remote sensing
MDPI

Article

Development of a UAV-Based Gamma Spectrometry System for Natural Radionuclides and Field Tests at Central Asian Uranium Legacy Sites

Christian Kunze [1,*], Benedikt Preugschat [2], Robert Arndt [1], Felix Kandzia [1], Benjamin Wiens [3] and Sven Altfelder [4]

[1] IAF-Radioökologie GmbH, Wilhelm-Rönsch-Str. 9, D-01454 Radeberg, Germany; arndt@iaf-dresden.de (R.A.); kandzia@iaf-dresden.de (F.K.)
[2] Federal Institute for Geosciences and Natural Resources (Bundesanstalt für Geowissenschaften und Rohstoffe, BGR), Stilleweg 2, D-30655 Hannover, Germany; benedikt.preugschat@bgr.de
[3] Third Element Aviation GmbH, Brönninghauser Str. 38, D-33729 Bielefeld, Germany; bw@3rd-element.com
[4] International Atomic Energy Agency, VIC, Wagramer Straße 5, A-1220 Vienna, Austria; s.altfelder@iaea.org
* Correspondence: kunze@iaf-dresden.de

Citation: Kunze, C.; Preugschat, B.; Arndt, R.; Kandzia, F.; Wiens, B.; Altfelder, S. Development of a UAV-Based Gamma Spectrometry System for Natural Radionuclides and Field Tests at Central Asian Uranium Legacy Sites. *Remote Sens.* **2022**, *14*, 2147. https://doi.org/10.3390/rs14092147

Academic Editor: Qinghua Guo

Received: 15 March 2022
Accepted: 27 April 2022
Published: 29 April 2022

Abstract: Uranium mining and processing had been widespread in Central Asia since the mid-1940s. However, with the establishment of the newly independent states in the 1990s, many of the former uranium mining and processing facilities and their associated wastes (dumps and tailings) were abandoned and have since posed a threat to the environment. The fact that the sites were left behind without proper remediation for a long time has led to the uncontrolled spread of radioactive and toxic contaminants in the environment due to landslides or flooding. Knowledge of the exact location of some waste facilities was lost as a result of social disruptions during the 1990s. In order to assess radiological risks and plan and implement adequate, sustainable, and environmental remediation measures, the radiological situation at the uranium legacy sites must be repeatedly mapped with the best possible accuracy in terms of both sensitivity and spatial resolution. In this paper, we present the experimental use of an unmanned aerial vehicle (UAV) equipped with gamma spectrometry systems as a novel tool for mapping, assessing, and monitoring radioactivity at sites affected by uranium mining and processing and other activities related to enhanced natural radioactivity. Special emphasis is put on the practical conditions of using UAV-based gamma spectrometry in an international context focusing on low- and medium-income countries. Challenges and opportunities of this technology are discussed, and its reliability and robustness under field conditions are critically reviewed. The most promising future application of the technology appears to be the radiological monitoring, institutional control, and quality assurance of legacy sites during and after environmental remediation. One-off administrative and logistical challenges of the technology are outweighed by the significant amount of time and cost saved once a UAV-based gamma spectrometry survey system is set up.

Keywords: unmanned aerial vehicles; gamma spectrometry; uranium legacy sites; radiation risk assessment; institutional control; long-term monitoring

1. Introduction

Airborne radiation surveys have long been in use to explore natural resources associated with increased radiation levels, to characterise radioactive contamination, or to locate and identify lost radioactive sources. In particular, the measurement of gamma radiation fields is a convenient and well-established method due to its long range of detection compared to other types of radiation (e.g., mobile alpha spectrometry [1]). In fact, airborne radiation surveys are part of an entire family of field-based mobile methods, including handheld, backpack-, pushcart- and automobile-based devices [2,3]. All of these techniques have been available for many decades and have therefore been extensively described in the literature. They may be complemented by other field methods, such as X-ray fluorescence (XRF) [4].

Among mobile radiation detection approaches, airborne techniques offer unique advantages such as large areas that can be covered; however, at the same time, they pose a number of challenges in their practical application, such as the need for careful planning and the trade-off of less spatial resolution than would be typically available from ground-based methods [5–7].

Apart from methods that simply record total count rates, more advanced systems provide spectral information, allowing to differentiate between decay series or, depending on their spectral resolution, individual radionuclides. While simple pulse counting is sufficient in many practical applications, such as the identification of a lost source of known radionuclide composition, spectral information is required if no prior information on the relevant nuclides is available and is a decisive factor for radiological characterisation. Well-known examples of mobile gamma spectrometry range from precision farming with the tractor-mounted, gamma spectrometry-based determination of K-40 and other natural nuclides to identify certain soil textures [8] to mineral exploration surveys using helicopter-borne gamma spectrometers [9].

Airborne gamma spectrometry is traditionally associated with manned helicopters flying at an altitude of the order of 100 m or more. The typical ground speed is several tens of meters per second. An early application of traditional airborne radiometric surveys were areas contaminated with mining waste at abandoned mines in the Witwatersrand, where gold- and uranium-bearing conglomerates were exploited [10]. More recently, the dynamic developments of unmanned aerial vehicles (UAV, or "drones") over the past decade have brought about the availability of entirely novel systems, combining the advantages of helicopters (efficient coverage of large areas) with low operating altitudes and, hence, better spatial resolution and a higher sensitivity of radiation anomalies. Yet challenges remain, and a number of issues must be taken into consideration when planning and carrying out UAV flight missions, as has been pointed out in detail by Connor et al. [11], Furutani et al. [12], and, most recently, by Marques et al. [3].

UAV-based systems are also a promising application that can be used to evaluate the long-term developments of the contamination situation along extended river systems and floodplains to estimate the environmental half-lives of certain radioactive contaminants [13].

In comparison to vehicle-, backpack-, or handheld-based systems, mounting gamma-sensitive detectors on a UAV avoids the attenuation of gamma radiation by the human body, the backpack carrying frame, or the vehicle. The attenuation depends on the specific constructive details and material of the carrier or vehicle, detector height above ground, and gamma ray energy. For example, if the detector is carried in a backpack, i.e., at a height of approximately one meter above ground, some authors [14] have established an attenuation of around 20–30% in such configurations, which is critical, given the relatively low specific activity of some wastes at uranium legacy sites (ULS). On the other hand, even for a gamma spectrometer mounted to a UAV, the attenuation of the spectrometer casing or, in some cases, the UAV frame, must be taken into consideration, albeit usually at a much lower level.

In the past, UAV-based gamma spectrometry has mainly focused on artificial radionuclides in the context of nuclear accidents such as Chernobyl (Ukraine) and, more recently, Fukushima (Japan) [12,15], on the search for lost/orphan sources such as Cs-137 or Co-60 [16] and other radioactive materials in industrial areas [17] and inside plant buildings [18], on airborne aerosol monitoring [19], or in the decommissioning of nuclear installations [20]. In the context of natural radionuclides, apart from geological exploration [21], several publications have been devoted to the investigation of contaminated areas left behind after uranium mining and processing activities [22,23].

The added value of the multi-sensor designs of UAVs for non-radioactive parameters, including multi-spectral imaging and thermal, dust, and gas sensors, has recently been pointed out [16,24]. Multi-drone applications have also been proposed [25], flying more complex patterns (e.g., spiral shapes) at different heights, with the proposed advantage of faster and more robust results as compared to single drones.

There is an increasing global interest in the assessment of past activities of uranium mining and processing as part of the nuclear fuel cycle, as well as in the control and mitigation of their impact. Sustainable uranium production, including the environmentally safe remediation of mine sites and associated waste facilities, are important prerequisites of the social license to operate the ongoing and future front-end activities of the nuclear fuel cycle. Central Asian countries formerly belonging to the Soviet Union are heavily affected by a substantial number of uranium legacy sites (ULSs) [26].

A peculiarity of ULSs in Central Asia, most prominently in Kyrgyzstan, is their vulnerability to erosion during floods and heavy rainfall and landslide-induced damage of waste containment structures. Increased seismic activity in the region exacerbate these risks [27,28]. Steep terrain, instable slopes, landslides, mudflows, and mining and processing waste facilities that are difficult to access are characteristic for many ULSs in Central Asia. In addition to the technical aspects of ULSs, there is a considerable transboundary conflict potentially arising from this unresolved issue [29,30].

There is an urgent need for efficient radiological site characterisation as a basis for planning remediation measures. After the completion of the environmental remediation of ULSs, a walk-away solution rarely exists [31]. Instead, post-remediation institutional control and monitoring are required to ensure that remediation objectives are sustainably met over the long term [32]. If damage of cover systems on radioactive waste facilities is detected, corrective measures must be implemented to prevent the uncontrolled spread of radioactive contamination into the environment [33], particularly on floodplains downstream of the legacy sites. It may also be argued that the monitoring of ULSs for signs of damage such as erosion of cover systems or contamination of large areas by radioactive waste could be achieved visually by a camera drone. Changes might manifest themselves by discoloration where a soil cover is eroded to the waste underneath, or by specific feature such as erosion gullies. However, visual inspection, e.g., by UAV-mounted cameras or satellite imaging, is often insufficient for the detection of evolving erosion or gradual radioactive contamination. An additional aspect to take into consideration when using cameras on a UAV is privacy and data protection. The use of cameras on a UAV is also restricted (or requires separate permits) in some legislations, including Central Asian countries. Finally, in the field of radiation safety, both radiation safety regulators and the concerned public will insist on radiation readings, instead of proxy information such as camera images.

Due to severe constraints to funding and human and technical resources, Central Asian countries have called upon the international community to support their endeavours to remediate ULSs, which is reflected in the resolutions of the United Nations and the International Atomic Energy Agency (IAEA), respectively [34,35]. The World Bank and the European Commission (EC) have invested substantially into remediation planning at a number of sites [36], and the Environmental Remediation Account (ERA) administrated by the European Bank for Reconstruction and Development (EBRD) is currently disbursing funds for environmental remediation of ULSs in Kyrgyzstan and Uzbekistan [37]. The international consensus on the need for international technical assistance is enshrined in the Strategic Master Plan (SMP) of the IAEA’s Coordination Group for Uranium Legacy Sites (CGULS), released in 2017 [38] and updated in 2021 [39]. One key requirement of the SMP [38] is to “further enhance the capabilities and capacities of Central Asia for long-term monitoring, surveillance and maintenance of remediated sites to ensure their continuing safety (i.e., post-remediation activities)”.

A promising method to meet this demand of Central Asian countries is a gamma spectrometry system mounted to a UAV. Such a system has been developed and tested in two field campaigns at ULSs in Kyrgyzstan and Kazakhstan within the scope of the project

Development of a UAV-Based Gamma spectrometry for the Exploration and Monitoring of Uranium Mining Legacies (DUB-GEM) [40–42]. As opposed to drone-based gamma surveys after radiological and nuclear emergencies, this project focuses on relatively low levels of radioactivity associated with former uranium mining and ore processing. For remediated sites, it focuses on the detection of rather small contamination spots that may serve as warning signs of damages in cover systems and contamination events in their early stages. This requires periodically repeated fly-overs of the remediated sites. It should also be noted that contamination below the surface, such as radionuclide plumes in the groundwater, cannot be detected by UAV-based or surface-based gamma spectrometry due to the significant shielding of the soil.

Significant cost advantages of in situ methods for site characterisation over laboratory-based methods have been highlighted by Monken-Fernandes [43], as well as the faster availability of the results of in situ characterisation programmes and the possibility to survey large areas instead of sampling selected spots. Spot-sampling may lead to non-representative results due to inhomogeneities. However, it should be noted that, in practice, UAV-based gamma spectrometry, too, requires a limited number of laboratory analyses of the materials in question for calibration purposes (ground truthing).

This paper intends to provide a practical perspective and to outline areas of applications where the maximum benefit can be extracted from UAV-based systems in the context of ULSs. In particular, it addresses the opportunities and limitations of such systems from the perspective of the environmental remediation of ULSs in remote areas of low- and medium-income countries.

This contribution attempts to tie in general observations (operational, logistics, and achievable spatial and spectral resolution) with the objectives, challenges, and achievements of an R&D project in the practical context of uranium legacy sites, which, apart from technical aspects, have a strong regulatory and political component. The latter cannot be disregarded when planning and implementing UAV surveys and developing a vision of future opportunities for UAV-based radiation monitoring systems. In the light of these goals, the remainder of this paper is structured as follows:

Section 2 discusses some conceptual considerations of the UAV-based gamma spectrometry system against the practical, technical, and administrative considerations previously discussed in the literature [3,11,12].

- Technical details and innovative aspects of the UAV and gamma spectrometers are described in Sections 3 and 4, respectively;
- Following the conceptual part, Section 6 presents the results of the survey flights, including maps of the activity distribution of the nuclides of the U-238, Th-232 series, and K-40, respectively, on selected ULSs in Mailuu Suu (Kyrgyzstan);
- Finally, Section 7 provides a summary and our main conclusions on the conditions under which ULS-based gamma spectrometry brings to bear its advantages most effectively.

This paper puts much emphasis on the practical conditions of the operation of UAV-based gamma spectrometers that appear to have received little attention in other publications but are important when assessing the merits and opportunities of this technology. The physical foundations of gamma spectrometry have been dealt with in detail in standard textbooks [44] and are not reiterated in this paper.

2. Conceptual Considerations of UAV-Based Gamma Spectrometry for ULS

2.1. Operation of UAV

UAV-based gamma detection systems combine the advantages of flying over the terrain of interest with the ability to fly at low altitudes, which significantly increases the efficiency of the gamma-counting device, while, at the same time, reduces the "visible" area (detector footprint) on the ground, thus improving the spatial resolution. Typical flight altitudes of helicopters are in the order of 100 m above ground level (AGL), which is at least in part due to legal requirements. By contrast, a UAV (such as the octocopter used in this project) can fly as low as several meters AGL. However, flight safety and practical considerations dictate that the altitude should not be lower than approximately 3 m. Even though some authors have reported lower altitudes [45], this is only possible if the terrain and any smaller objects such as trunks, small trees, and shrubs are well known. Another limitation is related to the downwash of the drone and the resulting dust generation from dry radioactive material. This may raise concerns over the potential radiation exposure of the flight crew, however can be easily avoided by choosing a take-off/landing pad in an off-site, uncontaminated area.

Favourable weather conditions are critical for UAV operations. At wind speeds significantly higher than 10 m/s and/or rain, drizzle, and fog, larger UAVs cannot be safely operated (the same limitation, albeit at higher wind speeds, applies to helicopters). A central requirement for each flight is a clear line of sight.

