The effect of flight line spacing on radioactivity inventory and spatial feature characteristics of airborne gamma-ray spectrometry data.

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Airborne Gamma Spectrometry (AGS) is well suited to the mapping of radioactivity in the environment. Flight parameters (e.g. speed and line spacing) directly affect the rate of area coverage, cost and data quality of any survey. The influences of line spacing have been investigated for data from inter-tidal, coastal and upland environments with a range of ^{137}Cs activity concentrations and depositional histories. Estimates of the integrated ^{137}Cs activity ('inventory') within specified areas and the shapes of depositional features were calculated for subsets of the data at different line spacings. Features with dimensions greater than the line spacing show variations in inventory and area of less than 3%, features with dimensions less than the line spacing show larger variations and decreased probability of detection. The choice of line spacing for a task is dependent on the dimensions of the features of interest and required edge definition. Options for line spacing for different tasks are suggested. It is noted that for regional mapping, even 5-10 km line spacing can produce useful data.

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1. Introduction

Airborne Gamma-ray Spectrometry (AGS) rapidly determines the distribution of radionuclides in the environment using sensitive gamma-ray detectors mounted in low flying aircraft (IAEA 1991, 2003, ICRU 1994). Typically the detector would consist of 16 litres, or more, of NaI(Tl) scintillator, often with supplementary data from one or more germanium (Ge) semiconductor detectors. Equipment consisting of spectrometry systems, radar altimeter, GPS receiver and data logging computer are used to record and analyse a series of gamma-ray spectra tagged with positional and ground clearance data. Normally, small helicopters or fixed wing aircraft are used although the same technique (often with smaller detectors) can be used from ground based platforms such as four wheel drive vehicles.

The technique depends on the penetrating nature of gamma-rays in air, with, for example, the 662 keV gamma-ray from ^{137}Cs having a half distance in air of approximately 70 m. Thus, such radiation can be readily detected at ground clearances of ~100 m or less. The circle of investigation for a static detector is approximately 4-5 times the ground clearance for high energy photons (Sanderson *et al.* 1994a). Every measured spectrum is thus spatially averaged over an area covered by such a circle of investigation extended along the line of flight for the duration of the measurement.

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AGS techniques were developed for geological mapping and uranium exploration, but are increasingly recognised as important tools for environmental studies (Sanderson *et al.* 1994a,b, IAEA 2003) and for nuclear emergency response (Darwin and McColl 2000, Flor *et al.* 2000, Honkamaa and Kettunen 2000), especially where there are time constraints. The appeal of airborne rather than ground based radiometric detection lies in the ability of AGS to provide a quick and efficient method to record radioactivity deposition over large spatial extents with varied terrain. Moreover, the remote sensing nature of the measurements minimises exposure of survey teams to contamination or radiation hazards.

AGS data are typically collected from a series of parallel survey flight lines. The ability to provide meaningful environmental radiometric deposition information as cost effectively as possible is explicitly linked to the survey line spacing adopted. The IAEA has noted that for reconnaissance scale geological surveys 1 km line spacing is typical, with smaller line spacing for detailed surveys (IAEA 1991). The constraints of available time and resources for environmental research and emergency response may make it necessary to adopt less optimal flight parameters.

A study has been undertaken to assess the impact of spatial and temporal effects on the reproducibility of radiometric data (Sanderson *et al.* 2001). As part of this larger study, the work reported here has the objective of determining how accurately a range of flight line spacings (ranging in distance from 50 m to 10 km) reproduce a number of characteristics of environmental radiometric features.

For this work, AGS data was collected using a combined spectrometry system; with a 16 litre NaI(Tl) detector, consisting of four 10x10x40 cm NaI(Tl) crystals giving a 40x40 cm square detector with a depth of 10 cm, and a 50% relative efficiency Ge (GMX) detector. The NaI(Tl) and Ge detectors were sampled at 2 s and 4 s intervals respectively. A GPS receiver was used to label AGS data with latitude and longitude positions with a precision of 5 to 10 m, and radar altimetry was used to record ground clearance. Measurements were made from a twin engined AS355 Squirrel helicopter with an aircraft flying speed of approximately 120 km h^{-1} at around 50-70 m ground clearance. The activities of ^{137}Cs plus the naturally occurring isotopes ^{40}K, ^{214}Bi and ^{208}Tl, and total gamma-ray dose rates were determined from the spectra recorded using a data reduction algorithm based on spectral windows (IAEA 1991, 2003, ICRU 1994, Sanderson *et al.* 1994a,b, Cresswell *et al.* 2006). The work reported here focussed on the distribution of ^{137}Cs, which exhibits a series of distinct environmental features in the survey areas. The ^{137}Cs distribution has greater spatial variability than naturally derived radioactivity, with estuarine and terrestrial activity distributions showing markedly different behaviour. The conclusions from the analysis of ^{137}Cs distribution would still be applicable to mapping other sources of radioactivity using AGS.

