Aerial monitoring of environmental radioactivity

Chief Scientist's Group report

September 2025

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Dr Robert Bradburne
Chief Scientist

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Foreword

This document has been prepared for the Environment Agency by Eden Nuclear and Environment Ltd, working under the Radioactive Substances Regulation (RSR) - Ad-hoc Monitoring and Technical Support Framework Services Contract. Sub-contracts were placed with researchers from the University of Bristol who provided relevant examples of radiation monitoring research using UAVs, based on deployments by them and by a connected company Imitec Ltd. The technologies discussed in the report are an illustration of the scientific capabilities of UAV systems for monitoring radioactivity in the environment, now and in the future. It is not an exhaustive account of all UAV technologies and ancillary components which could be used for the purposes of environmental radioactivity monitoring. The inclusion of technologies and techniques in this document is not a statement of recommendation by the Environment Agency or any of the report’s authors.

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Executive summary

Uncrewed Aerial Vehicle (UAV) technology has developed at pace in the last ten years. UAVs are finding many roles in the nuclear industry and have uses in on site surveying and measurement, asset inspection, and environmental monitoring. The Environment Agency needs to understand the benefits and limitations of UAVs in order to inform its assessments of potential industry proposals to use these technologies for environmental monitoring. Knowledge in this area may also support the independent environmental monitoring programmes undertaken by the Environment Agency and its partners.

This report explores the potential applications of UAV technology for the monitoring of environmental radioactivity. It is presented as two main sections. In the first, published literature and information from the last 10 years is reviewed relevant to the use of UAVs for environmental radioactivity monitoring. A wide literature search has been conducted. Publications have been identified that deal with UAV technology, radiation monitoring equipment suitable for field deployment, and applications in environmental radiation monitoring, including measurements of Chornobyl and Fukushima nuclear power plant fallout. Ancillary technologies that may enhance UAV radiation detection systems such as signal processing and visualisation schemes are also investigated in this work.

There are several advantages to the use of UAVs for environmental radioactivity monitoring which include:

- They may allow monitoring in areas which may be difficult or unsafe for a human operator to access, such as a coastal sandbank.
- Rapid monitoring where ground-based monitoring would be slower, or damaging, such as over fields of crops or a protected habitat. Speed of monitoring benefits may accrue if the limiting factor is the time taken to access an area, rather than that needed for detection of the radiation.
- A greater understanding of the distribution and migration of radioactive species across the environment may be achieved, if repeat monitoring of large areas can be performed in conjunction with mapping technology.
- Visualisation and processing of large volumes of data to aid understanding. For example, viewing data on a map, or ideally, viewing measurements repeated over time, may allow conclusions to be drawn about the rate by which a contaminant is moving off land and into drainage systems or other environmental sinks. This information can also be used to determine the effectiveness of environmental remediation measures (if applied).
- For radiation incident scenarios, UAVs may be deployed with a lower risk to personnel who might otherwise need to enter the contaminated region. The radiation detection capability might even extend to monitoring of a plume containing

contaminated material, which might be more difficult and potentially dangerous using conventional mobile monitoring technology.

There are limitations to UAV use and existing ground-based monitoring methods may remain the most promising approach for some applications and environments. The main disadvantages of UAVs are:

- Unlike fixed monitoring stations, UAVs do not readily allow continuous measurements at precisely known positions.
- Some environments may be difficult for UAVs to access, such as up against cliffs or close to buildings, or where the ground is forested. Hand-held, back-pack, or wheeled vehicle systems may be better suited for these types of monitoring conditions.
- UAVs cannot get close or onto the ground, which may be necessary for detection of some types of radiation (such as alpha or beta radiation). As a result, current UAV systems are generally confined to monitoring gamma radiation. In contrast, a person can place a radiation detector in close proximity to the ground.
- A person at the site of a detected ‘hot spot’ of radioactive contamination can also investigate its physical, chemical, and radiological characteristics further by direct sampling and measurement, including laboratory analysis, as appropriate. UAVs cannot readily perform these additional types of characterisation.

