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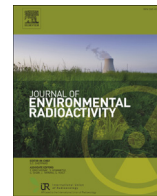
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The use of unmanned aerial systems for the mapping of legacy uranium mines



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ABSTRACT

Historical mining of uranium mineral veins within Cornwall, England, has resulted in a significant amount of legacy radiological contamination spread across numerous long disused mining sites. Factors including the poorly documented and aged condition of these sites as well as the highly localised nature of radioactivity limit the success of traditional survey methods. A newly developed terrain-independent unmanned aerial system [UAS] carrying an integrated gamma radiation mapping unit was used for the radiological characterisation of a single legacy mining site. Using this instrument to produce high-spatial-resolution maps, it was possible to determine the radiologically contaminated land areas and to rapidly identify and quantify the degree of contamination and its isotopic nature. The instrument was demonstrated to be a viable tool for the characterisation of similar sites worldwide.

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1. Introduction

Cornwall, south-west England, has a rich and expansive metallic mining heritage. The region has exploited its granite-derived high-grade mineral vein deposits for economic gain since pre-history, with its landscape having been heavily impacted as a result. Significant exploitation of these deposits was performed at the turn of the nineteenth century fuelled by the industrial revolution and the associated demand for minerals. The workings from this era have left a lasting mark on the land, and are recognised as important to the national heritage of the region thus supporting economic activity associated with tourism. One such mine, South Terras, actively produced high grade uranium and radium ores, from 1870 to 1930. The mine is situated near Tolgarrick Mill, 1.6 km south-west of the village of St Stephen, 22.5 km south-west of St. Austell. It is documented that radium arising from the operation was utilised by Marie Curie for her ground-breaking research on radioactivity.

Its purlieu lay in the valley of the River Fal, working a mineral lode associated with the southern portion of the metamorphic aureole surrounding the St. Austell granite, which is thought to run approximately half a mile north of the South Terras workings (Dines, 1956). The normal tin mineral lodes run east–south-east, but the

crosscourse lode containing the late stage, low temperature uranium minerals runs ten degrees west of north and carries nickel, cobalt, arsenic, bismuth and silver in addition to uranium (Smale, 1993).

During operation of the site, the primary ore mineral worked in the mine was pitchblende [UO₂–U₃O₈] but a secondary zone of mineral enrichment occurred in the upper levels of the mine consisting of torbernite [Cu(UO₂)₂(PO₄)₂·12H₂O] and autunite [Ca(UO₂)₂(PO₄)₂·10–12H₂O]. These two minerals provided the majority of uranium production at South Terras. The primary mineralisation phase is thought to have occurred at around 225 Ma and was subsequently followed by remobilisation and partial loss of radiogenic lead 60 Ma (Smale, 1993). Within the mine the ore grade was particularly high, with sections of the primary lode containing up to 30% uranium by weight. Once extracted, processing of raw material was conducted on-site in neighbouring buildings. Between the periods 1873–1881 and 1900–1910, the mines were documented to have produced 736 tons of uranium ore (Dines, 1956).

Owing to the absence of legislation regarding radiological contamination at the time of the workings, little occurred to control the amount of environmental pollution. As a result, with the eventual abandonment of the mine in 1927, a significant degree of radiological contamination existed on the site, which has previously received only limited characterisation, unpublished in the public domain.

The buildings associated with the mining and subsequent processing works exist to the north-west of the site, as outlined in a

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plan of the works produced by Ashwell in 1889 (Fig. 1). These buildings have since degraded following the overgrowth of woodland. The current overgrown state of the site presents a challenge to traditional characterisation methods, such as walk-overs, for mapping the distribution of residual contamination.