Three areas of NW England and SW Scotland, within close proximity of each other, were surveyed for this study: the Inner Solway Firth, NW Cumbria and SW Cumbria, encompassing the Cumbrian mountains. The survey areas in this study were chosen to represent diverse landscapes and radiation environments, and to explore the effectiveness of the AGS technique in reproducing radiometric information from such contrasting features for a range of flight line spacings. Two different types of environment were selected for this study: estuarine salt marshes and intertidal areas with ^{137}Cs activity deposited through marine pathways, and upland areas in West Cumbria with ^{137}Cs activity deposited through atmospheric pathways. The survey areas are shown in figure 1.

The Inner Solway Firth features, surveyed between 20th and 28th April 1999 with a 50 m line spacing, covered an area of 10x6 km encapsulating two large salt marshes (Rockcliffe Marsh and Burgh Marsh) and a couple of much smaller features (area A). A larger 30x20 km area (area B) was surveyed at the same time with a 250 m line spacing, but is not considered in this paper. The survey was undertaken at low tide, when the mud flats were exposed. The radiation environment of this area is dominated by the salt marshes, which contain very high levels of ^{137}Cs due to the deposition of sediments contaminated by discharges from the Sellafield reprocessing plant, often exceeding 100 kBq m^{-2}. The activity is buried under relatively low activity sediment, reflecting the ^{137}Cs discharge history of Sellafield which peaked in the late 1970's and early 1980's (Gray *et al.* 1995). The salt marsh features are bounded by terrestrial environments with ^{137}Cs activity concentrations consistent with global weapons testing fallout (<4 kBq m^{-2}), and exposed mud flats of sediment which also has low ^{137}Cs activity concentrations (10-20 kBq m^{-2}). The 50 m data set was sub-sampled to produce two 100 m, five 250 m and ten 500 m line spacing permutations, representing contemporary subsets of the same survey data at increasing line spacings.

The Cumbrian surveys covered two areas of 40x40 km (area C) and 50x50 km (area D), encapsulating mountainous terrain. These were surveyed between 13th and 26th June 2000 at 500 m and 2.5 km line spacing for areas C and D respectively. The ^{137}Cs distribution in this area is dominated by atmospheric deposition following the Windscale fire and Chernobyl accidents, with a contribution from weapons testing fallout. This activity is mostly on the higher ground, reflecting rainfall patterns at time of deposition. The distribution pattern is more diffuse than on the estuarine salt marshes, with only the larger lakes providing definite boundaries. At the southern edge of the SW Cumbrian area a few small salt marshes have high activity concentrations of Sellafield derived ^{137}Cs. The 500 m data set from the NW Cumbria site was sub-sampled to produce two 1 km, five 2.5 km and ten 5 km line spacing data sets. Some of the survey lines correspond to the continuation of the 2.5 km spaced lines in the SW Cumbria survey, a composite data set was produced by combining these lines with the SW Cumbria data. This composite data was then used as a 2.5 km line spacing data set, and sub-sampled to produce two 5 km and four 10 km line spacing data sets.

2. Methodology

A data processing algorithm, based on that used for geophysical mapping but extended to include anthropogenic radionuclides, is used to convert the number of counts in spectral windows corresponding to naturally occurring and anthropogenic radionuclides to calibrated activity concentrations. The IAEA recommended method used three windows for naturally occurring ^{40}K, U-series and Th-series activity (IAEA 1991, 2003). The extension to this adds an additional two windows for anthropogenic activity

(Sanderson *et al.* 1994a,b), in this work for ^{137}Cs and ^{60}Co (Sanderson *et al.* 2001, Cresswell *et al.* 2006). Background count rates, resulting from internal activity in the detector and aircraft and a cosmic ray component, are determined over water and subtracted from the gross count rates in each spectral window. Interferences between spectral windows, due to gamma rays associated with one nuclide falling within the window set for another and scattering in the ground and air paths, are removed using a stripping matrix determined from measurements made with calibration pads in the laboratory. Altitude correction and sensitivity calibration factors, confirmed against measurements conducted during hover manoeuvres over a calibration site sampled in a spatially representative manner (Tyler *et al.* 1996), are then applied to the stripped count rates.

For ^{137}Cs, typical gross count rates for a 16 litre NaI(Tl) detector range from 50-100 cps for weapons testing activity concentrations (typically <4 kBq m^{-2}) to greater than 500 cps on the Sellafield contaminated salt marshes. For activity concentrations above weapons testing levels, uncertainties on the calibrated values for a single measurement are typically less than 30% (Cresswell *et al.* 2006). For naturally occurring activity, typical gross count rates for K, eU and eTh are 20-100 cps, 10-40 cps and 5-30 cps respectively. The lower count rates result in increased uncertainty in the calibrated values for single measurements, greater than 50% in some cases. The algorithm used in interpolating and mapping the data uses values from several measurement points, thus significantly reducing the overall random uncertainties in the final mapped product.

