorporate data from a larger number of individual measurements, and so have a lower limit of detection. However, information on the distribution of activity within these cells would be lost. The regridding of data with a relatively high detection limit could be used to identify areas where further measurements would be needed to define the extents of contamination at levels below the detection limit of initial measurements.

4.5 Effect of Survey Line Orientation

A 10×10 km area centred on Ennerdale Water was surveyed as part of the larger north west Cumbria area using flight lines oriented north-south with a 500 m line spacing on the 14th and 15th June 2000. This area was surveyed again on the 18th June 2000 using flight lines oriented east-west, also with a 500 m line spacing. The data from these 2 surveys were regridded and ^{137}Cs inventories estimated, these are given in Table 4.9.

There is a 4% reduction in the activity levels observed with the east-west orientated lines compared to the north-south lines. This reduction in activity is well within the changes observed in other environments as a result of changes in soil moisture over similar time scales, for example the Inner Solway shows a 15% change over a couple of days (see section 5.2). The first couple of days of the June 2000 survey, and at least a couple of days before that, were dry and relatively clear. The north-south lines in this area were flown when low cloud prevented surveys of the higher ground further east. The east-west lines flown after several days of persistent cloudy weather with some light drizzle. This extra soil moisture could easily account for the observed difference in inventory estimates.

Figure 4.14 shows the ^{137}Cs distribution observed in this area from the two data sets. It can be seen that the main features, including the low activity area of Ennerdale Water and enhanced activities over the upland areas, are generally well reproduced. There are, however, some notable differences between the two distributions. The higher activity areas of Lowther Park to the west of this area and on Lamplugh Fell just to the east of Cogra Moss evident in the north-south oriented data set are largely absent in the east-west set, conversely the higher activity area to the west of Cogra Moss on the northern edge of the area in the east-west data is absent from the north-south data. In addition, the higher activities on the upland areas observed in the north-south data set are more fragmented in the east-west data, in particular the ridge between Great Borne and Starling Dodd to the north of Ennerdale and parts of the fells of Haycock and Caw Fell to the south east of the area show significantly less activity in the east-west data set.

Many of the differences observed between the two data sets are consistent with the observation that features that are narrow compared to the line spacing may not be well represented. The ridge between Great Borne and Starling Dodd is a feature orientated east-west, and is fairly narrow with the activity concentrated in a region only a couple of hundred metres across. The radiation features to the east and west of Cogra Moss are both small, of a couple of hundred metre dimensions, and although the Lowther Park feature is relatively large this is the combination of several relatively small features in close proximity. Lowther Park is a forested area, and it is possible that these small features are associated with clearings in the trees.

	North-South	East-West
Total Inventory (TBq)	1.940±0.002	1.860±0.002

Table 4.9: ^{137}Cs inventory estimates for 10x10 km area surveyed with 500 m line spacing oriented north-south and east-west.

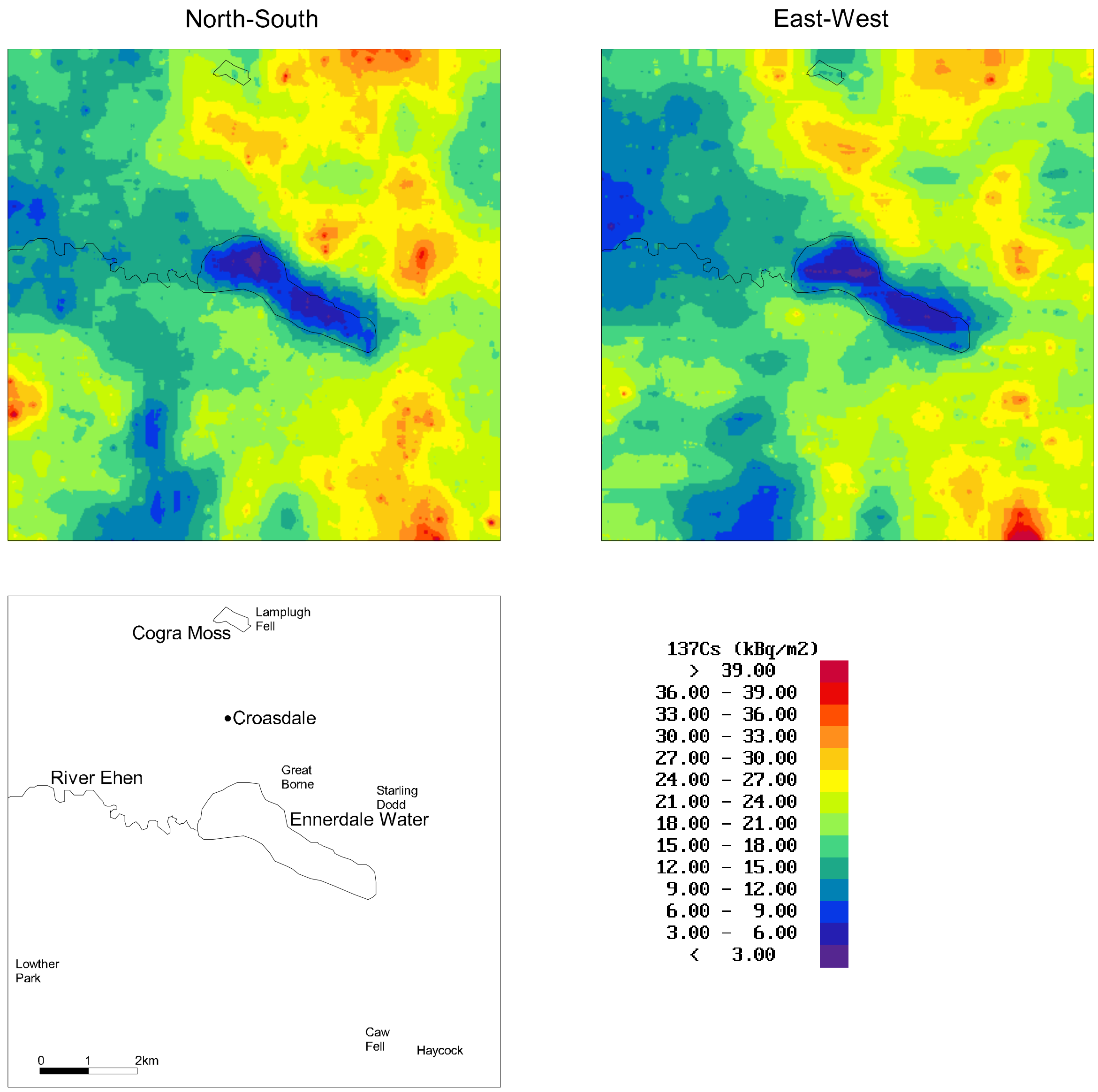

Figure 4.14: ^{137}Cs distribution for a 10x10 km area surveyed with 500 m line spacing orientated north-south and east-west

4.6 Summary

The influence of line spacing on AGS results has been investigated by calculating radionuclide inventories and applying some geostatistical techniques to data sets at various line spacings produced by subsampling the 50 m line spacing data from area A collected in April 1999 and the 500 m and 2.5 km line spacing data from areas C and D collected in June 2000.

The inventory analysis has shown that the inventory for a large area is robust, with only slight variation with line spacing. The inventory estimates of smaller areas, however, are much more variable with increasing line spacing. Similarly, analysis of the shapes of radiometric features also shows that large features are reproduced with increasing line spacing, whereas smaller features show considerable variability in shape for larger line spacing.

In general, radiometric features with dimensions perpendicular to the flight lines at least twice the line spacing will be fairly accurately reported, in terms of both inventory and shape. Except for the narrowest line spacings (50 or 100 m), the shapes and inventories for features smaller than this are subject to significant uncertainties. Except for point sources, there is little extra information on the shape and inventory of features gained with line spacings less than 250 m, although narrower line spacings would result in a higher density of measurements with a correspondingly lower limit of detection.

For larger line spacings, it is evident that even 10 km line spacings generate the broad distribution pattern and inventory of Chernobyl derived activity on the Cumbrian uplands, although the fine detail is not as well reported.

Detection limits do show a dependence on line spacing, although they are dominated by integration times, with lower detection limits for the higher measurement density produced by narrower survey lines. With surface deposition, 250 m line spacing using an 8 s integration time would give a 1 kBq m^{-2} detection limit for ^{137}Cs in the absence of significant interferences from other radioisotopes. Longer livetimes, closer line spacing or slower survey speeds would result in a reduction in the detection limits.

5. ASSESSMENT OF ENVIRONMENTAL CHANGE USING AGS

5.1 Analytical Approaches

Several data sets are available to assess changes in the radiation environment over a range of time scales. Data from the surveys conducted during this project allow changes over a few months to a year to be assessed, whereas data from previous surveys in the area allow changes over several years to be assessed.

Any changes that have occurred will be analysed by regridding data from two surveys onto the same grid, and then calculating absolute and proportional differences between the regridded data. Some of the inventory and shape analysis methods used in the comparison of data with different line spacings will also be used in the comparison of these data sets.

The data collected during the course of this project has all been analysed in the same manner, using the same stripping matrices and calibration factors. However, previous surveys have used different detector systems, with stripping matrices determined by different methods and calibrated to different radiation environments. The data from these earlier surveys had to be recalibrated to account for these differences prior to regridding. In addition, over the longer time periods radionuclear decay will be an important consideration.

5.2 Short Term Changes

It has been demonstrated in sections 3.2-3.3 that the detector system introduces very little variability in the radiometric data collected over the short time scale of a survey. There are, however, some environmental factors (for example soil water content) that may affect the measurements of the radiation field on very short timescales.

The April 1999 survey of area A was conducted at both 50 and 250 m line spacing. The wider line spacing survey was conducted immediately after a period of wet weather, with the 50 m line spacing survey after this following a few days of dry weather. Figure 5.1 shows the ^{137}Cs activity distribution for the two data sets, with the ^{137}Cs inventories given in Table 5.1. It is evident that the ^{137}Cs activity measured by the 250 m line spacing survey is some 15% less than that measured by the 50 m line spacing survey. This difference is significantly larger than the variations that may be expected from the difference in line spacing.

Although γ-radiation penetrates 10's of metres in air, such radiation is strongly absorbed by water. Hence changes in soil moisture content, for example following heavy rain, would result in increased absorption of the γ-radiation and a reduction in the activity measured. This could explain the difference between the two surveys of area A conducted in April 1999, during the first survey the ground was fairly wet as a result of the rain, whereas the ground had dried out by the time the second survey was conducted. Where there is very superficial activity, for example fresh deposition following a nuclear accident, this would have little impact unless there was considerable areas of standing water. In coastal regions the tidal state will also significantly affect the activity measured from muds and saltmarshes.