Topographic features such as steep slopes (tailings dams, waste rock dumps with slopes of natural angle of repose), which are inaccessible to ground-based systems and therefore, at first glance, lend themselves to investigation by UAVs, and may exhibit strong uphill thermal currents, making the control of a UAV very difficult. In this context, it is noted that larger drones are more robust during wind gusts due to their larger inertial mass. Field campaigns with UAVs may therefore require patience until weather conditions improve, which may turn out to be a logistical challenge, especially if they are strictly time-limited, for example, in international campaigns.

Vegetation is another important feature that needs to be taken into account when interpreting the gamma spectra, especially if there is a dense foliage of trees or dense and high vegetation on the ground. This has been discussed in [46], for example, but is not relevant in the scarce vegetation environments such as the sites in Central Asia where the test flights were carried out. Nevertheless, even scarce vegetation such as individual trees require a minimum flight altitude, as is discussed later on.

Battery life is practically the most significant limiting factor of UAV operation. Battery management requires careful planning to ensure that a maximum number of flights can be carried out during a field campaign. A sufficient number of batteries that can be charged and rotated between flights and the availability of fuel-powered generators ensure minimal downtime and maximum utilisation of daylight time. Solar cells mounted onto the UAV are an option to extend flight time significantly [47]; however, this requires an area that is typically only available on fixed-wing drones and for a rather low payload. The octocopter that has been developed in this project does not allow to use this option.

UAVs use GPS as part of the flight control system. However, if ULSs are located in steep and narrow valleys (such as the ULSs of Mailuu Suu, Kyrgyzstan, see below), GPS may not be as reliable as is commonly known from flatter topography. This may make flight planning a challenging task. The presence of different communication channels including radios, mobile phones of flight personnel and passers-by, mobile network (LTE) and other wireless data links between the UAV, gamma spectrometers, and ground station including First Person View (FPV) equipment may lead to difficulties in controlling the flight. Therefore, it is important to equip the UAV with fallback communication channels to ensure uninterrupted operation. The option of relay drones or a more extensive reliance on sensors that would relax the requirement to use visual line of sight (VLOS) as a primary control was not available in Central Asia, given the logistical and administrative effort that would have been required, and has therefore not been followed during the development of the UAV within this project.

Altitude control of UAVs is often (including this project) based on a laser rangefinder. However, operability of the rangefinder may be compromised if air humidity condenses on the lens. This has been observed when flying from a sunny place into a narrow, shady valley with higher relative humidity. In addition, the optical properties of the ground surface may not sufficiently reflect the laser beam so that the rangefinder does not return correct flight altitudes. These problems, which were encountered during the test flights in

Kyrgyzstan and Kazakhstan, are expected to be overcome by the replacement of laser rangefinders by radar (microwave) devices in forthcoming test flights.

Finally, fire safety is an issue, especially during dry summer periods, when the UAV is accidentally grounded on inaccessible areas (e.g., steep slopes or beyond a river course) and LiPo cells catch fire. The damage caused by dry grassland catching fire is incalculable, both from a material and reputational perspective.

From the above considerations it is clear that detailed prior knowledge of the site conditions and proper mission planning are crucial to successfully implement UAV missions and avoid costly failures, especially at sites with challenging and costly equipment logistics.

2.2. Spatial Resolution of UAV-Based Gamma Spectrometry

The lateral resolution of UAV-based gamma surveys is directly related to the flight altitude above ground level, the ground speed, and the contrast between radiation background and localised sources that are to be detected. If no collimator is used (which would significantly increase the necessary payload or decrease the flight time), significant contributions to the count rate originate from a radius on the ground that is of the order of the flight altitude [48]. Using rather simple mathematics, it can be shown that a point source on the surface can be identified against the background count rate of the detector if

$$v \ll \frac{(Ca_0)^2}{\dot{N}_0 h^3} \text{ and } v \ll \frac{h}{\tau}$$

where

C is the efficiency of the detector,

a is the activity of the source,

$\dot{N}_0$ is the background count rate,

v is the ground speed,

h is the flight altitude above ground, and

τ is the integration time window of the gamma spectrometer.

It can further be shown that, in order to detect the presence of two separate point sources of roughly the same activity at surface level, and if, for simplicity, the background count rate is neglected, for the ground speed v, the following condition must hold:

$$v \ll \frac{Ca_0}{50\,h}$$

with the symbols explained above. Separate point sources that do not meet this condition appear as a single hotspot. Note that this condition is only relevant if the spacing between the point sources is in the order of the flight altitude h. If they are much farther apart from each other, the situation turns into that of two fully independent single point sources (see above).

Detectors with directional sensitivity (e.g., equipped with collimators as proposed by Brewer [49]) may be a useful future development to improve spatial resolution. However, the additional payload that comes with a collimator significantly limits the available flight time and thus coverage rate. Miniature Compton cameras with directional sensitivity as described in [50,51] may be an alternative to improve directional sensitivity but lack energy resolution between the natural decay series and have therefore been excluded from this project.

However, the limited spatial resolution is not necessarily a critical drawback in the context of ULSs, since the average exposure on an extended area is the quantity of interest for site characterisation in the pre-remediation risk assessment phase (as opposed to, for example, lost point sources of high activity that must be identified with high precision on a scrap yard or in an industrial plant [17]). Exposure scenarios at ULSs typically include pastureland and the extended exposure of farmers, hikers, or pedestrians walking over or near contaminated areas. Remediation of such areas often involves the placement of inert covers to reduce gamma radiation and prevent the erosion of, and inadvertent access to, radioactively contaminated material. The information that triggers corrective measures after closure/remediation are enhanced radiation levels at the surface of remediated waste facilities. The exact lateral dimensions of cover damages are less critical initially and may be determined on the ground anyway. Therefore, localisation algorithms, which have been reviewed and compared in great detail in [11,49], for example, are not further discussed here.

An ambiguity that cannot be resolved by airborne techniques is the depth distribution of radioactive contamination. The limiting case of the purely surficial deposition of radioactivity (such as Cs-137 immediately after an accident, or deposition of a thin layer of radioactive tailings along river courses and on floodplains immediately after a dam failure) can be treated rather conveniently, since the model can assume an infinitely thin layer of radioactive material. Without prior information on the properties of the contamination, in situ gamma spectrometry (including UAV-based systems) is not capable of delivering a depth-resolved distribution of the specific activity in the ground. Advanced approaches such as the evaluation of differential peak heights of nuclides to infer the attenuation properties of soil or mine waste [52] are difficult, even when using HPGe detectors, but are not applicable to scintillation detectors due to their insufficient energy resolution. Ground truthing is required to provide the necessary additional input. Vegetation layer and ground roughness (especially at oblique angles) introduce the additional attenuation of the gamma radiation, as was pointed out in [53].

Moreover, the spectral resolution of individual nuclides within the U-238 and Th-232 decay series is not possible using scintillation detectors [44]. UAV-borne gamma scintillation spectrometers alone cannot therefore be used to differentiate between materials with radioactive equilibrium (approximately present in ore and waste rock) and those without (tailings, uranium concentrate). Complementary information is required, e.g., from historic site characterisation [54] or sampling of the objects in question (ground truthing) prior to, or after, the actual flight mission.

2.3. Logistical and Administrative Considerations

Even though a main argument for the use of UAVs is their advantages in inaccessible or difficult terrain over ground-based systems (backpack, pushcarts, cars), a reconnaissance walkover is required to at least identify smaller obstacles or features of the relief that may not be visible in a FPV system but are fatal when the UAV inadvertently hits them. Examples include high voltage power lines, poles, sign-posts, or tree trunks. Higher flight altitudes may help to avoid this problem, but this would come at the expense of spatial resolution and detector count rate. In practical surveys, this requires a reasonable trade-off between minimum flight altitude on one hand and the required resolution and sensitivity on the other. Even though internet-based aerial photographs such as Google Earth and high-resolution topographic maps that were produced in previous remediation design projects for several ULSs are available [36], the safe use of drones on unknown terrain requires experienced pilots and some kind of prior access for humans.

The operation of UAVs in remote areas requires the access of the flight team, including the UAV, batteries, and other equipment, which may be bulky. The take-off and landing patch must be reasonably close to the objects of interest (tailings, waste rock dumps, etc.), so that the available flight time is used to fly over the objects and is not wasted on accessing the objects from a distant base of operations. However, UAVs also allow for the bridging of obstacles that would otherwise limit site access, such as rivers or ravines. UAVs with higher payloads, such as the system used for the investigation of the ULSs described in this paper, require mobile, fuel-powered generators to charge the batteries between flights if a large number of test flights over an entire day is necessary to test different detector types and settings, variations of flight parameters, sensors, etc., as in this research project. For routine operation, if the necessary flight time is restricted to one survey flight per ULS object, a small number of pre-charged battery sets will be sufficient.

During field campaigns, the flight team and the equipment (tools, chargers, batteries, spectrometers, laptop/tablet computers for data evaluation) must be protected from the elements, for which tents, folding chairs, and tables are practical. Minivans and pickup trucks for personnel and equipment require trafficable access to the site or at least to a base of operations nearby with direct line of sight. Prior site reconnaissance and potential physical works are also necessary to provide such an access.

Aviation regulations are generally less stringent for UAVs than for helicopters. However, import restrictions on UAVs exist in several of the Central Asian countries in which this project has been implemented, and customs regulations in these countries are difficult to interpret. An additional barrier for the rapid and easy deployment of the UAV developed in this project is that it is regarded as a potential dual-use good that can be used for both civilian and military applications and therefore requires a special permit. Restrictions on air transport also apply to lithium polymer (LiPo) batteries, making delivery to the site challenging. Volatile customs regulations of some Central Asian countries add to the uncertainties.

Operators of large UAVs such as the one developed and used in this project must be highly qualified and experienced. In addition, regulations of Central Asian countries require that the pilot in command (PIC) is a citizen of the country in which the flight is carried out. Availability of the necessary specialists is limited. Therefore, for the flights in Kyrgyzstan and Kazakhstan within this project, nationals of Kyrgyzstan and Kazakhstan were trained using course materials in line with EASA rules, offered by the civil aviation authority of Germany [55] translated into Russian.

All technical data, preliminary flight plans, and other administrative information had to be submitted to the civil aviation authorities of Kyrgyzstan and Kazakhstan for approval. Even though there are significant political initiatives of Central Asian governments under the Center for Emergency Situations and Disaster Risk Reduction that are supposed to simplify the use of UAVs in the management of emergency situations [56], the dynamically evolving regulatory frameworks of some Central Asian countries added to the administrative burden of logistics and flight planning.

It should also be borne in mind that a UAV of 25 kg maximum take-off mass (MTOM) generates considerable noise, which may attract public attention even in remote locations. This may be critical, as it often reinforces the (unwarranted) impression of the local population that ULSs are very dangerous and therefore advanced technology is needed to tackle the problem. This impression would be counter-productive, given that a public environment in which reliable information is scarce and official sources are not entirely trusted by the local population [57,58]. In recent years, significant effort has been put into developing strategies involving the general public of all Central Asian countries in the remediation of ULS [36]. One of the key components is to disseminate reliable facts and monitoring results of the ULSs, and to explain these data in a plain, accessible language to local residents. Dissemination of basic information on new and previously unseen technology deployed at the ULSs such as UAVs need to be included in the protocol of flight preparation. More importantly, this information must be integrated into the wider scope of local stakeholder involvement over several years, from site characterisation to the implementation phase of remediation measures into the long-term surveillance and monitoring of the ULSs.

Prior to the logistically complex campaign of test flights in Central Asia, the UAV-based gamma spectrometers were tested at various uranium legacy sites of Wismut GmbH [59] and a thorium legacy site in Oranienburg near Berlin [60,61], both conveniently located in Germany. This turned out to be an indispensable experience, as it allowed the developer team of both the UAV and the gamma spectrometers to iron out teething problems before embarking on the more challenging campaign in Central Asia.

3. Description of the UAV Developed in the Project

One of the key trade-offs in UAV development is that between empty weight, the weight of flight batteries, payload, and the achievable flight time. The UAV design was driven by the objective to scale up production according to industrial standards, using high-quality, light-weight materials common in manned aviation, and with significant effort put into weight optimization. Within the DUB-GEM R&D project, a number of design options were considered, followed by a selection of the configuration that was then further optimised. Options that were compared, and the associated decision criteria, include the following:

- Battery powered vs. combustion engines: Combustion engines were initially investigated as potential alternative to battery powered systems but were discarded early in the development process due to restrictions on transportation and fire safety, especially in a crash scenario and dual-use concerns (long flight times). Electrical motors are superior to combustion engines in terms of reliability and maintenance requirements. In addition, combustion engines were not considered environmentally friendly;
- Fixed wing vs. copter design: Multi-copter, Vertical Take-Off and Landing (VTOL) systems and fixed-wing systems have been considered during the conceptual phase. However, VTLO and fixed-wing systems are not well suited to very low ground speed and to hovering in order to investigate individual radiation hot spots on the ground, which was one of the key objectives of this project;
- Quadrocopter vs. hexacopter vs. octocopter: Based on the experience of the UAV developer team, octocopters provide the best redundancy, therefore this option was eventually preferred. Each of the four arms carries two coaxial motors, so that only four arms are necessary and frame mass is minimised.

In the following, the technical characteristics of the final, bespoke design of the UAV are briefly summarised:

- Length of the body: 1.6 m;
- Overall dimensions with propellers: 2.2 m;
- MTOM: 25 kg;
- Maximum payload: 7 kg;
- Redundant propulsion systems;
- 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 inertial measurement unit (IMU) and gyro sensors;
- Laser range finder (LRF);
- Temperature and pressure sensors;
- First person view (FPV) camera.

Communication systems operate in the following frequency bands:

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

Encrypted payload data may be transmitted via UMTS to the ground station (laptop/tablet computer).

Several battery packs, each consisting of two 22 V/30 Ah LiPo batteries, were rotated between flights and charged on site using a 2000 W mobile generator.

The UAV is aerodynamically optimized to operate in forward flight operations, see Figure 1. This enables efficient power consumption during flight operation. Standard UAV systems are designed to fly equally in each direction; however, for this special use case, the efficiency was increased with an optimized system layout.

Figure 1. View of the UAV: note the gamma spectrometer mounted from below to the drone.

It was prepared for two payload integration options to accommodate gamma spectrometer from different manufacturers, though was not restricted to gamma spectrometers. The payload integration system can also accommodate other sensor types.

4. Description of the Gamma Spectrometers

4.1. Detectors Used

Two detector systems have been developed in this project: A $CeBr_3$ scintillation detector manufactured by Medusa (Groningen, The Netherlands) and a twin detector consisting of a smaller NaI detector and a $CeBr_3$ provided by innoRIID (Grevenbroich, Germany). A recent comparative survey of scintillator crystal materials is given in [62].

