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Enhancing the resolution of airborne gamma-ray data using horizontal gradients

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ABSTRACT

The spatial resolution characteristics of airborne gamma-ray data are largely controlled by survey elevation and line separation. In the UK, although low nominal surveys altitudes may be permitted, regulatory zones with elevations in excess of 180 m are required above conurbations. Since the data, typically in the form of grids, are evaluated alongside many other detailed geoscientific spatial datasets their absolute resolution limits, together with their spatial characteristics, become relevant. Here, using published software, we study the theoretical resolution characteristics of this form of survey data obtained with a line separation of 200 m. Of particular interest is the airborne response behaviour when non-uniform distributions of radioactivity are encountered. Although ultimately a function of the radioelement-concentration contrast encountered, the calculations reveal that such zones are most difficult to identify when their scale length decreases below the scale of the line separation. This limited resolution then further decreases with elevation. In order to increase our ability to resolve the edges of non-uniform source regions we calculate the horizontal gradient magnitude (HGM) of the observed data. While the data used can be the estimated radioelement concentrations (potassium, thorium and uranium) or their ratios, we demonstrate that the total count is particularly suited to this type of analysis. The theoretical calculations are supported by an examination of survey data across a series of isolated bodies (offshore islands). This empirical study indicates the practical limits to resolution when using the horizontal gradient and these are governed by the survey line separation. The HGM response provides an enhanced mapping of the edges of zones associated with a contrast in flux behaviour. The edges are detected using the maxima in the response and these can be additionally examined using grid curvature analysis. The technique is assessed using recent survey data containing geological, soil and environmental influences. The results demonstrate the spatially pervasive nature of flux contrasts associated with soil and environmental contributions which potentially mask, or perturb, the underlying bedrock geological response.

1. Introduction

Radiometric, or gamma-ray spectrometric surveys are used to calculate concentrations of the radioelements potassium, thorium and uranium by measuring the gamma-rays which the radioactive isotopes of these elements emit during radioactive decay. The fundamentals of airborne radiometric surveys are described by Minty (1967). The geochemical interpretation of such data, in the regolith context of Australia, is discussed by Dickson and Scott (1997). Their application to soil/regolith mapping is described by Wilford et al. (1997). In the UK, airborne total gamma count surveys were first flown over SW England in 1957–9 as part of the UK Atomic Energy Authority uranium exploration programme (Kimbell et al., 2003). Higher resolution, regional scale, multi-parameter, airborne geophysical surveys commenced in 1998 (Peart et al., 2003). Since then a number of further surveys, incorporating radiometric spectrometric data and using flight-lines spaced at 200 m have been conducted at relatively low nominal altitudes (56 to 90 m). A feature of these surveys is a regulatory requirement to increase survey elevation (to >180 m) over conurbations.

The modern surveys have been conducted for resource, soil and environmental assessments. Soils in the UK generally formed after the last ice age (<12,000 years ago) and are therefore distinct from the ancient soils of Pangea (e.g. those of Africa and Australia). Two particular aspects of gamma-ray flux behaviour arise in the case of the UK (i.e. a temperate, mid-latitude zone) and these are (a) the prevalence of a 'lower-bound' on soil moisture and (b) the occurrence of low density, organo-mineral and organic soils (Beamish, 2015). The soil, when sufficiently thick, attenuates the flux. The degree of attenuation with depth is governed by the density and wetness of the soil profile as described by Beamish (2013, 2015). The conceptual model of soil-superficial-bedrock behaviour is that the bedrock acts as a parent material to the soil so that the particle size, mineralogy and radioelement concentrations of the soil derive from the bedrock material. Significant exceptions

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may occur in the case of material transport (e.g. weathering, erosion, groundwater flow and leaching).

Since the radiometric data are evaluated alongside many other detailed geoscientific datasets the absolute resolution limits of the airborne data, together with their spatial characteristics, become relevant. In order to assess the volume of material contributing to the gamma-ray flux measured by an airborne detector, the concept of a circle of investigation was presented by Duval et al. (1971). It was found that altitude is the most important parameter in determining the volume of material that produces a given percentage of the total observed flux and the results discussed by Duval et al., (1971) are often quoted. The calculations however only relate to an infinitely large, homogenous material.

Further calculations relating to the design parameters for airborne surveys were presented by Pitkin and Duval (1980) building on the earlier work. The study included the effects of finite 'anomalous' source regions (e.g. regions of enhanced radioactivity) and therefore the calculations can be used to assess the spatial mapping capabilities for any specified airborne survey. Here we revisit the calculations of Pitkin and Duval (1980) using software made available by the U.S. Geological Survey: USGS (Duval, 1997). The calculations performed here provide detector flux responses due to finite source concentrations at survey elevations of 60 and 120 m. Here we primarily consider circular source regions (e.g. a localised soil or environmental response) and an infinite linear strip (e.g. a geological response). Linear dimensions of the source region range from 50 to 400 m and are considered in relation to a flight line spacing of 200 m. For more extensive sources, the detector response becomes uniform across the source region before the source edge modifies the response.

