

Drone-based investigations of uranium mining legacies: an airborne gamma spectrometry method to support, inspect, and monitor mine closure processes

B Preugschat *Federal Institute for Geosciences and Natural Resources, Germany*

C Kunze *IAF-Radioökologie GmbH, Germany*

B Wiens *Third Element Aviation GmbH, Germany*

S Altfelder *International Atomic Energy Agency, Austria*

Abstract

The rapid technical development of drones (UAV; unmanned aerial vehicle) in combination with improved and miniaturised measurement technology enables a cost-effective and fast deployment in post-mining areas. Drone-based geophysical methods can be used to assess post-mining areas to facilitate remediation planning, and to monitor them as part of long-term institutional control in the post-closure phase.

A case study of drone-based gamma spectrometric investigations is presented, using the example of legacies of former uranium mining. This type of legacy poses a direct threat to humans and the environment and is still present in the Central Asian countries of Kyrgyzstan, Kazakhstan, Uzbekistan and Tajikistan. In the DUB-GEM project (Development of a UAV-Based Gamma Spectrometry for the Exploration and Monitoring of Uranium Mining Legacies), a drone-based detector system was developed to investigate and monitor these legacies. Two scintillation detectors (CeBr₃, NaI) with different crystal volumes can be used alternately. The drone is a custom-built heavy lift system with a maximum take-off mass of 25 kg. The measurement data can be displayed in real time at a ground station. This allows locating hotspots during the survey and planning subsequent detailed measurements. The use of drone-based systems is particularly advantageous in mining regions that are difficult to access and potentially harmful for human health. This paper shows the results of drone-based gamma spectrometry investigations obtained during a measurement campaign in Central Asia in 2021.

The drone prototype developed in the project is also capable of carrying other sensors with a payload of up to 7 kg. In subsequent projects, a new department of the Federal Institute for Geosciences and Natural Resources (BGR) – Research and Development Centre for Post-Mining Areas (FEZB) – will investigate the post-mining areas of former lignite mining in Germany using further geophysical sensor technology.

Keywords: UAV, drone, gamma spectrometry, uranium mining legacies, post-mining areas, FEZB

1 Introduction

1.1 Background of uranium legacy sites in Central Asia

After the establishment of the newly independent states in Central Asia in the 1990s, many former uranium mining sites were abandoned without prior remediation. Today's uranium legacy sites (ULS) from former uranium mining still pose a threat to human health and the environment in some regions of Central Asia. The ULS are mainly located in mountainous regions (Figure 1). Due to geo-risks such as landslides, which can be triggered by seismic or heavy rainfall events, there is a permanent risk of displacement of radioactive and toxic material from the waste dumps and tailings (Li et al. 2021a). A particular hazard in the Ferghana Valley is the risk of radioactively contaminated material entering from the ULS located in Charkasar, Yangiabad, Shekafter, Mailuu Suu and Min-Kush. There are numerous rivers and other water bodies in the Ferghana

Valley, which are interconnected and make it an important agricultural hub in the region. Contamination with radioactive or toxic substances would lead to an ecological and economic disaster in this region and might also cause transboundary conflicts between riparian states (Li et al. 2021b).