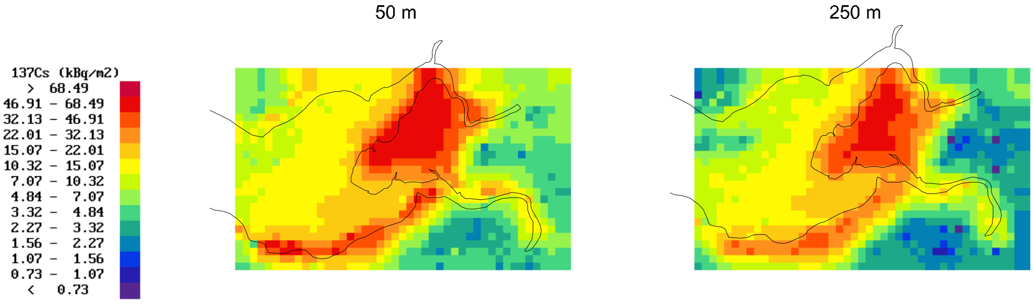

Figure 5.1: ^{137}Cs activity distribution in area A determined from 50 m and 250 m line spacing surveys conducted in April 1999

	50 m	250 m
Total Area (GBq)	1100±13	903±17
Rockliffe Marsh (GBq)	468±3	396±3
Burgh Marsh (GBq)	381±7	318±5

Table 5.1: ^{137}Cs inventories for area A, Rockcliffe and Burgh Marshes determined from 50 m and 250 m line spacing surveys conducted in April 1999

Another component in the radiometrics that is highly variable in the short term are signals from radioactive gases, either natural radon migration or discharges of ^{41}Ar and ^{16}N from nuclear facilities. These are strongly dependent on atmospheric conditions, particularly wind speed and direction, and generate strong signals due to their relative proximity to the aircraft. Also, in the case of radon there is a potential to contaminate the aircraft with short lived radioactive daughters that would result in increased detector backgrounds even in the absence of significant radon still in the atmosphere.

In the context of a planned survey, such as those carried out in this project, some of these sources of variability can be removed by, for example, selecting to fly coastal regions at low tide. There was also the opportunity to re-survey areas which had been flown during periods of high radon concentrations in the atmosphere. In the event of a nuclear emergency the ability to alter flight plans to avoid such influences may be limited, and one should be aware of the possible presence of such variability in the radiation environment. Techniques exist for analysis of data recorded with high atmospheric radon activity, or contamination of the aircraft with daughter nuclides, (Sanderson *et al*, 1997c) although it would be expected that in such situations the uncertainties in the analysis, and hence limit of detection, would increase.

5.3 Seasonal Changes

5.3.1 Changes to Tie Line Data Sets

Tie lines between Bowness Common and Bassenthwaite Lake were flown in each of the three surveys conducted for this project. The lines flown in April 1999 follow a slightly different route than those for March and June 2000, and so only the later two sets of tie lines will be considered to investigate any changes in the radiation environment along these lines. It has been shown (section 3.3) that, with the exception of one line which was flown slightly to the east of the others, within each survey the tie line data show the same radiometric features with little difference between each line. To enable comparison between lines, with readings at different locations along the line the data were resampled into 100 m sections by applying an inverse distance weighting function. Figure 5.2 shows the difference between the ^{137}Cs, ^{40}K and ^{214}Bi activity for March and June 2000.

For the terrestrial environment south of the estuarine salt marshes the means and standard deviations of the resampled tie line data were determined for the March and June 2000 data sets and the difference between them. These are given in Table 5.2. It can be seen that there is no significant overall change in the mean activity levels in the general environment.

The most prominent change between the two data sets is in the ^{137}Cs activity, with the June 2000 tie line data having higher activity at points across Newton Marsh. The largest of these is to the southern, landward, edge of the merse showing an enhancement of 40 kBq m^{-2}, this could be due to a slight difference in flight path between the two surveys with the March lines being slightly further east, although this is not as evident in the positions of the readings as the difference with the more easterly flight line within each data set. Alternatively, this could reflect potential drying out of the back of the salt marsh.

There is also a smaller enhancement in ^{137}Cs activity of 10 kBq m^{-2} across the merse, and slightly lower activity on the muds of the River Wampool immediately to the north of the merse. These small enhancements may also be the result of slightly dryer conditions. The reduced activity on the muds is most likely the result of a slightly higher tidal state in June than when the tie lines were flown in March.

There is a slight reduction in natural activity levels in June compared to March 21-23 km north of Bassenthwaite, at the extreme western edge of Wedholme Flow.

	March 2000	June 2000	Difference
^{137}Cs (kBq m^{-2})	5.6±2.9	5.0±2.9	-0.7±2.9
^{40}K (Bq kg^{-1})	281±80	283±91	3±63
^{214}Bi (Bq kg^{-1})	15.6±6.9	17.6±7.2	2.0±6.2

Table 5.2: Mean and standard deviation for the March and June 2000 data, and the difference between them for the resampled tie line data south of Newton Marsh.

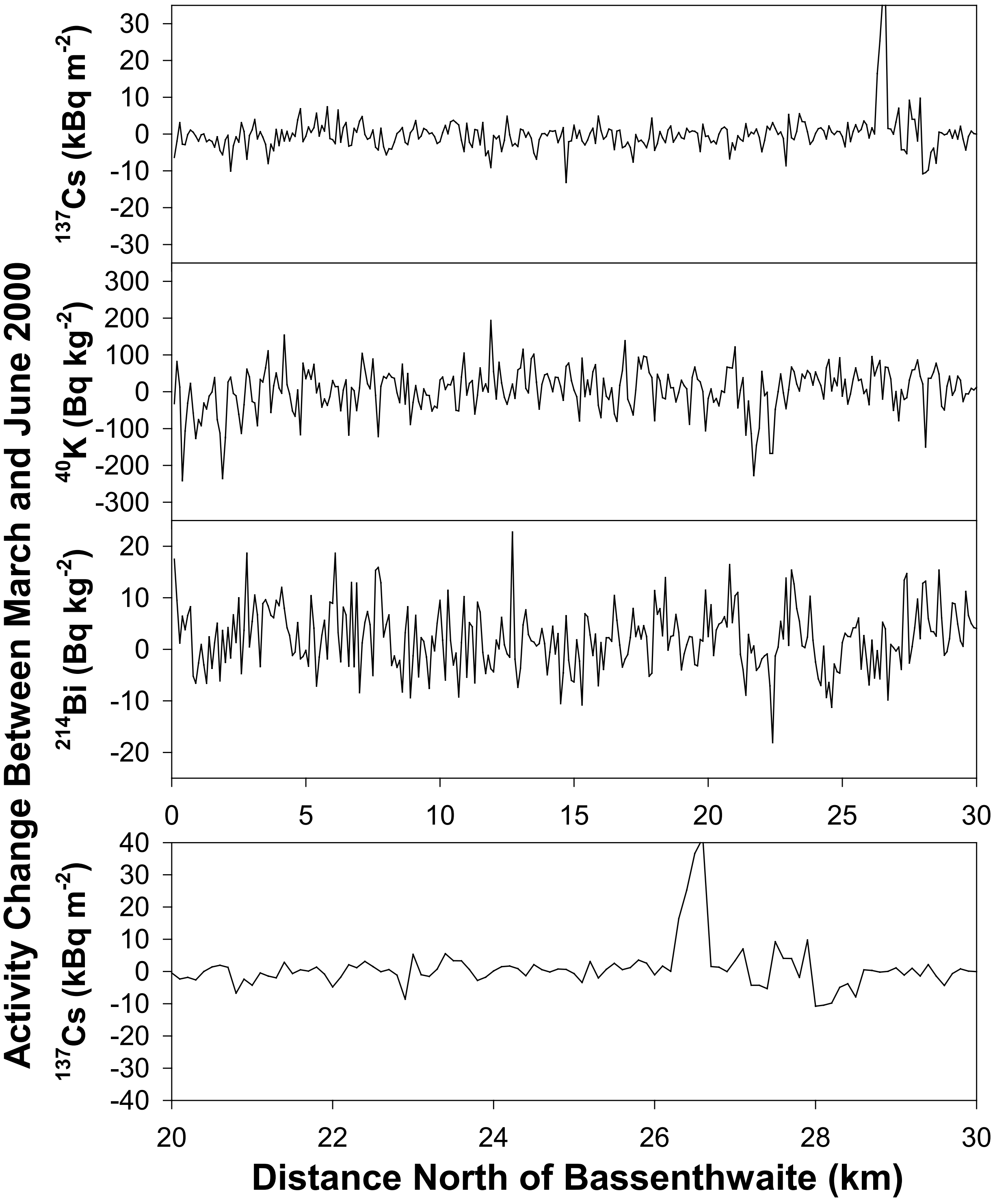

Figure 5.2: Changes in ^{137}Cs, ^{40}K and ^{214}Bi activity along the tie lines between March and June 2000. Note that the ^{137}Cs activity change across the Newton Marsh feature is shown in greater detail at the bottom.

5.3.2 Changes to Area A Between 1999 and 2000

Area A over Rockcliffe Marsh and the Inner Solway was surveyed in April 1999 at 50 m and 250 m line spacing, and again in June 2000 at 250 m line spacing. It has already been noted that the ^{137}Cs activity determined from the 250 m line spacing data is some 15% less than that determined from the 50 m line spacing data, probably because the soil had a lower water content when the 50 m line spacing data was collected. The June 2000 survey was conducted under dry conditions, and so the 50 m line spacing survey data collected in April 1999 are more likely to have been collected under comparable environmental conditions as the summer survey, and are used here to investigate changes over this timescale. The ^{137}Cs activity data from the April 1999 50 m line spacing survey and the June 2000 survey were regridded into 250 m cells to facilitate analysis of any changes in the radiation environment between April 1999 and June 2000.

Table 5.3 gives the ^{137}Cs inventories for the whole of area A as well as rectangular areas covering Rockcliffe Marsh and Burgh Marsh. The changes between the total inventories given in this table are within the range of variations for the 250 m line spacing subsampled data sets determined from the April 1999 data (section 4.2.3). The changes in the inventories of individual features are only slightly outside that range, and so may be due to the effect of the larger line spacing survey conducted in June 2000.

The ^{137}Cs activity distribution for the two regridded data sets is shown in Figure 5.3. The activity distributions for the two data sets show very similar levels and patterns. To highlight the subtle changes between the two data sets, the difference between cells in the two regridded data sets can be calculated. These differences, as both absolute and fractional changes relative to April 1999 are also shown in figure 5.3. It should be noted that small absolute changes can result in very large fractional changes in areas of low activity.

There are three areas with significant reductions in activity levels; a small saltmarsh on the northern edge of the Solway, Rockcliffe Marsh and Burgh Marsh. The first of these is a feature that is absent in some of the resampled 250 m line spacing subsets of the 1999 data (section 4.3.2), and it's absence in the June 2000 data may be due simply to the effect of the greater line spacing. The other two areas with reduced activity are reproduced in all the resampled 250 m line spacing subsets, so the changes observed here are not likely to be due entirely to line spacing effects.

	April 1999	June 2000
Total Area (TBq)	1.10±0.01	1.15±0.01
Rockcliffe Marsh (GBq)	468±3	458±3
Burgh Marsh (GBq)	381±7	424±4

Table 5.3: ^{137}Cs inventories for area A and Rockcliffe and Burgh Marshes determined from April 1999 and June 2000 data.

