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Demonstration of lightweight gamma spectrometry systems in urban environments

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Abstract

Urban areas present highly complex radiation environments; with small scale features resulting from different construction materials, topographic effects and potential anthropogenic inputs from past industrial activity or other sources. Mapping of the radiation fields in urban areas allows a detailed assessment of exposure pathways for the people who live and work there, as well as locating discrete sources of activity that may warrant removal to mitigate dose to the general public. These areas also present access difficulties for radiometric mapping using vehicles or aircraft. A lightweight portable gamma spectrometry system has been used to survey sites in the vicinity of Glasgow to demonstrate the possibilities of radiometric mapping of urban areas, and to investigate the complex radiometric features such areas present. Variations in natural activity due to construction materials have been described, the presence of ^{137}Cs used to identify relatively undisturbed ground, and a previously unknown NORM feature identified. The effect of topographic enclosure on measurements of activity concentration has been quantified. The portable system is compared with the outputs that might be expected from larger vehicular or airborne systems. For large areas airborne surveys are the most cost effective approach, but provide limited spatial resolution, vehicular surveys can provide sparse exploratory data rapidly or detailed mapping of open areas where off-road access is possible. Backpack systems are ideally suited to detailed surveys of small areas, especially where vehicular access is difficult.

Keywords

Mobile Gamma Spectrometry, Urban Environments, Topographic Enclosure

1. Introduction

Radiometric surveys are routinely conducted for a variety of purposes, including monitoring contamination, tracing environmental pathways, geophysical exploration and security applications (Sanderson *et al.* 1994a, b, IAEA 2004). Urban environments present particular challenges to radiometric techniques, and have been relatively neglected in survey programmes that have favoured the less complicated rural areas. Rural areas typically have relatively simple environments, in most areas with limited topographic or land use variation within the field of view of radiometric detectors. On the other hand, urban areas can include significant geometrical variation from buildings and rapidly changing land use with roads, buildings, gardens, parks and other surfaces. In addition, there may be a substantial variety of construction materials with different natural activity concentrations and, particularly in the case of structural steel, potentially incorporating anthropogenic activity. Industrial activity may result in contamination with Technologically Enhanced Naturally Occurring Radioactive Material, TENORM (Vearrier *et al.* 2009).

Airborne surveys are restricted by the need to obtain specific clearances for low altitude flights, especially for urban areas where there are a greater number of obstacles to navigation compared to rural environments. Airborne surveys of urban areas have been conducted at low level, below 100m ground clearance, in response to specific potential radiological hazards; eg: potential uranium contamination in Newbury and Thatcham that may have been released during an aircraft fire on the nearby Greenham Common airbase in 1957 (Sanderson *et al.* 1997, 2000a), and radium contamination in Carlisle associated with the disposal of luminous aircraft dials

(Sanderson *et al.* 2000b). Ground vehicle systems are commonly used on roads, where a large proportion of the field of view is the road surface (Korsbech *et al.* 1999, Mellander *et al.* 2002, Sanderson *et al.* 2003), although may be used on open ground with a suitable off-road vehicle. Backpack systems carried by pedestrians offer the possibility of coverage of any accessible space, and even areas within buildings once a positional reference system has been established. Backpack systems have been available for many years, with systems developed by the Swedish Radiation Safety Authority (formerly the Swedish Radiation Protection Institute (SSI)) in the mid 1990s (Sanderson & Ferguson 1997, CORDIS 2002) and now produced by several manufactures, particularly for use in security applications. A backpack system has recently been used to compare data from airborne and ground based measurements in rural areas of Sweden (Kock & Samuelsson 2011). A backpack system has also been used to measure dose rates around nuclear sites in Ghana (Amekudzie *et al.* 2011).

In addition to access, urban areas present other challenges for radiometric surveys. Sparse vehicular surveys of Copenhagen (Aage *et al.* 2006), and elsewhere, have demonstrated the highly variable dose rates of urban environments compared to local rural areas. Systems are calibrated to open field conditions, where the source geometry is approximately controlled. However, the source geometry of urban areas is much more complex with enclosed geometries and building material variations. These effects need to be considered in interpretation of the data calibrated under the assumption of open field geometries. The use of collimators to restrict the field of view of in-situ detectors to mitigate the potentially complex geometry has been suggested (ICRU 1994), and is an approach regularly used in decommissioning nuclear facilities or assessing contamination on nuclear sites where additional radiation sources in the vicinity are present (eg: Hrnecek & Feichtinger 2005). This approach requires extended measurements from fixed locations, and the use of heavy collimators, that make it impractical for large area surveys.