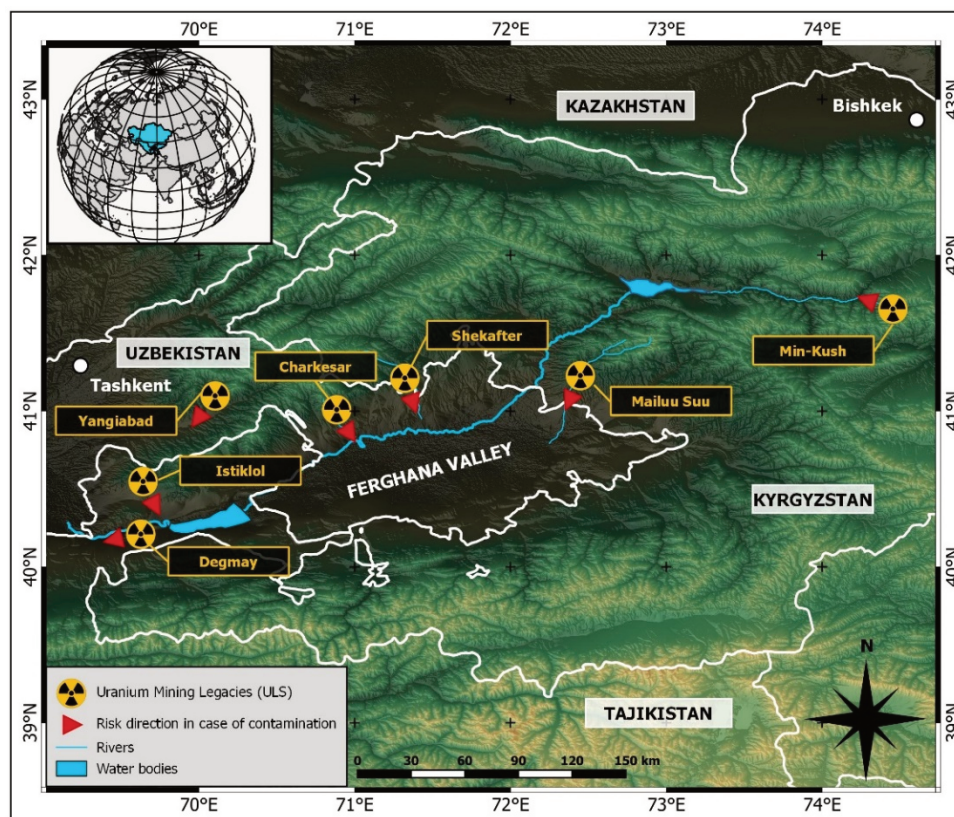


Figure 1 Uranium mining legacy sites around the Fergana Valley. Own representation based on IAEA (2021)

In order to be able to cope with the enormous tasks of remediating their ULS, countries of Central Asia have asked the international community to provide technical and financial support for the remediation work. Against this backdrop, decisions were taken at the international level in 2013 and 2018 in the UN General Conference on the urgent need for remediation of these sites by the international community. The consensus on the need for international technical assistance is an essential part of the Strategic Master Plan of the International Atomic Energy Agency's (IAEA) (2021) Coordination Group Uranium Legacy Sites. In 2016, on the initiative of the EU, the Environmental Remediation Account for Central Asia was established at the European Bank for Reconstruction and Development to finance the remediation of radioactively contaminated sites in Kyrgyzstan, Uzbekistan and Tajikistan.

In the DUB-GEM project (Development of a UAV-Based Gamma Spectrometry for the Exploration and Monitoring of Uranium Mining Legacies), funded by the German Federal Ministry of Education and Research (BMBF), a drone-based detector system is being developed by a German consortium led by the Federal Institute for Geosciences and Natural Resources (BGR), with IAF-Radioökologie GmbH and Third Element Aviation GmbH as consortium partners, to enable the exploration of contaminated sites from former uranium mining. The advantage of unmanned aerial vehicle (UAV)-based gamma spectrometry is the rapid characterisation of ULS.

1.2 Drone technology in mining areas

The opportunities for the application of drone-based methods for mining exploration are attracting increasing interest worldwide. The photogrammetry method is particularly prominent – for example, for measuring the volumes of heaps or for creating digital elevation models (Kim et al. 2022; Ren et al. 2019).

With the development of miniaturised detectors, a variety of other sensor systems can be used on drones to investigate different geoscientific and geotechnical issues (Coetzee & Larkin 2011; Furutani & Minami 2021; Simek 2010). In this context, it is particularly important to comply with legal regulations for drone operation, such as the maximum take-off weight (MTOM).

1.3 Reference to previous works

A detailed description of the logistical, technical and administrative challenges as well as a consideration of the spatial resolution and a comparison of the results of the gamma spectrometric measurements of Mailuu Suu with the analysis of soil samples can be found in the sources Kunze et al. (2022) and Preugschat et al. (2022). Results and findings from these papers are also used in the present work.

1.4 Objectives of the present work

The paper reviews the results of case studies to evaluate the broader application of drone-based gamma spectrometry in order to transfer the findings to similar areas of uranium mining. For this purpose, measurement data from former uranium tailings pound Culmützsch (Germany) and the waste dump WD3 in Mailuu Suu (Kyrgyzstan) are considered in the present work.

2 Drone-based measurements in mine closure processes

2.1 Scope of UAV for uranium mining sites

In the following, the possible applications of drone-based gamma spectrometry in mine closure processes are outlined.