The main purpose of testing the innoRIID twin detector was to compare the benefits of better spectral resolution of the $CeBr_3$ crystal, compared with a NaI system, and to quantitatively assess whether the larger volume (and associated higher cost) of the $CeBr_3$ crystal of the Medusa system, compared with the smaller innoRIID system, is warranted when flying over ULSs. Further on in this paper, we restrict the discussion to the results obtained with the Medusa $CeBr_3$ detector.

The choice of a large crystal in the Medusa gamma spectrometer was derived from many years of experience in airborne gamma spectrometry at BGR. It provides a sufficiently high counting rate and thus improves the statistics. This is especially advantageous for weak sources or high flight speeds.

In all detectors, time steps for data acquisition were 1 s. The time period for averaging the count rates can be varied in the spectrum evaluation procedure, see below.

Comparing the crystal options shown in Table 1, it has been found that neither the slightly better spectral resolution of the $CeBr_3$ crystal of the innoRIID detector, nor the larger NaI crystal of the Medusa system, add substantial value for the specific requirements of investigating uranium legacy sites, and that a small, rather inexpensive NaI crystal, such as the one in the innoRIID system, is fully sufficient. This has important implications for the future design of UAV-based systems which may be much lighter, cost-effective, and easier to operate than the current system. It is noted that none of the tested scintillation detectors are capable of identifying individual nuclides within the U-238 and Th-232 decay series, respectively. In fact, the relevant, detectable gamma emitters are Bi-214 and Ac-228/Tl-208, respectively.

Table 1. Detector systems used in the DUB-GEM project.

	$CeBr_3$ (Medusa)	**NaI (innoRIID)**	**$CeBr_3$ (innoRIID)**
Crystal dimensions (inches)	3 × 6	3 × 3	2 × 2
Crystal volume (cm^3)	700	350	100
FWHM at 662 keV (%)	<3.9	<7.2	<4.2
Number of spectral channels	2048 *	1024	1024

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

4.2. Calibration

Detector calibration encompasses both energy and efficiency calibration [7], and both are considered separately in the following:

The FSA implemented in the Medusa spectrometer allows an automatic energy calibration. The energy positions of spectral peaks are adjusted so that no separate calibration procedure is required, see Hendricks et al. for details [63]. In addition, the Medusa detector used in this project has been fully characterised using a Monte Carlo model and Medusa's "Stonehenge" calibration set-up [64].

By contrast, the twin-crystal innoRIID detector (see Table 1) had to be energy-calibrated manually after every change of batteries using a potassium chloride (KCl) specimen. The calibration takes approximately 10 min and has turned out to be an inconvenient interruption of the pre-flight procedure. Post-flight recalibration of the spectra is a potential workaround if time is of the essence (e.g., approaching bad weather front).

Efficiency calibration of the gamma spectrometers was carried out on permanent square-shaped concrete calibration pads of an area of 400 m^2, located at the former uranium mine site of Reust (Thuringia, Germany) and made available by Wismut GmbH (see also [65] for a comprehensive review of calibration pads).

Both energy and efficiency calibration of the Medusa spectrometer have proved to be very robust and reliable. Calibration parameters were repeatedly verified using sources in the laboratory and in the field, repeatedly flying over the Wismut calibration pads described above. Even during a crash of the UAV from an altitude of approximately 10 m with the Medusa spectrometer attached, the in-house check carried out by Medusa confirmed that the detector parameters had remained unchanged.

5. Data Processing and Presentation of Results

Data processing is implemented at two levels:

- Total count rates of the spectrometer are transmitted by the UAV in real time to generate a live "radiation heatmap" during the flight operation. This requires only a limited bandwidth of the data link between the operator and the UAV-based gamma detector, however allows the operator to focus on areas with high activity during the flight (e.g., by hovering over the hot spot);
- Due to bandwidth limitations of the data link, the detailed spectrum analysis is carried out after landing. During the flight, raw spectra, GPS data, and time stamps are recorded on a USB device which can be removed from the spectrometer and readout and processed by a laptop computer.

The spectrum analysis uses the window method and, alternatively, the full spectrum analysis (FSA) method (see [7] and references therein for details of both methods). The model that calculates the specific activity from the count rates in each range of the spectrum has been calibrated using the energy-dependent detector efficiency. The maps of the specific activity shown in Section 6 below were all produced with the full spectrum method. They are based on the following assumptions incorporated into the calculation model of the Medusa gamma spectrometer [63,66]:

- Homogeneous vertical extension of the specific activity to infinite depth;
- Homogeneous lateral extension of the specific activity within the detector footprint;
- Bulk density of the soil of 2.32 g/cm^3;
- Secular equilibrium of all nuclides within the U-238 and Th-232 decay chains, respectively.

The software developed by BGR and applied in producing the maps shown in Section 6 uses the spline interpolation method [67]. The mathematical procedure to calculate the specific activity is based on the algorithm very recently developed by van der Veeke and co-workers and has been described in much detail in [68]. The algorithm has been devised in a way that the resulting radionuclide concentrations at every height agree with the radionuclide concentration measured on the ground. This required an altitude correction that not only accounts for a larger distance between the source on the ground, but also makes sure that the interpolated activity plots do not show an apparent precision that is not physically possible.

Obviously, some of the model assumptions may not hold true under real conditions. For example, the equilibrium of the uranium decay chain is severely disturbed in some materials, as it turned out to be for the ULS in Mailuu Suu (see Section 6 below). However, the assumptions are a reasonable point of departure to estimate the specific activity of the waste material investigated to an order of magnitude, as is shown in the example given in Section 6.

Vegetation is negligible at the test sites in Central Asia, as discussed in Section 6 below. However, if there was non-negligible vegetation, a correction such as the formulae derived by Ahl and Bieber [46] must then be applied, using parameters depending on site-specific vegetation patterns.

Finally, the graphic representation of the interpolated data has a great impact on the usefulness of the results. Colour-coded maps of the elevated activities of radionuclides or decay series against the background have proven more convenient and intuitive for rapid evaluation than the "peak representation" that was used in [69], for example, and allows easier overlaying of the results with other thematic maps, e.g., topography, delineation of ULS waste facilities, etc.

Amestoy et al. [70] have pointed out that environmental parameters, mainly rainfall and soil moisture, have an effect on the count rate in the U, Th, and K windows, albeit to varying degrees. Indeed, variations of the count rates between periods with different external conditions may be significant. For example, after rainfall events, the washout of gamma-emitting radon progeny (mainly Bi-214) leads to an increase in gamma radiation from the ground and thus to an overestimation of the specific activity of nuclides from the uranium decay series. For example, Amestoy et al. [70] have determined that, on average, the activity of uranium series nuclides is overestimated by 30% at a real specific activity of U-238 of 38.9 Bq/kg. Due to the short half-life of gamma-emitting radon daughters, this effect is most relevant within a few hours after the rainfall episode. After the increase in gamma radiation during a precipitation event, the reverse effect is often observed several hours later and is explained by the transport of radon dissolved in infiltrating water into greater soil depths [71].

An additional source of uncertainty is moist or water-saturated soil. It has a higher density and hence a higher absorption of gamma radiation. Therefore, in lower-lying areas and depressions where water accumulates or is perched, the interpretation of airborne gamma data becomes rather difficult if no additional information is available.

At ULSs, the uranium content in the ground is usually much higher (e.g., in the order of 1000 Bq/kg for waste rock material), so that the washout effect is less pronounced in relative terms. Nevertheless, this needs to be taken into account when interpreting the time series of consecutive surveys, especially since the erosion patterns of waste cover systems or areal contamination processes involve small changes of the gamma radiation in their initial stages, which must be reliably detected.

Apart from the washout of radon progeny, the dynamics of radon in the soil under the influence of temperature and atmospheric pressure fluctuation, precipitation, and wind speed is an important process for the gamma radiation from the ground. A comprehensive theoretical treatment of the connection between meteorological parameters and radon concentrations in the soil was developed by Schubert and Schulz [72].

Therefore, some correction is required to account for additional gamma radiation due to the dynamics of radon progeny under changing weather conditions to make survey results comparable. These corrections require more knowledge on soil characteristics and meteorological conditions which are highly complex (see discussion in [73]) and will have to be collected during future research.

However, no absolute values are of interest here except for the relative activity levels along the flight path. During the flight duration of much less than an hour, neither meteorological conditions nor soil moisture changed significantly if at all.

6. Field Tests of the UAV-Based Gamma Spectrometry System in Central Asia

6.1. Investigation Area

Test flights were carried out at the following locations:

- Mailuu Suu in southern Kyrgyzstan;
- Muzbel' in southern Kazakhstan, close to the border with Kyrgyzstan, occasionally also referred to as Kurday, where the country's uranium mining activities started in the 1950s and ended in 1965 [74–76].

This section focuses on Mailuu Suu to discuss the results of the UAV-borne gamma spectrometry. Uranium mining and ore processing took place in Mailuu Suu between 1946 and 1968. An overview of the Mailuu Suu ULS with more than 30 waste rock dumps and more than 20 tailings management facilities is provided in [77,78]. The number of legacy objects is difficult to ascertain, since some are hard to identify after mining activities ceased 50 years ago. The environmental impacts of radioactive waste facilities are exacerbated by the strong seismic activity of the region [79], potentially leading to the damage of waste containment structures and uncontrolled release of radioactive wastes into the Mailuu Suu River and its tributaries and consequently leading to transboundary impacts in Uzbekistan, approximately 30 km downstream from the Mailuu Suu ULS.

The following ULS at Mailuu Suu were investigated during the flight campaign:

- Waste rock dump No. 2 (WD2) in the Kulmensay valley;
- Waste rock dump No. 3 (WD3) northwest of dump No. 2 on a high plain above the Mailuu Suu River.

The two sites were selected because of their relatively good accessibility and the presence of areas with an increased ambient gamma dose rate at the surface compared to the regional background. An overview of the locations of the sites is provided in Figure 2.

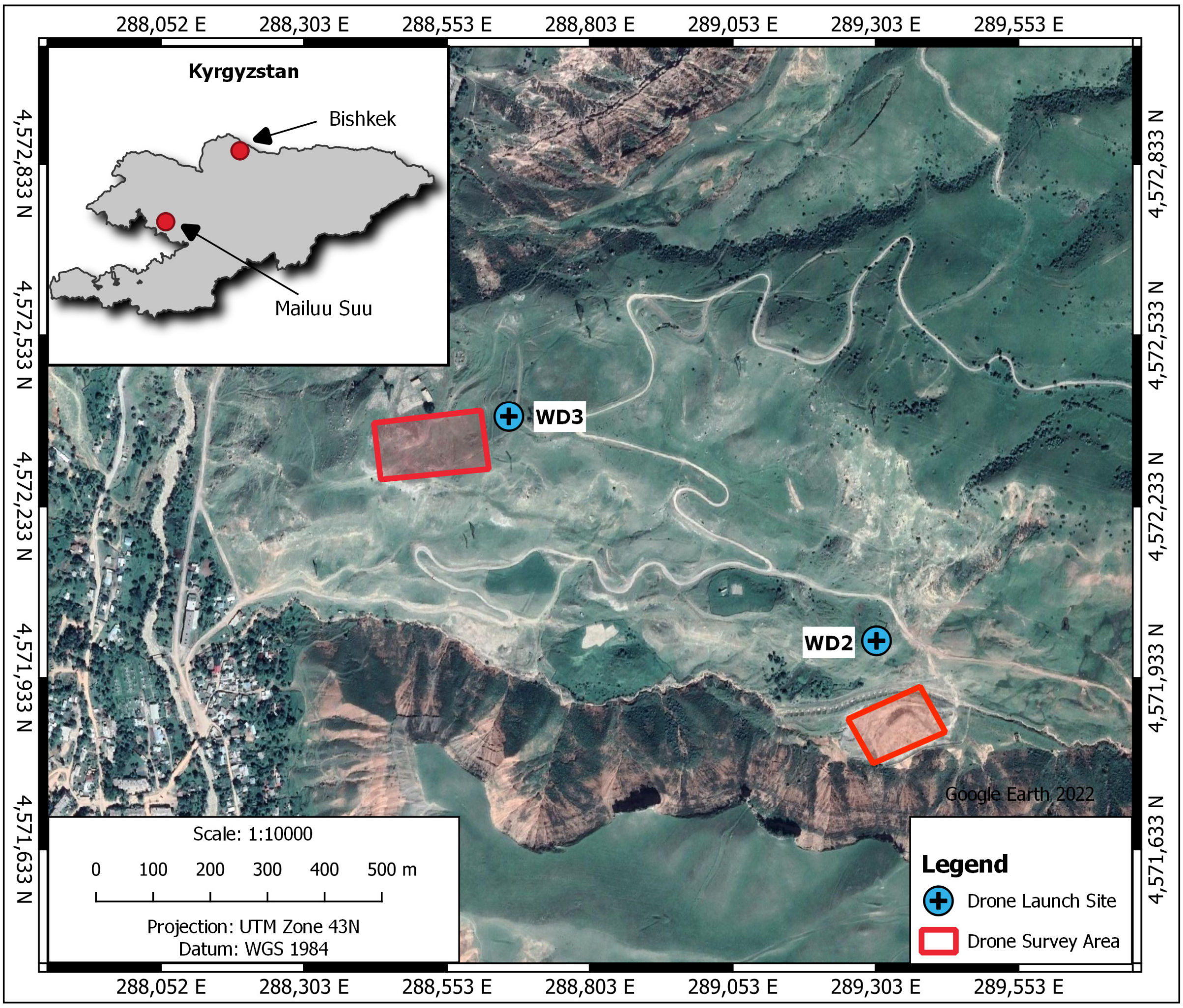

Figure 2. Map showing the locations of WD3 and WD2 at Mailuu Suu.

By way of example, the results obtained at WD3 are presented in the following. Key characteristics of the waste rock dump WD3 are provided in Table 2 along with previous site investigations ([78], and unpublished data from Soviet archives). Unlike tailings management facilities, the waste rock dumps were not covered with inert soil. Hotspots with increased specific activity give rise to significantly increased levels of gamma radiation in some areas.

Table 2. Key characteristics of WD3 in Mailuu Suu from historic sources and recent site investigations under different projects.