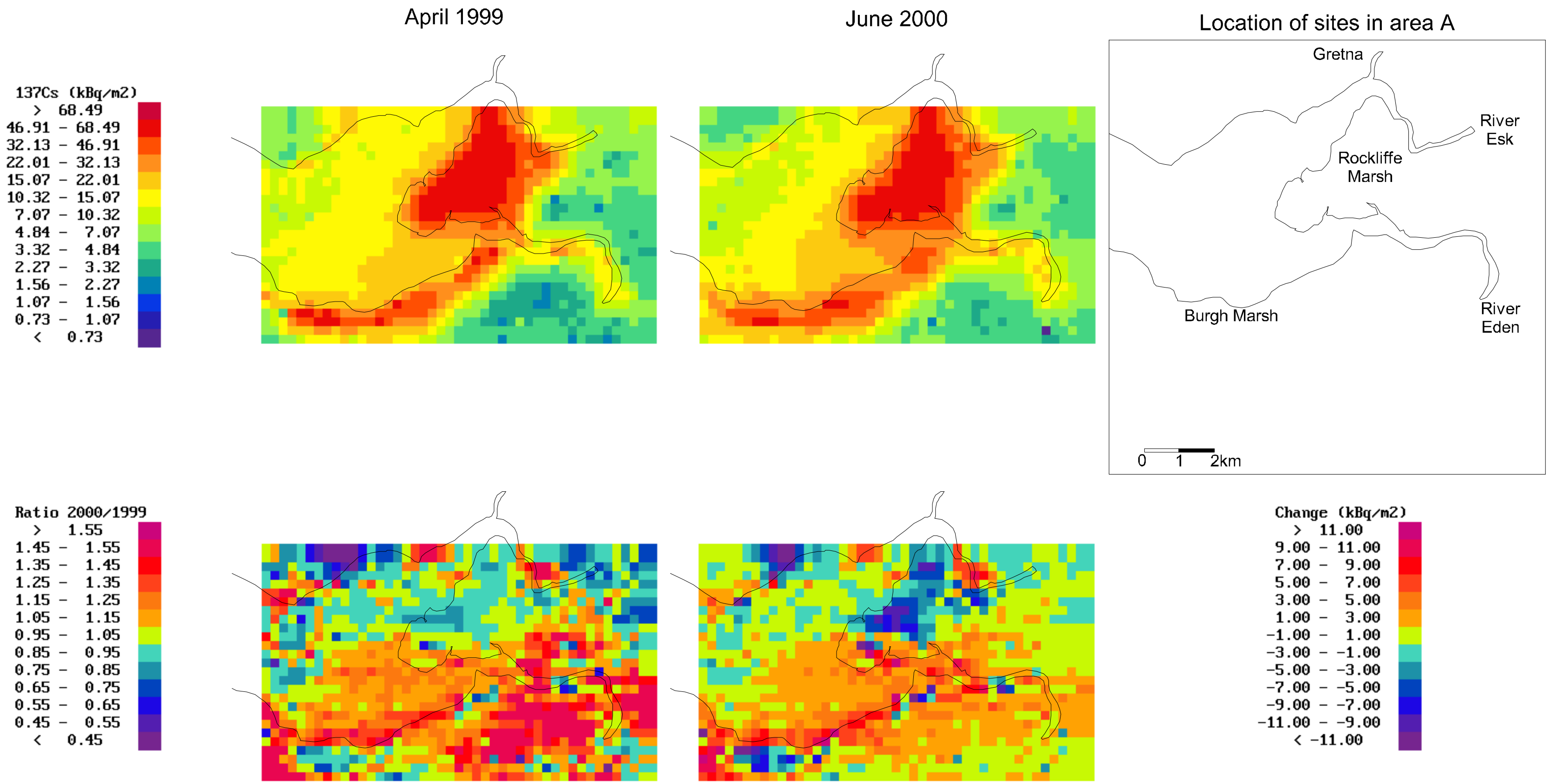

Figure 5.3: ^{137}Cs activity levels in area A measured in April 1999 and June 2000, with the changes between these two surveys shown as the ratio of activity in June 200 to the activity in April 1999 and the difference in activity levels

The salt marshes around the Solway have pronounced sub-surface activity maxima reflecting historic discharges from the Sellafield plant. Older sediment with higher activities are buried beneath more recent sediment with much lower activity concentrations. An increase in the amount of sediment on the marshes would thus increase the mean mass depth of the activity, and a reduction in the activity measured. A comparison of the mean mass depths and sensitivity calibration constants determined from Caerlaverock and Wigton Bay merses in 1992 and 1993 respectively (Tyler *et el*, 1996a) gives a reduction in sensitivity of 6% for an increase in mass depth of 0.4 g cm^{-2}. To account for the observed reduction in activity, of approximately 2%, the mean mass depth would need to increase by approximately 0.13 g cm^{-2}. In comparison, the average annual increase in mass depth at Caerlaverock determined from the cores collected in February 1992 and April 1999 (Sanderson *et al*, 2000) is 0.3 g cm^{-2}, and so the extra sedimentation needed to account for the observed reduction in the activity is conceivable.

There are also some areas with increased ^{137}Cs activity; some small patches on the north side of the Solway and the River Esk, along the northern edge of Burgh Marsh, the muds in the southern side of the Solway and along the River Eden. The small features to the north are consistent with variations due to line spacing effects. The slight increase of approximately 2 kBq m^{-2} in activity over the estuarine muds and around the River Eden are probably artifacts due to a slight oversubtraction of background in the April 1999 data set, although this may be due to the deposition of ^{137}Cs contaminated estuarine muds on the flood plains of the lower reaches of the river during flooding associated with high tides in the winter of 1999. The increase in activity along the northern edge of Burgh Marsh is consistent with the observation made during the April 1999 survey that the merse is rapidly eroding as a result of the channel of the River Eden moving south (Sanderson *et al*, 2000). The erosion face of the salt marsh will uncover buried sediments which have greater activity concentrations, significantly reducing the mean mass depth at the very edge of the merse.

The nature and extent of sediment movement on the salt marshes could be assessed by some further ground based field work. In April 1999 five cores were collected from Rockcliffe Marsh, and another from Burgh Marsh, together with in-situ gamma spectrometry measurements. The collection of further cores from these sites would show how much sediment has accumulated on the merse, and examination of the eroding face of Burgh Marsh would show how much of the buried higher activity sediments have been revealed.

5.4 Longer Term Changes

5.4.1 Comparison Between Areas A and B with the 1992 Chapelcross Survey

The 1992 survey of Chapelcross (Sanderson *et al*, 1992) was conducted using a 500 m line spacing, with a 16 litre NaI(Tl) spectrometer operating at approximately 10% resolution for the 662 keV peak, and a 10 s integration time. The data was calibrated using a working calibration from the 1990 Ayrshire survey (Sanderson *et al*, 1990c), although a hover manoeuvre was conducted at the Caerlaverock calibration site. The Caerlaverock data were not used to calibrate the data to maintain consistency with earlier surveys and because of uncertainty about the weighting to be applied to each shell of the pattern, which has since been clarified (Tyler, 1994, 1996a).

The data collected in April 1999 used a similar spectrometer, with slightly better resolution at around 9%, with 250 m line spacing and 3 s integration time for area B and 50 m line spacing and 2 s integration time for area A. The data for this survey was calibrated to the Caerlaverock saltmarsh, which was resampled during the survey. It has been shown (section 5.2) that there is a difference in the two data sets recorded in April 1999, probably as a result of changes in soil water content with the 250 m line spacing survey having been conducted under wetter conditions. This data was more likely to have been conducted under similar conditions to the 1992 survey, which took place in February and so is likely to have been conducted with fairly wet soils. In addition, the 250 m line spacing data set covers a larger area allowing comparisons between more features. For these reasons, the 250 m line spacing data from April 1999 will be compared with the 1992 data to investigate changes in the radiation environment over this period.

To provide consistency between these two data sets, the 1992 data was recalibrated to the activity at Caerlaverock using the corrected weighting scheme. This gave a sensitivity calibration constant of 0.383 kBq m^{-2} cps^{-1} compared to 0.198 kBq m^{-2} cps^{-1} used in the original analysis of the 1992 data, and 0.340 kBq m^{-2} cps^{-1} used to analyse the 1999 data. The difference between the calibration constants calculated here and that originally used is consistent with differences in source burial; the 1992 data was originally calibrated to terrestrial sites with fairly superficial Chernobyl derived activity whereas in the saltmarsh environment the activity is buried by successive tidal deposits which have significantly lower activities than older deposits. In 1992 the Caerlaverock site had a mean mass depth for ^{137}Cs of 13.2±2.1 g cm^{-2} and 15.7±1.2 g cm^{-2} in 1999. It would be expected that the increased mass depth in 1999 would result in a reduced sensitivity (and hence larger calibration constant), however the opposite has occurred implying that the detector sensitivity has improved by approximately 20%. There are a number of factors that might result in improved detector sensitivity; including the improved resolution reducing the interferences between peaks, and improvements to the determination of the stripping matrix; however none of these would be expected to produce such a large improvement in sensitivity.

The data from the 1992 Chapelcross baseline survey and the April 1999 area B survey were regridded into a common area using a 250 m cell size with the range and power used in the 1992 survey. Figure 5.4 shows the regridded ^{137}Cs activity distribution in 1992 and 1999, showing a general decrease in activity across most of the area.

There are a number of areas where the activity levels have been reduced by more than radiometric decay; Burgh Marsh, saltmarshes to the west of Bowness Common, around the River Annan and to the west of Annan, and in the immediate vicinity of the Chapelcross Power Station. There are also a few areas with increased activity; particularly small areas of saltmarsh to the sides of the reduced activity feature west of Bowness Common and the middle of Burgh Marsh.

Some of the variation in the small saltmarsh features, especially the increased activity in the middle of Burgh Marsh, are possibly due to the effect of the 500 m line spacing used in the 1992 survey with a contribution from effects of the 250 m line spacing used in the 1999 survey. The reduction in activity for Burgh Marsh is the most pronounced change in the radiation environment over this period, which corresponds to substantial erosion of the marsh following a change in the course of the channel of the River Eden through the estuarine muds. When the area was surveyed in 1992 the salt marsh extended more than 1 km into the estuary, with the river channel some 500 m north of this. During the 1999 and 2000 surveys the salt marsh was only a couple of hundred metres wide at its narrowest, with the river channel along the very edge of the marsh. The channel of the Eden is known to switch between these two courses every few years (Jones *et al*, 1997), with buildup of Burgh Marsh when the northern course is followed and erosion when the southern course is taken.

There is a general reduction in the activity of the exposed muds in the estuary between 1992 and 1999, resulting from the dilution of ^{137}Cs activity in sediments and solution following very large reductions in ^{137}Cs discharges from Sellafield since the mid 1980s (Gray *et al*, 1995). Since the other saltmarshes are not along main river channels, reduction in activity on these is probably due to sedimentation covering the activity in a greater depth of less active material. The reduction in activity around Chapelcross reflects a strong ^{137}Cs signal associated with the site observed in 1992 that was not present in 1999.