2.1.1 *Support*

As a requirement for a remediated state of contaminated sites from uranium mining, maximum dose rates are usually defined that must not be exceeded immediately after remediation is completed and sustainably over the long-term. Usually, the dose rates are measured on foot using gamma detectors in backpacks or handheld devices. Using drone-based gamma spectrometry, the task of measuring can be completed more quickly – even in difficult terrain, such as on steep slopes. Drone-assisted gamma spectrometry can be used to ensure uniform coverages of contaminated sites and avoids the risk of missing out on hot spots.

2.1.2 *Inspection*

In contrast to monitoring, inspection is a one-off or infrequent examination. A drone-supported inspection is carried out, for example, at the end of the remediation measures in order to obtain a reference condition of the remediation body. Other possible applications of drone-based inspection are the detection of ‘forgotten’ contaminated sites and damage assessment after natural events, such as seismic and heavy rainfall events, which can cause landslides and/or erosion gullies and compromises the functionality of cover systems on radioactive mining and milling wastes.

2.1.3 *Monitoring*

During remediation, it is worthwhile to have at one’s disposal an efficient means of monitoring radiation levels on large areas. Since remediation works may last over several years, repeated flyover of drone-based gamma spectrometry systems provides useful operational information on the progress of the remediation works and helps identify areas where cover placement is insufficient or where covers may have been eroded prior to the completion of the works.

Post-remediation monitoring at remediated uranium mining sites is one of the long-term and aftercare tasks associated with this ULS. In fact, this is part of long-term stewardship and institutional control measures

(Kunze 2013). Regular drone-based gamma spectrometric monitoring can detect changes in the remediation body at an early stage and, if necessary, initiate remediation measures.

2.1.4 Consideration of benefits and constraints

In addition to the previously mentioned fields of application in uranium mining remediation, the use of drones has certain benefits and constraints. Therefore, a few of these reasons are listed below.

2.1.4.1 Benefits

- Simple and versatile deployable:
 - New technological developments simplify operation and automation.
 - There are many applications where drones with different sensors can be used in mining areas.
- Safety:
 - Minimisation of danger and health risks – for example, in mountainous, boggy, dust or radioactive environments for the technicians.
- Reproducibility:
 - High flight precision due to GPS/GNSS, different internal sensors (accelerometer, compass, inertial measurement unit [IMU]) and the possibility of RTK correction.
 - Pre-programmed flight paths can be flown again at any time for environmental monitoring.
- Economical:
 - The investigation of large areas is faster than walking or ground-based methods and less expensive than helicopter-based exploration methods.
 - The maintenance of drones is also less expensive and more ecological compared to other methods.

2.1.4.2 Constraints

- Legislative uncertainties:
 - Laws are different in every country; applying for a flight permission could be complex and time consuming.
- Safety:
 - The rotors and the LiPo batteries of drones can be dangerous.
- Weather:
 - Drone operation is weather dependent; drones cannot fly if the temperature is too high or too low, in heavy rain, snow or fog, or at high wind speeds, etc.
- Knowledge and skill:
 - Only trained pilots should operate drones.

Some of the mentioned constraints can be overcome by establishing a regular drone service. In general, it can be said that the use of drones is an efficient and cost-effective method for investigating uranium mining sites.

3 Methodology

A central component of the DUB-GEM project was the development of a drone detector system to complete the tasks of ULS investigation. Figure 2 shows the result of this work – the bespoke project drone in operation

at Mailuu Suu on waste dump WD3. The main technical features of the drone and the gamma spectrometer are described below.

The drone can fly in fully automatic mode along a pre-programmed route, whereby the pilot can always intervene in the flight by means of a remote control. Manual flight control in difficult terrain where flights are complicated to plan in advance can also be carried out. A camera integrated in the front of the drone and using a first-person view (FPV) system supports the pilot in this.

The detectors and the drone communicate during the measurements so that a data stream from the measuring device can be monitored in real time and visualised in the form of a 'heat map'. This makes it possible to identify hotspots during the flights and to sample them separately. Full data evaluation takes place in the post-flight phase.



Figure 2 Investigation site in Mailuu Suu, Kyrgyzstan. The DUB-GEM project drone during the survey flights

3.1 DUB-GEM project drone

In the following is a brief description of the characteristics of the UAV:

- Length of the body: 1.6 m.
- Overall dimensions with propellers: 2.2 m.
- MTOM: 25 kg.
- Maximum payload: 7 kg.
- Redundant propulsion system: eight engines on four drone boom.
- Operating temperature: 0°C to +45°C.
- Wind stability: 12 m/s (incl. wind gusts).