Parameter	**WD3, Mailuu Suu**
Footprint of waste rock dump (ha)	1.89 [78,80]
Waste volume (m^3)	70,000 [78], 250,000 [80]
Average specific activity of U-238 (Bq/g)	0.9 [unpublished archive data on uranium content of waste rock from mine no. 6], supported by sample KS_S0401 in [80]
Average specific activity of Ra-228 (Bq/g)	<0.1 [80]
Average specific activity of K-40 (Bq/g)	0.6 [80]
Percent of the total surface with gamma dose rates H*(10) of <150 nSv/h in 1 m above surface	12 [80]

Percent of the total surface with gamma dose rates H*(10) of 150…300 nSv/h in 1 m above surface	30 [80]
Percent of the total surface with gamma dose rates H*(10) of 300…500 nSv/h in 1 m above surface	30 [80]
Percent of the total surface with gamma dose rates H*(10) of 500…1000 nSv/h in 1 m above surface	23 [80]
Percent of the total surface with gamma dose rates H*(10) of >1000 nSv/h in 1 m above surface	5 [80]
Local background of the gamma dose rate H*(10) in the Kulmensay valley in 1 m above surface (nSv/h)	139 [80]

It must be noted that, unfortunately, historic data are not necessarily reliable, and are beset with inconsistencies. They serve only as a starting point but require interpretation and judgment. In fact, some assumptions, especially on the nuclide vector of the alleged waste rock, have turned out to be wrong, as will be discussed below.

The following Figure 3 shows an aerial view of WD3. In the next subsection, the spatial distribution of the calculated specific activity of nuclides of the uranium and thorium series and K-40, respectively, are shown as calculated from the UAV-based spectrometry data, while, in Section 6.3, the reliability of the results is discussed and compared with information from other sources.

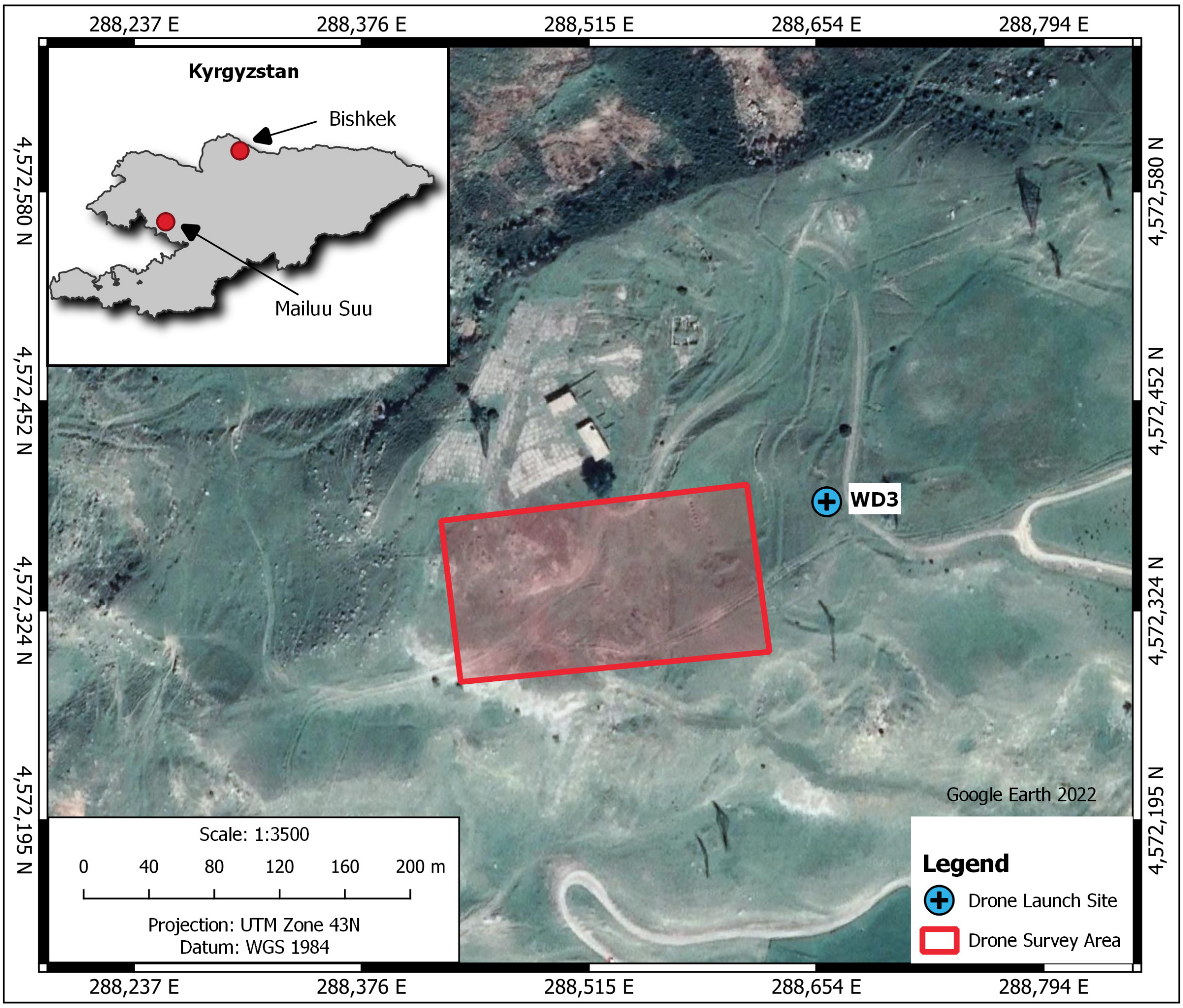

Figure 3. Aerial view of the investigation area at WD3 in Mailuu Suu.

The basic parameters of the test flights carried out at ULS in Kyrgyzstan (Mailuu Suu) in the period 5 through 10 October 2021 are summarised in Table 3:

Table 3. Key characteristics of UAV flights.

Parameter	Value
Altitude	10 m AGL
Ground speed	3 m/s Slower or hovering at hot spots on an ad-hoc basis
Duration of a single flight mission	20 min, typically including 5 min for approach to the ULS from launch pad, and return
Flight pattern in automatic flight mode	Parallel lines covering the entire lateral extension of the ULS
Spacing of flight lines	10 m
Surface coverage rate	10.8 ha per hour, or 2.7 ha per mission

The duration of each mission was limited by the capacity of the batteries. When the battery voltage approached 42.6 V, down from a nominal 44.4 V of fully charged batteries, or a cell voltage 3.55 V and 3.6 V, respectively, the UAV returned to the launch pad. For the next mission, a fresh set of fully charged batteries was inserted into the UAV (either pre-charged or on-site-generator-charged).

It is noted in passing that the situation encountered during the test flights at the ULS of Muzbel' (Kurday, Kazakhstan) was more difficult due to adverse weather conditions such as strong and very gusty winds and unforeseen thermal currents on steep slopes. Both the altitude and flight patterns were rather unstable, and the UAV had to be controlled manually for most of the flight time.

Moisture did not have a significant impact on the measured spectra since, during the test flights, the weather was dry; moreover, in the week before the test flights, the weather in the wider area was reported to be mostly dry [81].

6.2. Results

Figures 4–7 visualise the results of the drone-based measurements at WD3 in Mailuu Suu (Kyrgyzstan) and subsequent data processing. Figure 4 shows the total count rate in counts per second (cps) without any processing, except spline interpolation of the data points. The next three figures (Figures 5–7) show the results of data processing, i.e., the specific activities in Becquerel per kilogram of K-40 and the U-238 and Th-232 decay series, respectively. These results have been calculated with the full spectrum method.

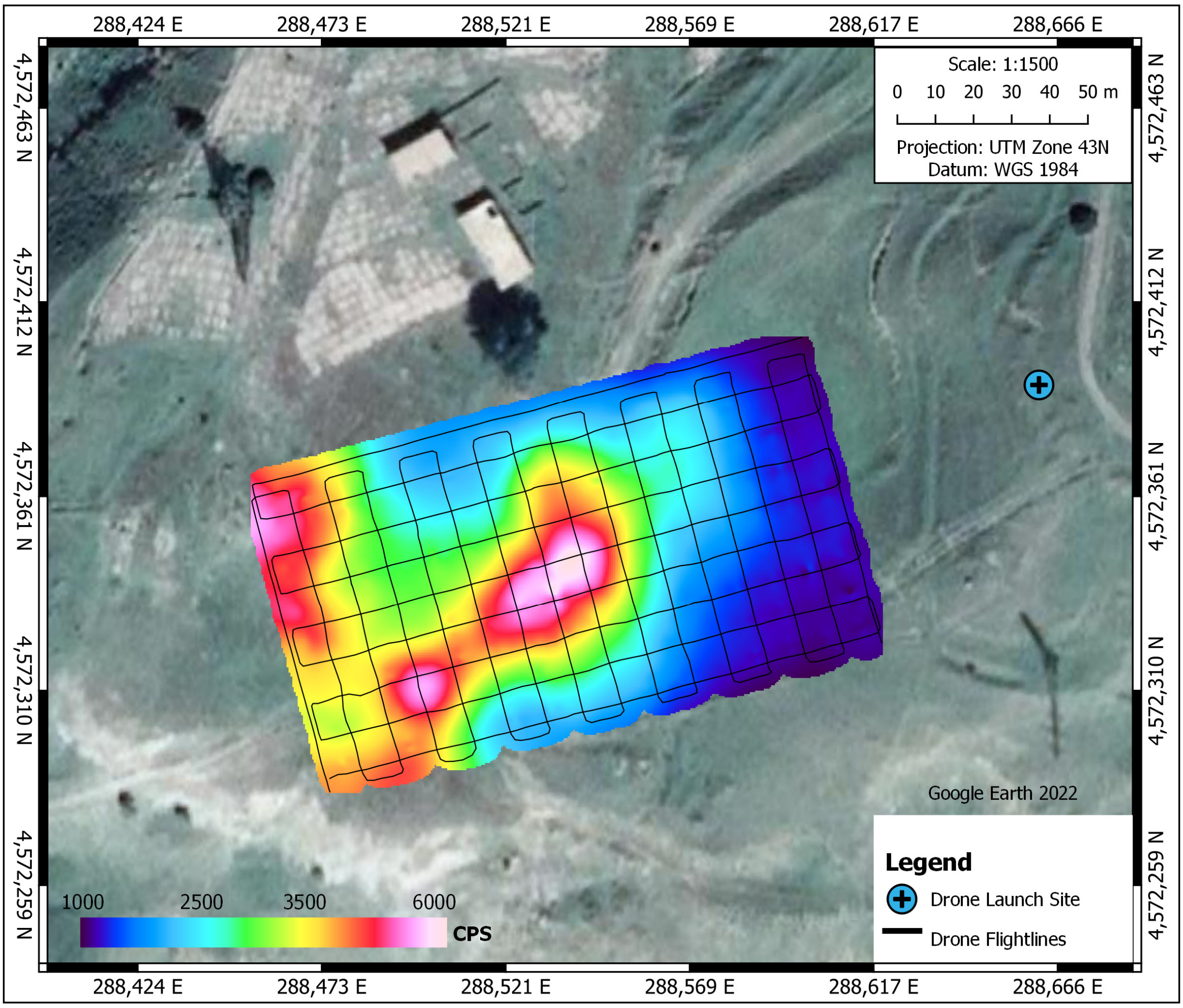

Figure 4. Total count rate of the investigation area.

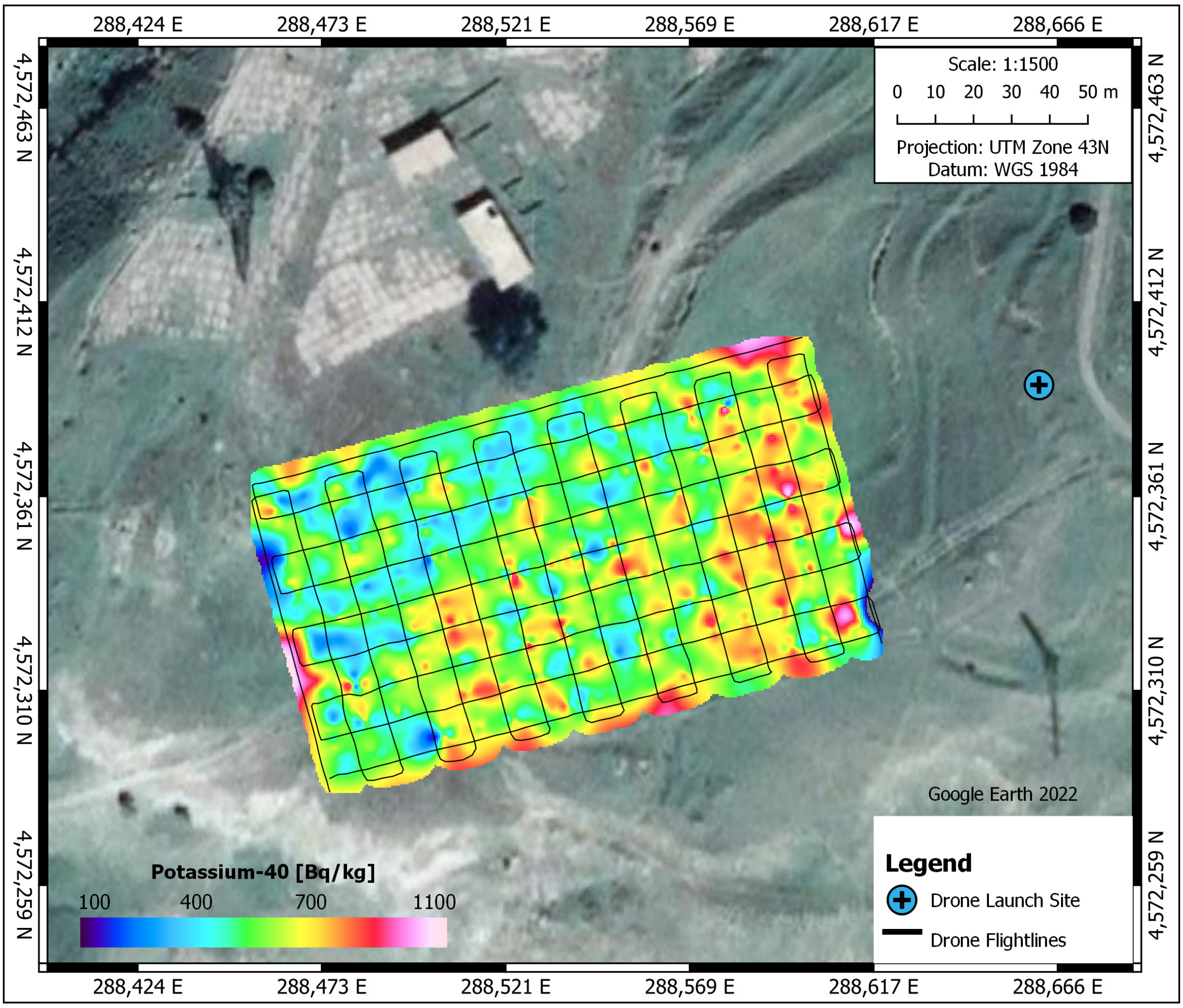

Figure 5. Specific activity of K-40 in the investigation area.