Airborne radiation monitoring has previously been conducted over the St Stephen region, with the most recent survey conducted as part of the Tellus South-West project (Beamish, 2014), led by the British Geological Survey (BGS). This survey, conducted in light-weight aircraft with an altitude of 56 to over 200 m at speeds typically between 60 and 70 m s⁻¹ using a 200 m survey line separation identified a radiation anomaly at the South Terra site. Typically, standard regional airborne radiometric surveys use bulky and heavy suitcase style detectors, carried by large helicopter or fixed-wing vehicles (Schwarz et al., 1995a,b; Sanderson et al., 1995; Mellander, 1995; Okuyama et al., 2008; Sanada and Torii, 2014; Sanada et al., 2014). However, challenges are presented with these systems when attempting to produce high spatial resolution data owing to the high altitudes at which they must operate; with

resolutions averaging upwards of 300 m (Sanderson et al., 1995). Helicopter or fixed-wing based systems are often expensive (both the aircraft and detector) and require well-trained pilots for their operation, therefore making such a technique unfeasible to characterise small sites. Here we present how a small unmanned aerial system (MacFarlane et al., 2014) operating at low altitude [<15 m] can be used to determine the extent of residual radiological contamination over a disused mining site, providing an accurate assessment of the distribution of radio-contamination, down to the metre scale. Such a tool is complementary to existing high altitude, lower resolution aerial surveys and slower ground-based methods. With increased resolution defining the minimum areas of contamination, the costs associated with the subsequent site remediation are significantly reduced. The ability to locate small (metre scale) regions of high activity, which should be avoided is essential to radiation protection, particularly for tourism.

Low-altitude characterisation of contamination has occurred following the accident at the Fukushima Daiichi Nuclear Power Plant in eastern Japan. Sanada and Torii (2014) and Sanada et al.