Assistance systems and sensors include the following:

- Global Navigation Satellite System (GNSS).
- Compass.
- Triple redundant IMU and gyro sensors.
- Laser range finder and/or radar.

- Temperature and pressure sensors.
- FPV camera.

Communication systems in the following frequency band:

- 868 MHz.
- 2.4 GHz (triple redundant).
- 4G, Universal Mobile Telecommunications System (UMTS-3G), 2G.
- 5.9 GHz.

The measurement data is transmitted in encrypted form via the mobile phone network to a ground station where it can be visualised in real time. The UAV flies with two LiPo battery packs simultaneously, each with 22 V at 30 Ah.

3.2 Scientific equipment: gamma spectrometer

Within the framework of the DUB-GEM project, two gamma spectrometers for measuring ionising radiation via the ULS were acquired: For the Medusa gamma spectrometer, two scintillation detectors (CeBr₃, CsI) with 700 ml crystal volume each are available, which can be used separately. In the innoRIID gamma spectrometer, two scintillation detectors (CeBr₃, NaI) with 350 ml and 100 ml crystal volume are integrated, which simultaneously measure the gamma radiation.

A comparison of the properties of the scintillation detectors is shown in Table 1.

Table 1 Comparison of the scintillation detectors used in the project

	Units	CeBr ₃ (Medusa)	CsI (Medusa)	NaI (innoRIID)	CeBr ₃ (innoRIID)
Crystal size	in	3 × 6	3 × 6	3 × 3	2 × 2
Crystal volume	ml	700	700	350	100
FWHM at 662 keV	%	<3.9	<8.6	<7.2	<4.2
Number of channels	–	2,048*	2,048*	1,024	1,024

*Alternative configurations with 300, 512, 1024 channels may be selected.

3.3 Data processing

Gamma spectra are recorded during the flights. From the gamma spectra, the specific activities of the decay series uranium-238 and thorium-232 as well as potassium-40 are determined by post-flight processing under the assumption of radioactive equilibrium and a number of other assumptions. Two different approaches are used for this: the classical window method (IAEA 2003) and the full spectrum analysis (Hendriks et al. 2001). The calculated specific activities are then presented in the form of activity distribution maps.

4 Survey areas

In the following, two applications of drone-based gamma spectrometry from mining are discussed in two use cases: on the one hand, the technology is to support remediation and, on the other hand, the procedure is used for post-remediation monitoring and inspection.

4.1 Drone-based gamma spectrometry during remediation

The first measurement area to be presented here is located in Culmitzsch, Thuringia, Germany. It is a former tailings impoundment that is currently being remediated by Wismut GmbH. The tailings are divided into two

basins: Basin B to the north and Basin A to the south. Aerial surveys were carried out in both tailings basins in 2020 and 2021. The remediation of Basin B is completed, and only Basin A is currently undergoing remediation. The Culmitzsch tailings pond is shown in Figure 3 based on surveys in 2021.