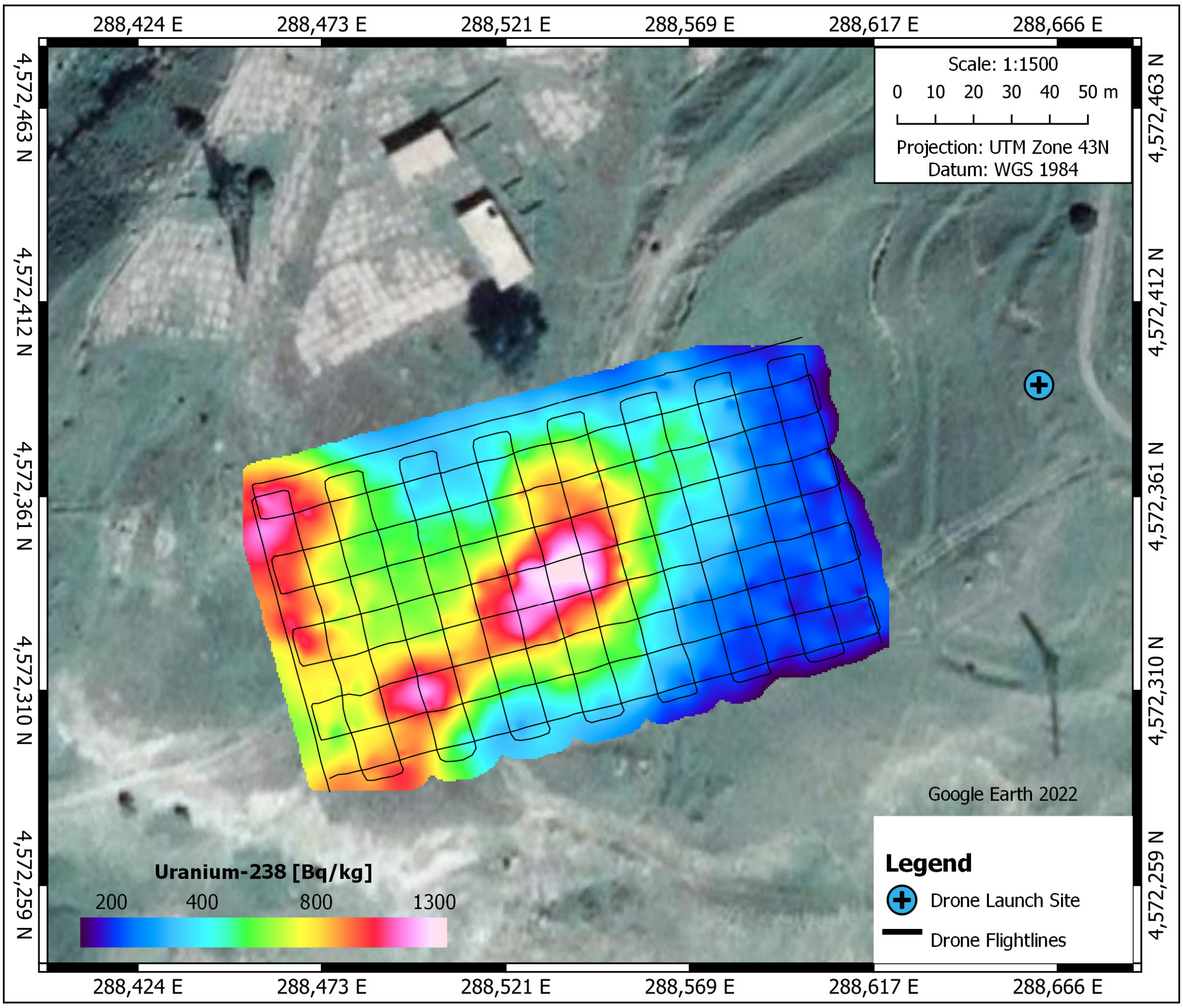

Figure 6. Specific activity of U-238 in the investigation area.

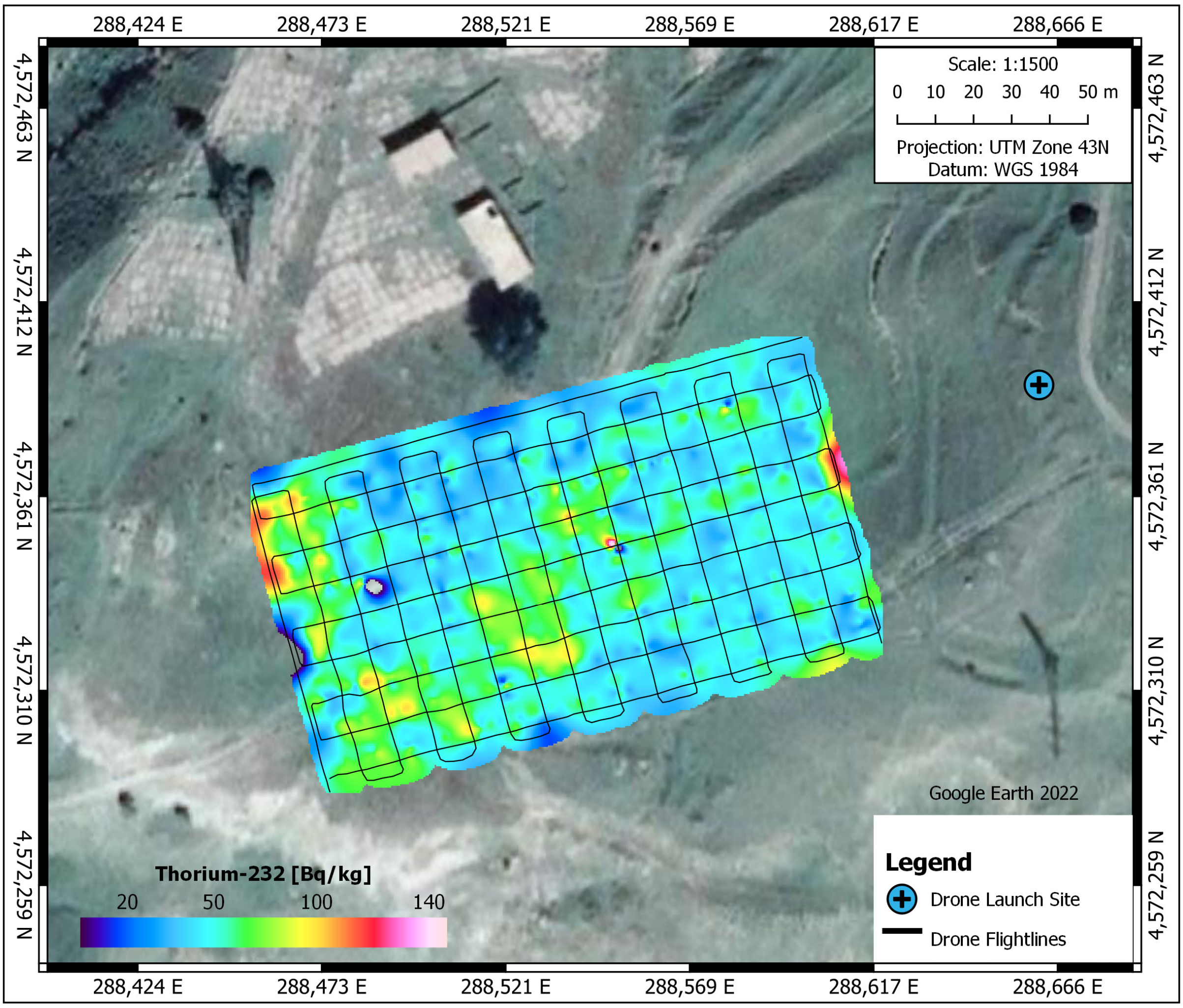

Figure 7. Specific activity of Th-232 in the investigation area.

6.3. Discussion and Interpretation of the Results

The results of the test flights confirm what has been known from prior site investigations, namely a strong dominance of the uranium series compared to the thorium decay series and K-40 and the high-specific activity material cropping out on a significant portion of the waste rock dump surface.

The distribution map of K-40 in Figure 5 shows areas of locally increased specific activity (e.g., at the NE corner and the W edge of the flight area), which may partly be due to inhomogeneities of the soil mineralogy. However, the apparently higher specific activity of K-40 at the edges of the flight area are not fully supported by UAV-based data and may partly be caused by calculation artifacts overestimating the small fluctuations of the count rates within the flight area. It should also be noted that even high levels of K-40 are not reflected in the map of total counts in Figure 4, since K-40 is a relatively weak gamma emitter compared to Bi-214, for example, which dominates the overall gamma radiation at the site.

In the map of the thorium decay series, it is not possible to discern any anomaly of the spatial distribution. By contrast, anomalous structures are clearly visible in the map of the uranium decay series. The anomalous structures in Figure 6 correlate strongly with the cps values shown in Figure 4.

In some places on the edges of the mining wastes, the soil cover is eroded over the years, and the wastes with areas with increased specific activity are visibly exposed. This is manifested in the uranium map by a higher specific activity of Ra-226 and its gamma-emitting decay products (mainly Bi-214).

The existence of historical data and a recent site characterisation for the ULS at Mailuu Suu is a unique opportunity to assess the results of the UAV-based survey with respect to localisation and the absolute values of the specific activity of the radioactive wastes.

Figure 8 shows the results of UAV-based gamma spectrometry overlain by the results of a walkover survey of the ambient dose rate (ADR) H*(10) of the gamma radiation. These data were obtained within the scope of the EC INSC project for the preparation of remediation measures at Mailuu Suu [80] and were peer reviewed by an independent group of experts convened by the IAEA.

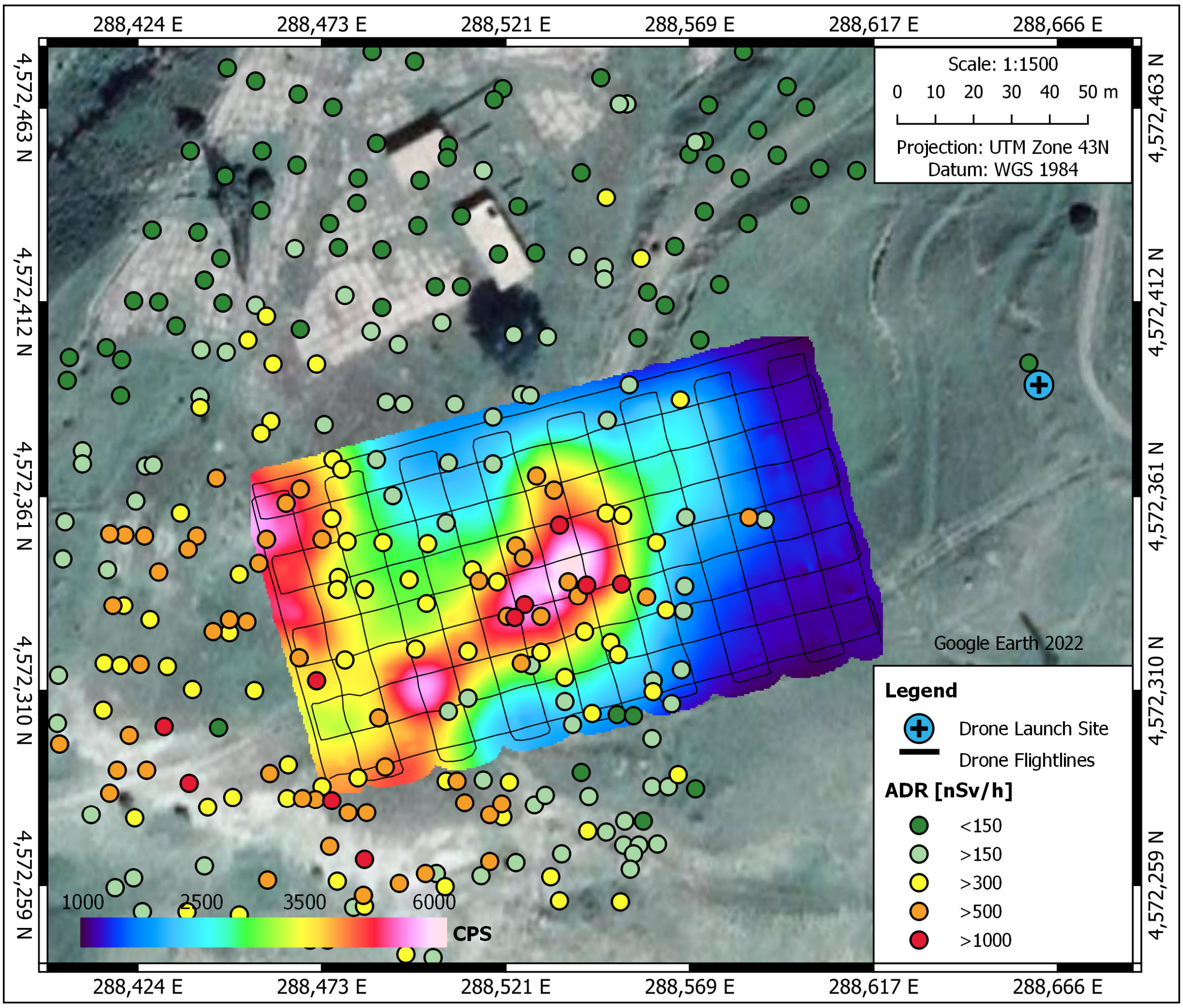

Figure 8. Overlay of the specific activity of U-238 calculated from UAV data with the ADR measured during a walk-over survey in 2019 (data and image reproduced with permission by G.E.O.S.-WISUTEC).

It is obvious from both the walk-over and UAV-based data that the delineation of ULS objects from historic records does not necessarily coincide fully with the real extension of the wastes. Nevertheless, Figure 8 allows a first plausibility check of the UAV-based results. Taking the example of the hot spot in the centre of the flight area, a comparison between the UAV data and the ground data indicates that the ADR of H*(10) > 1000 nSv/h corresponds to a calculated specific activity of 1000…1300 Bq/kg. Using the well-known relationship between ADR and the specific activity of Ra-226 in the ground, assuming dry soil, infinite vertical homogeneity, and a flat surface (often referred to as 2π geometry), a specific activity a(Ra-226) of 1000 Bq/kg corresponds to an ADR of H*(10) = 520 nSv/h in 1 m AGL [82]. It is obvious that, although delivering results in the correct order of magnitude, the UAV-based data seem to underestimate the specific activity of the material compared to ground-based ADR measurements. This may be due to a number of reasons, which deserve closer attention.

First, the ground-based ADR survey may not be unbiased. Site investigation staff tend to record ADR point data where they are highest, indicating a piece of uranium-mineralised rock, a heap of low-grade ore, or other singular features.