Small portable systems have the potential to map the variations in natural and anthropogenic activity with spatial resolution of a few metres or less, in locations where the general public live, work and spend their leisure time. A portable gamma spectrometry system developed at the Scottish Universities Environmental Research Centre (SUERC) was used in this study. Surveys of the vicinity of SUERC and the University of Glasgow are presented that demonstrate the capability of such systems to conduct surveys with high spatial resolution, issues relating to source geometry, and the identification of anthropogenic radiation signals due to construction materials, residual industrial legacies, fallout radionuclides and sources.

2. Method

The SUERC Portable Gamma Spectrometry system comprises a 3x3” NaI(Tl) detector with digital spectrometer, automatic gain correction, GPS receiver and a computer running a complete data acquisition and spectral analysis package from the airborne system. The complete system (detector, computer and harness) weighs approximately 4kg, which is lighter than comparable systems. Spectra are recorded continuously with integration times of typically 5-10s in 512 channels over an energy range of 30keV to 3MeV while the operator carries the system at slow walking speeds of 0.5-1.0 m s^{-1}. During survey, spectra are analysed using a spectral windows method with stripping of interferences between radionuclide windows (Cresswell *et al.* 2006, Sanderson *et al.* 1994a, IAEA 1991). The data are processed to produce distribution maps of the activity concentration (Bq kg^{-1}) for naturally occurring radionuclides (^{40}K, ^{214}Bi in the ^{238}U decay series and ^{208}Tl in the ^{232}Th decay series), activity per unit area (kBq m^{-2}) for ^{137}Cs and other fallout nuclides and gamma dose rate (mGy a^{-1}). Waterfall plots of the gross and differential spectra, produced by subtracting a filtered rolling average background from each measurement (Cresswell & Sanderson 2009), are displayed to aid the user in identifying potential anomalies. Alarms can be triggered on count rates or significance thresholds. Analysis may also include least squares spectral fitting of natural components, and other data reduction techniques. Data outputs include the European Radiometric and Spectrometry (ERS) data format (Guillot 2003) to facilitate data exchange between organisations.

Two sites have been used to demonstrate the system capability, each survey using a pair of detector systems. The first was the Scottish Enterprise Technology Park (SETP) in East Kilbride, which is light commercial site occupied by the National Engineering Laboratory (NEL), Building Research Establishment, SUERC and several other technology companies. An accelerator mass spectrometry laboratory, with two accelerators, is located on the site. The Kelvin Laboratory, owned by the University of Glasgow Department of Physics and Astronomy, was located on the site and housed a linear accelerator that was closed down in the late 1980s. SUERC was originally established by a consortium of Scottish Universities in the early 1960s to operate a small research reactor which was shut down in 1995 with the reactor buildings removed in 2001/2 and the site was delicensed in 2008. There is an ongoing programme of renovation on the site, including demolition of old buildings and new construction along with landscaping operations. The site was surveyed in August 2009, with additional measurements taken in October 2010, with a high density pattern of survey lines approximately 1-2m apart covering approximately 5 ha.

The second site was the main campus of the University of Glasgow, and includes a variety of buildings of different ages, with extensive landscaping features. The 19th century buildings are mainly sandstone construction, with more modern buildings using brick and concrete. Within the buildings housing the Department of Physics and Astronomy there is a neutron source and isotope store. Sealed and unsealed radioactive materials have been used for research purposes in many buildings. The campus was surveyed in November 2010 in a low density pattern following the paths and roadways to cover the majority of the site.

3. Results

3.1 Calibration

Background measurements recorded from a plastic hulled boat on Loch Lomond produced count rates for the total gamma dose rate window (450-3000keV) of 5.0 ± 0.1 cps, corresponding to a dose rate of 0.03 mGy a^{-1}. These measurements included data collected with the systems on the back of an operator and with the systems as far from the operators as possible. There was no significant difference in the background rates due to activity within the body of the operator. Stripping matrices were determined from measurements with doped concrete calibration pads and anthropogenic sources. Estimates of conversion factors between stripped count rate and radionuclide concentration were derived from experimental and theoretical studies using similar detectors for in-situ gamma spectrometry in the early 1990s (Allyson 1994, Tyler 1994). For natural activity the calibration assumes a uniform activity distribution within the detector field of view, and for ^{137}Cs a shallow depth profile (2 g cm^{-2} mean mass depth) appropriate for Chernobyl fallout at that time. The gamma dose rate is proportional to the integral count in a scintillator above a threshold energy (Løvborg & Kirkegaard 1974, Mercier & Falguères 2007), in the region of 250-500 keV for NaI(Tl) detectors, for this work a 450 keV threshold was used, following the method of Murray *et al.* (1978).