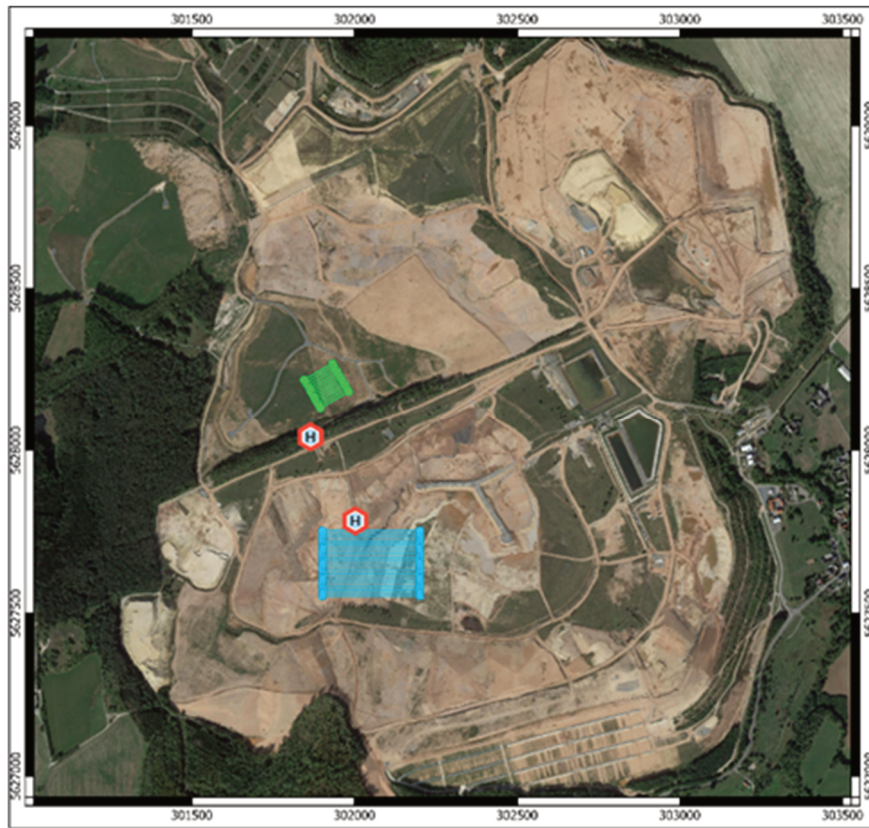


Figure 3 The Culmitzsch tailing pond in Thuringia, Germany, with both basins

4.2 Drone-based gamma spectrometry for monitoring of ULS

The second site under consideration is located in Mailuu Suu, Kyrgyzstan, and shown in Figure 4. Here, the fully remediated waste dump WD3 is investigated. The survey area was chosen so that part of it lies outside WD3 in order to have a reference area in the dataset.

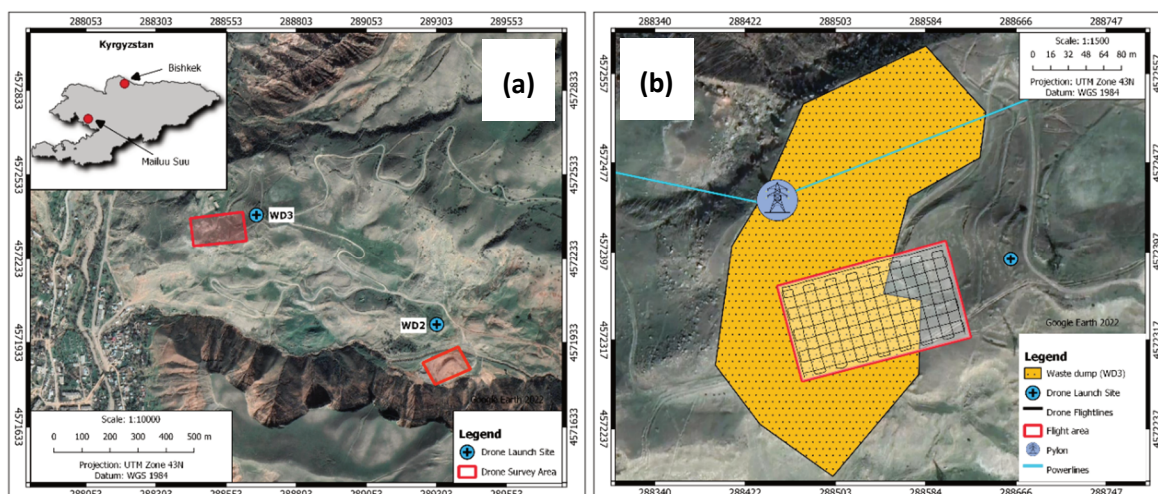


Figure 4 Investigation site in Mailuu Suu, Kyrgyzstan. (a) Investigation areas WD2 and WD3; (b) Site characteristics of investigation area WD3 (right)

5 Results and discussion

5.1 Drone survey in Germany

The results of the measurements and data processing from the Culmitzsch tailings are shown in Figure 5.

Strong similarity can be seen in the anomaly structures of the total count rate and the specific activity of uranium-238, so that the main component of the total count rates originates from the uranium series.