To obtain a more reliable, quantitative basis for assessing the UAV-based results, seven samples were taken after the test flights from the surface of WD3 and analysed by an HPGe gamma spectrometer in the accredited laboratory of IAF-Radioökologie GmbH. The samples were taken close to the edges of, or outside, the investigation area and at hotspots inside. The rationale of the former was to obtain additional points to support the interpolation procedure. The rationale of the latter was to confirm the calculated maximum specific activity. It turned out that the hotspots are caused by several pieces of highly mineralised rock, rather than homogeneously distributed material of increased specific activity. This situation is very common, and therefore always needs to be taken into account at ULSs. Unfortunately, the rock samples from the hotspots were taken from the authors at the border control, and therefore could not be analysed in the laboratory in Germany. Figure 9 shows the results of the laboratory analyses and a graphical representation of the sampling points and a comparison with the UAV-based results is given in Figure 10. Both series coincide reasonably well.

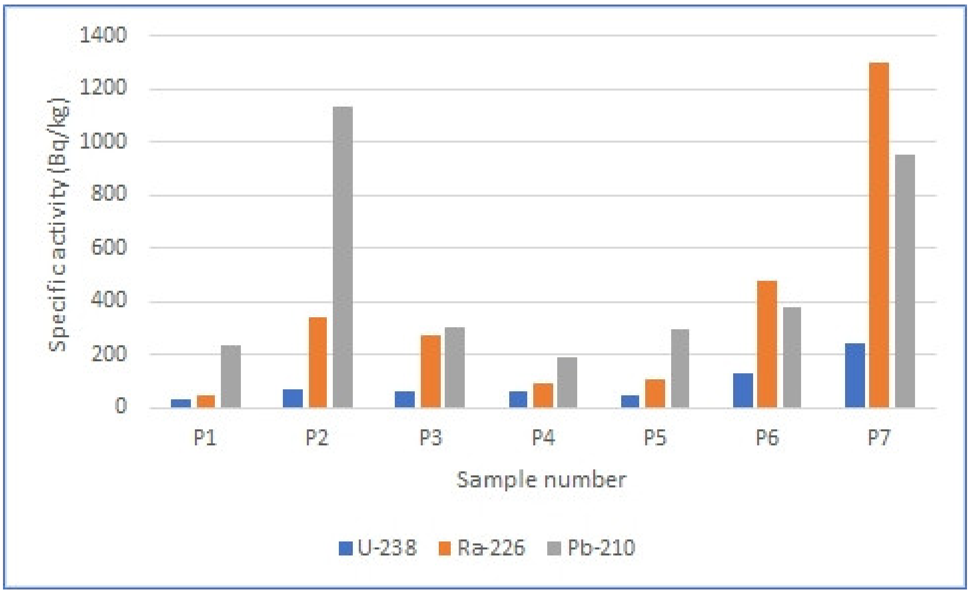

Figure 9. Specific activity of Ra-226 in waste rock samples taken at WD3, determined by conventional laboratory gamma spectrometry.

From Figure 9, it is obvious that the material on WD3 is not ordinary waste rock in the conventional sense (i.e., secular equilibrium along the U-238 decay chain), but instead exhibits a marked disequilibrium between U-238 and Ra-226 (and also Pb-210, which is less relevant in this context).

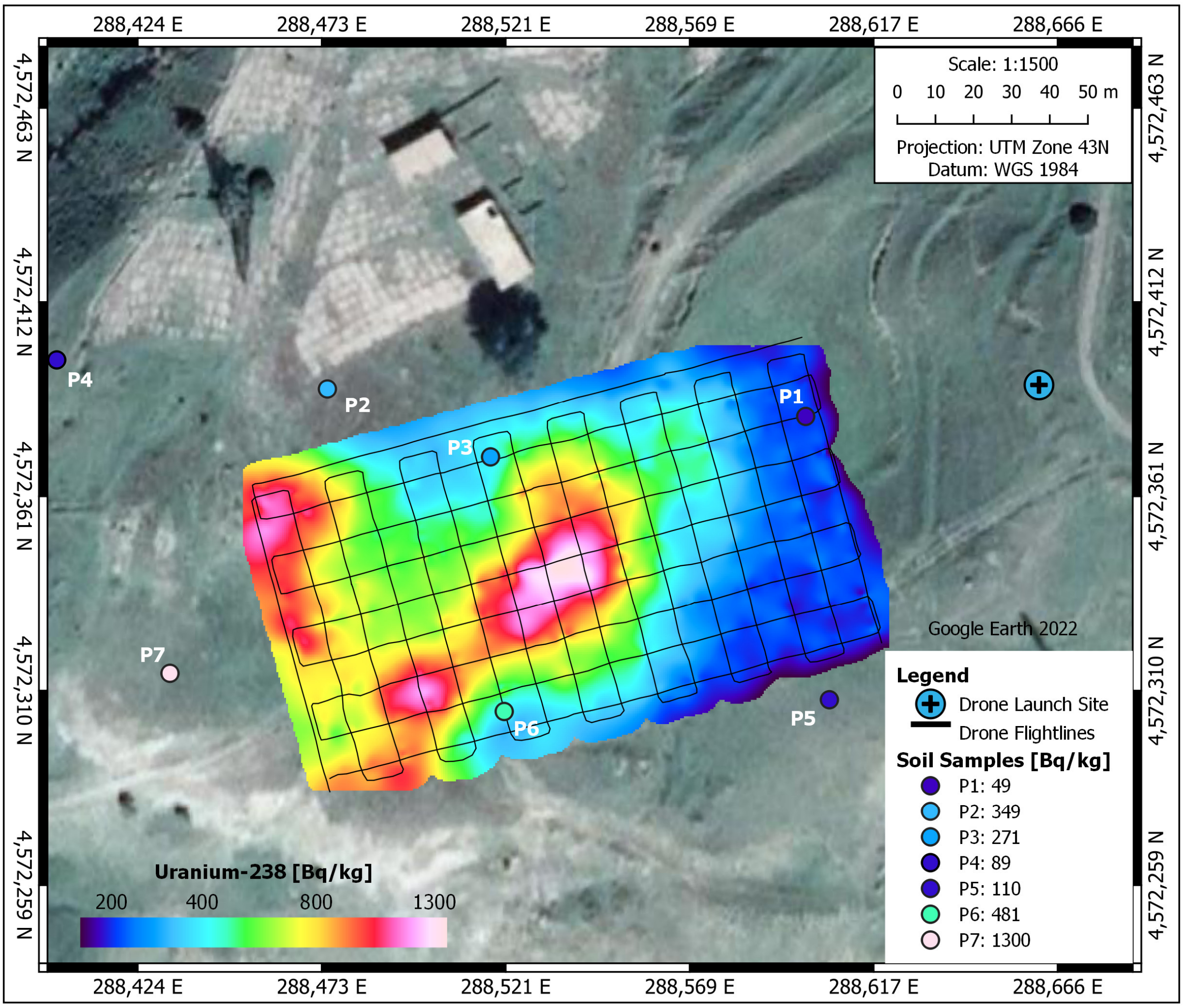

Figure 10. Overlay of the specific activity calculated from UAV data with the results of a ground truthing sampling campaign.

The marked disequilibrium between U-238, Ra-226, and Pb-210 in waste rock deposited in the Kulmen Say Valley has also been noted by other authors in previous projects. The results of a site investigation programme in 2005–2006 [83], the activity ratio of Ra-226 to U-238 and Pb-210 to Ra-226 was approximately 2 and 0.7, respectively (gamma spectrometry was carried out by the accredited laboratory of Wismut GmbH).

These findings lead us to the following tentative conclusions:

- Due to the disequilibrium, the results calculated from the UAV-based gamma spectra in this particular case of waste from mine no. 6 relate to Ra-226, rather than U-238. The waste at WD3 may also contain some tailings material due to the close proximity of a tailings pond (TP11). Erosion over the past decades may have washed tailings downhill, or tailings have been co-disposed with waste rock during active mining production. The latter scenario appears more plausible, since tailings (including TP11) have been covered with inert soil, and both a visual check of the soil cover and walk-over gamma surveys in 2019 [80] and in 2021 by the authors confirmed that the cover is largely intact;
- On maps generated using UAV-based data, areas of homogeneously distributed increased specific activity cannot be distinguished from highly mineralised pieces of rock that are typical of ULS waste rock dumps. The latter appear as areal sources due to the limited spatial resolution and the interpolation procedure;

- If not systematically carried out on a dense, regular grid, walk-over gamma surveys may miss out on hot spots, such as the patch in the centre of the investigation area;
- By contrast, the averaging procedure of the UAV-based gamma spectrometry tends to underestimate the specific activity in hot spots if there are significant spatial inhomogeneities of the specific activity.

7. Summary and Conclusions

This paper has reported the development of a UAV-based gamma spectrometry system, much needed by Central Asian countries in the context of the environmental remediation of their uranium legacy sites. It has been shown that the developed system is technically reliable and meets the requirements of the partner countries. The sensitivity of the UAV-based gamma spectrometers is sufficient to survey waste disposal areas with the specific activity typically encountered at ULSs and to detect hot spots in ULSs with a typical lateral extension of a few meters and in the correct order of magnitude.

The lateral resolution of UAV-based gamma surveys is limited to the order of magnitude of the flight altitude. The spectral resolution of scintillation detectors is limited to the decay series; individual nuclides cannot be resolved. However, these physical limits are not critical for the applicability of these systems for the monitoring of ULSs.

Nevertheless, the UAV-based gamma spectrometry system and the interpretation of the results still require further development. Priority areas of research are summarised below:

- The impact of strong disequilibria between nuclides of the same decay chain (U-238 in the case of the Mailuu Suu ULS) on the calculation procedure must be investigated in order to more reliably determine the specific activity of the material on the ground;
- Correction of the impact of soil moisture on the gamma spectra and the subsequent calculation algorithms is a decisive factor for the reliability of the results. This is an area where significant research is currently ongoing. For the time being, empirical correction factors should be used, which must be obtained on a site-specific basis, taking into account local soil characteristics;
- Such correction procedures are particularly important for the comparison of results from repeated surveys (e.g., annual flyovers as part of a long-term institutional control programme of remediated ULSs) and the conclusions drawn on the potential evolution of erosion or contamination patterns;
- Due to the limited spatial resolution of drone-based data, areas of homogeneously distributed increased specific activity cannot be distinguished from highly mineralised pieces of rock that are typical of ULSs;
- Currently, there are no data available on the repeatability of the UAV-based survey results. This requires repeated survey flights of the same ULS objects over an extended period of time. Suitable arrangements must be found with the ULSs' owners/operators in the Central Asian countries, which in turn requires additional funding.

Since there are numerous factors that impact the results derived from the UAV-based surveys of ULSs, the importance of expert judgment and thorough interpretation of the data must be emphasised. The authors caution against the "naïve" use of data, where several unknown factors still require further research.

However, apart from presenting the scientific and technical approaches for developing both the UAV and the spectrometer, the second important objective of this paper was to outline the logistical requirements and administrative challenges that have been addressed only in passing by previous authors. These are essential when assessing the practical needs, opportunities, and limits of the future application of UAV-based radiation monitoring systems. An initial site reconnaissance mission and proper mission planning are required to ensure flight safety and to acquire some key characteristics of the legacy sites to be investigated. All these challenges and requirements translate into high up-front cost and may severely limit the practical application of UAV-based systems on a larger scale.

Our main conclusion in this respect, therefore, is that UAV-based gamma spectrometry systems are most cost-effective when used for periodically repeated flyovers of the same legacy sites over many years. Drone-based investigations may start during the site characterisation phase to establish pre-remediation baseline conditions, continue during the remediation phase to follow the progress of the works and, most important, extend many years into post-remediation to monitor the long-term stability of the remediated sites.

The flights can be automated, using the same flight routes and parameters for all subsequent missions and comparing consecutive results to detect gradual changes such as deteriorating cover systems, evolving landslides, or when erosion patterns become visible. The high initial cost required to set up an investigation programme at a ULS is thus spread over many years, making the technology much more economically attractive than just a one-off mission.

Logistical challenges, which were to a significant degree due to battery management for the extensive test flights under this project, can be reduced in routine operation. If the necessary flight time is restricted to one survey flight per ULS object, a small number of pre-charged battery sets will be sufficient, and mobile generators are no longer needed.

Funds from international technical co-operation projects in the field of uranium mine closure and environmental rehabilitation may be used to purchase UAV-based radiation monitoring systems as part of ULS remediation programmes. Since the cost to purchase a complete system currently amounts to a five- to six-digit Euro figure, and the system would be idle for a large part of the year, sharing the system, and thus expenses, may be considered in multiple dimensions:

- One UAV could be used with several detectors, including cameras for landslide observation within the national emergency preparedness and response programme, or other radiation detectors for the identification of orphan sources within a national nuclear safety programme;
- Several countries in the region (Central Asia, or other regions) with the same challenges in the context of ULSs may share one UAV system for long-term surveillance;
- Renting out the system to private customers, e.g., with the need for industrial inspection, possibly as a package with piloting the drone, may recoup some of the cost.

These future use scenarios also make the optimisation and standardisation of interfaces between the UAV and payload equipment desirable. From the experience obtained during the development phase and test flights, it is concluded that at least the following connections should be available from the UAV: power supply for payload equipment, GPS data, and a simple, serial data transfer from the payload equipment to the ground station using the data link of the UAV.

It must also be noted that the rapidly increasing capabilities of 3D printing of UAV frames and the availability of commoditised components such as motors, controllers, etc., may make it possible in the near future for UAVs to be manufactured domestically in low-income countries, so that the hassle to ship UAVs across international borders is avoided. Even though gamma detectors must still be imported, this development will foster the widespread use of UAV-based systems for a large variety of applications, including monitoring of ULSs.

Even though automation of the flights will lead to significant cost reductions, the need for the presence of human flight operators will probably remain for safety reasons. Even in a scarcely populated landscape with few man-made or natural obstacles to UAV operation, regular visual inspection of the flight area is necessary since alternative sources such as satellite imagery are often not sufficient to detect new objects or other changes that may impact flight safety.

Maintenance of UAVs between deployments must be taken seriously to ensure the continued reliability and fitness for purpose of the equipment. This requires discipline, specialisation, and a well-developed management system, backed up by sufficient human resources and funding. While the purchase of equipment by ex-Soviet Central Asian countries may be financially supported by technical assistance programs of international organisations, annual expenses over the long-term must be paid by the recipient countries, which may pose a serious challenge due to severely constrained national budgets [38]. Maintenance includes technical aspects; however, perhaps to an even higher degree, it includes a human factor. Competence of staff, acquired through formal and practical training, must be preserved by continued practice. Fluctuation of qualified staff to better paid positions is a particularly pressing issue in low-income countries; therefore, a UAV team of at least two staff members is recommended. These trained experts will best preserve and develop their knowledge if they carry out periodic flight missions over the course of the year. This, in turn, supports the concept discussed above, namely sharing UAV-based systems between multiple users or even countries with similar interests.