Recently, statistical methods have been applied to spectral data to reduce the noise levels in surveys. These include Noise Adjusted Singular Value Deconvolution (NASVD) (Hovgaard 1997, 1998, 2000), Maximum Noise Fraction (MNF) and enhanced MNF (eMNF) (Green *et al.* 1988, Dickson and Taylor 2000, 2001). These methods analyse the entire data set, extracting principal components used to reconstruct cleaned spectra which can then be analysed by standard methods. The strengths and weaknesses of these methods have been assessed by Dickson (2004), showing that these techniques work better on larger data sets and that cleaning the data can result in a loss of quantitative accuracy. Moreover, for quantification of ^{137}Cs activity concentrations, these methods and the standard spectral windows method have been shown to produce comparable results (Sanderson *et al.* 2003, Cresswell *et al.* 2006). As this work involved producing data sets with differing number of measurements, and the number of measurements affects the outcome of the newer statistical approaches, the standard spectral windows method is preferred for this work.

To account for variations in sample density within different data sets, the data were regridded into a regular array of square cells of known area. An inverse distance weighting (IDW) 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 of the continuous radiometric surface. This is a simple algorithm, that can be used for a range of different distributions depending upon the parameters used. It allows boundaries between features to be clearly delimited. The applicability of other interpolation methods, such as Triangulated Irregular Network interpolation and Kriging, to AGS data have been examined extensively elsewhere (Hope 1998, Krejčíř 1999, White 2000), and found to be less satisfactory than IDW algorithms for the work presented here.

The mean activity concentration (in kBq m^{-2} or Bq kg^{-1}) in each cell ($\overline{A_j}$) is the weighted mean activity concentration of the data points that contribute to that cell.

$$\overline{A}_j = \frac{\sum_i A_i r_i^p}{\sum_i r_i^p} \qquad (1)$$

Where A_i is the measured activity concentration 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. This function gives very large weightings for small ranges, approaching infinity as the range tends to zero, resulting in disproportionate weight being given to measurements very close to the centre of the cell. To overcome this a constant weighting, corresponding to a range of 20 m, was used in this work for ranges less than 20 m.

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

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

$$\Delta\overline{A}_j = \frac{\sqrt{\sum_i (\Delta A_i r_i^{\,p})^2}}{\sum_i r_i^{\,p}} \qquad (2)$$

where ΔA_i is the uncertainty on A_i as a result of counting errors, spectral stripping and calibration. The standard deviation between measurements (σ_j) is given by Lyons (1986):

$$\sigma_j = \sqrt{\frac{1}{(n_{eff}-1)} \frac{\sum_i (A_i - \overline{A_j})^2 r_i^{\,p}}{\sum_i r_i^{\,p}}} \qquad (3)$$

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

$$n_{eff} = \frac{\left(\sum_i r_i^{\,p}\right)^2}{\sum_i (r_i^{\,p})^2} \qquad (4)$$

These terms were calculated independently, and the larger of the two used as the uncertainty on A_i.

In order to compare different line spacing data sets, two types of measure were used. The first is an estimate of the total ^{137}Cs activity within specified areas (referred to as the inventory of that area). The second are a variety of spatial characteristics, the dimensions and shapes of features defined by thresholds in the activity per unit area and statistical similarities determined by utilizing the Kappa Index of Agreement (KIA). For the salt marsh environments of the Inner Solway Firth the radiometric features have also been compared to the physical shapes of the salt marshes derived from satellite imagery. A Landsat Thematic Mapper data set for the Inner Solway taken at noon on 27th April 1999 was obtained. A simple first order atmospheric correction was applied using the darkest pixel subtraction technique, followed by a geometric correction to convert the image from UTM to British National Grid coordinates. The data were then classified into a number of land classes including salt marsh and exposed mud flats.

2.1 Inventory estimates

The total activity in each cell is simply the mean activity per unit area, with an uncertainty given by the largest of $\overline{A_j}$ or σ_j, of that cell multiplied by the cell area. The ^{137}Cs inventory of an area within the survey is then simply the sum of the activity in each cell in that area.

2.2 Spatial characterisation

A qualitative visual comparison was conducted of the radioactivity distribution from the regridded data sets for the various line spacings mapped 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.

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 in the salt marsh environments were determined. In the Inner Solway area, the ^{137}Cs activity per unit area due to fallout from Chernobyl and atmospheric weapons testing is <4 kBq m^{-2}. The mud flats in the estuary have 10-20 kBq m^{-2} ^{137}Cs activity, with 30-250 kBq m^{-2} ^{137}Cs activity on the saltmarshes. A threshold of approximately 30 kBq m^{-2} was selected as an appropriate value to define the extents of the radiometric features of Rockcliffe and Burgh salt marshes. This threshold clearly marks the boundary between the salt marsh and the terrestrial environment, though the boundary with the mud flats is less clearly defined. Data for each line spacing permutation were imported into a GIS package, and the resulting images reclassified to show those areas with activity concentrations above or below the threshold value. Area and perimeter computations were conducted for each of the line spacing permutations for each marsh individually, to examine the extent to which spatial characteristics are reproduced in resampled permutations of the original data sets. A similar analysis was conducted on the salt marsh boundaries identified on the Landsat TM image, and compared with the radiometric features.