Measurements on Caerlaverock merse, Dumfries and Galloway, were conducted using one of the detectors used in this work in a prototype configuration. An expanding hexagonal calibration pattern had been established on this site in 1992 (Sanderson *et.al.* 1992, Tyler *et.al*. 1996) and renewed in 1999. Three calibration sites were established in the outer Solway as part of the ECCOMAGS International Intercomparison Exercise (Sanderson *et al* 2003, 2004) in 2001. These were revisited with one of the systems used here, with a small number of soil cores taken to examine potential environmental change since initial sampling. Table 1 shows the activity concentrations at the centre points of these calibration patterns using the working calibration, compared with data from soil sampling. It can be seen that the working calibration for the backpack system produced activity concentration estimates for natural radionuclides that are 20-40% less than the soil core data. The ^{137}Cs activity per unit area calibration assumed a shallow depth profile, and significantly underestimates the activity per unit area of the deeply buried sediment on the salt marsh. Fluence calculations from ICRU (1994) for ^{137}Cs gamma rays from different depth profiles suggest that a correction factor of 2.34 be applied for the difference between the working calibration depth profile (2 g cm^{-2}, giving a fluence at 1m of 0.813 s^{-1}Bq^{-1})

and the measured depth profile on the terrestrial sites (approximately 10 g cm^{-2}, giving a fluence of 0.347 $^{-1}$Bq^{-1}). This still leaves a significant difference between the backpack and soil core data. For both natural activity and ^{137}Cs the difference between field measurements and soil samples is attributed to attenuation by the operator. This operator effect is being investigated further to better quantify the effect.

Typical uncertainties on natural activity concentrations for single 5-10s measurements are 20-40%, 30-80% and 30-70%, with detection limits of approximately 50, 10 and 3 Bq kg^{-1}, for ^{40}K, ^{214}Bi and ^{208}Tl respectively. Detection limits for near superficial ^{137}Cs are approximately 2 kBq m^{-2}, and for an unshielded source at 10m distance are estimated to be 5-10MBq.

3.2 Effect of Topographic Enclosure

Calibration is usually conducted using open field geometries, either theoretically or experimentally, with such calibrations being relatively simple to perform and to trace to independently verified measurements. However, such calibration will result in systematic variations where the topography varies from an open field, for example due to buildings. To investigate this effect, some further measurements were conducted in East Kilbride in the vicinity of the Technology Park in July 2011. These included several locations where footpaths pass under roads, producing topographies that vary from near open field to near fully enclosed over short distances.

Figure 1 shows the variation in natural activity concentration and dose rate at different positions within two of these enclosed features. It can be seen that the dose rates within the underpasses increased from 0.20-0.25 mGy a^{-1} to 0.40-0.50 mGy a^{-1}. There was a corresponding increase in ^{40}K activity concentration from approximately 150 Bq kg^{-1} to 450 Bq kg^{-1}. For one underpass, there was a single measurement with higher ^{214}Bi activity concentration, and there was some evidence of a small increase in ^{208}Tl activity concentration in the two underpasses.

Assuming similar compositions for the construction materials and natural geology and soils, this variation will be the result of the changing topographic enclosure. Coefficients to correct activity concentrations determined for an open field calibration for measurements within fully enclosed topographies can be estimated as the ratio of count rates (or calculated activity concentrations, which are proportional to count rate) for open field and enclosed geometries. These ratios are 151:440, 26:44 and 4.8:9.9, with corresponding geometrical correction coefficients of 0.34 ± 0.03, 0.58 ± 0.16 and 0.48 ± 0.07, for ^{40}K, ^{214}Bi and ^{208}Tl respectively. The topographic enclosure as a solid angle can be estimated from digital mapping products, and a suitable correction applied to the measured data, as demonstrated for data from the University of Glasgow below.