The ^{137}Cs inventory estimates of the total common area (bounded by OS grid references NY100590 and NY350700) and rectangular areas covering Rockcliffe and Burgh Marshes (bounded by OS grid references NY300600 to NY335655 and NY260590 to NY330620 respectively) were determined, and are given in Table 5.4. The inventories for the 1992 data are also given accounting for seven years radiometric decay. As noted in section 5.2, the Rockcliffe and Burgh Marsh inventories for the 1999 250 m line spacing data set are 15% less than the inventories calculated from the 50 m line spacing area A data as a result of changes in soil water content.

It can be seen that there has been a decrease in activity in the total area greater than that due to radiometric decay. The reduction in inventory for Rockcliffe Marsh is some 15% greater than radiometric decay, which would require an increase in mass depth of 10.0 g cm^{-2} over this period which corresponds to an average annual sedimentation rate of 0.14 g cm^{-2}. This is consistent with the 0.13 g cm^{-2} of sedimentation required to account for the reduction in activity observed in the year between April 1999 and June 2000. There is a very large reduction in the inventory of Burgh Marsh, reflecting the observation that the edge of the merse has significantly eroded since 1992. The erosion of this feature accounts for approximately a third of the ^{137}Cs activity removed from this area after accounting for radiometric decay.

	1992	1992 decay corrected	April 1999
Total Area (TBq)	3.20±0.05	2.72±0.04	1.86±0.04
Rockcliffe Marsh (GBq)	542±8	461±7	396±3
Burgh Marsh (GBq)	755±16	642±14	318±5

Table 5.4: ^{137}Cs inventory for common area surveyed in 1992 and April 1999, with the 1992 inventory decay corrected to April 1999.

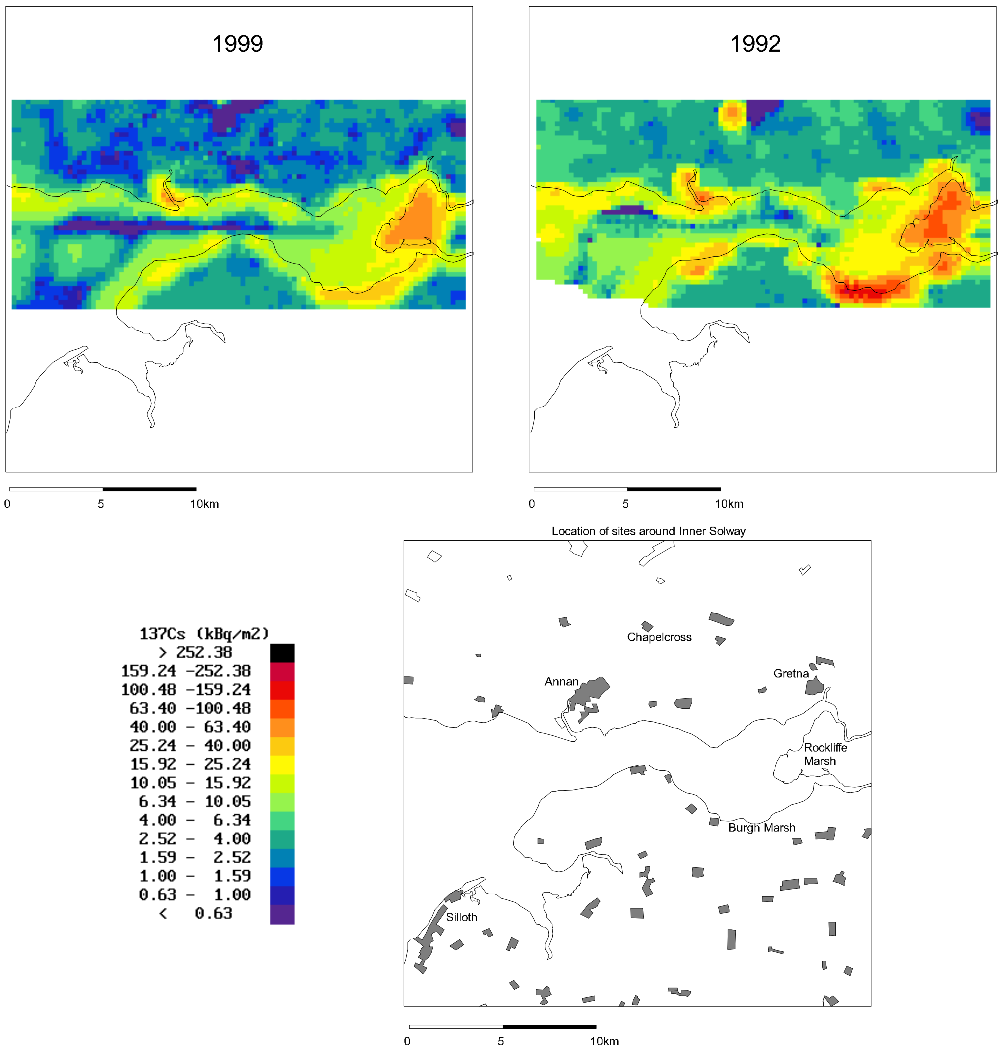

Figure 5.4: Regridded ^{137}Cs activity distributions from the 1992 and 1999 surveys of the Inner Solway

5.4.2 Comparison Between Areas C and D with the 1988 MAFF Survey

The 1988 survey of West Cumbria (Sanderson *et al*, 1989) was conducted using a prototype spectrometry system comprising a 7 litre NaI(Tl) crystal with 13-15% resolution, a multichannel analyser and laptop computer. The survey was flown at 500 m line spacing with gross counts in six spectral windows recorded every 30 s. Integrated spectra for each 10 km long line were saved at the end of each line. Spectral interferences were removed using a stripping matrix derived from measurements of point sources and solutions, and a working calibration based on overflights of 10 sites was used.

The most significant difference between this survey and later surveys is the stripping matrix used. Later experience with pads and absorbers indicates that the use of point sources and solutions underestimates the scatter from high energy γ-rays into lower energy windows. For the 2614 keV ^{208}Tl and 1765 keV ^{214}Bi γ-rays, used to determine the Th and U series activities, this effect is small. However, the increased scatter from the 1460 keV ^{40}K γ-ray into the windows for ^{137}Cs and ^{134}Cs is significant.

Unfortunately it is not possible to reassemble the prototype detector and measure a new stripping matrix using pads and absorbers. Comparisons between stripping matrices used with the 16 litre detector recorded with point sources (Sanderson *et al*, 1990c) and those recorded with pads and absorbers (Sanderson *et al,* 1994d) indicates that the scatter from ^{40}K into the ^{137}Cs and ^{134}Cs windows should increase by factors of 3 and 2 respectively, with other elements of the matrix being approximately the same. The stripping matrix used in the 1988 analysis was modified accordingly, and the same calibration points used to derive a revised calibration. The revision in the calibration method resulted in a change in the calibrated ^{137}Cs activities of less than 10%.

The 1988 survey was calibrated to terrestrial, rather than estuarine, activities. The different depth profiles of these environments would affect the calibration, with an estuarine calibration over estimating terrestrial activities. Recalibrating the 1988 data to an estuarine environment comparable to that used to calibrate the 2000 data set would not be simple since the 1988 data does not include measurements of the Caerlaverock merse. It has been noted that the calibration

	1988	1988 decay corrected	June 2000
Total Area (TBq)	9.35±0.02	7.01±0.02	7.22±0.02
Black Combe (GBq)	496±3	372±3	319±1
Corney Fell (GBq)	704±3	528±3	469±2
Loweswater Fell (GBq)	636±3	477±3	453±1
Lowlands (GBq)	851±16	638±12	732±8

Table 5.5: ^{137}Cs inventory for common areas surveyed in 1988 and June 200, with the 1988 inventory decay corrected to June 2000.

to Caerlaverock used in 2000 overestimated the ^{137}Cs activity at Croasdale by 20%, so a data set with 20% less ^{137}Cs activity has been produced to compare with the 1988 data.

The resulting recalibrated data sets were regridded into 250 m cells. Table 5.5 shows the ^{137}Cs inventories for the common area of the two surveys, and selected areas within this common area. These areas correspond to Black Combe (SD120840-160880), Corney Fell and part of Ulpha Fell (SD130880-170970), Loweswater Fell (NY100160-150210) and a lower lying area to the west of Corney Fell (SD100890-130970, and SD100970-NY140040). The change in activity within the total area common to the two surveys is largely consistent with radiometric decay, the slight excess activity in the later survey is probably due to a slight difference in calibration between the two surveys. Despite significant changes to the equipment and analysis methods since the trial flights in 1988 it is evident that the activities determined from that data are in broad agreement with those determined by modern equipment and methodology.

Figure 5.5 shows the ^{137}Cs activity distribution in 1988 and June 2000 with the ratio of activities and change in activity. This shows the general reduction in activity above radiometric decay (corresponding to an activity ratio of 0.75) on the higher ground. There are increases in activity along lower ground to the west of Corney Fell, over higher ground to the north and north east of Wast Water, and on the estuarine salt marshes of the Rivers Esk and Mite. Bad weather during the 1988 survey limited the ability to survey the higher ground near Wast Water, and the increase in activity observed may be due to the collection of data from these areas in the June 2000 survey. There appears to be a redistribution of activity along the River Esk, and to an extent along the Mite, with a reduction in activity at Muncaster and increased activity upstream. This may be due to changes in the river channel resulting in movement of sediment, or possible flooding above the normal intertidal limit.

The increase in activity on lower lying ground to the west of the fells is more interesting. This implies a movement of activity from the high ground to lower lying areas, and indeed the increase of approximately 100 GBq is similar to the activity lost from the surrounding high ground, after accounting for radiometric decay. There are hints that there is also an increase in activity to the east of these fells, although there is very little data for this area from the 1988 survey. Given that the method has been shown to produce comparable results within a few percent for the survey area as a whole, it is probable that this increased activity in the lower lying areas and corresponding decrease in activity in the high ground is a genuine redistribution of activity.

There are a number of possible mechanisms for such a redistribution of ^{137}Cs. In general, the upland areas are characterized by peaty soils in which radiocaesium is relatively mobile and available for uptake into plants, whereas the lower lying ground has more mineral rich soils which have a much higher ability to fix radiocaesium. One possible redistribution mechanism is that the activity is moved by sheep, which graze on the high ground and accumulate activity in their bodies and are then brought down to lower lying pastures where the activity is removed via excreta where it rapidly becomes fixed in the mineral rich soils. It has been estimated (Beresford *et al,* 1989) that for typical levels of contamination in sheep and lowland grazing densities this process could result in an increase in lowland activities of 20 Bq m^{-2} each time sheep are brought down from the fells. This mechanism could thus account for, at most, about 5% of the observed increase in activity in the lowland areas.