In the second section of this report, the potential capabilities of future UAV systems for monitoring environmental radioactivity are considered. UAV technology is still advancing, with diverse applications being found. It will be shown that UAV radiation detection systems are also a developing technology. These developments may offer benefits in radiation monitoring activities, as performed by regulators and the operators of nuclear facilities. Nevertheless, it is unlikely that UAVs would fully surpass the advantages and benefits of traditional fixed monitoring points or ground-based capabilities (including manual sampling and monitoring). Available evidence suggests that UAVs could be effectively utilised as an additional technology in the ‘toolkit’ of techniques that can be deployed for environmental radioactivity monitoring. Recommendations have been made in relation to possible further consideration of the practicability of greater deployment of UAV technology in the context of monitoring radioactivity in the environment.

1 Introduction

1.1 Background

The Environment Agency regulates radioactive waste disposals and discharges in England from nuclear sites, as well as the keeping and use of radioactive materials and the accumulation of radioactive waste on non-nuclear sites. As part of this regulation, the Environment Agency and its partners undertake independent environmental monitoring near nuclear sites to assess impacts of artificial sources of radioactivity in the environment to people and wildlife. This can be time consuming and labour intensive. There is also a requirement for nuclear site licensees to establish their own environmental monitoring programmes, using Best Available Techniques (BAT). UAVs represent one possible technique that could be useful for environmental radioactivity monitoring.

Leaving aside military uses, UAVs are finding applications in many civil areas, for example to allow visual monitoring of power lines (National Grid, 2024) and mapping of agricultural land to determine growth patterns. They are also now increasingly used to deliver items, together with uses that include commercial, scientific, and medical applications. An example of the latter is their use to conduct surveillance and control of the vectors for malaria (i.e. mosquitos) (Mechan et al., 2023). These applications have features in common with the use of UAVs for radiation monitoring. That is, they typically require a package of monitoring equipment to be lifted to a known position, allowing viewing and measurement of whatever parameter is of interest. On that basis, it is unsurprising that UAVs have also been considered a potential tool for radiation monitoring purposes (Woodbridge et al., 2023).

The Environment Agency needs to understand how UAV systems could assist environmental radioactivity monitoring programmes, now and in the future, in order to assess future nuclear industry proposals to use aerial technologies. This requires staying abreast of the benefits and limitations of established and new UAV technologies. It is also important for the Environment Agency to determine whether UAVs could potentially support its own environmental monitoring activities. The aims of this project are to review published literature and information about developments in UAV technologies for environmental radiation monitoring, and to assess the likely future capabilities of such systems. Technological developments in both UAV technology and radiation detection systems suitable for use on UAVs are covered, together with other relevant topics such as data processing and visualisation methods that can be used in conjunction with UAVs.

It is essential to consider wider applications of UAVs, because their potential market for specific radiation monitoring applications is limited. In contrast, the overall market for UAV technology for all civil applications is large, with an estimated size of $10BN/year (Commercial UAV News, 2023). It therefore seems likely that the UAV platforms could be used for radiation monitoring will be general purpose types, with the radiation monitoring payload provided by a specialist company with the expertise to integrate radiation monitoring devices with an ‘off-the-shelf’ UAV. It seems sensible to consider the capabilities of the UAV separately from that of the packages that allow for radiation monitoring. The latter tend to be produced by comparatively small companies and are often bespoke for the application. This allows the companies producing radiation monitoring equipment to have a measure of 'UAV platform independence.'

1.2 Approach

The first half of this report (Sections 3-6) is a literature review of developments of UAV technologies for radiation monitoring that have taken place over the last 10 years, although occasional references to older articles are made (where appropriate). In this section of the report, the term radiation is used to denote gamma radiation unless specifically stated. Many reports are available in the literature, including review articles, examples of applications, and technology developments. The literature review is categorised accordingly. This details the likely applicability of the present generation of UAV based radiation detectors for the environmental monitoring situations that are potentially relevant to radioactive substances regulation. The potential for UAV systems to collect environmental samples for later laboratory analysis is not considered in this report.

The second half of this report (Section 7-11) is a 'horizon scanning' exercise which looks ahead to technological developments that can be anticipated in the future. These will most probably increase the range of applications possible, and the capability of UAV based environmental radiation monitoring systems. It is often the case that developing technologies find applications that are beyond those originally envisaged. This may well be the situation with UAVs and radiation monitoring. However, to constrain the areas investigated to those of immediate relevance, there is an initial consideration of typical environmental monitoring tasks performed by the Environment Agency, licensed nuclear site operators, and their contractors.

A brief examination of potential safety and environmental protection barriers to the deployment of UAVs for general environmental monitoring purposes is provided in Appendix A.