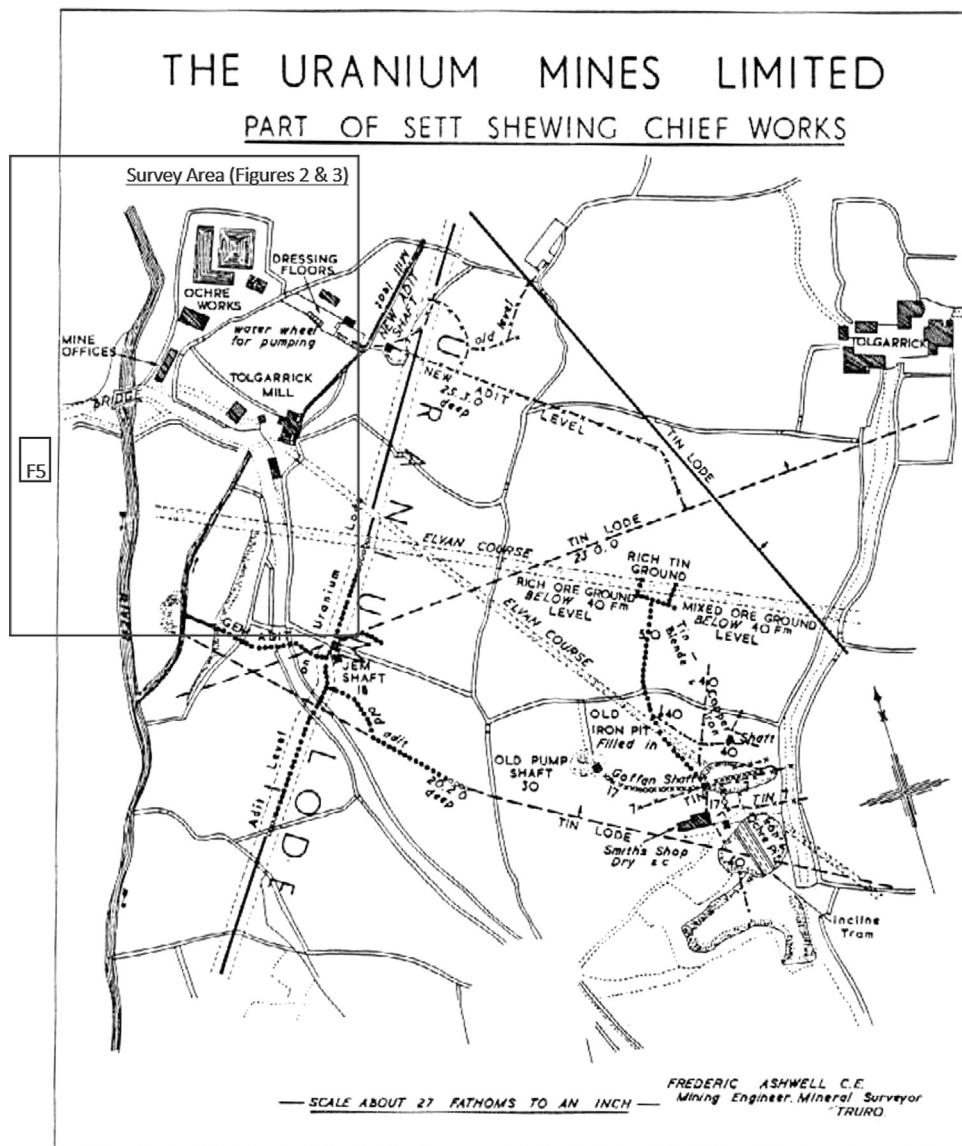


Fig. 1. Plan of the Uranium Mines property, redrawn from the original by F. Ashwell, which accompanied the prospectus issued by Uranium Mines Ltd in 1889 (C.R.O. X 116/42). The surveyed South Terras mining operations (Figs. 2 and 3) are identified in addition to the location of Fig. 5.

(2014) presented the use of a helicopter with associated sensing capability at an altitude of 80 m to produce distribution maps with a pixel size of 5 m, improving on coarser maps obtained by manned helicopters (MEXT, 2011). The feasibility of autonomous unmanned helicopters was first demonstrated earlier by Okuyama et al. (2008) to monitor contamination following a nuclear emergency.

2. Experimental

Development of the unmanned radiation detection system is detailed in MacFarlane et al. (2014) [<http://www.sciencedirect.com/science/article/pii/S0265931X14001489>]. The integrated mapping platform used for the present work was an AARM-X8 multi-rotor aerial vehicle supplied by ImiTec Limited, controlled by an Arducopter autopilot system. A high frequency (10 Hz) GPS module was used to rapidly and accurately determine system location; at each recorded location a spectrum of the energy of incoming incident radiation was recorded using a lightweight gamma-ray spectrometer. A small volume [100 mm³] uncollimated CZT coplanar-grid Kromek™ GR1 detector was used in this study. The energy range of the spectrometer, and that used during the study, was 30 keV to 3.0 MeV [U peak energies: 31.1–1001.0 keV, Th peak energies: 31.1–2615.0 keV], with an energy resolution of 2.0–2.5% FWHM @ 662 keV. Electronic noise on the detector was <10 keV FWHM (GR1, Kromek). Simultaneously, whilst measuring radiation intensity, a laser rangefinder system (AR2500, Acuity) reported the height of the device above the ground surface to a high degree of accuracy [10 mm at <100 m]. An Arduino Mega ADK microcontroller unit was used to combine the three converging data streams, sampling at 2 Hz. The data were stored locally on the instrument and concurrently transmitted to the user in real time [500 ms delay] as a 128 bit encrypted data stream to a remote base station. The sensors, consisting of the single-point rangefinder and gamma spectrometer, were mounted on a gimbaled stage such that they both remain directed normal to the surface, regardless of pitch of the aerial platform. The instrument was operated at a height of 5–15 m above ground level of the take-off location, determined by barometric pressure controlled autonomously – mapping out a pre-determined route, at an equivalent ground speed of 1.5 m s⁻¹.

The final survey map consisted of several individual survey flights with the data-sets of each combined. This resulted in an encompassing survey grid of the site (Fig. 2). The overall flight time to gather the approximate 300 m × 400 m area was 5 h.

Variation in the altitude used for mapping was in response to the topography of the area. The former mine site is encircled with gently sloping grassed fields that dip towards the workings. With the location of the past workings existing within a thickly vegetated copse. Regions without tree cover (to the north and west of the site) were surveyed at an altitude of 5 m, whereas the central area of the former works, covered extensively by forest, was surveyed at an altitude greater than the tallest tree, at 15 m. A regular survey grid over the site was not possible due to the contrasting altitudes used. The summation of multiple flights commencing from the site centre, produced a high density of data.