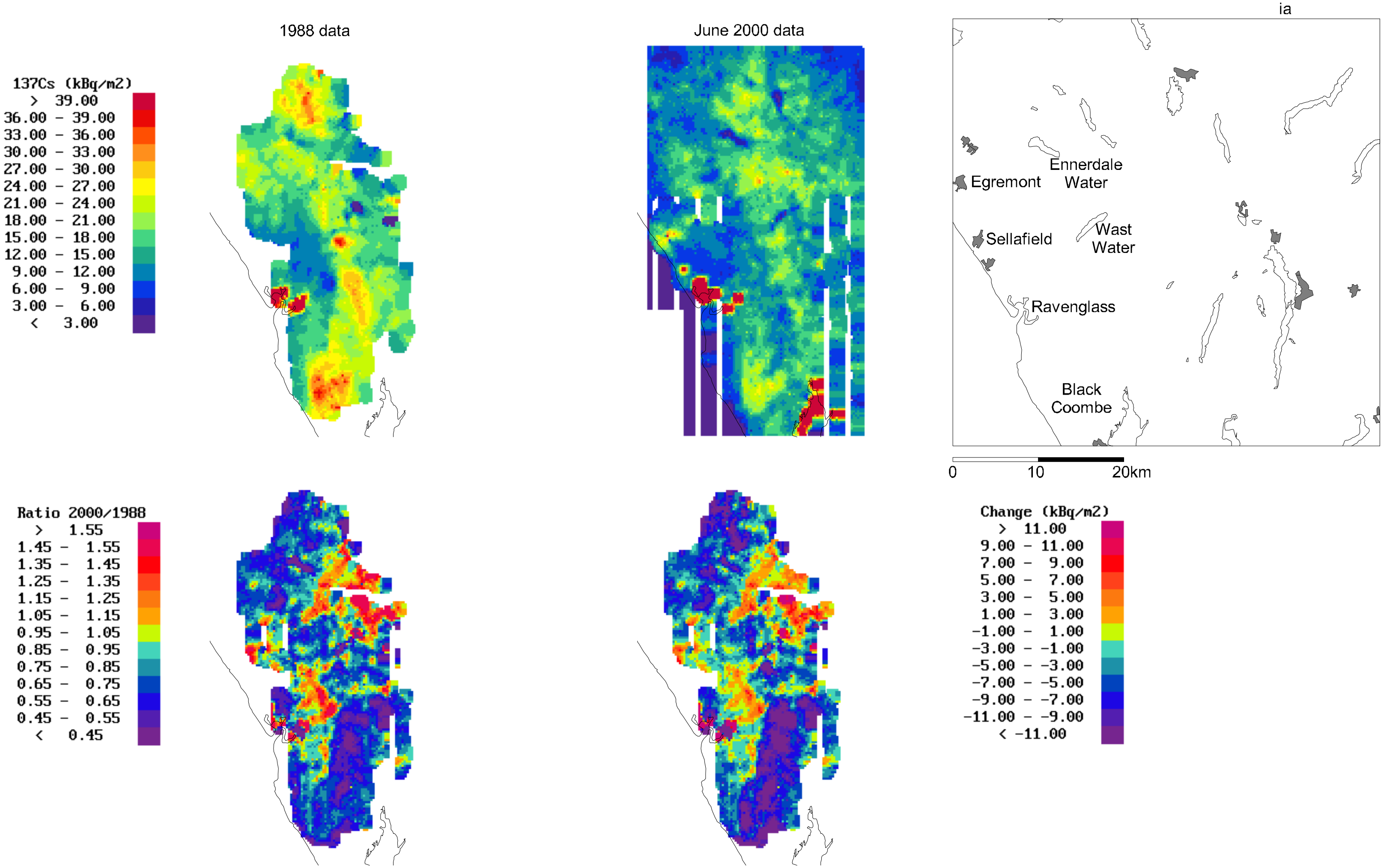

Figure 5.5: ^{137}Cs activity levels in West Cumbria in 1988 and 2000 (after recalibration), with activity ratios and changes

An alternative redistribution process is physical transportation of the activity through solution. In the upland peaty areas ^{137}Cs is relatively available, and some of the activity will be dissolved in ground water. As this water flows downhill into soils with a higher mineral content the ^{137}Cs will be sorbed onto mineral grains and be locked into these soils. Such processes have previously been observed in airborne (Sanderson *et al*, 1990c) and ground based (Tyler, 1994) measurements of the Raithburn Valley in northern Renfrewshire. A simple model can be used to predict ^{137}Cs redistribution through such processes (Tyler & Heal, 2000). This models ^{137}Cs migration using the topographic index which takes the form of $\ln(a/\tan B)$, where a is the upslope area contributing to the flow and B is the local slope gradient, this parameter can be calculated from a digital terrain model (DTM). Small values of the topographic index indicate low water flow and are associated with areas near the catchment boundary where the soil is likely to be peaty with relatively high ^{137}Cs mobility, large values of the topographic index indicate major flow pathways normally associated with valley flows. This model fitted the observations of the redistribution of weapons testing ^{137}Cs in the Raithburn Valley, indicating that about 20% of the total deposition had been transported from the upland catchment to lower ground in approximately 30 years since deposition. It should be possible to apply such a model to the Cumbrian uplands, although since the area is very much larger it would be a considerable task. Nevertheless, if this produces similar levels of ^{137}Cs migration it would account for most of the 10-15% activity redistribution observed.

5.5 Summary

By comparing data sets collected within this project and earlier data for common areas in the Solway and West Cumbria it has been possible to identify changes in the radiation environment of these areas over time scales ranging from a few days to several years.

During the course of the April 1999 survey changes were observed over a timescale of a few days due to the water content of the soil. In addition, some highly variable radiation fields generated by activity from natural (radon) and anthropogenic (^{16}N and ^{41}Ar) gases were observed.

Changes to the radiation environment of the Inner Solway between April 1999 and June 2000 were observed, resulting from erosion of Burgh Marsh revealing more active buried activity and sedimentation of Rockcliffe Marsh.

Comparison between the 1992 Chapelcross baseline survey and the April 1999 surveys showed several changes to the radiation environment of the Inner Solway. After accounting for radiometric decay, the reduction in activity on Rockcliffe Marsh is consistent with increased sedimentation depositing lower activity material on the merse at a rate similar to that needed to account for the reduced activity between April 1999 and June 2000. There has been a significant reduction in the activity of Burgh Marsh, reflecting the substantial erosion that has occurred.

Long term changes to the radiation environment in West Cumbria were assessed by comparing the 1988 MAFF survey data with the June 2000 survey. This has resulted in only a very small net change in the total activity of this area, after accounting for radiometric decay, showing that despite significant changes in the instrumentation and methodology that activity levels calculated from data recorded during the earlier survey fairly accurately mapped the distribution of the activity at the time. Comparison between the two data sets do, however, show some considerable redistribution of the activity in this area, with activity migrating from the high ground to lower elevations, probably as a result of physical movement of activity by particulates and solution.

6. SUPPLEMENTARY MEASUREMENTS

6.1 Ge Detector Data

It is known (Sanderson *et al* 1992) that the estuarine salt marshes of the Solway are contaminated with ^{241}Am. The 59.5 keV γ-ray from ^{241}Am is strongly absorbed by material between the source and detector, so to measure ^{241}Am activity a low level survey with externally mounted detectors should, if possible, be conducted to allow sufficient full energy radiation to reach the detector. Thin window Ge (LoAx) detectors have very high resolution spectral response to low energy γ-rays, with reduced background due to scattering of higher energy γ-rays within the crystal, so they are potentially useful for measurements of low energy γ-rays such as those emitted by ^{241}Am. One of the supplementary aims of the first phase of survey during this project was to evaluate the feasibility of mapping ^{241}Am using externally mounted thin Ge (LoAx) detectors. To this end, a flight at low level (approximately 20 m ground clearance) was conducted across the merse at Caerlaverock on the 27th April 1999 following a calibration hover manoeuvre. During this flight only one detector was operating, since during the course of the survey problems were encountered with the detectors as a result of water penetration into electronics, resulting in only one detector being operational for much of the survey.

Figure 6.1 shows the spectrum produced by summing the individual spectra recorded with the LoAx detector for this flight. This spectrum shows clear peaks from ^{137}Cs and ^{40}K activity, there is also a slight peak slightly above the expected position of ^{241}Am γ-rays which may be an ^{241}Am signal since the detector gain is unlikely to be perfectly linear. It is, however, evident that even if this is a signal due to ^{241}Am there is clearly very little surface contamination on the merse, and this signal is too small to enable the distribution of any surface activity to be determined using this equipment.

Laboratory measurements of the cores collected from the calibration site show that there is ^{241}Am within the merse, however it is buried below less active material which would shield the source. The core from the centre of the calibration pattern has a mean mass depth of approximately 14 g cm^{-2}, with 50% of the ^{241}Am activity below 10 cm burial depth.

For the later survey phases conducted in March and June 2000 a single 50% relative efficiency Ge (GMX) detector mounted inside the aircraft was used to provide supplementary radiometric data. Initial analysis of data from the March 2000 survey indicated the presence of low levels (1-2 kBq m^{-2}) of ^{60}Co activity on the saltmarshes around Ravenglass and on Muncaster Fell. ^{60}Co has a distinctive pair of γ-rays at 1173 and 1332 keV which, in NaI(Tl) spectra, are strongly interfered with by the 1461 keV γ-ray from ^{40}K. Since there was also an association with enhanced ^{40}K activity in the same area of Muncaster Fell, this apparent ^{60}Co feature may have been an artifact of poor spectral stripping. Only a few short spectra were recorded with the GMX detector over these features in March 2000, with insufficient statistical precision to confirm whether or not the ^{60}Co signals were due to genuine contamination. Additional survey flights at low speed were conducted over these features in June, resulting in a larger number of GMX spectra being recorded. The ^{60}Co γ-rays were not observed in any of these spectra, indicating that the ^{60}Co signals observed in these areas in March 2000 were, indeed, artifacts of the spectral stripping algorithm.