2 Methodology

2.1 Scope of Literature Review

For the literature review, the intention has mainly been to identify and comment on all major technologies and applications relevant to the use of UAVs for environmental radioactivity monitoring. Initial searches showed that many published articles reported research and development studies rather than straightforward applications of standard technology. As such, useful articles often contained information on a particular radiation monitoring system as well as details of an application. For these reasons it seemed most useful to organise this report into separate sections first reviewing and summarising the technology (Sections 3 and 4). The application of UAVs for radiation monitoring is then addressed (Section 5). This approach was adopted even if individual referenced articles covered both the technology and its application for radiation monitoring. To have done otherwise would have led to a structure where it might have been difficult to identify key themes in the reviewed articles. Using this approach, UAV applications for radiation monitoring have been grouped into seven different themes as identified during the examination of the literature. For example, it became apparent from initial searches that the International Atomic Energy Agency (IAEA) had played a leading role in promoting these applications. It was therefore useful to identify and discuss that organisation's activities as its own theme. The seven UAV application themes are:

- IAEA activities.
- Case studies reported at the IAEA Brno meeting.
- Fukushima related radiation mapping activities.
- NORM identification and mapping.
- Perspectives from Portugal.
- Monitoring after nuclear power plant accidents.
- Detection of lost or maliciously placed sources.

There are other potential uses of UAVs for monitoring radioactivity in the environment that may be of value in agriculture and mineral resource mapping. Examples include repeat mapping of fields to show where watering is required, as dry soil will exhibit increased gamma radiation levels when measured from a point above the ground. Similarly, fertiliser levels can be determined as the potassium-40 (^{40}K) in potash fertilisers is measurable. It should also be possible to estimate snow depths, which may have a value in predicting the prospects of flooding when the snow melts. These potential applications of UAVs for radiation mapping are noted for completeness but are not discussed further in this report. Furthermore, it has not been the intention within this report to deal extensively with the various techniques and devices for radiation detection. Nevertheless, a brief explanation is provided, where appropriate.

Both standard search engines and more academically oriented ones (e.g. Google Scholar) were used for the literature survey. Many relevant articles were found, more than could be addressed in this report. It was therefore decided to report a range of work. Thus, IAEA activities were given prominence as were surveys for measuring fallout from the Chornobyl and Fukushima nuclear power plant accidents. Developments and studies have been occurring worldwide, and it seemed important not to be overly selective on a geographic basis. As an example, papers with Portuguese authors were considered, even though that country does not have a domestic nuclear power industry. There were also articles found from some of the major technology developing nations, such as the UK, USA, and China.

2.2 Environmental Monitoring Scenarios

A significant amount of research and development has been undertaken involving UAVs, including many applications of aerial monitoring of gamma radiation. To help organise this knowledge in a relevant context for this project, reviewed literature was mapped to five environmental monitoring scenarios. These scenarios were considered to provide reasonable coverage of the diverse types of environmental radioactivity monitoring that the Environment Agency, the nuclear industry, and their contractors might undertake.

The environmental monitoring scenarios used were:

- Activities to inform the remediation of a legacy industrial site.
- Routine surveys close to a permitted discharge from a nuclear site.
- Localisation of point sources (e.g. heterogeneous particles or lost sources).
- Mapping widespread contamination in the environment following a nuclear accident.
- Mapping a release in the urban environment (e.g. a radiological terrorist incident).

These five environmental monitoring scenarios are distinct from the seven themes used to help examine the applications of UAVs for radiation monitoring and should be considered separately. The literature review concludes with a consideration of the five environmental monitoring scenarios that includes discussion of the likely scenarios and whether UAV based monitoring would be of assistance (Section 6).

2.3 Scope of Horizon Scanning

In this second part of the report, emerging technologies, and opportunities for improved capabilities suitable for aerial monitoring of environmental radioactivity, are discussed in a 'horizon scanning'" exercise. It is clearly not possible to state definitively when (or if) a particular innovation will reach a point of maturity where it is practicable in industrial applications. Nevertheless, varying levels of resource are being devoted to product development in relevant areas. Indeed, several research trends were identified from the work performed in the literature review and following consultations with Environment Agency staff and the project team members (including the University of Bristol). These trends were further investigated and have been reported (Sections 7-11). Prominence was given to techniques that show promise for practical application, rather than being prospects for the distant future. Inevitably there is not an absolute split between the contents of the literature review and horizon scanning. Some future developments for example, are discussed in the literature review in the context of present limitations (e.g. on battery technology).