Bi-variate statistics were then employed to provide a quantitative evaluation of 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. A range of bi-variate statistical techniques were considered, and Kappa Index of Agreement (KIA) chosen for this purpose (White 2000). The KIA statistic describes the degree of agreement between two sets of categorical data (Cohen 1960) and is calculated through the development of an error matrix, with the columns on the matrix depicting the categories for one map, and the rows the same categories for the second. Individual sample points are represented in the matrix according to the categories found at its location on the two maps. Values of the KIA statistic vary from 1.0 (perfect agreement) to 0.0 (agreement is entirely by chance), with values of less than zero indicating that the agreement is less than that from chance. A potential limitation of KIA for this work is that it utilises categorical classifications of essentially quantitative data. In this work, the categories used were defined as the ranges of ^{137}Cs activity per unit area corresponding to the different colours of the plotted maps.

3. Results

The methodologies outlined above have been used to assess how accurately data from different flight line spacings reproduce the activity distribution in a given area of the study sites, in the Inner Solway and West Cumbria.

3.1 Inner Solway (area A)

Table 1 shows the values for the parameters determined by the methods used in this study for the various flight line spacings for the Inner Solway data.

For the area of the Inner Solway surveyed, estimates of the total ^{137}Cs inventory are approximately 1.1 TBq, with the spread in estimates increasing 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. The bulk of the ^{137}Cs activity in this site is on Rockcliffe Marsh, with the majority of the rest on Burgh Marsh. 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 of the site. However, for Burgh Marsh the inventory estimates are much more variable, with some estimates for the 500 m line spacing data sets up to 20% less than the inventory estimate for the 50 m line spacing data set.

Figure 2 shows the regridded data from the Inner Solway site 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 (reported in Sanderson *et al* 2001), 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, to the south east of Rockcliffe Marsh, has not been recorded in all of these data sets. 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 salt marsh on the northern side of the Solway is also not observed in some of these data sets. In all of the data sets there are only small changes in the Rockcliffe Marsh feature.

Tabulated results from shape geometry calculations summarised in table 1 indicate a trend of increased variability of geometric feature shape characteristics between permutations with increasing line spacing for both Rockcliffe and Burgh Marshes. For Rockcliffe Marsh, increased line spacing also results in a slight increase in the area of the radiometric feature, whereas for Burgh Marsh the area of the feature slightly decreases. Both changes in area are within 1σ.

For all line spacings, the radiometric feature for Rockcliffe Marsh is larger than the extents of the marsh derived from satellite imagery. This is what would be expected from the nature of the data, with the radiation field extending beyond the boundaries of the source. However, for Burgh Marsh the opposite occurs with the radiometric feature being smaller than the extents of the marsh derived from satellite imagery. This implies that even at 50 m line spacing, some parts of Burgh Marsh fail to fully register in the radiometrics data. The most likely reason is that sections of the marsh are so narrow that only a fraction of the detector field of view includes the salt marsh feature, resulting in the average value for the activity per unit area recorded by the spectrometer being significantly less than the maximum activity per unit area in the measurement area.

The KIA statistic, computed relative to the 50 m line spacing survey data for the whole Inner Solway area are also given in table 1. Like the other measures, the KIA statistic also shows increasing dissimilarity and range in KIA values with increasing line spacing.

3.2 West Cumbria (areas C and D)

Table 2 shows the values for the parameters determined by the methods used in this study for the various flight line spacings for the NW Cumbria data.

For the NW Cumbria survey area, a total ^{137}Cs inventory of 15.8 TBq has been calculated, corresponding to a mean activity per unit area of 9.9 kBq m^{-2}. The variation in total inventory for the different line spacing sets is given in table 2. 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.

Figure 3 shows the regridded data for the NW Cumbria site (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. Again the finer detail of the activity distribution in the upland areas and the definition of the lakes, evident in maps of the total data set without regridding (Sanderson *et al.* 2001), has been lost through regridding of the 500 m line spacing data into the relatively large cell size. The low activity features associated with Derwent Water (to the south of Keswick) and Bassenthwaite Lake (to the north east of Keswick) are still evident on the map for the 500 m line spacing data. These features are visible in one of the 1 km line spacing maps, two of the 2.5 km maps and three of the 10 km maps. In two of the 10 km maps a low activity feature is present to the south of Derwent Water, which corresponds to a low activity feature along Borrowdale observed in the total data set but emphasised in these data. The 5 km line spacing data still shows the larger features in the area, the higher radioactivity on the uplands to the south and lower activity to the north east.

For the combined 2.5 km line spacing data sets for the West Cumbria upland areas a total ^{137}Cs inventory of 37.8 TBq has been calculated, corresponding to a mean activity per unit area of 10.8 kBq m^{-2}. The variation in total inventory for the different line spacing sets is also given in table 2. 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.

Figure 4 shows the regridded data for the West Cumbria site and the corresponding 2.5 km line spacing data from the NW Cumbria site 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 NW Cumbria, 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 radioactivity 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.

4. Discussion and conclusions

The effect of line spacing on the quality of data produced by Airborne Gamma-ray Spectrometry (AGS) has been investigated using ^{137}Cs data collected from a series of surveys conducted in NW England and SW Scotland to assess temporal and spatial aspects on AGS data. Contemporaneous data sets with increasing line spacing were produced by subsampling the full data set for each area under consideration. The effect of increased line spacing has been assessed by several methods.