3.3 Site Surveys

Scottish Enterprise Technology Park

Maps of the distribution of natural activity concentrations, dose rate and ^{137}Cs activity per unit area for the Scottish Enterprise Technology Park surveys are shown in Figure 2. Approximately 5900 spectra were collected over a period of 4 days, with 9 hours survey time. Airborne survey data collected in 1990 (Sanderson *et al.* 1990) included lines over rural areas along the northern and southern edges of East Kilbride, at 3-6km from the Technology Park site. Interpolation of this data, using an inverse distance weighting algorithm, predicts activity concentrations for the natural radionuclides on the site of 140±15 Bq kg^{-1}, 8.5±1.0 Bq kg^{-1} and 6.0±1.0 Bq kg^{-1} for ^{40}K, ^{214}Bi and ^{208}Tl respectively. For ^{40}K and ^{214}Bi these correspond to approximately the first quartiles, and for ^{208}Tl the mean, of the distributions reported here. If the interpolated airborne data are representative of the underlying geology and soils, then construction materials have significantly enhanced the ^{40}K and ^{214}Bi activities without significantly increasing the ^{208}Tl series activity.

At the southern corner of the SUERC building there were a set of three doped concrete calibration pads which show clearly in the natural activity maps. Granite gravel chippings outside the Rankine Buildings and the corner of the two blocks of the SUERC building showed elevated ^{214}Bi, ^{208}Tl and ^{40}K activity. Near the former civil defence bunker (GWR) site to the north of the survey area enhanced ^{214}Bi and ^{208}Tl activity, without an enhancement in ^{40}K, is the result of industrial furnace slag used in the hard core associated with road construction. Laboratory analysis of a sample of this material gave activity concentrations of 120 ± 7 Bq kg^{-1} ^{40}K, 98 ± 5 Bq kg^{-1} ^{214}Bi, and 77.5 ± 1.2 Bq kg^{-1} ^{208}Tl. The backpack measurements at this location, averaged over all the material within the detector field of view, give activity concentration estimates of 194 ± 8 Bq kg^{-1} ^{40}K, 39 ± 3 Bq kg^{-1} ^{214}Bi, and 9.7 ± 0.4 Bq kg^{-1} ^{208}Tl (mean ± standard error on 52 measurements). The sample analysed has a lower ^{40}K concentration than the area where it was collected, and higher ^{214}Bi and ^{208}Tl concentrations. If the grab sample is representative of the TENORM material used in the construction of this road, then an estimate can be made of the amount of TENORM incorporated the road. For ^{214}Bi, the feature represents an increase of 22 ± 3 Bq kg^{-1} relative to the local background suggesting that 22 ± 4% of the road material is TENORM. For ^{208}Tl, the corresponding values are 5.4 ± 0.5 Bq kg^{-1} and 7 ± 1%. Thus, with these assumptions, TENORM comprises 5-25% of the hard core for this road feature.

The ^{137}Cs activity per unit area map shows where the soil has remained undisturbed since the 1986 Chernobyl accident, with activity retained in the wooded areas around the edge of the site. The grass area to the south of the two SUERC buildings retains Chernobyl ^{137}Cs with the exception of a large square area which marks the location of the decommissioned reactor building. The removal of this building has left no measurable anthropogenic activity on the site. The gamma ray dose rate reflects the natural activity.

University of Glasgow

Maps of the distribution of natural activity concentrations, dose rate and ^{137}Cs activity per unit area for the survey of the University of Glasgow campus are shown in Figure 3. Approximately 4400 spectra were collected over 2 days, with 3.5h survey time. The natural activity largely reflects the underlying geology and materials used for construction of roads and buildings. Outside the entrance to the Main Building facing University Avenue, and near the library, granite cobble stones show enhanced ^{214}Bi, ^{208}Tl and ^{40}K activity. A small feature immediately to the south of the main building is a granite bench near the flag pole.

To the west of the surveyed area, elevated ^{40}K activity is observed along a walkway between two parts of the Sir Graeme Davis Building, with activity concentrations of 800-900 Bq kg^{-1} ^{40}K, 40-100 Bq kg^{-1} ^{214}Bi and 10-15 Bq kg^{-1} ^{208}Tl recorded. These compare to activity concentrations of 200-250 Bq kg^{-1} ^{40}K, 15-30 Bq kg^{-1} ^{214}Bi and 3-5 Bq kg^{-1} ^{208}Tl to the north and south of this walkway in more open topographies. Application of the topographic correction factor estimated in section 3.2 to the measurements within the walkway reduce the ^{214}Bi and ^{208}Tl activity concentrations to values consistent with those nearby, however the corrected ^{40}K activity concentration would still be approximately 270-300 Bq kg^{-1}. The exterior of this building and paving consists of a polished dark stone, which appear to be enhanced in ^{40}K relative to the local environmental materials.