Dissemination of basic information on UAV-based technology deployed at a ULS needs to be included into the protocol of flight preparation. Even more important, this information must be integrated into the wider scope of local stakeholder involvement over several years, from site characterisation to the implementation phase of remediation measures into long-term surveillance and the monitoring of the ULSs.

Despite the initial challenges, the authors expect that automated, cost-effective, and weight-optimized, UAV-based gamma spectrometry systems will once become standard applications for the long-term surveillance of remediated ULSs in Central Asian countries.

Author Contributions: Conceptualization: C.K., S.A., B.P.; Methodology: R.A., F.K., B.P.; Field work: R.A., F.K., B.P., B.W.; Visualization: B.P.; Writing: C.K., S.A., B.P. All authors have read and agreed to the published version of the manuscript.

Funding: The study was funded by the German Federal Ministry of Education and Research (BMBF) under the CLIENT II program, Grant No. 01LZ1706A-C. Throughout the project, the IAEA's CGULS has facilitated participation of Central Asian experts in practical workshops and coordination meetings and provided logistical assistance for the field work. IAEA CGULS also provided support to practical training of Central Asian experts during the field tests described in this paper.

Data Availability Statement: Not applicable.

Acknowledgments: The authors are indebted to Daniela Heilfort and Jens Mossig of IAF, Carsten Plath, and Malte Ibs-von Seht of BGR, Michael Wolkstein and Christian Behrens of 3EA, Ulan Ibakov of WISUTEC Central Asia, Asel Seitkazieva and Aibek Kozibaev of the Tailings Management Agency of the Ministry of Emergency Situations of the Kyrgyz Republic, Maksat Sharipov of the Nuclear and Radiation Safety Department of the Atomic and Energy Supervision and Control Committee of the Ministry of Energy of the Republic of Kazakhstan, Vladislav Bensman of Ecoservice-S (Kazakhstan), Tinara Shaildaeva (Kyrgyzstan) and Viktoria Ignatiuk of the IAEA for invaluable conceptual and practical contributions to this project. The authors also thank anonymous reviewers for their valuable comments which have greatly improved the paper.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

List of Abbreviations

ADR	Ambient dose rate of gamma radiation
AGL	Above ground level
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Agency for Geosciences and Resources)
CGULS	Co-Ordination Group of Uranium Legacy Sites
DUB-GEM	Development of a UAV-Based Gamma spectrometry for the Exploration and Monitoring of Uranium Mining Legacies (project acronym)
EASA	European Union Aviation Safety Agency
EBRD	European Bank for Reconstruction and Development
EC	European Commission
ERA	Environmental Remediation Fund

FPV	First Person View
FSA	Full spectrum analysis
FWHM	Full width at half maximum
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HPGe	High purity Germanium
IAEA	International Atomic Energy Agency
IMU	Inertial measurement unit
INSC	Instrument for Nuclear Safety Co-Operation
LiPo	Lithium polymer
LRF	Laser Range Finder
LTE	Long-term evolution mobile communications standard
MTOM	Maximum take-off mass
SMP	Strategic Management Plan
UAV	Unmanned Aerial Vehicle
ULSs	Uranium legacy sites
UMTS	Universal Mobile Telecommunications System
USB	Universal serial bus
VLOS	Visual line of sight
VTOL	Vertical take of and landing
WD	Waste dump
XRF	X-ray fluorescence

References

1. Dubot, D. In situ methods for characterization of contaminated Sites. In Proceedings of the Technical Meeting on In-Situ Methods for Characterization of Contaminated Sites, IAEA, Vienna, Austria, 5–9 July 2010. Available online: http://www-pub.iaea.org/MTCD/Meetings/PDFplus/2010/38924/TM-38924/Presentations/Dubot.pdf (accessed on 23 October 2021).
2. da Silva, N.C. Use of in-situ gamma spectrometry for environmental monitoring of a former disposal site of by product from monazite chemical processing. In Proceedings of the Technical Meeting on In-Situ Methods for Characterization of Contaminated Sites, IAEA, Vienna, Austria, 5–9 July 2010. Available online: http://www-pub.iaea.org/MTCD/Meetings/PDFplus/2010/38924/TM-38924/Presentations/da%20Silva.pdf (accessed on 23 October 2021).
3. Marques, L.; Vale, A.; Vaz, P. State-of-the-Art Mobile Radiation Detection Systems for Different Scenarios. *Sensors* **2021**, *21*, 1051. https://doi.org/10.3390/s21041051.
4. Patterson, J.I.H. Recent Advances in Handheld XRF for Site Remediation. In Proceedings of the Technical Meeting on In-Situ Methods for Characterization of Contaminated Sites, IAEA, Vienna, Austria, 5–9 July 2010.
5. International Atomic Energy Agency. *Radiometric Reporting Methods and Calibration in Uranium Exploration*; Technical Reports Series 174; International Atomic Energy Agency: Vienna, Austria, 1976.
6. International Atomic Energy Agency, 1979, *Gamma-Ray Surveys in Uranium Exploration*; Technical Reports Series No. 186; International Atomic Energy Agency: Vienna, Austria, 1979.
7. International Atomic Energy Agency. *Guidelines for Radioelement Mapping Using Gamma Ray Spectrometry Data*; TECDOC 1363; International Atomic Energy Agency: Vienna, Austria, 2003.
8. Pätzold, S.; Leenen, M.; Heggemann, T.W. Proximal Mobile Gamma Spectrometry as Tool for Precision Farming and Field Experimentation. *Soil Syst.* **2020**, *4*, 31. https://doi.org/10.3390/soilsystems4020031.
9. *Application of uranium exploration data and techniques in environmental studies. Proceedings of the Technical Committee Meeting, Vienna, Austria, 9–12 November 1993*; TECDOC 827; International Atomic Energy Agency: Vienna, Austria, 1993.
10. Coetzee, H.; Larkin, J. Airborne Radiometric Surveying for the Management of Health, Safety and the Environment in the Uranium Mining Industry: Potential Applications and Limitations. In *The New Uranium Mining Boom—Challenge and Lessons Learned*; Merkel, B.; Schipek, M., Eds.; Springer: Heidelberg, Germany; Dordrecht, The Netherlands; London, UK.; New York, NY, USA, 2011.
11. Connor, D.; Martin, P.G.; Scott, T.B. Airborne radiation mapping: Overview and application of current and future aerial systems. *Int. J. Remote Sens.* **2016**, *37*, 5953–5987. https://doi.org/10.1080/01431161.2016.1252474.
12. Furutani, T.; Minami, M. Drones for Disaster Risk Reduction and Crisis Response. In: *Disaster Risk Reduction - Methods, Approaches and Practices;* M. Sakurai, R. Shaw, Eds.; Springer, Berlin, Germany, 2021; Chapter 4, ISBN 978-981-16-0359-4 ISBN 978-981-16-0360-0 (eBook), https://doi.org/10.1007/978-981-16-0360-0.
13. Simek, P. Evolution of Contamination in the Plouènice River Basin (Bohemia) due to uranium mining in the period 1992–2009. In Proceedings of the Technical Meeting on In-Situ Methods for Characterization of Contaminated Sites, IAEA, Vienna, Austria, 5–9 July 2010. Available online: http://www-pub.iaea.org/MTCD/Meetings/PDFplus/2010/38924/TM-38924/Presentations/Simek.pdf (accessed on 23 October 2021).

14. Buchanan, E.; Cresswell, A.J.; Seitz, B.; Sanderson, D.C.W. Operator Related Attenuation Effects in Radiometric Surveys. *Radiat. Meas.* **2016**, *86*, 24–31. https://doi.org/10.1016/j.radmeas.2015.12.029.
15. Sanada, Y.; Torii, T. Aerial Radiation Monitoring around the Fukushima Dai-Ichi Nuclear Power Plant Using an Unmanned Helicopter. *J. Environ. Radioact.* **2015**, *139*, 294–299. https://doi.org/10.1016/j.jenvrad.2014.06.027.
16. Pöllänen, R.; Toivonen, H.; Peräjärvi, K.; Karhunen, T.; Ilander, T.; Lehtinen, J.; Rintala, K.; Katajainen, T.; Niemelä, J.; Juusela, M. Radiation Surveillance Using an Unmanned Aerial Vehicle. *Appl. Radiat. Isot.* **2009**, *67*, 340–344. https://doi.org/10.1016/j.apradiso.2008.10.008.
17. Aleotti, J.; Micconi, G.; Caselli, S.; Benassi, G.; Zambelli, N.; Bettelli, M.; Calestani, D.; Zappettini, A. Haptic Teleoperation of UAV Equipped with Gamma-Ray Spectrometer for Detection and Identification of Radio-Active Materials in Industrial Plants. In *Factories of the Future—The Italian Flagship Initiative*; Tolio, T., Copani, G., Terkaj, W., Eds.; Springer Open: Berlin, Germany, 2019; Chapter 9, ISBN 978-3-319-94357-2, 978-3-319-94358-9. https://doi.org/10.1007/978-3-319-94358-9.
18. Boudergui, K.; Carrel, F.; Domenech, T.; Guenard, N.; Poli, J.-P.; Ravet, A.; Schoepff, V.; Woo, R. Development of a Drone Equipped with Optimized Sensors for Nuclear and Radiological Risk Characterization. In Proceedings of the 2nd International Conference on Advancements in Nuclear Instrumentation, Measurement Methods and Their Applications, Ghent, Belgium, 6–9 June 2011; pp. 1–9. https://doi.org/10.1109/ANIMMA.2011.6172936.
19. Cao, Y.; Tang, X.-B.; Wang, P.; Meng, J.; Huang, X.; Wen, L.-S.; Chen, D. Spectrum Correction Algorithm for Detectors in Airborne Radioactivity Monitoring Equipment NH-UAV Based on a Ratio Processing Method. *Nucl. Instrum. Methods Phys. Res. Sect. A Accel. Spectrometers Detect. Assoc. Equip.* **2015**, *797*, 290–296. https://doi.org/10.1016/j.nima.2015.07.012.
20. Martin, P.G.; Moore, J.; Fardoulis, J.S.; Payton, O.D.; Scott, T.B. Radiological assessment on interest areas on the Sellafield nuclear site via unmanned aerial vehicle. *Remote Sens.* **2016**, *8*, 913.
21. Parshin, A.; Grebenkin, N.; Morozov, V.; Shikalenko, F. Research Note: First results of a low-altitude unmanned aircraft gamma survey by comparison with the terrestrial and aerial gamma survey data. *Geophys. Prospect.* **2018**, *66*, 1433–1438.
22. Limburg, H.; van der Veeke, S.; Koomans, R. Towards drone-borne gammaray mapping of soils. *First Break.* **2019**, *37*, 55–61.
23. Martin, P.G.; Payton, O.D.; Fardoulis, J.S.; Richards, D.A.; Scott, T.B. The use of unmanned aerial systems for the mapping of legacy uranium mines. *J. Environ. Radioact.* **2015**, *143*, 135–140. https://doi.org/10.1016/j.jenvrad.2015.02.004.
24. Ren, H.; Zhao, Y.; Xiao, W.; Hu, Z. A review of UAV monitoring in mining areas: Current status and future perspectives. *Int. J. Coal Sci. Technol.* **2019**, *6*, 320–333. https://doi.org/10.1007/s40789-019-00264-5.
25. Han, J.; Xu, Y.; Di, L.; Chen, Y. Low-cost Multi-UAV Technologies for Contour Mapping of Nuclear Radiation Field. *J. Intell. Robot. Syst.* **2013**, *70*, 401–410. https://doi.org/10.1007/s10846-012-9722-5.
26. International Atomic Energy Agency. *Assessment and Proposals for Uranium Production Legacy Sites in Central Asia: An International Approach*; International Atomic Energy Agency: Vienna, Austria, 2010.
27. Torgoev, I.A.; Aleshin, Y.G.; Ashirov, G.E. Environmental Effects of Possible Landslide Catastrophes in the Areas of Radioactive Waste Warehousing in Kyrgyzstan (Central Asia). In *The Areas of Radioactive Waste Warehousing in Kyrgyzstan (Central Asia), Proceedings of The First World Landslide Forum*; United Nations University: Tokyo, Japan, 2008; pp. 599–602.
28. Li, F.; Torgoev, I.; Zaredinov, D.; Li, M.; Talipov, B.; Belousova, A.; Kunze, C.P. Schneider: Influence of Earthquakes on Landslide Susceptibility in a Seismic Prone Catchment in Central Asia. *Appl. Sci.* **2021**, *11*, 3768. https://doi.org/10.3390/app11093768.
29. Sevcik, M. Uranium Tailings in Kyrgyzstan: Catalyst for Cooperation and Confidence Building? *Nonproliferation Rev.* **2003**, *10*, 147–154.
30. Daneykin, Y.; Andreevsky, E.; Rogozhin, M.; Sernetsky, O. Threats and Challenges to the Regional Security in Central Asian Region (the Example of the Republic of Kyrgyzstan). *Procedia—Soc. Behav. Sci.* **2015**, *166*, 86–91.
31. Kunze, C. Insurability of Unknown Post-Closure Liabilities. *J. Can. Inst. Min.* **2013**, *4*, 254–264.
32. International Atomic Energy Agency. *Lessons Learned from Environmental Remediation Programmes*; IAEA Nuclear Energy Series No. NW-T-3.6; International Atomic Energy Agency: Vienna, Austria, 2014.
33. Li, F.; Torgoev, I.; Zaredinov, D.; Li, M.; Talipov, B.; Belousova, A.; Kunze, P.C. Schneider: Landslide-Induced Mass Transport of Radionuclides along Transboundary Mailuu-Suu River Networks in Central Asia. *Remote Sens.* **2021**, *13*, 698. https://doi.org/10.3390/rs13040698.
34. UN General Assembly. Resolution A/RES/68/218 "The Role of the International Community in the Averting the Radiation Threat in Central Asia". 68th Session. 20 December 2013. https://www.insdip.com/en/68o-periodo-de-sesiones-2013-2014-agnu/ (accessed on 28 April 2022)
35. International Atomic Energy Agency. *General Conference Resolutions*; 2009-14: GC(53)/RES/10, Para 65; GC(54)/RES/7, Para 54; GC(55)/RES/9, Para 66; GC(56)/RES/9, Para 64; GC(57)/RES/9, Para 86; GC(58)/RES/10, Para 90; IAEA, Vienna, Austria, 2009.
36. Kunze, C.; Hartsch, J.; Metschies, T.; Schmidt, P.; Uhlig, L.; Wagner, F.; Walter, U. Technical Assistance and Know How Transfer to Central Asian Countries in the Environmental Remediation of ULS: Current State, Outlook and Lessons Learned. In Proceedings of the Shaping the Future: Long-Term Experiences and Innovations in Mine Remediation–Proceedings des Internationalen Mining Symposium WISSYM 2019, Chemnitz, Germany, 9–11 October 2019.
37. European Bank for Reconstruction and Development. *Uranium Legacy in Central Asia: Significant Progress, but Funding Gap Remains*; European Bank for Reconstruction and Development: London, UK, 2021. Available online: https://www.ebrd.com/news/2021/uranium-legacy-in-central-asia-significant-progress-but-funding-gap-remains.html (accessed on 23 October 2021).