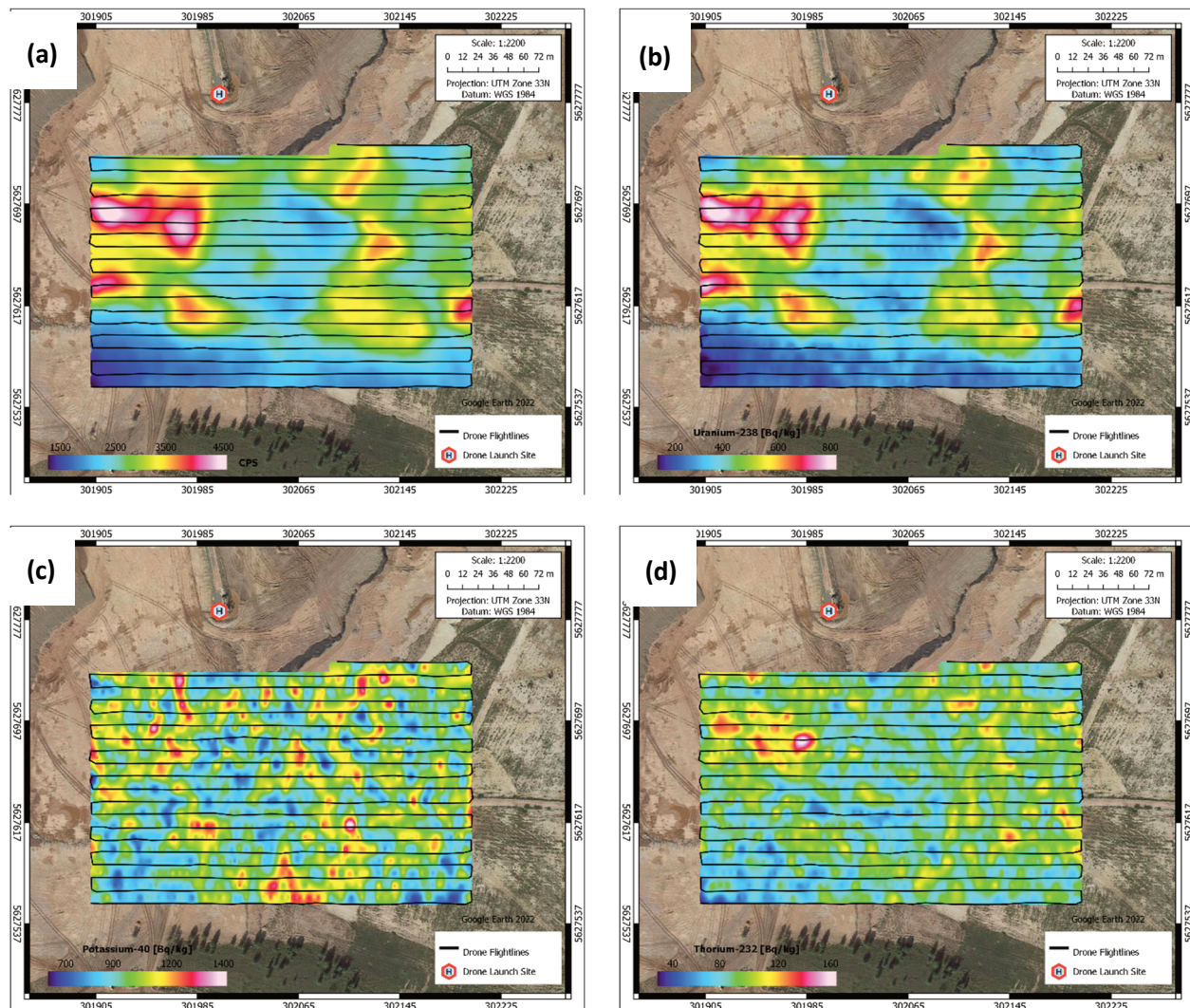


Figure 5 (a) Results of the data processing of the dataset from the Culmitzsch tailings pond. Total counts rate in cps; (b) Specific activities in Bq/kg for uranium; (c) Potassium; (d) Thorium

5.2 Drone survey in Kyrgyzstan

The results of the measurements and data processing from the waste dump WD3 in Mailuu Suu are shown in Figure 6

Strong similarity can be seen in the anomaly structures of the total count rate and the specific activity of uranium-238, so that the main component of the total count rates originates from the uranium series.

The anomalies clearly visible in Figure 6a and 6b may be due to bare waste rock material with no cover, which could also be observed in the field.