The strong feature in the Kelvin Building is associated with stored radionuclides and a neutron source in the Physics Department, and is the only significant anthropogenic contribution to the dose rate. The ^{137}Cs distribution reflects grass areas that have remained undisturbed since the 1986 Chernobyl accident, south of the main building towards Kelvingrove Park and on the lawn to the west of the main building in Professors Square. Some lower levels of ^{137}Cs are apparent in the quadrangles of the main building, possibly reflecting lower deposition of Chernobyl activity within the sheltered space enclosed by the building.

Discussion and Conclusions

The demonstration surveys presented here have shown the potential complexity of the radiation fields of built environments. Construction materials can have natural activity concentrations greater than the local geology, enhancing the natural activity, or have lower activity concentrations and shield the underlying geological signal. Some TENORM used as hard core for road construction was located within the Scottish Enterprise Technology Park (SETP). The system is clearly able to identify and locate TENORM, or other materials, that might present a radiological hazard and thus facilitate remedial action. Surveys of brown field sites prior to redevelopment or land contaminated by waste are entirely feasible.

The complexity of urban environments is an important issue in the use of radiometric surveys to locate anomalous radiation signals. In particular, the identification of TENORM would require more than a simple local enhancement of natural series activity, as this could be the result of construction materials. The material identified on the SETP site showed enhanced ^{214}Bi and ^{208}Tl activity concentration without a corresponding enhancement in ^{40}K activity concentration. Relationships of this sort between different natural activities would be needed to help identify TENORM.

The effect of topographic enclosure in built environments, with measurement geometries varying significantly from an open field calibration, is another significant factor. It has been shown that measurements in a tunnel increase measured activity concentrations for natural radionuclides by a factor of 0.3-0.6. A correction for such effects, which in principal could be applied in real time, would allow better discrimination between anomalous signals arising from changes in building materials or the presence of sources and topographic effects.

The work presented here has used a spectral windows approach to quantify individual radionuclides. Anomalies were identified by visual examination of the mapped outputs and individual spectra. Other methods to process data and identify anomalies are presented in the literature; including least squares fitting, subtraction of a time averaged background (Cresswell & Sanderson 2009, Kock *et al.* 2010), and statistical analysis of spectra to extract principle components (Dixon 2004). The effects of topographic enclosure and localised variations in construction materials described in this paper result in differences in the measured spectrum compared to open field geometries with uniformly distributed activity. It is expected that any method of spectral analysis will reproduce the effects described here. It is likely that any robust, semi-automatic source detection system used in urban areas will need to utilise multiple data analysis methods to cope with the particular challenges such environments pose.

The ability of the system to map low-level ^{137}Cs activity is also demonstrated in this work. This allows the identification of areas where the ground has been disturbed since the last deposition event. It should also be of benefit in studies using ^{137}Cs activity as an environmental tracer, for example in soil erosion assessments.

The survey work presented here has demonstrated the utility of the system to collect high density data for detailed studies of small areas, and lower density data generating an overview of larger areas. A single system can collect 300-600 spectra per hour, depending on integration time, with 3-4 line km per hour. The area sampling rate of 10^4-10^5 m^2 h^{-1} is lower than carborne (10^5 – 10^6 m^2 h^{-1}) or airborne (10^6 – 10^7 m^2 h^{-1}) systems, but still allows near total detailed coverage of 2-3ha in a full working day. The backpack system is ideally suited to detailed surveys of small areas, either as stand-alone investigations or to complement larger area surveys, for example in follow-up investigations of features observed from the air. The backpack system can locate small scale features of dimensions down to less than a metre, depending on sampling density, clearly delineating the extent of extended features. Such systems are suitable for applications where detailed spatial mapping of natural and anthropogenic radioactivity within relatively small areas would be beneficial.