In the analysis software, radiation intensity was depicted by a scaled colour overlay. Maps were produced such that the colour depicted the radiological intensity as counts per second normalised to a height of 1 m, divided over the possible source area. Each of the data points consisted of; (i) the GPS latitude and longitude location of the device, (ii) the height above the measurement surface (determined by the on-board laser rangefinder) and (iii) a gamma spectrum for the region. This gamma spectrum was converted to a CPS value for the plotting of intensity. To produce the intensity map, each of the data points was normalised for height above surface,



Fig. 2. Satellite image overlain with the flight path of the aerial system. Shown here is the summation of multiple 30 min missions. Area identified in Fig. 1.

using the value produced by the rangefinder following an inverse square law of radiation dispersion originating from a point source. For previous airborne surveys collected at heights of 50–250 m (Minty, 1997; Minty et al., 1997), an exponential fall-off of radiation intensity was used to correct for detector height above the ground. Similar processing of the data obtained using the low altitude UAS at the South Terras site suggests that an inverse square correction is more accurate for measurements in the 5–15 m range.

In the ground-based surveys, the person holding the detector may intercept and attenuate as much as 30% of the incident gamma rays that would otherwise hit and be registered by the detector; a significant effect (Johns and Cunningham, 1983). Through using an aerial platform, this bodily attenuation is eliminated.

This corrected signal was assumed to be emitted uniformly from the entire area the measurement could be obtained from; an area determined by a factor of the height and numerical aperture of the detector, in addition to the uncertainty of the UAS position. Where data regions of radiological intensity over-lapped, these regions produced constructive interference. In this manner, by taking several hundred measurements over an area, the degree of radiological contamination at ground level could be determined. Work by Gillmore et al. (2001) previously detailed the levels of radon at the site. By comparison, the present work has neglected the contribution of radon to contamination levels measured.

Validation of data gathered by the UAS instrument was made using handheld measurements. This was gathered using the same CZT detector held at a height of 1 m above ground level. At each recorded point, a GPS position and gamma ray spectra were recorded.

3. Results and discussion

The radiation contamination map obtained from the UAS instrument is presented in Fig. 3. Elevated background radioactivity levels, in comparison to readings taken at localities away from the mine, are observed across the entirety of the South Terras site;

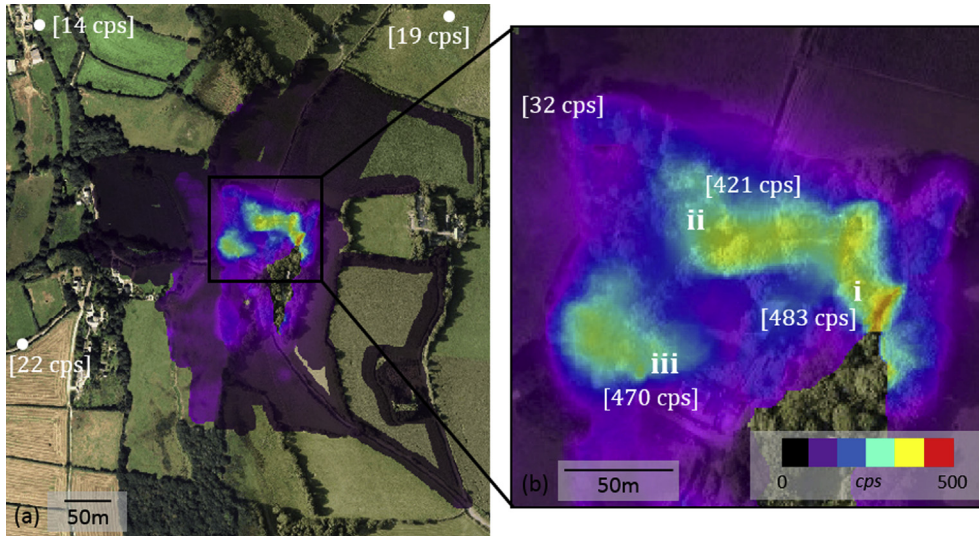


Fig. 3. Radiological map of the entire survey region (Figs. 1 and 2) produced using the aerial system (a) at a height of 5–15 m and (b) central area comprising three distinct hotspot localities.

however, there exist significant localised bodies of more intense radioactivity. In particular, there is a hotspot on the east of the site (i) corresponding to the location of the dressing floors (Fig. 1). Here ore material was separated from the mined country rock before being sent on for subsequent processing.