In the Inner Solway, which includes a number of salt marshes and intertidal areas contaminated by radioactive discharges from Sellafield, flight line spacing permutations ranging from 50 m to 500 m were examined. Even at the widest line spacing, inventory estimates give variation of less than 10% for the smaller Burgh Marsh and less than 4% for the larger Rockcliffe Marsh and the whole area. 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 affected. Thus, Rockcliffe Marsh is relatively well mapped with all permutations up to 500 m, whereas the smaller Burgh Marsh is detected with decreasing edge detail in the sparser data sets. This is also reflected in the shape parameterisation. 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 its length. The flight lines were flown parallel to the long axis of the marsh, so at 500 m line spacing a very small number of flight lines actually intersect the marsh.

For larger dimensions, the ^{137}Cs inventory for the northern part of the Chernobyl deposited area of West Cumbria varies by less than 4%, even for the widest line spacings. In the upland areas the overall outline of the general deposition areas is broadly delimited, even with 2.5 or 5 km line spacing. Even a 10 km line spacing over the West Cumbrian fells shows the general outline of the depositional area. However, local variations which may be significant to environmental research are not clearly defined by such sparse surveys.

While these findings are qualitatively unsurprising, in that the loss of information, such as definition of the boundaries and activity concentrations, about small features is to be expected when the survey line spacing is significantly larger than them, this work has helped quantify the level of information loss with increased line spacing. For features with dimensions comparable to the line spacing, such as Burgh Marsh, variations in inventory estimates of about 10% are observed. However, for much larger features such as the upland deposition in West Cumbria even line spacings of 10 km show variations in inventory of only a few per cent.

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, and available time and resources. The IAEA noted that typically 1 km line spacing is used for geological mapping (IAEA 1991). But it is perhaps helpful to note that data with flight 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 may 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 m and 1 km may be both practical and adequate. It should be noted, that for typical survey ground clearances of around 70 m the detector field of view has a radius of 200-300 m. Thus, line spacing of 250 m ensures total survey coverage with some overlap between adjacent lines, and line spacing of 500 m gives almost total coverage assuming the flight lines are perfectly parallel. Increasing the ground clearance would increase the detectors field of view, increasing the ground coverage at larger line spacing, but would result in greater attenuation of the gamma rays and increased uncertainty associated with each measurement.

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 less than 100 m might be required. In these cases, a reduced survey height, if possible, would also help in reducing the detector field of view and hence increase spatial resolution.

The techniques developed here for comparing data sets at different line spacings are also applicable in other comparisons. For example, they can be used to characterise changes in the same environment over time, either for studies of environmental change or to map fresh deposition after an emergency where baseline data is available. They can also be used to compare the performance of different measurement teams and analytical methods.

This paper has concentrated on the distribution of ^{137}Cs. The conclusions drawn can, however, be applied to natural series activity. In general, natural series activity distributions show both large scale features (from, for example, underlying bed rock and soils) as well as small scale features (such as volcanic intrusions through the bed rock), and features such as faults may produce definite boundaries between different activity distributions. Like the ^{137}Cs distributions studied here, the optimal line spacing for mapping natural series activity distributions would depend upon the survey requirements as to whether the dominant local geological structures are more important, or the more local variations caused by faults and volcanic intrusions which can often be the sites of uranium mineralisation important in economic applications of the technique.