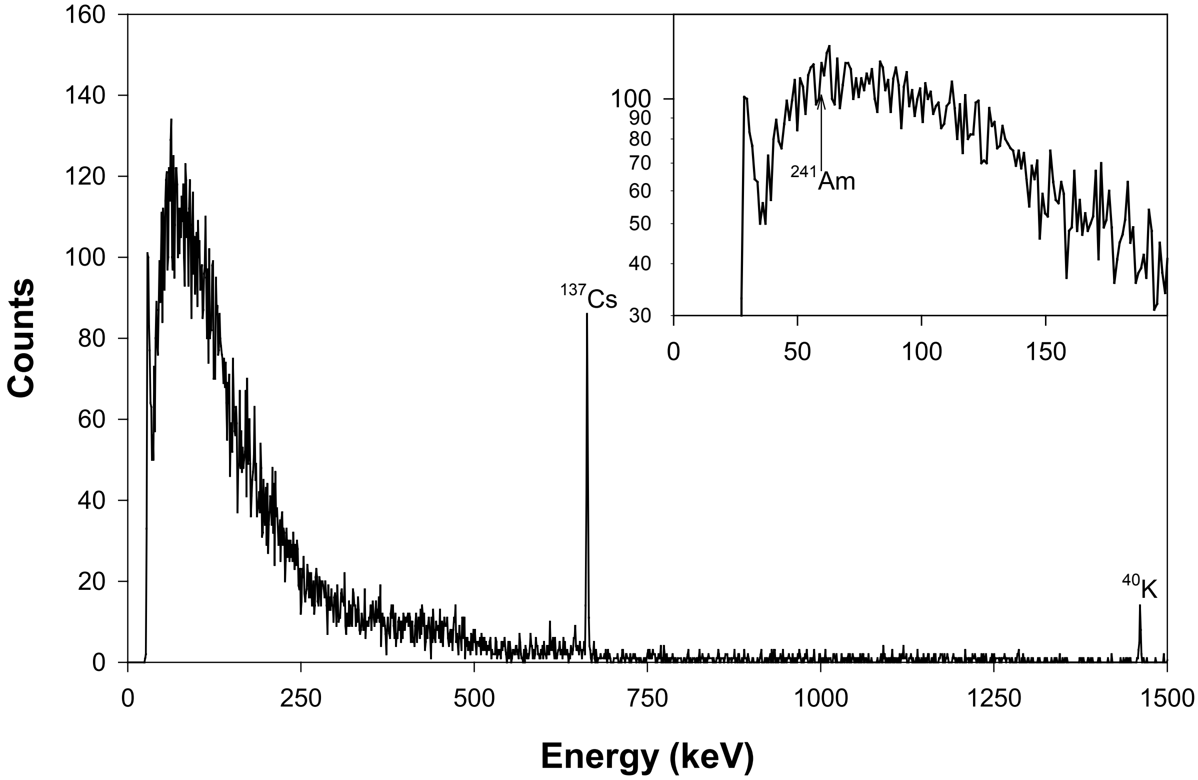

Figure 6.1: Summed LoAx spectrum (total livetime 282s) from low ground clearance flight across Caerlaverock 27/4/1999. Inset low energy part of spectrum shows the location of the ^{241}Am γ-ray peak.

6.2 Satellite and Photogrammetric Imagery

During this project the potential for using remote sensing data, from satellite imagery or video and digital photogrammetry from the aircraft during survey flights, to provide additional information that may aid in the interpretation of the radiometrics was investigated. During all three phases of survey work a standard 8 mm video camera was mounted inside the aircraft looking down through a clear plastic window bubble at the front left of the aircraft, although a fault developed in this during the June 2000 survey. The possibility of using a digital stills camera, similarly mounted inside the aircraft, to generate high resolution digital terrain models (DTMs) was also investigated during the April 1999 survey.

A LandSat image taken at noon on 27th April 1999 covering the survey areas in NW England and SW Scotland was purchased, and processsed by P.A. Atkin and A.N. Tyler in the University of Stirling. The processing involved corrections for atmospheric scatter and absorption, with true colour composite images and classification maps being produced. The images produced were registered to the British National Grid using 98 ground control points derived from the OS Landranger maps. Figure 6.2 shows the images produced for areas A and B.

The satellite images show very good correspondence to the radiometric features observed in these areas. In particular, the wet peat areas that show very low levels of activity, the saltmarshes and

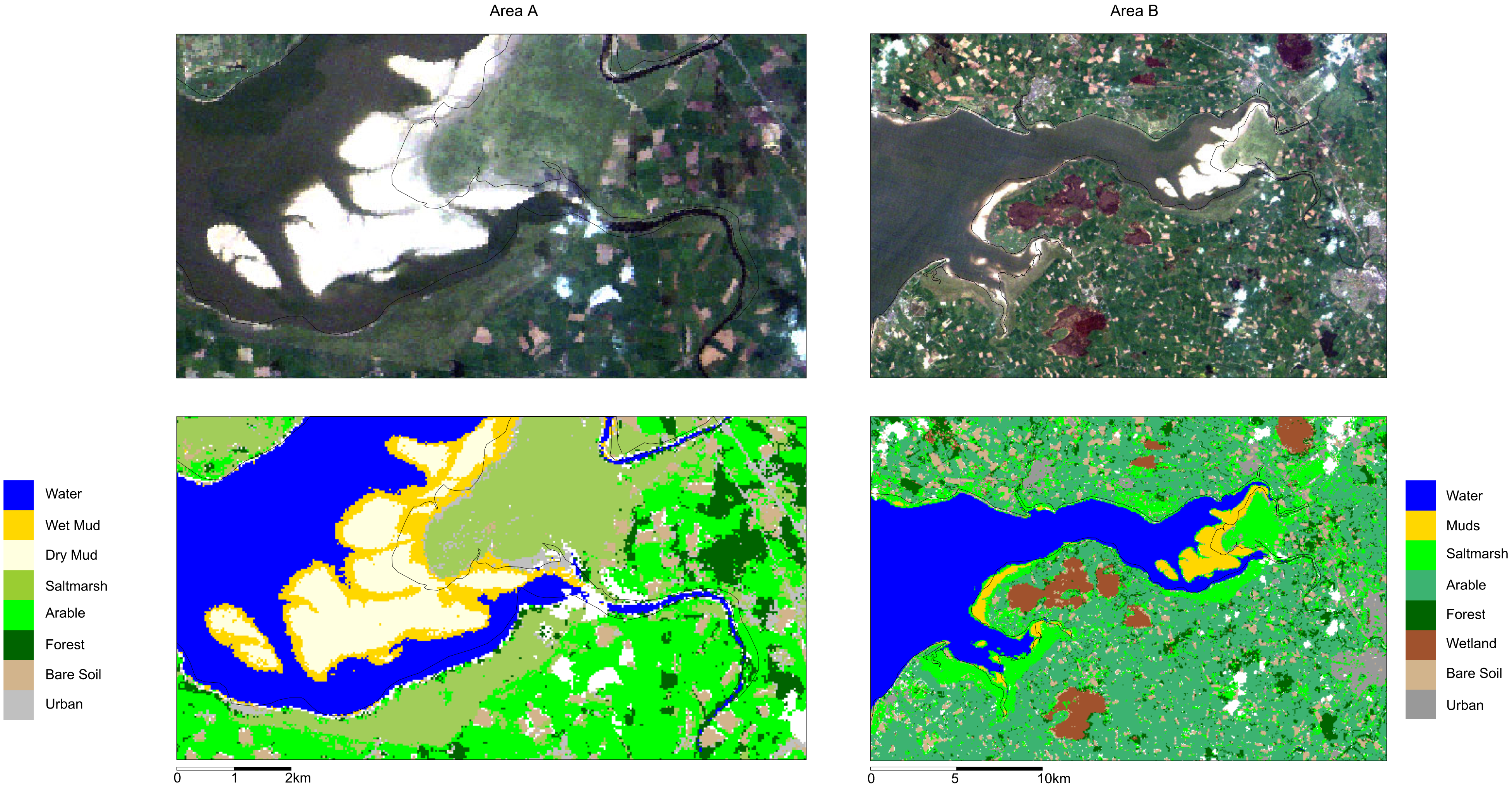

Figure 6.2: True colour composite and thematic maps for areas A and B derived from LandSat data

muds with high ^{137}Cs activities and the river channels. The boundaries of Rockcliffe and Burgh Marshes derived from the thematic map of area A were used in the analysis of the shapes of these features at various line spacings (section 4.3.2). Some features, especially the position of river channels and coastlines, are in slightly different positions in the satellite images than the 1998 OS Strategi data.

It is possible that the differences observed between the digital map data and the radiometrics or the satellite imagery result from incorrect registration of the radiometrics and satellite data, however, these were registered independently and agree with each other indicating that the discrepancy is in the OS data. Small errors will enter the 1:250000 Strategi data as a result of digitisation and generalisation of higher resolution maps, however the discrepancies between the OS data and the radiometrics are much larger than might be expected from such errors. It is more likely, in this highly dynamic environment, that the digital data do not represent the current environment. In the event of a nuclear emergency affecting such environments the currency of digital map products may be important in determining the extent of contamination in relation to ground features. In this case the use of contempory remote sensing imagery may provide a more accurate representation of the physical environment.

The video camera mounted inside the helicopter had a relatively narrow field of view, even with a wide-angle lens fitted, covering some 30-40 m depending on ground clearance. Thus, even at 50 m line spacing, it would not be possible to produce a mosaic image covering the entire area surveyed. The definition of the images is, however, very good with objects a few cm across easily identifiable. These images could, therefore, be used to quantify various environmental factors in the survey area at precisely the same time as the survey is conducted. Although study of these images has not been conducted, the amount of foliage in trees, tidal levels in coastal regions, the amount of standing water on peat lands and other environmental information could all be readily accessed from these images. Providing it is possible to synchronise the video with the radiometric record it could be possible to identify features on the ground associated with particular radiometric signals if the aircraft flew directly over these features.

During the April 1999 survey, a small number of images were recorded with a digital camera mounted inside the aircraft looking down through the front left clear plastic window to explore the possibility of using such digital-photogrammetric methods to generate digital terrain models (DTMs). The analysis of these images is still on-going and will be reported separately.

7. DISCUSSION AND CONCLUSIONS

7.1 Survey Results

The project reported here has resulted in both the generation of significant new bodies of airborne radiometric data, with over 150000 NaI(Tl) spectra gathered from a radiologically important part of the UK stretching from the Inner Solway to the Duddon Estuary. The data gathered in the three survey phases are of interest in their own right as well as serving as the basis for both describing their contemporary radiation environments and assessing change both relative to past surveys and to future change. Taken together with the complete set of surveys conducted in the past by SURRC since 1988 there is now radiometric coverage of the majority of Scotland south of the Clyde and a substantial part of northwest England.

Within the Inner Solway the data collected provide a valuable record of the coastal sedimentary environment and its response both to the past discharges of radioactivity from Sellafield, and their decreases over the last 10-20 years. Salt marshes and mud flats remain as repositories for significant inventories of environmental radioactivity, and these new data provide clear evidence for continuing areas of sedimentation and also highlight areas where coastal erosion is both exposing and dispersing former sinks for environmental contamination. The juxtaposition of remote sensing data has provided a clear demonstration of the strong links between landscape compartment and environmental radioactivity, both in the coastal environment and in the wetland areas. The strong correlations between the shapes of radiometric and landscape features provide a compelling confirmation of the effectiveness of AGS techniques in defining real areas with common radiation environments. In dynamic coastal environments some features were noted, for example in the lower reaches of the River Esk, where even relatively recent digital maps mispositioned environmental features relative to both satellite imagery and radiometrics. This underlines the importance of using contemporary land classification information in making detailed interpretation of high resolution AGS data, which may be relevant to some aspects of late stage emergency response.