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		^{137}Cs kBq m^{-2}	^{40}K Bq kg^{-1}	^{214}Bi Bq kg^{-1}	^{208}Tl Bq kg^{-1}
Caerlaverock Merse	Soil Samples April 1999	60.8 ± 9.8 (48.3 ± 7.8)	257 ± 6	10.9 ± 0.5	4.6 ± 0.2
	Backpack March 2009	9.51 ± 0.13	226 ± 8	5.3 ± 1.7	2.2 ± 0.2
Wigtown Merse	Soil Samples Nov 2001	224.7 ± 10.9 (174 ± 8)	409 ± 12	15.2 ± 0.4	7.8 ± 0.6
	Soil Samples Sept 2012	55 ± 1	299 ± 9	13.6 ± 0.9	6.7 ± 0.1
	Backpack Sept 2012	8.4 ± 0.1	275 ± 11	5.9 ± 1.4	5.0 ± 0.4
Inch Farm	Soil Samples Nov 2001	20.8 ± 1.0 (16.1 ± 0.8)	337 ± 18	19.9 ± 0.7	9.5 ± 1.2
	Soil Samples Sept 2012	14.6 ± 0.2	324 ± 9	23.9 ± 0.5	8.8 ± 0.1
	Backpack Sept 2012	3.5 ± 0.1	268 ± 8	14.7 ± 1.7	5.6 ± 0.4
Castle Kennedy	Soil Samples Nov 2001	6.30 ± 0.35 (4.9 ± 0.3)	272 ± 16	15.4 ± 1.3	6.0 ± 0.6
	Soil Samples Sept 2012	5.0 ± 0.2	215 ± 8	18.6 ± 0.6	5.9 ± 0.1
	Backpack Sept 2012	0.7 ± 0.1	169 ± 9	8.6 ± 1.6	3.7 ± 0.4

Table 1: Activity concentrations determined from measurements at Caerlaverock Merse calibration site in April 1999 and March 2009, and ECCOMAGS calibration sites in November 2001 and September 2012. Decay corrected activity concentrations for the 1999 and 2001 ^{137}Cs measurements are given in parentheses.

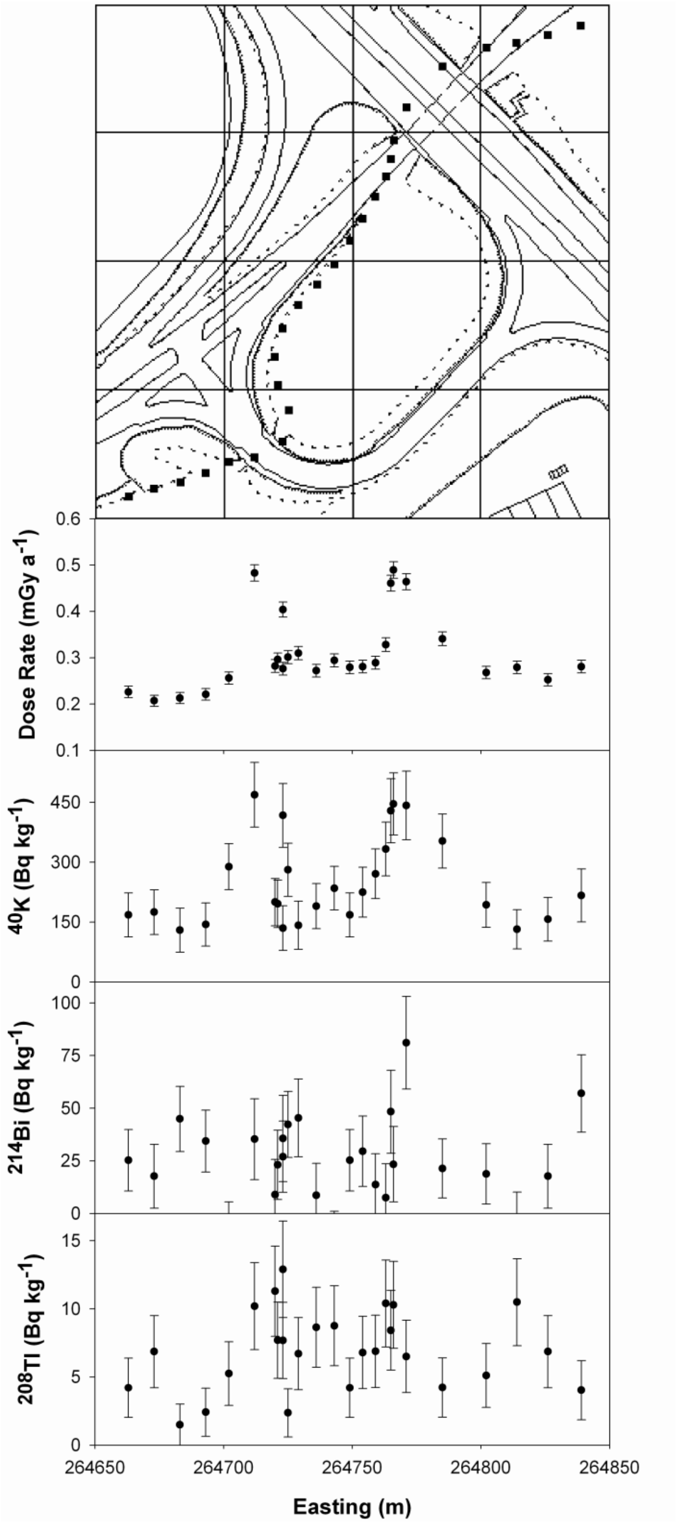

Figure 1: Measured dose rate and natural activity concentrations for a survey route passing through two underpasses, with the locations of the measured points.