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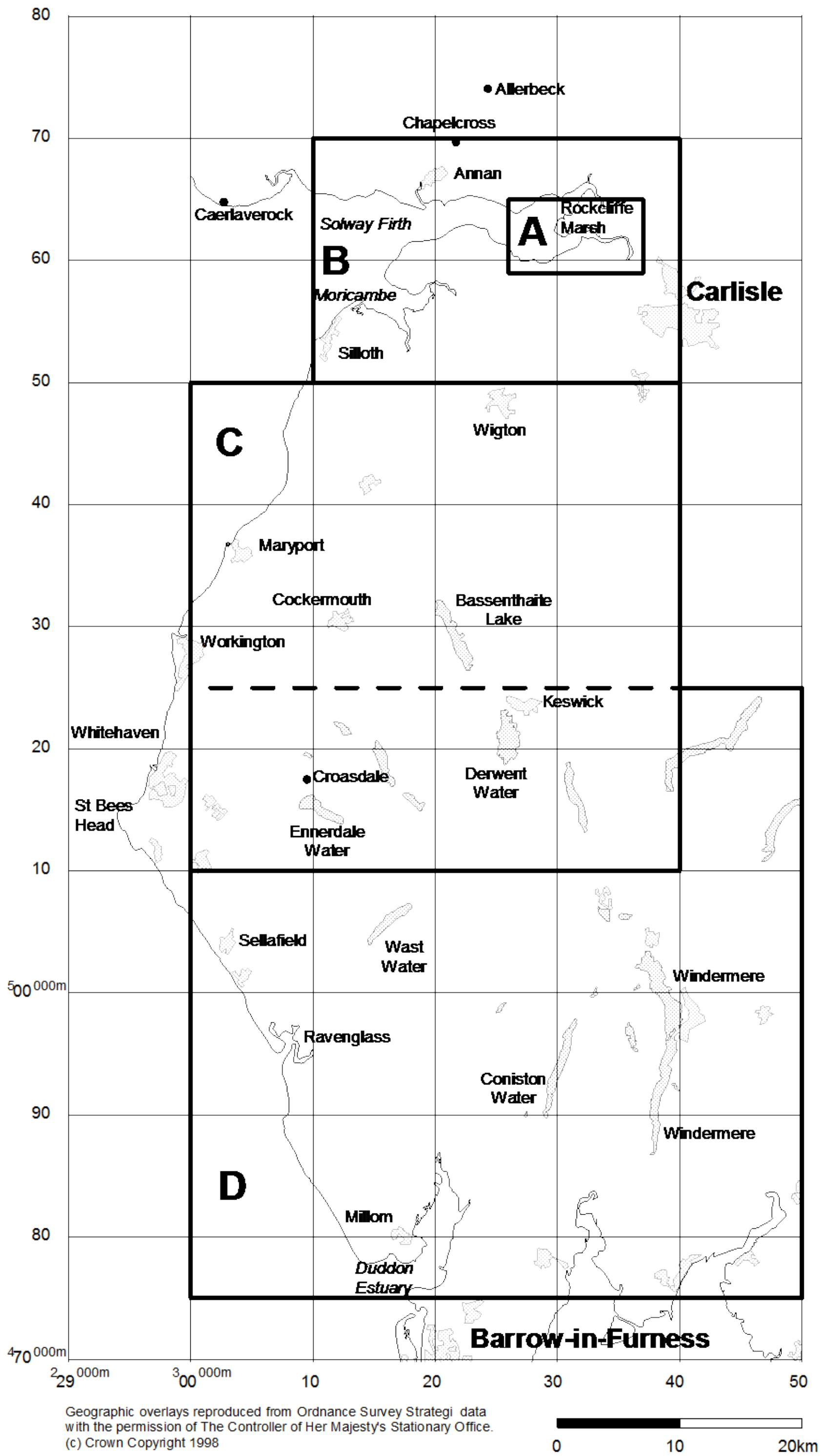

Figure 1: The survey areas for this study.

Table 1: Parameters determined for the various flight line spacings for the Inner Solway data, with the shape parameters determined for Rockcliffe and Burgh Marshes from a LandSat image. The figures in italics are the mean and standard deviation of the values for each set of permutations of each line spacing.

Line spacing (m)	^{137}Cs inventory (GBq)			Rockcliffe shape parameters			Burgh shape parameters			KIA
	Total	Rockcliffe	Burgh	A (km^2)	P (km)	P:A	A (km^2)	P (km)	P:A	
50	1100±5	468±3	381±7	7.46	17.44	2.34	2.43	15.47	6.36	-
100	1070±5	462±3	369±8	7.45	17.27	2.32	1.98	11.89	6.00	0.443
	1100±5	466±3	378±10	7.40	17.08	2.31	2.36	15.38	6.52	0.595
	1085±21	*464±3*	*374±6*	*7.43±0.04*	*17.18±0.13*	*2.32±0.01*	*2.2±0.3*	*14±2*	*6.3±0.4*	
250	1100±6	476±4	377±5	7.51	17.62	2.35	1.82	11.92	6.56	0.334
	1130±8	472±4	405±22	7.17	16.58	2.31	2.77	16.58	5.98	0.364
	1100±8	468±4	382±13	7.23	17.06	2.36	2.53	17.27	6.84	0.255
	1090±7	461±5	376±7	7.50	15.99	2.13	2.34	15.42	6.59	0.366
	1110±5	473±3	388±6	7.62	16.60	2.18	1.96	13.35	6.80	0.372
	1106±15	*470±6*	*386±12*	*7.4±0.2*	*16.8±0.6*	*2.27±0.10*	*2.3±0.4*	*15±2*	*6.5±0.3*	
500	1120±7	483±4	369±12	7.97	19.77	2.48	1.64	19.77	12.04	0.239
	1090±7	485±4	373±11	7.55	16.56	2.20	1.86	12.81	6.88	0.258
	1100±7	485±4	388±11	7.55	16.56	2.20	2.17	13.23	6.10	0.255
	1120±8	489±4	400±9	7.60	15.53	2.05	2.89	14.62	5.05	0.366
	1130±7	488±4	392±8	7.62	16.60	2.18	1.96	13.35	6.80	0.372
	1090±7	475±4	408±8	7.39	16.95	2.14	2.70	18.93	7.01	0.249
	1120±7	488±4	386±43	7.90	15.88	2.01	2.19	16.30	7.46	0.222
	1060±7	467±4	357±8	7.57	16.35	2.16	1.60	16.35	10.21	0.243
	1080±6	456±4	350±44	7.65	16.47	2.15	1.53	15.05	9.83	0.236
	1070±6	457±4	331±6	7.80	18.02	2.31	1.54	11.93	7.77	0.237
	1098±24	*477±13*	*375±24*	*7.7±0.2*	*16.9±1.2*	*2.17±0.14*	*2.0±0.5*	*15±3*	*8±2*	
Landsat				6.09	15.74	2.59	3.52	16.92	4.81	