3 Background to UAV systems for monitoring environmental radioactivity

In the first half of the report, the likely requirements and monitoring strategy for a UAV radiation monitoring system are briefly considered (Section 3). It is assumed that the system would be deployable as part of an environmental monitoring programme.

The literature survey is then presented, firstly according to the typical elements of a UAV radiation monitoring system (Section 4) and secondly, addressing specific examples of monitoring applications (Section 5).

3.1 High level requirements for a UAV radiation monitoring system

This section contains an outline framework for considering typical environmental radioactivity monitoring requirements, which is based on what is currently possible technologically. Potential monitoring strategies are therefore considered, as are scanning patterns. This is not a definitive 'requirement specification' but it is intended to assist an analysis on what is currently possible and the necessary compromises that inevitably exist in the development of engineered systems. One clear example is the compromise between payload weight and flight duration, which applies to all aerial technologies.

A UAV radiation monitoring system is likely to consist at a minimum, of a UAV of one of several possible types, radiation measurement technology, and positional measurement systems to determine lateral position (e.g. a Global Positioning System (GPS)) and height above the ground (e.g. a laser range finder). It may also have more sophisticated positional measurement systems capable of recording the surface topography below, such as a scanning Light Detection And Ranging (LiDAR) system or a 3D image recording system. Signal processing to improve the imaging capability may also be used, either in real time or off-line. The capabilities of these ancillary components of a UAV system are explored in later sections (Sections 4.5 and 11). Communication with the base station is also needed for navigation purposes. Monitoring data can either be stored on board of the UAV for later download or transmitted as it is collected. It is noted that radiation measurements are not particularly challenging in terms of data transmission bandwidth requirements. Conventional communications technology, such as is provided by phone (i.e., Global System for Mobile Communications (GSM)) networks, suffices for most applications.

There is no single radiation detection and measuring technology that is of universal applicability. This can be illustrated using two generic monitoring scenarios. To detect low levels of radiation for routine monitoring, a large detector volume will normally be more efficient. It can potentially detect the desired intensity of radiation in a shorter time, allowing faster movement over the ground. A limiting factor is likely to be the maximum weight that can be carried by a particular model of UAV i.e. larger detector volumes are associated with higher weights. A system optimised for sensitivity might be useful in scanning large areas of land to identify whether there is any contamination present and ideally to distinguish naturally occurring radioactive material (NORM) from anthropogenic radiation.

Other monitoring scenarios may require the identification and quantification of detected radiation at much higher intensities, for example, after a major nuclear accident. Here, the requirements are somewhat different to those associated with routine monitoring scenarios. Information on the spatial distribution of environmental contamination and the associated public health risks is ideally needed in real-time to inform the emergency response. For nuclear accident scenarios, electronically faster and smaller-volume detectors can achieve measurements at higher radiation dose rates before reaching signal saturation. If semiconductor detectors capable of spectrometry are used, then the identities of radionuclides present can also be quickly determined, thereby enabling accurate dose quantification to underpin risk assessments.

It is possible that two types of radiation detector could be present on the same UAV if the payload were within the UAV's capability. This approach would seek to exploit the benefits of differing detector technologies. Alternatively, two UAV systems could be used, as could a single UAV with interchangeable detection systems.

Other factors that will need consideration in any practical system would include:

- Ease of deployment. UAVs generally have limited range; therefore, they will often need to be launched from a point near to the site to be monitored. This favours systems that can be transported easily, such as ones that can fit into a car or van and be lifted by a single person.

- Ease of maintenance. This includes possible decontamination of UAVs which have passed through a radioactive plume and subsequently become contaminated. Such considerations favour UAVs that can be wiped clean or washed easily.