38. International Atomic Energy Agency. Strategic Master Plan for Environmental Remediation of Uranium Legacy Sites in Central Asia. In Proceedings of the 61st IAEA General Conference, Vienna, Austria, 18 September 2017.
39. International Atomic Energy Agency. Strategic Master Plan for Environmental Remediation of Uranium Legacy Sites in Central Asia. In Proceedings of the 65th IAEA General Conference, Vienna, Austria, 21 September 2021; 2nd ed., revised and updated.
40. International Atomic Energy Agency. *IAEA Harnesses Drone Technology to Support Safer Environmental Remediation in Central Asia*; International Atomic Energy Agency: Vienna, Austria, 2021. https://www.iaea.org/newscenter/news/iaea-harnesses-drone-technology-to-support-safer-environmental-remediation-in-central-asia (accessed on 23 October 2021).
41. Arndt, R.; Kunze, C.; Mossig, J.; Schulz, H. Drone-based gamma spectrometry at NORM and uranium legacy sites. In Proceedings of the 2nd Workshop of the European NORM Association (ENA), Vienna, Austria, 20–22 October 2020.
42. Preugschat, B.; Seht, M.I. Gamma spectra from uranium mining residues simulated for airborne geometries and detectors. In Proceedings of the General Assembly 2020 of the European Geosciences Union (EGU), Online, 4–8 May, 2020. https://doi.org/10.5194/egusphere-egu2020-5074.
43. Monken-Fernandes, H. The IAEA Project to Develop a Mobile Unit for Site Characterization. In Proceedings of the Technical Meeting on In-Situ Methods for Characterization of Contaminated Sites, IAEA, Vienna, Austria, 5–9 July 2010. Available online: http://www-pub.iaea.org/MTCD/Meetings/PDFplus/2010/38924/TM-38924/Presentations/Monken%20Fernandes.pdf (accessed on 23 October 2021).
44. Gilmore, G. *Practical Gamma-Ray Spectroscopy*, 2nd ed.; reprinted with corrections; Wiley: Chichester, UK, 2011; 387p.
45. MacFarlane, J.W.; Payton, O.D.; Keatley, A.C.; Scott, G.P.T.; Pullin, H.; Crane, R.A.; Smilion, M.; Popescu, I.; Curlea, V.; Scott, T.B. Lightweight Aerial Vehicles for Monitoring, Assessment and Mapping of Radiation Anomalies. *J. Environ. Radioact.* **2014**, *136*, 127–130. https://doi.org/10.1016/j.jenvrad.2014.05.008.
46. Ahl, A.; Bieber, G. Correction of the attenuation effect of vegetation on airborne gamma-ray spectrometry data using laser altimeter data. *Near Surf. Geophys.* **2010**, *8*, 271–278.
47. Burnette, H. AFRL Incorporates Solar Cell Technology into Small Unmanned Aircraft Systems, Wright Patterson Air Force Base, 19 October 2012. Available online: https://www.wpafb.af.mil/News/Article-Display/Article/399512/afrl-incorporates-solar-cell-technology-into-small-unmanned-aircraft-systems/ (accessed on 28 April 2022).
48. Sanderson, D.C.W.; Allyson, J.D.; Tyler, A.N.; Scott, E.M. Environmental Applications of Airborne Gamma Spectrometry. In *Application of uranium exploration data and techniques in environmental studies. Proceedings of the Technical Committee Meeting, Vienna, Austria, 9–12 November 1993*; International Atomic Energy Agency: Vienna, Austria, 1993.
49. Brewer, E.T. Autonomous Localization of $1/R^2$ Sources Using an Aerial Platform. Master's Thesis, Virginia Tech, Blacksburg, VA, USA, 2009. Available online: https://vtechworks.lib.vt.edu/handle/10919/36378 (accessed on 13 November 2021).
50. Baca, T.; Stibinger, P.; Doubravova, D.; Turecek, D.; Solc, J.; Rusnak, J.; Saska, M.; Jakubek, J. Gamma Radiation Source Localization for Micro Aerial Vehicles with a Miniature Single-Detector Compton Event Camera. In Proceedings of the 2021 International Conference on Unmanned Aircraft Systems (ICUAS), Athens, Greece, June 2021; pp. 338–346.
51. Jiang, J.; Shimazoe, K.; Nakamura, Y.; Takahashi, H.; Shikaze, Y.; Nishizawa, Y.; Yoshida, M.; Sanada, Y.; Torii, T.; Yoshino, M.; et al. A Prototype of Aerial Radiation Monitoring System Using an Unmanned Helicopter Mounting A GAGG Scintillator Compton Camera. *J. Nucl. Sci. Technol.* **2016**, *53*, 1067–1075. https://doi.org/10.1080/00223131.2015.1089796.
52. Długosz-Lisiecka, M.; Bem, H. 2021, Fast procedure for self-absorption correction for low gamma energy radionuclide 210Pb determination in solid environmental samples. *J. Radioanal. Nucl. Chem.* **2013**, *298*, 495–499. https://doi.org/10.1007/s10967-012-2404-8.
53. Schwarz, G.F.; Rybach, L.; Barlocher, C.K.; Klingele, E.E. Development and Calibration of an Airborne Radiometric Measuring System. In *Application of uranium exploration data and techniques in environmental studies. Proceedings of the Technical Committee Meeting, Vienna, Austria, 9–12 November 1993*; International Atomic Energy Agency: Vienna, Austria, 1993.
54. International Atomic Energy Agency. *Integrated Approach to Planning the Remediation of Sites Undergoing Decommissioning*; IAEA nuclear energy series No. NW-T-3.3; International Atomic Energy Agency: Vienna, Austria, 2009.
55. Luftfahrtbundesamt [Federal Civil Aviation Authority of Germany]. 2021, Onlinekurs Fernpiloten [online course for UAV operators]. Available online: https://lba-openuav.de/onlinekurs/ (accessed on 30 October 2021).
56. Center for Emergency Situations and Disaster Risk Reduction. Development of UAV in the field of emergency situations. 2021. Available online: https://cesdrr.org/uav (accessed on 13 November 2021).
57. Environment and Security Initiative UN Development Program (ENVSEC). Project for Stakeholder Involvement in Solving the Problems of Uranium Tailings in Central Asia, 2016, Report on Risk Perception And Capacity Needs, Bishkek. 2016; *unpublished*.
58. Abdirasulova, G. Access of residents of the town of Mailuu Suu to ecological information. Results of a Survey. [*Доступ к экологической информации жителей города Майлуу-Суу. Результаты мониторинга*]; European Union: Bishkek, Kyrgyzstan, 2017.
59. Hagen, M.; Jakubick, A.T. The uranium mining legacy of Eastern Germany: From remediation to regional development. In Proceedings of the International Atomic Energy Agency (IAEA), Low Environmental Impact Uranium Mining and Remediation: 15 Years of Multinational Experience through Uranium Mine Remediation Exchange Group (UMREG), TECDOC 1431, Vienna, Austria, 2011.
60. Kahnwald, S. Clean up of a radioactively contaminated legacy site in Oranienburg, Germany. In Proceedings of the 2nd Workshop of the European NORM Association (ENA), Vienna, Austria, 20–22 October 2020.

61. Leopold, K. Chemical types of bounding of natural radionuclides in TENORM (Technologically Enhanced Naturally Occurring Radioactive Materials). Ph.D. Thesis, University Duisburg-Essen, Duisburg, Germany, 2007.
62. McGregor, D.S. Materials for Gamma-Ray Spectrometers: Inorganic Scintillators. *Annu. Rev. Mater. Res.* **2018**, *48*, 245–277. https://doi.org/10.1146/annurev-matsci-070616-124247.
63. Hendriks, P.H.G.M.; Limburg, H.; Meijer, R.J. Full-spectrum analysis of natural γ-ray spectra. *J. Environ. Radioact.* **2001**, *53*, 365–80. https://doi.org/10.1016/S0265-931X(00)00142-9.
64. Limburg, H. Calibration Procedure. The Medusa Institute. 25 October 2021. Available online: https://the.medusa.institute/display/PD/Calibration+procedure (accessed on 28 April 2022).
65. Grasty, R.L.; Holman, P.B.; Blanchard, Y.B. Transportable calibration pads for ground and airborne gamma-ray spectrometers, Geological Survey of Canada. *Geol. Surv. Can.* **1999**, *90*, 23.
66. Van der Graaf, E.R.; Limburg, J.; Koomans, R.L.; Tijs, Transportable calibration pads for ground and airborne detectors for laboratory and in situ gamma ray measurements. *J. Environ. Radioact.* **2011**, *102*, 270–282. ISSN 0265-931X. https://doi.org/10.1016/j.jenvrad.2010.12.001.
67. Bronstein, I.N.; Sememdiaev, K.A.; Musiol, G.; Mühlig, H. *Handbook of Mathematics*, 6th ed.; Springer: Heidelberg, Germany, 2015.
68. van der Veeke, S.; Limburg, J.; Koomans, R.L.; Söderström, M.; de Waal, S.N.; van der Graaf, E.R. Footprint and height corrections for UAV-borne gamma-ray spectrometry studies. *J. Environ. Radioact.* **2021**, *231*, 106545. https://doi.org/10.1016/j.jenvrad.2021.106545.
69. Schwarz, G.F.; Rybach, L.; Klingele, E.E. Data Processing and Mapping in Airborne Radioactivity Surveys. In *Application of uranium exploration data and techniques in environmental studies. Proceedings of the Technical Committee Meeting, Vienna, Austria, 9–12 November 1993*; International Atomic Energy Agency: Vienna, Austria, 1993.
70. Amestoy, J.; Meslin, P.-Y.; Richon, P.; Delpuech, A.; Derrien, S.; Raynal, H.; Pique, E.; Baratoux, D.; Chotard, P.; van Beek, P.; et al. Effects of environmental factors on the monitoring of environmental radioactivity by airborne gamma-ray spectrometry. *J. Environ. Radioact.* **2021**, *237*, 106695.
71. Ohno, M.; Okamoto, K.; Umegaki, K.; Fujiyoshi, R. Results of simultaneous monitoring of soil 222Rn and moisture at different depths in a forest site in Fukushima Prefecture, Japan. *J. Radioanal. Nucl. Chem.* **2016**, *310*, 1013–1020. https://doi.org/10.1007/s10967-016-4946-7.
72. Schubert, M.; Schulz, H. Diurnal Radon Variations in the Upper Soil Layers and at the Soil-Air Interface Related to Meteorological Parameters. *Health Phys* **2002**, *83*, 1.
73. Siino, M.; Scudero, S.; Cannelli, V.; Piersanti, A.; D'Alessandro, A. Multiple seasonality in soil radon time series. *Sci. Rep.* **2019**, *9*, 8610. https://doi.org/10.1038/s41598-019-44875-z.
74. Fyodorov, G.V. Uranium production and the environment in Kazakhstan. In Proceedings of the International Symposium on the Uranium Production Cycle and the Environment, Vienna, Austria, 2–6 October 2000; International Atomic Energy Agency (IAEA): Vienna, Austria, 2002.
75. Uralbekov, B.M.; Smodis, B.; Burkitbayev, M. Uranium in natural waters sampled within former uranium mining sites in Kazakhstan and Kyrgyzstan. *J. Radioanal. Nucl. Chem.* **2011**, *289*, 805–810. https://doi.org/10.1007/s10967-011-1154-3.
76. Pandey, U. Assessment of gamma and radon in the Kurday mining site, Kazakhstan. Master's Thesis, Norwegian University of Life Sciences, Department of Plant and Environmental Sciences, As, Norway, 2021.
77. Kunze, C.; Walter, U.; Wagner, F.; Schmidt, P.; Barnekow, U.; Gruber, A. Environmental impact and remediation of uranium tailings and waste rock dumps at Mailuu Suu (Kyrgyzstan). In *Low Environmental Impact Uranium Mining and Remediation: 15 Years of Multinational Experience through Uranium Mine Remediation Exchange Group (UMREG)*; TECDOC 1431; International Atomic Energy Agency (IAEA): Vienna, Austria, 2007.
78. Vandenhove, H.; Clerc, J.J.; Quarch, H.; Aitkulov, A.; Savosin, M.; Torgoev, I.; Mirzachev, M. 2011, Phased Remediation Approach for Prevention of Risks Linked with Uranium Tailings in Mailuu-Suu, Kyrgyzstan. In *Low Environmental Impact Uranium Mining and Remediation: 15 Years of Multinational Experience through Uranium Mine Remediation Exchange Group (UMREG)*; TECDOC 1431; International Atomic Energy Agency (IAEA): Vienna, Austria, 2011.
79. Havenith, H.B.; Torgoev, I.; Meleshko, A.; Alioshin, Y.; Torgoev, A.; Danneels, G. Landslides in the Mailuu-Suu Valley, Kyrgyzstan—Hazards and Impacts. *Landslides* **2006**, *3*, 137–147. https://doi.org/10.1007/s10346-006-0035-2.
80. WISUTEC. Report on Task 3.2 "Site Characterisation of the Mailuu Suu Uranium Legacy Site", INSC EuropeAid/138036/DH/SER/KG "Conducting an Integrated Environmental Impact Assessment and Feasibility Study for the Safe Management and Remediation of the Uranium Legacy Complex of Mailuu-Suu—Contract MC4.01/14". 2019; *unpublished*.
81. Weather Data of Andijan Airport. Available online: https://www.wunderground.com/calendar/uz/%D0%B0%D1%81%D0%B0%D0%BA%D0%B0/UTFA/date/2021-10 (accessed on 15 April 2022).
82. Federal Office for Radiation Protection of Germany; Department of Radiation Protection and Environment. *Calculation Guide for the Determination of Radiation Exposure Due to Environmental Radioactivity in Mining*; BfS-SW-09/11; Salzgitter: Salzgitter, Germany, 2011.
83. Schmidt, P.; Barthel, U. *Appendix 1 (Radiological Assessment) to the Environmental Impact Assessment for the Remediation of WD1 and WD2, Mailuu Suu*; Component A.; Disaster Hazard Mitigation Project (DHMP): Chemnitz, Germany, 2006.