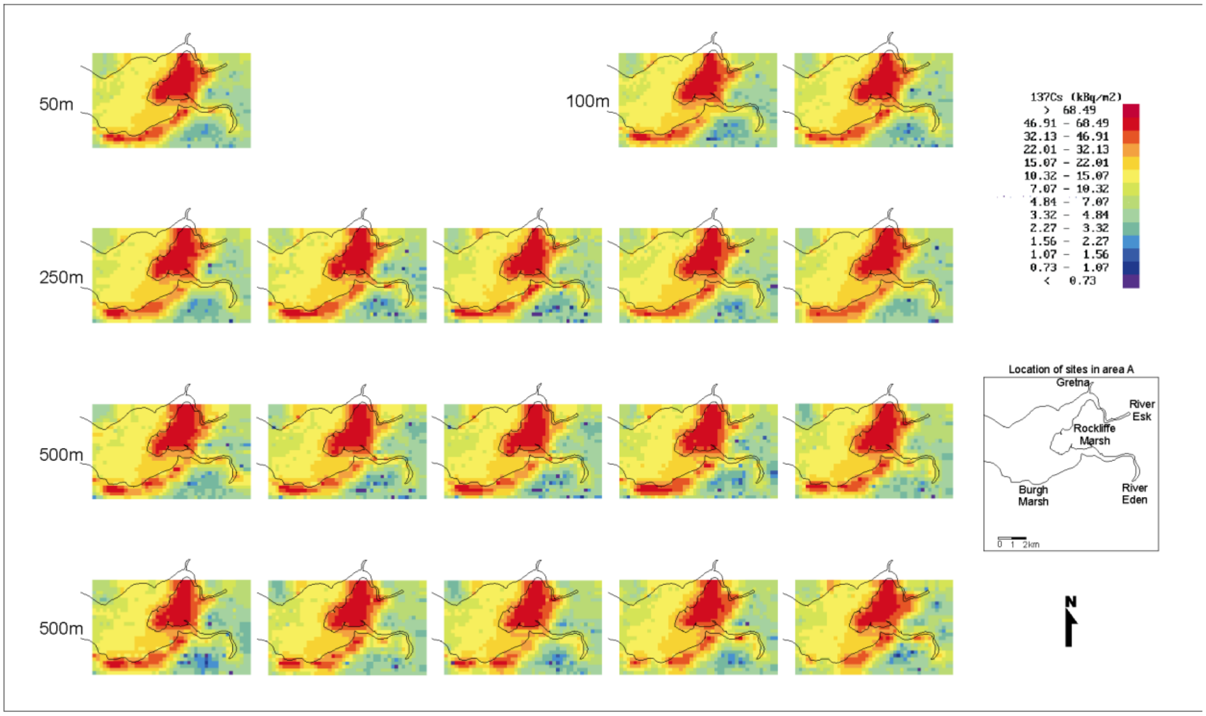

Figure 2. Regridded maps of ^{137}Cs activity in the Inner Solway for different line spacings.

Table 2. Parameters determined for the various flight line spacings for the NW Cumbria data. The figures in italics are the mean and standard deviation of the values for each set of permutations of each line spacing.

Area C		Areas C and D		
Line spacing (km)	^{137}Cs Inventory (TBq)	Line spacing (km)	^{137}Cs Inventory (TBq)	KIA
0.5	15.90±0.02	2.5	37.80±0.07	-
1	16.10±0.01	5	37.80±0.10	0.774
	15.80±0.03		37.80±0.09	0.686
	16.0±0.2		*37.80±0*	
2.5	16.10±0.03	10	37.70±0.15	0.345
	16.00±0.03		38.30±0.09	0.224
	15.60±0.03		37.80±0.09	0.009
	16.00±0.03		37.50±0.11	0.249
	16.00±0.03		*37.8±0.3*	
	15.9±0.2			
5	15.90±0.03			
	15.50±0.03			
	15.40±0.02			
	15.80±0.04			
	16.40±0.03			
	16.40±0.04			
	16.80±0.02			
	16.10±0.03			
	16.30±0.02			
	16.00±0.03			
	16.1±0.4			