3.2 Radiation monitoring strategy

It is important to note that the Earth's surface continually emits ionising radiation. The intensity of this naturally emitted radiation is typically low and harmless to humans and wildlife, but it varies spatially due to changes in rock and soil types as well as due to the presence of surface water. The intensity of natural airborne radiation also varies temporally e.g. releases from soils can be sensitive to atmospheric pressure and as a result vary with synoptic weather conditions. When monitoring radioactivity in the environment, it may be that the measurement of the natural variation is important, for example, when monitoring soil water content. Alternatively, it may be that mapping is necessary to determine the abundance and distribution of anthropogenic radioactive contamination. Accordingly, there are several distinct types of radiation monitoring that may be needed:

- Surface contamination mapping. The requirement is likely to be surveying of a large area at a defined sensitivity. Example applications would include post-radiation incident scanning to assess the extent of contamination, searching for radiation anomalies in areas with NORM, (including variations over time), characterising the accumulation of radionuclides in nearby environmental sinks after permitted discharges from nuclear sites, and searching for lost or maliciously placed radioactive sources. Here the requirement is for basic characterisation to detect anomalous variations over large areas, so detector types such as Geiger-Muller (GM) tubes and scintillator-type detector systems may be adequate.

- Radiation dose mapping, which is also sometimes referred to as dose assessment. Here a more quantified analysis is needed, resulting in a measurement of a dose rate or a similar quantity. This might be needed to assess the variations of dose rate across an area following a nuclear accident to determine which areas should be avoided or evacuated. In such a case, calibrated spectrometer detectors would be needed. These would be scintillation or semiconductor types which have a capability to measure the energy of the incident radiation, essential information for calculating dose. Height above ground measurements would also be needed to allow accurate ground-based dose calculations to be made from aerial measurements.

- Hot spot location i.e. characterisation. Some historic contamination events, such as historic (authorised) discharges from the Sellafield and Dounreay nuclear facilities areas have resulted in the environmental presence of isolated particles which have high radioactivity. These particles are sometimes known as radioactive 'hot' particles. Environmental monitoring responsibilities require affected areas to be routinely scanned and the comparatively rare and isolated particles to be identified, characterised, and safely removed. Characterisation is likely to require detectors optimised for radionuclide identification e.g. ones that can measure the gamma spectrum, such as solid-state types (semiconductor or scintillator-based spectrometers). Additionally, the detectors would need to be well calibrated, so that a quantified measurement of the radionuclide activity can be obtained.

- Radioactive plume tracking during radiation incidents. This is a highly specialised post-accident scenario where it is considered necessary to assess the spread of radioactivity in real-time, emanating from the accident site. The source of the plume may be outside the UK. It is likely that plume tracking would be conducted in conjunction with modelling and fixed monitoring activities e.g. via the Radiological Response Emergency Management System (RREMS). RREMS is an important component of the UK national capability for responding to a major radiation incident. It consists of fixed gamma dose rate monitoring sites across the UK, along with mobile monitors and mapping tools for displaying plume models. One early monitoring objective would be to validate the data being used in modelling. UAVs offer several advantages, including safety, as historically, manned aircraft were used for such missions. It seems likely that an extended range would be a desirable feature of such a system which might favour fixed rather than rotary-wing UAVs.

It is also possible that a hybrid approach would be adopted, such as the use of UAVs for location only. Ground based investigations might then be performed once the approximate location has been determined. However, in the context of scenarios with greater contamination, such as after nuclear accidents, this approach introduces a potential risk for the human operators within the ground-team. This is because the radiation dose has not been predetermined.

3.2.1 Survey methods

Radiation intensity from a localised source will decrease with increasing distance. There are two main reasons for this. The first is attenuation of the radiation by the air through interaction with atmospheric gas and water molecules. The second is geometrical dilution, which from an isotropic point source of radiation, will follow an inverse square law effect. This means that there is an exponential decrease of radiation intensity with increasing distance.

Aerial radiation surveys are typically conducted by flying the UAV at a fixed height above the ground in a series of parallel survey lines which cover the area of interest with a slight overlap. Care must be taken to avoid tall obstacles and to adhere to rules and regulations for UAV flying that are set by the Civil Aviation Authority (CAA). For example, UAVs should not fly more than 120 m (400 ft) above the ground surface. While this research focusses on the technological capabilities of UAVs for monitoring environmental radioactivity, it is nonetheless useful to briefly discuss potential legal restrictions (see Appendix A for further details).

To maximise the detection signal in an environmental gamma-radiation survey, it will be necessary to identify the optimal height for the UAV to fly at, such that it is clear of any potential obstacles, but not so high that the desired radiation emitted from the ground surface cannot be detected. Flying at a lower altitude means that the detection system will intercept more radiation from the ground, equating to a higher sensitivity. Also, due to the nature of radiation attenuation, lower energy gamma radiation will be attenuated down to a given intensity over shorter distances than higher energy radiation. Hence, the higher above the ground a measurement is made, a smaller amount of low energy radiation will reach the detector to be measured (compared to high energy radiation). This is partly why UAVs may be considered superior to manned aircraft for aerial radiation surveys as they are able and permitted to fly at much lower heights.