The behaviour of the anomalous response characteristics indicate that the lateral scale of the source response is governed by the scale length of the anomalous region. The edges of the source region are identified by the response decrease to a background value. This type of behaviour is also found in potential field data. Magnetic and gravity spatial derivatives have a well-established role in the interpretation of such data. Many methods have been developed to estimate the edge-location of singular bodies (Nabighian et al., 2005). In the same context of edge detection we here consider the behaviour of the horizontal gradient magnitude (HGM) of the anomalous radiometric response. The horizontal gradients are calculated from the set of theoretical anomaly response profiles and it is demonstrated that maxima are associated with the source edge locations except for the smallest bodies. A uniform HGM response (no horizontal gradient) is necessarily associated with extended uniform source regions. Based on the these results, it is suggested that a horizontal gradient analysis of airborne radiometric data offers enhanced resolution of regions characterised by changes in concentration and hence flux behaviour.

The majority of airborne radiometric data are assessed using gridded data sets that comprise the three main radioelements (and their summary ternary image) together with their associated ratios. Additionally total count (TC) data are used to summarise the total flux observed across a broader energy range. In theory horizontal gradient analysis can be applied to any of the three individual radioelement distributions, their ratios and the total count. The radioelement concentration data and total count are one-sided, positive response measurements with a noise floor that permeates the low count behaviour. The ratio information is subject to error propagation from the constituent data and is correspondingly noisier. The horizontal gradient calculation may amplify the noise content of a particular data set and it is relevant to consider the signal to noise characteristics of the data used. In previous UK studies of the attenuation characteristics of radiometric data (e.g. Beamish, 2013) the total count, being a spectral summation, has been used to provide a high signal-to-noise ratio and is also used here in assessing the HGM response.

Since the theoretical calculations are idealised (no noise), we consider the HGM response obtained from survey data across a control study area. The data used are total count obtained across a series of small islands in which the background material (the sea) provides a null response. The degree to which the outline of each island may be detected in the HGM edge response is demonstrated. We also assess the application of curvature analysis (Blakely and Simpson, 1986; Phillips et al., 2007) to map peak (ridge) locations determined by the HGM analysis. The control study uses high-contrast materials so that it also necessary to consider the general case of survey data which encounter more spatially-complex soil, environmental and bedrock variations. Recent UK survey data are used to study the behaviour of the HGM response. A 22 × 20 km study area from SW England provides examples of geological, soil and environmental responses and their characterisation using the HGM total count response. The study is then extended to the local scale to examine the detailed characteristics of some of the soil and environmental responses detected. Finally the HGM response obtained using total count is compared with the ternary response obtained using the HGM of the three individual radioelements.

2. Theory

2.1. Field of view

In order to assess the volume of material contributing to the gamma-ray flux measured by an airborne detector, Duval et al. (1971) introduced the concept of a circle of investigation. The authors performed theoretical calculations based on a flat homogenous material that is infinitely large and infinitely thick (the so-called infinite source). The calculations are valid for gamma-ray energies from 1.5 to 3.0 MeV and therefore for energies associated with the 3 main naturally-occurring radioelements. The effects of altitude, air and source material density together with their attenuation coefficients were investigated. It was found that altitude is the most important parameter in determining the volume of material that produces a given percentage of the total observed flux. In a more wide-ranging set of theoretical calculations, Pitkin and Duval (1980) considered the broader design requirements of airborne surveys in terms of their resolution capabilities. The parameters considered included aircraft speed, flight line spacing and detector volume. The calculations were based on the same conceptual model of the infinite source yield and circle of investigation and relate the airborne detector response to the ground area viewed by the detector. Importantly, the study included the effects of finite 'anomalous' source regions (e.g. a region of enhanced radioactivity) and therefore the calculations can be used to assess the spatial mapping characteristics for any specified airborne survey.

Duval (1997) produced a U.S. Geological Survey (USGS) report, providing and describing, a set of gamma-ray modelling programmes that are based on the previous publications and allow the user to perform their own evaluations. This software is used here to provide an understanding of UK airborne data with an elevation range from 60 to 120 m and a flight line spacing that is typically 200 m. Initially we consider a so-called strip model which extends the circle of investigation analysis to a moving detector (here we use a velocity of 64 $m \cdot s^{-1}$). Flux contributions from strips parallel to the flight path are summed in order to provide a spatial description of the areal contribution from an infinitely thick source. Secondly we consider the effects of anomalous finite gamma-ray sources. These are finite areas defined by a relative increase in their source concentration. The areas considered can be circular, rectangular or an infinite linear feature of constant width (any orientation to the flight line). The latter is probably more relevant to a geological context, although all three display similar edge behaviour in relation to the intrinsic scale of the anomalous feature. Here, for brevity, we consider circular features. The calculations use a set of defined parameters. The parameters used here are (i) a material attenuation coefficient of 0.0444 $cm^2 \cdot g^{-1}$ (e.g. at energies associated with potassium), (ii) a detector area of 0.02 m^2, (iii) a detector photo-peak efficiency of