An additional anomaly located at the northern most point on the site (ii) also displays elevated levels of radiation. This is associated with the remaining legacy buildings and firing chimney; both of

which are still prominent features on site. These buildings (labelled as Ochre Works within Fig. 1) were used for the processing of ores, but unexpectedly – this locality appears less active than the nearby dressing floor.

Neighbouring the site entrance there exists a small spoil heap (iii) comprising waste material resulting from the separation process. This is shown clearly by the UAS instrument as the western most area of abnormally high radiation intensity. Recent works to

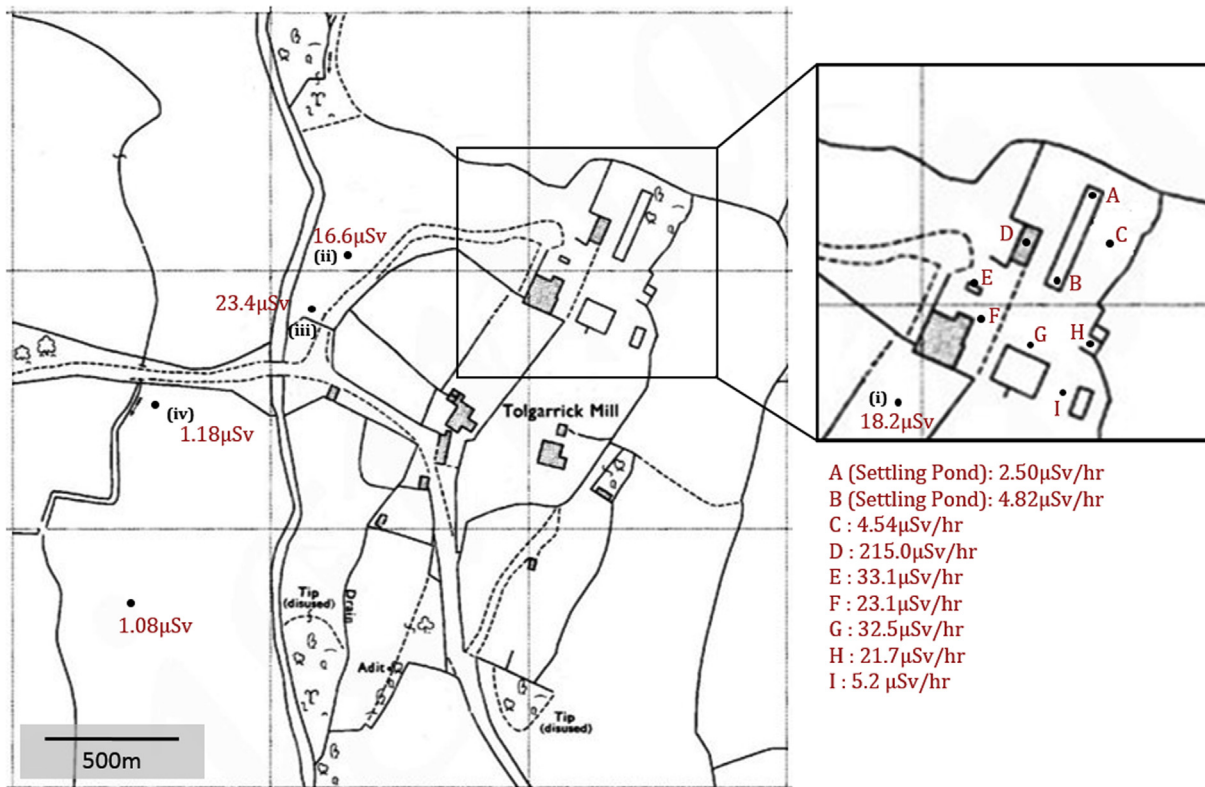


Fig. 4. Dose measurements taken across the South Terras survey area (Figs. 1 and 2). Localities (i–iv) referenced to those in Figs. 3 and 5. Adapted from the 1970 Ordnance Survey map of the area – © HM Stationery Office 2014.