The second phase of survey provided a high resolution data set describing the coastal environs of the Sellafield site. Many of the features observed had been noted in general terms in previous surveys. The new data sets confirm the presence of Sellafield derived activity in estuarine and salt marsh environments and their flood plains, as well as activity on the beach between Sellafield and St Bees, together with direct radiation observed close to the site and signals from gaseous discharges from the Calder Hall reactors. New data have been recorded which provide a valuable demonstration of the high dose rate response of AGS to the contained activity within the Drigg repository, and enclosed sources within containers stored temporarily on the railway sidings leading to Drigg. The spatial response and registration of these features in their known locations provides further verification of the ability of AGS to locate discrete sources of activity correctly; another feature which is highly relevant to emergency response. This survey also identified a number of areas of enhanced activity associated with former industrial wastes containing low levels of uranium series activity. Detailed survey of the former RAF Carlisle sites, which had been subject to radium decontamination confirmed that levels of radiation were consistent with the local natural background at the time of survey. This gives some reassurance that the decontamination activities had succeeded in removing all significant sources from near surface locations.

The third phase of survey provided extensive data from the area between the Solway and Duddon estuaries including upland areas which had received deposition from the Chernobyl accident and the Windscale fire. A repeat survey was also conducted of Rockcliffe Marsh to permit evaluation of environmental changes over a 15 month period.

7.2 Reproducibility and Line Spacing Effects

AGS data are subject to both random uncertainties associated with the counting statistical limitations of short measurements in the environment and uncertainties due to the corrections and calibration procedures used in quantification. Both types of uncertainties have been considered in this work, the greatest systematic uncertainties in calibrated data being associated with potential variations in the depth distribution of environmental radioactivity. For these surveys a mass depth of approximately 15 g cm^{-2} was observed at the Caerlaverock calibration site, producing a calibration which was applicable to the test site at Croasdale Farm in West Cumbria within 20%. For areas with ^{137}Cs activity below 10 kBq m^{-2} the statistical counting errors are the dominant source of uncertainty. By contrast on estuarine and salt marsh areas statistical errors on individual 2 s observations are less than 10%. The statistical limits on individual 2 s data are to a significant extent mitigated by averaging operations involved in both mapping and regridding areas for inventory analysis. Moreover, in considering potential detection limits applicable to emergency response the greater sensitivity of superficially deposited activity (which gives approximately 3.5 times greater count rates per unit activity per unit area) compounds these benefits. Therefore, short acquisition times capable of providing spatial location of strong radiation sources within 50-100 m dimensions are warranted.

The observed reproducibility of the method has been demonstrated by analysis of repeat survey flights of a line across the Drigg waste store and tie lines between Bowness Common and Bassenthwaite Lake. It is also evident that over longer time scales the results of airborne surveys are highly consistent once radioactive decay, differences in calibration methods and known processes for change in the radiation environment are taken into account. Even with significant improvements in equipment and methodology the total ^{137}Cs inventory measured in West Cumbria in 1988 and June 2000 differs by only 3%, after correcting for radioactive decay and the effect of source burial on calibration sites. The work presented here confirms therefore, that AGS is capable of recording external radiation fields in a reproducible manner providing adequate steps are taken to control detector operating conditions and account is taken of spatial and temporal effects in the environment.

The effect of survey line spacing has been studied by subsampling the survey data into sets which can be treated as independent survey subsets collected at the same time. Environmental changes are therefore not significant when comparing such sets, although minor differences in spatial characteristics are to be expected. ^{137}Cs inventory estimates of the Inner Solway and West Cumbrian survey areas have been evaluated and compared for such subsampled data sets. The shapes of radiometric features have also been examined to assess the extent to which inventory and shape can be reproduced with increasingly sparse survey sets.

In the Inner Solway line spacing permutations ranging from 50 m to 500 m were examined. Inventory estimates for the larger salt marshes, and indeed for the whole area, were remarkably stable. The 50 m line spacing set giving an inventory of 1.1 TBq for the entire area, compared with a range from 1.06-1.13 TBq for the ten permutations of 500 m line spacing subsets from the same area. Moving to larger dimensions the northern part of the Chernobyl deposited area of West Cumbria provides an inventory of 15.9 TBq for the 500 m spaced data subsets compared with a range from 15.4-16.8 TBq based on the ten 5 km spaced subsets.

Both visual observations of remapped data and quantitative parameterisation of the shapes of major features confirm that environmental features of large dimensions in comparison with line spacing are well estimated by AGS methods. By contrast, when the spatial dimensions of individual features are comparable with line spacing the shapes of features and their detection probabilities are adversely effected. Thus, Rockcliffe Marsh in the Inner Solway with dimensions of the order of 5 km is relatively well mapped with all permutations up to 500 m, whereas some of the smaller salt marsh areas of the Inner Solway are detected with decreasing edge detail in the sparser data sets. In the upland areas the overall outline of the general deposition areas is broadly delimited, even with 2.5 or 5 km line spacing. However, local variations which may be significant to environmental research are not clearly defined by such sparse surveys.

Both cost and speed of survey are of course critically linked to line spacing. The work presented here has shown the influence of line spacing on data quality and information content. The appropriate choice of line spacing for work of this sort is clearly dependant on the purpose of the survey and the spatial dimensions of the environmental feature of interest. But it is perhaps helpful to note that data with line spacings of 2.5, 5 or 10 km would be expected to identify the majority of areas showing enhanced deposition following a major release of activity. On this basis it might be considered that such line spacing would be appropriate to initial rapid post-accident reconnaissance in the absence of well constrained meteorological predictions, or indeed to general baseline reference data sets on regional or even national scales. Where more detail is needed, for example in providing detailed deposition maps in areas shown to be of interest by first-pass survey of the type described above, or in small scale studies of local environments or the path ways associated with discharges from sites, line spacings of between 100 and 500 m may be both practical and adequate. It is only in cases where the highest possible sensitivity and density of information are required, for example detailed definition of activity distributions relative to individual field boundaries or searches for radioactive sources in complex or urban environments, where survey line spacings of 50 m or less might be required.

7.3 Environmental Change

It has been possible to demonstrate the ability of AGS techniques to detect, quantify and map changes in the radiation environment by comparison of the results of repeated surveys over common areas. Since different radiometric surveys have individual observations in different spatial locations, it is necessary to base such comparisons on regridded estimates placed onto a common spatial grid. Procedures to do this based on inverse distance weighted estimation have been developed and shown to be robust within this project. Both inventory analysis and spatial comparisons have been undertaken with interesting results.

In the Inner Solway the comparison between data collected in April 1999 and June 2000 has shown distinct areas of slight reduction in activity attributed to continuing accumulation of the less active estuarine sediments on top of salt marshes with buried activity maxima. At Rockcliffe Marsh the radiometric data are consistent with a sedimentation rate of 1.4 g cm^{-2} per year, which is well within the range of values inferred from analysis of soil cores. The eroding edges of Burgh Marsh and the southern limit of Rockcliffe Marsh can be clearly identified as a result of the exposure of previously buried sediments of higher activity. The data in this case are consistent with an annual retreat by erosion of Burgh Marsh of approximately 50-100 m, which again is broadly in line with observations based on maps. Small positive increases were also observed in an area of mud flats which may be a temporary sink for recently eroded active sediments. An area of low lying land near the Eden estuary shows slightly enhanced levels in the second survey in comparison with the first one. Further work would be needed to assess the hypothesis that this may be related to a combination of high tides and flooding in the winter of 1999.

In West Cumbria, although the inventory for the area covered by both the 1988 MAFF survey and the June 2000 survey is within 3% of the decay corrected value, there is evidence of transfer of a substantial amount of activity from upland to lowland contexts. Examination of partial inventories in different areas suggests that the losses from upland areas are approximately consistent with the gains in lowland areas. Consideration of likely stocking densities and effects of both transfer by livestock and by hydrological processes suggests that down wash or erosion mechanisms are likely to be the dominant process responsible. It would be of interest to examine the geographical and geomorphological contexts of these changes in more detail in the future.

Overall, the new survey results, their relation to known landscape features, and the analysis conducted so far have both confirmed the utility of the AGS technique for environmental research, and illustrated many of the key features of the method which are fundamentally relevant to its use in emergency response. The comparative techniques developed and illustrated in this project are directly relevant to quantification, location and demarcation of contaminated areas following environmental deposition of radioactivity. The techniques used for measurement and identification of environmental change are relevant to demonstration of increased activity levels relative to baseline data even in areas with complex deposition histories. Moreover, the data sets produced during this study represent a valuable resource for future environmental research.

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APPENDICES

A. Review of Stripping and Calibration Factors

Prior to each phase of survey and after the conclusion of field work spectral stripping coefficients for the NaI(Tl) spectrometer were determined using a series of doped concrete pads and perspex sheets to simulate the air path. Each sheet of perspex is equivalent to approximately 10m of air; the first sets of measurements used 5 sheets, whereas, in the final set 7 sheets were used which is more appropriate to the surveys which had an average ground clearance of approximately 70m. In March 2000 one of the crystals in the detector pack was replaced with a refurbished crystal with improved performance, and stripping factors were measured before and after this. In addition, for the final set of measurements a set of data was recorded with five perspex sheets on top of the detector to consider the effect of backscatter, and uncertainties on these measurements were determined. The resulting stripping factors are tabulated below.

	Window				
	^{137}Cs	^{60}Co	^{40}K	^{214}Bi	^{208}Tl
^{137}Cs	1	0.00148	0	0.0019	0
^{60}Co	0.412	1	0.241	0.040	0.0233
^{40}K	0.594	0.483	1	0	0
^{214}Bi	3.66	1.74	1.05	1	0.044
^{208}Tl	2.68	0.645	0.707	0.438	1

Table A.1: Stripping ratios measured April 1999 with 5 perspex sheets under the detector

	Window				
	^{137}Cs	^{60}Co	^{40}K	^{214}Bi	^{208}Tl
^{137}Cs	1	0.0563	0.0024	0.0011	0
^{60}Co	0.429	1	0.374	0.055	0.0362
^{40}K	0.584	0.452	1	0	0
^{214}Bi	3.24	1.51	0.924	1	0.066
^{208}Tl	2.51	0.648	0.613	0.433	1

Table A.2: Stripping ratios measured May 2000 (first set) with 5 perspex sheets under the detector

	Window				
	^{137}Cs	^{60}Co	^{40}K	^{214}Bi	^{208}Tl
^{137}Cs	1	0	0	0	0
^{60}Co	0.432	1	0.400	0.054	0.034
^{40}K	0.548	0.426	1	0.009	0
^{214}Bi	3.19	1.47	0.927	1	0.080
^{208}Tl	2.49	0.669	0.609	0.438	1

Table A.3: Stripping ratios measured May 2000 (second set) with 5 perspex sheets under the detector

	Window				
	^{137}Cs	^{60}Co	^{40}K	^{214}Bi	^{208}Tl
^{137}Cs	1±0.003	0.0148 ±0.0013	0.0243 ±0.0014	0.0084 ±0.00057	0.0048 ±0.00057
^{60}Co	0.508 ±0.0036	1±0.003	0.521 ±0.0026	0.0379 ±0.0010	0.0234 ±0.0011
^{40}K	0.673 ±0.0040	0.487 ±0.0031	1±0.005	0±0.00077	0±0.0009
^{214}Bi	3.374 ±0.0063	1.530 ±0.0034	0.921 ±0.0029	1±0.002	0.0677 ±0.00096
^{208}Tl	2.513 ±0.0073	0.671 ±0.0031	0.605 ±0.0028	0.457 ±0.0018	1±0.003

Table A.4: Stripping ratios measured Nov 2000 with 7 perspex sheets under the detector

	Window				
	^{137}Cs	^{60}Co	^{40}K	^{214}Bi	^{208}Tl
^{137}Cs	1	0.00483	0	0	0
^{60}Co	0.510	1	0.521	0.0366	0.0236
^{40}K	0.674	0.485	1	0	0
^{214}Bi	3.365	1.515	0.955	1	0.0747
^{208}Tl	2.532	0.687	0.622	0.454	1

Table A.5: Stripping ratios measured Nov 2000 with 7 perspex sheets under the detector, and 5 perspex sheets on top

The stripping factor measurements are fairly consistant with only slight variations between the values determined with 5 absorber sheets. There are some more significant differences when 7 sheets are used, with only a small difference due to absorbers on top of the detector. The stripping factors determined using 7 perspex sheets under the detector with absorbers on top were used in reanalysis of the survey data.