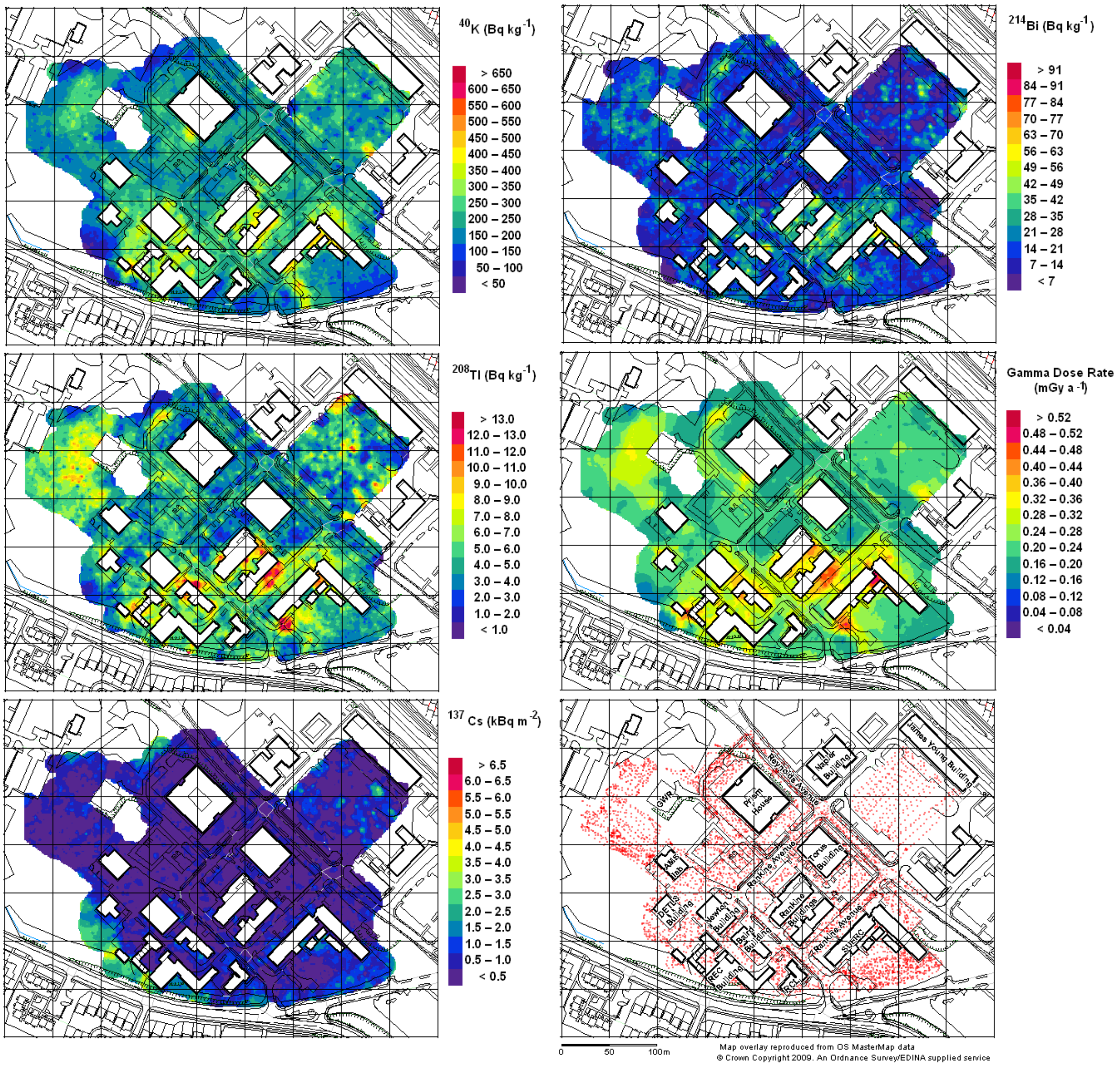

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Figure 2: Natural series (^{40}K, ^{214}Bi and ^{208}Tl), dose rate and ^{137}Cs activity distributions on the Scottish Enterprise Technology Park, with measurement locations shown.