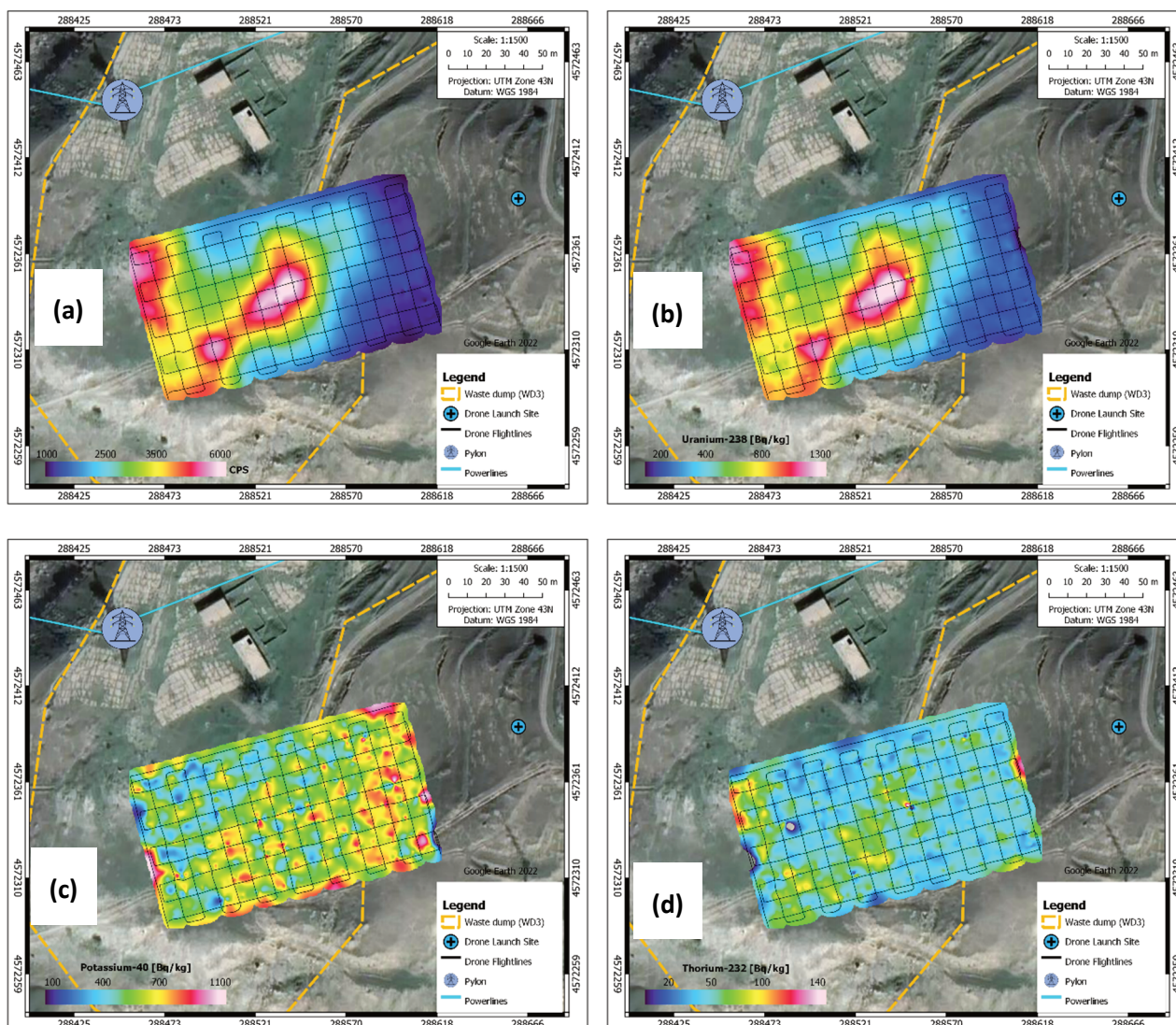


Figure 6 (a) Results of the data processing of the Mailuu Suu WD3 dataset. Total counts rate in cps; (b) Specific activities in Bq/kg for uranium; (c) Potassium; (d) Thorium

6 Conclusion

The drone-based detector system developed in the DUB-GEM project for the investigation of contaminated sites from former uranium mining was tested on different areas in Germany, Kyrgyzstan and Kazakhstan. The developed system provides reliable and reproducible values and is therefore suitable for meeting the requirements of the system.

The system can be used to determine contamination and the distribution of the specific activities of uranium-238, thorium-232 and potassium-40. In addition, the system can be used to find damaged or collapsed structures at remediated sites and to plan repair measures.

The method is suitable to accompany mining closure processes in the form of support, inspection and monitoring, especially repeated routine flights in the context of long-term institutional control.

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