Altitude correction and sensitivity calibration constants were determined from the data recorded at the Caerlaverock calibration site, after subtraction of an appropriate background and stripping. The data used includes data collected for another survey, of Belgian nuclear sites, conducted within the time frame of the survey work for this project using the same equipment.

The coefficients determined for each calibration data set are given in the table below. There is some variation within the altitude correction coefficients, with the variation between surveys similar to that within each survey. The coefficients determined from all the measured data points were used for all the survey data collected during this project.

Date	Ch1 (^{137}Cs)	Ch3 (^{40}K)	Ch4 (^{214}Bi)	Ch5 (^{208}Tl)	Ch6 (γ-dose)
20/4/1999	0.0124	0.00792	0.00518	0.00569	0.00763
27/4/1999	0.0133	0.0108	0.00734	0.00936	0.0110
14/3/2000	0.0134	0.0110	0.00941	0.00935	0.0104
22/3/2000	0.0134	0.0119	0.0109	0.00982	0.0108
8/5/2000	0.0121	0.0113	0.0109	0.00897	0.00960
13/5/2000	0.0115	0.0109	0.0118	0.00902	0.00977
13/6/2000	0.0131	0.00880	0.00697	0.00643	0.00938
18/6/2000	0.0117	0.0108	0.00356	0.00744	0.00903
26/6/2000	0.0135	0.00960	0.00481	0.00850	0.0107
all data	0.0132 ±0.0001	0.0100 ±0.0002	0.00661 ±0.00048	0.00768 ±0.00025	0.00945 ±0.00008

Table A.6: Altitiude correction coefficients determined at Caerlaverock calibration site

These altitude correction coefficients were used to determine count rates corrected to 100m ground clearance for the calibration manoeuvres, which are tabulated below. There are a couple of sets of data with significantly greater count rates in the natural ^{214}Bi and ^{208}Tl channels, and there are some data sets which have a slightly lower ^{137}Cs count rates than others probably due to slightly different tidal conditions.

Date	Ch1 (^{137}Cs)	Ch3 (^{40}K)	Ch4 (^{214}Bi)	Ch5 (^{208}Tl)
20/4/1999	144.0±4.3	45.6±5.4	7.12±0.44	9.60±0.50
27/4/1999	181.1±0.8	38.8±0.5	5.06±0.19	7.89±0.16
14/3/2000	152.9±1.3	36.0±0.6	4.76±0.23	7.85±0.20
22/3/2000	170.9±1.0	37.6±0.6	4.32±0.24	7.66±0.21
8/5/2000	167.5±1.1	32.3±0.4	2.25±0.21	7.33±0.17
13/5/2000	193.0±1.9	36.9±0.8	2.32±0.34	7.25±0.28
13/6/2000	175.1±2.1	37.8±1.4	16.22±0.57	11.59±0.47
18/6/2000	182.9±2.0	37.7±0.8	6.80±0.36	8.37±0.30
26/6/2000	158.0±2.0	36.5±0.8	3.44±0.37	7.48±0.40

Table A.7: Altitude corrected count rates (cps) determined at the Caerlaverock calibration site

The activity concentrations for ^{137}Cs and the naturally occurring ^{40}K, ^{214}Bi and ^{208}Tl nuclides were determined from cores collected in April 1999. The activity concentrations for each of the measured cores are given in the tables below. The average activity concentrations for the Caerlaverock site are 61±10 kBq m^{-2} for ^{137}Cs, 257±6 Bq kg^{-1} for ^{40}K, 10.9±0.5 Bq kg^{-1} for ^{214}Bi and 4.6±0.2 Bq kg^{-1} for ^{208}Tl.

The altitude corrected count rates for the combined data sets recorded over Caerlaverock with the higher count rates (>160 ^{137}Cs cps) were used, and sensitivity calibration factors determined for the whole survey. These are tabulated below, along with values used in other recent surveys. The calibration constant for ^{137}Cs is higher here than that used for the Newbury and Resume 95 surveys, which was calibrated to terrestrial Chernobyl fallout rather than Sellafield derived estuarine salt marsh activity which has a much deeper source burial. The calibration constants for the natural activity are fairly similar.

	Ch1 (^{137}Cs)	Ch3 (^{40}K)	Ch4 (^{214}Bi)	Ch5 (^{208}Tl)
Count Rate (cps)	179.6±0.7	37.7±0.3	5.38±0.21	8.04±0.13
Calibration Constant (kBq m^{-2} cps^{-1})	0.340±0.064	6.82±0.17	2.02±0.12	0.575±0.027
Newbury, Resume 95	0.11	6.77	3.16	0.47

Table A.8: Altitude corrected count rates and calibration constants for Caerlaverock and Vesivehmaa data

In addition to the Caerlaverock manouvres, a field behind the field station set up at Croasdale was also sampled and used as an additional calibration check. Cores were taken from 13 points on this field, a centre point and two hexagonal rings at 8m and 16m. These were divided into three sections; 0-5cm, 5-10cm and greater than 10cm depths; and subsamples of the ground material from each layer homogenised. Analysis of these samples gave a surface activity of 15.2±0.9 kBq m^{-2} assuming a uniform activity distribution across the field with a mean mass depth of approximately 8.5 g cm^{-2}. This is consistent with the mean mass depth expected from 15 year old Chernobyl fallout (ICRU 1994). The use of the calibration factors determined from the Caerlaverock data on data recorded over the field at Croasdale gave activity measurements of 18.3±5.3 kBq m^{-2} in March 2000 and 17.8±5.3 kBq m^{-2} in June 2000, which are 20% higher than the activity determined from the cores.

The data from all three surveys conducted for this project were recalibrated using these stripping and calibration factors.

Radial		Shell				
		0 (Centre)	2 (8m)	3 (32m)	4 (128m)	5 (256m)
1	Mean Mass Depth (g cm^{-2})	19.0	18.6	16.8	9.2	4.9
	Surface Activity (kBq m^{-2})	113.8±6.3	100.5±2.4	104.5±12.8	48.1±2.1	18.1±4.5
2	Mean Mass Depth (g cm^{-2})		16.8	15.4	11.1	8.5
	Surface Activity (kBq m^{-2})		88.7±2.9	66.1±4.0	47.5±4.4	34.2±1.1
3	Mean Mass Depth (g cm^{-2})		13.8	19.5	12.1	18.8
	Surface Activity (kBq m^{-2})		67.1±1.2	71.1±2.9	46.9±1.1	14.3±4.9
4	Mean Mass Depth (g cm^{-2})		13.4	23.2	19.6	
	Surface Activity (kBq m^{-2})		52.6±19.3	132.5±3.3	15.2±5.1	
5	Mean Mass Depth (g cm^{-2})		15.8	18.1	31.0	23.7
	Surface Activity (kBq m^{-2})		73.4±1.3	77.1±4.8	85.2±3.2	27.0±13.8
6	Mean Mass Depth (g cm^{-2})		17.0	17.3	7.6	5.0
	Surface Activity (kBq m^{-2})		56.3±6.5	64.2±2.2	20.6±1.9	20.3±5.8
Mean	Mean Mass Depth (g cm^{-2})	19.0	15.9±0.8	18.4±1.1	15.1±3.6	12.2±3.5
	Surface Activity (kBq m^{-2})	113.8±6.3	73.1±7.6	85.9±11.1	43.9±10.2	22.8±3.2
Weighting for 100m (%)			4.7	41.7	44.2	9.4

Mean activity: 60.8±9.8 kBq m^{-2}

Table A.9: ^{137}Cs activity concentrations from Caerlaverock cores

Radial		Shell				
		0 (Centre)	2 (8m)	3 (32m)	4 (128m)	5 (256m)
1	Activity (Bq kg^{-1})	249±8			243±38	
2	Activity (Bq kg^{-1})		246±14	233±13		
3	Activity (Bq kg^{-1})		257±13			287±11
4	Activity (Bq kg^{-1})		240±51		292±8	248±17
5	Activity (Bq kg^{-1})		246±11			
6	Activity (Bq kg^{-1})		252±11			296±86

Mean activity: 257±6 Bq kg^{-1}

Table A.10: ^{40}K activity concentrations from Caerlaverock cores

Radial		Shell				
		0 (Centre)	2 (8m)	3 (32m)	4 (128m)	5 (256m)
1	Activity (Bq kg^{-1})	9.7±0.5			14.2±1.2	
2	Activity (Bq kg^{-1})		10.6±0.6	9.3±0.4		
3	Activity (Bq kg^{-1})		9.5±0.5			9.9±0.7
4	Activity (Bq kg^{-1})		15.1±1.8		10.1±0.6	11.6±0.7
5	Activity (Bq kg^{-1})		9.9±0.3			
6	Activity (Bq kg^{-1})		11.0±0.4			9.7±1.3

Mean activity: 10.9±0.5 Bq kg^{-1}

Table A.11: ^{214}Bi activity concentrations from Caerlaverock cores

Radial		Shell				
		0 (Centre)	2 (8m)	3 (32m)	4 (128m)	5 (256m)
1	Activity (Bq kg^{-1})	4.6±0.5			5.1±0.6	
2	Activity (Bq kg^{-1})		4.6±0.2	4.3±0.3		
3	Activity (Bq kg^{-1})		4.8±0.3			3.7±0.3
4	Activity (Bq kg^{-1})		6.0±0.3		3.9±0.5	4.7±0.2
5	Activity (Bq kg^{-1})		4.5±0.2			
6	Activity (Bq kg^{-1})		4.5±0.2			4.2±0.6

Mean activity: 4.6±0.2 Bq kg^{-1}

Table A.12: ^{208}Tl activity concentrations from Caerlaverock cores