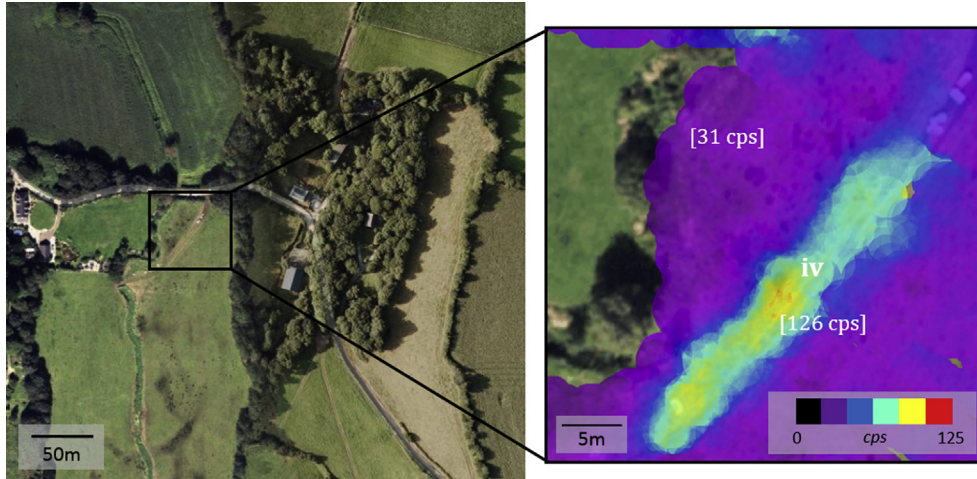


Fig. 5. Section of radiological map produced using the UAS (Fig. 1). Shown is a length of track in a neighbouring field to the mine workings, with elevated intensity over other agricultural land.

produce a farm storage area and nearby pathway has contributed to the increased distribution of elevated radioactivity, with construction material having likely originated from these nearby spoil heaps (Hooker et al. 1989; Read et al. 1991).

Measurements of counts, as well as dose rate, were made for validation across the South Terras site using a handheld SAM-940-3-G from Berkeley Nucleonics Corporation (BNC). The results are presented in Fig. 4. Comparatively high dose and count rates are seen to correlate with results obtained using the aerial system at localities (i)–(iv) (Figs. 3 and 5). High-dose rate spoil material near

the site entrance, despite existing in a small area – is clearly evident on the UAS map.

As well as detecting residual large area contamination resulting from former operations on the site, the UAS instrument was able to resolve radiation intensity down to the metre scale. Fig. 5 shows the south-west portion of the radiological map produced at the site, centred on an area of loose gravel track. Based on its radiological intensity and proximity to the mine workings, material to construct this path was likely obtained from the former spoil heaps that neighboured the mine.