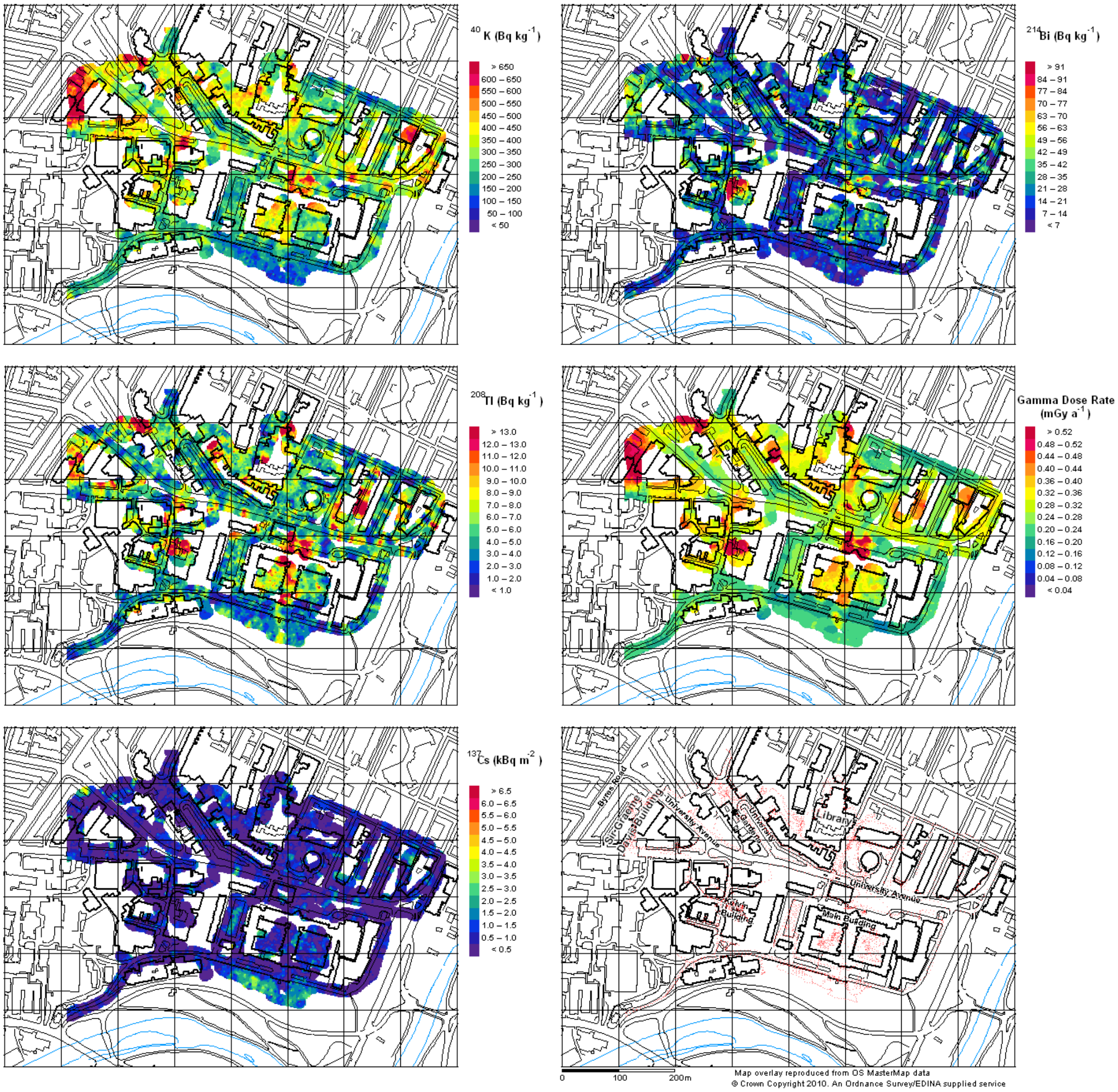

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Figure 3: Natural series (^{40}K, ^{214}Bi and ^{208}Tl), dose rate and ^{137}Cs activity distributions on the University of Glasgow campus, with measurement locations shown.