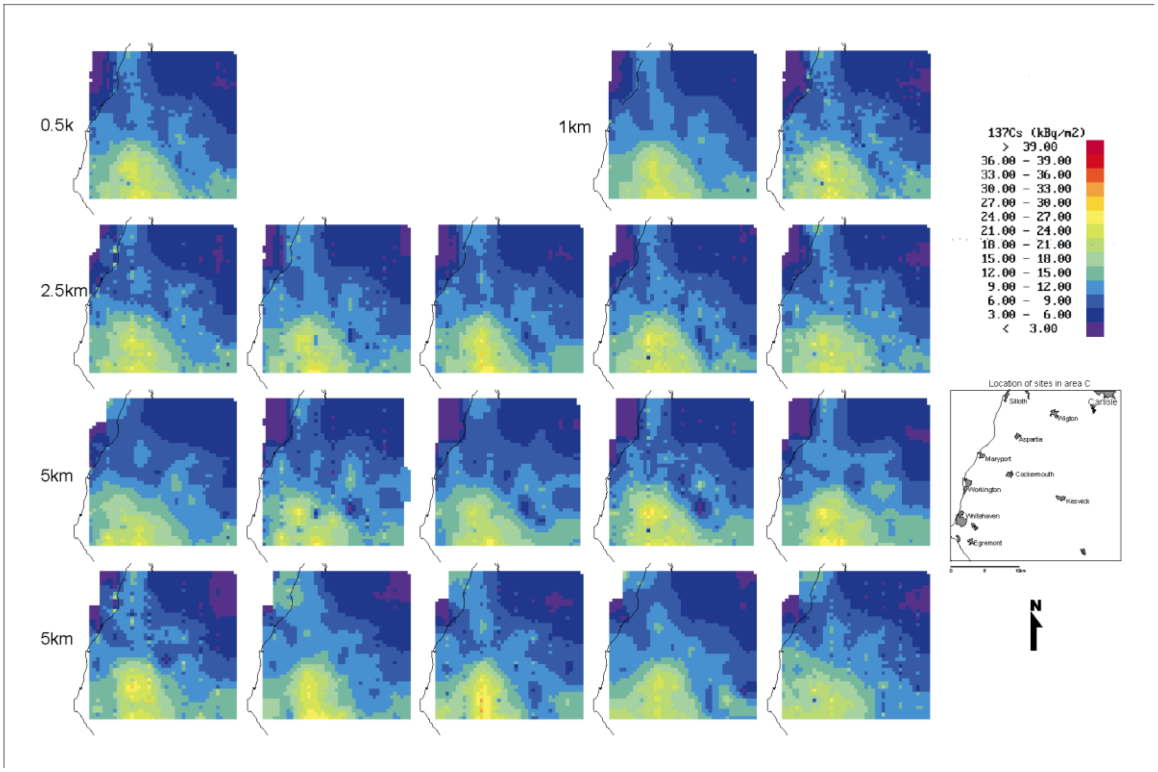

Figure 3. Regridded maps of ^{137}Cs activity in NW Cumbria for different line spacings.

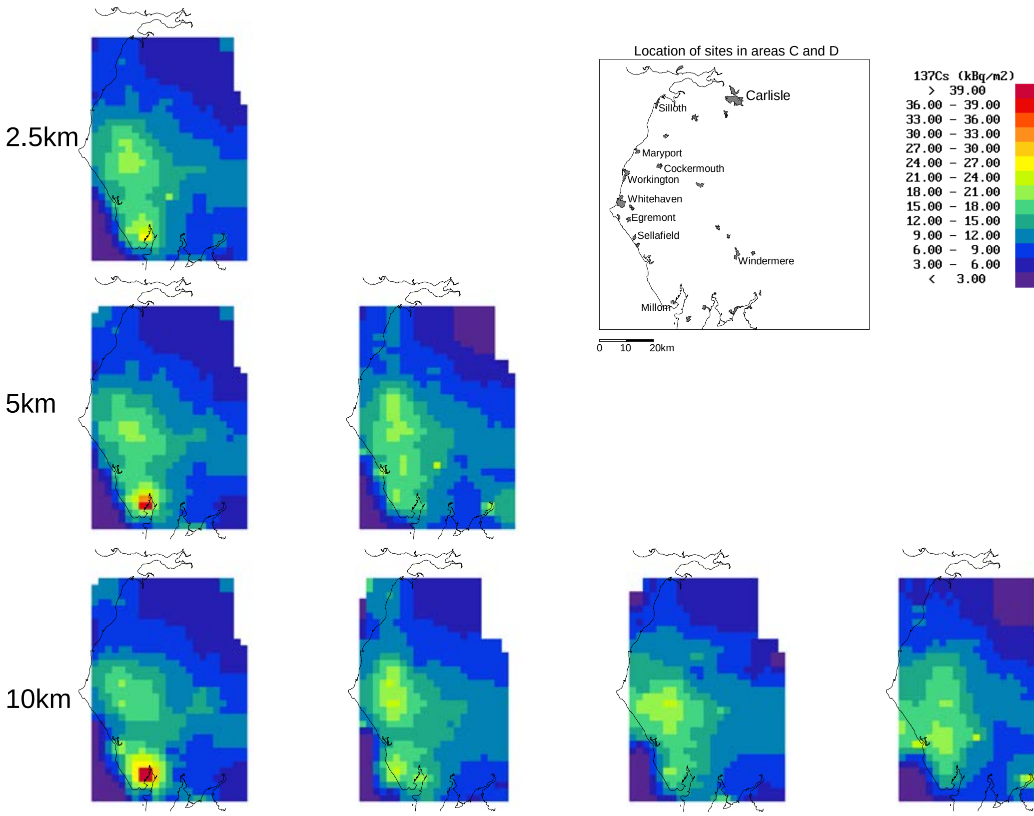

Figure 4. Regridded maps of ^{137}Cs activity in West Cumbria for different line spacings.