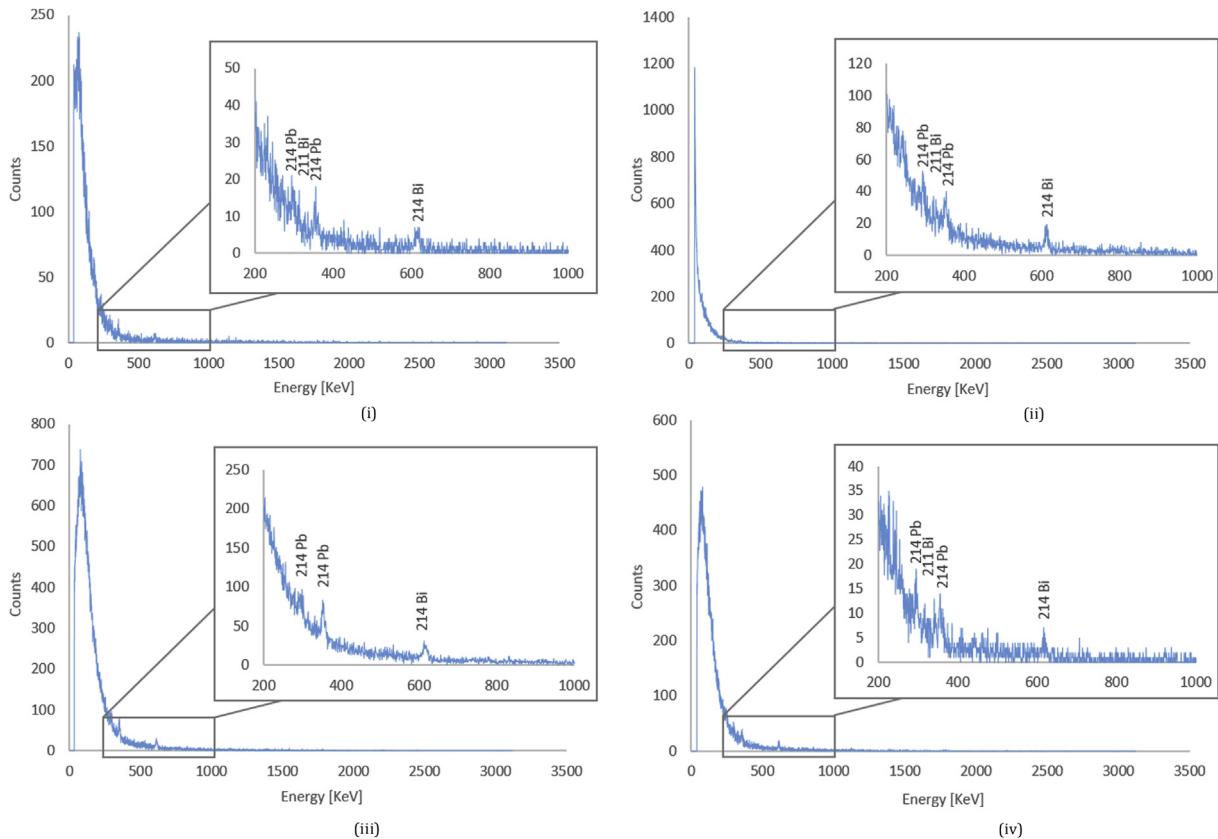


Fig. 6. Gamma spectrum obtained from each of the localities (i) to (iv), isotopic peaks are identified.

In addition to radiation intensity; mapping using a lightweight gamma-spectrometer enabled accurate isotopic fingerprinting of the region. Fig. 6 shows that in all cases (i, ii, iii and iv), the principle nuclides producing the gamma contamination are isotopes of lead and bismuth. As all four spectra are identical; it can be assumed that the contamination has arisen from the same source; the mining of uranium ore at the site.

4. Conclusions and future work

The system demonstrated here illustrates that small unmanned aerial systems can be utilised to provide high resolution radiation maps in the real-world environment. With this instrument it is possible to produce metre scale radiation intensity plots over a large area irrespective of terrain, at a much greater rate of collection than traditional methods. In addition to simplistic radiation intensity, the data gathered by the system can be used to determine the nature of the contamination through isotopic finger-printing. Such forensic analysis in this instance would allow for the targeted remediation of the site and other similar sites worldwide. Resolution of the system is high enough for sub-metre analysis.

Additional advantages of this low altitude unmanned aerial system include (i) a low cost of operation and upkeep with respect to fixed-wing surveys, (ii) rapid mobilisation to map contamination as well as (iii) the ability to undertake surveys completely autonomously. Current disadvantages of the system however, include a shorter flight time, a greater dependence on prevailing weather conditions and a smaller volume detector compared to higher altitude plane based systems.

Future work at the South Terras site will combine 3D scanning LiDAR with high spatial resolution radiation measurements to generate 3D maps of contaminant distribution. Further work will also seek to verify some of the other prominent hotspots identified by the Tellus South-West project.

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