A further issue to consider is the spatial resolution. A requirement for a high spatial resolution survey will necessitate a survey pattern which has a much smaller spacing between lines of measurement, as well as lower speeds and heights for UAV movement. Many more flight lines would likely be needed to cover a set area, which in turn means the survey takes longer to complete. If lower spatial resolution is acceptable, for example, for regional surveys, then survey flights can be conducted at a greater height and line spacing.

For all heights used, the length of time necessary to monitor a particular area will depend on the sensitivity and spatial resolution required, as well as the detector used. In some cases, such as for the examination of areas of low levels of natural radioactivity, it may be necessary for the UAV to survey slowly to give time for sufficient counts to be received at each detector measurement point. In more contaminated areas, greater UAV airspeed may be possible. The desirable survey speed may not therefore be the maximum that the UAV is capable of; it will typically be determined by the sensitivity of detection needed. Furthermore, it is understood that a general rule of thumb is that the spacing of the survey lines should be approximately the same as the height above ground used for the survey flight. The reasons for this are explained further in the Section 4.6.1 dealing with spatial resolution and are discussed in the literature (van der Veeke, 2023).

Broadly, it is assumed that UAV systems will have software that allows either manual control or automated modes and that these allow preset flight patterns to be performed. A brief discussion of regulatory, environmental and safety issues associated with automated flight patterns is provided in Appendix A.

4 Current UAV technologies for monitoring environmental radioactivity

The following UAV system components for environmental radioactivity monitoring have been identified and are covered in the next subsections:

- UAVs and their design characteristics.
- Radiation detection systems suitable for UAV use.
- Other relevant but non-radiation monitoring instrumentation that UAVs can be fitted with to provide complementary information.
- Data processing and analysis tools.

4.1 UAVs and their design characteristics

A typical arrangement for radiation monitoring is likely to consist of the motive power unit i.e. the basic UAV, ancillary measurement systems such as GPS, together with a radiation detection package. Data may be stored on board or transmitted to a ground station for processing. Issues to consider for the UAV system include the physical size, its weight, the maximum weight of the payload and the overall range or flight endurance time. To a certain extent, payload weight and range may be traded i.e. a longer range can be obtained with a lighter load. Weather susceptibility must also be considered. Both wind and rain can challenge the stability and performance of both UAVs and radiation detectors. A useful summary of UAV technology as it might be applicable to typical nuclear decommissioning tasks is available (NDA, 2019), although the report is not specific to radiation monitoring. It also covers applications such as building integrity monitoring and inspection.

It is the use of lithium-ion battery technology that has allowed UAVs to reach their present degree of utility. Typical flight times for multi-rotor UAVs are of the order of one hour. That technology appears to have temporarily reached a plateau with there being no immediate likelihood of battery powered devices with much better power to weight ratios or longer flight endurance times becoming widely available. Some technological developments for batteries are nevertheless underway which may eventually provide minor advantages, such as lithium solid state batteries (Boaretto et al., 2021). It is therefore possible that any improvement to UAV flight time and range capabilities in the next few years will be incremental rather than radical. For example, limited advances may also occur due to improved aerodynamics being obtained through design refinements.

However, in the longer term, it is possible that fuel cell technology could offer notable range improvements, although this may be at the expense of more difficult refuelling and a need for the use of hazardous fluids or compressed gases (Mariscal et al., 2024). Such potential technological developments are covered further in the second part of this report.

There are also variants on the common multi-rotor UAV design that allow greater ranges and flight times. These variants include fixed-wing devices. Some of these can vertically take-off and land (VTOL) but still maintain the range advantages of fixed-wing aircraft over those with rotors. Other devices that are being developed include those that derive at least part of their lift from lighter-than-air gases (e.g. helium). They have associated advantages for radiation monitoring because of their reduced effective weight, so collisions may be less serious. They may also have a lower downdraught which provides the advantage of not disturbing potentially contaminated ground.

A recent review of UAV technology and applications (Mohsan et al., 2023) does not cover radiation monitoring aspects in detail, but presents a good summary of the present capabilities of UAV platforms and the challenges for the future. It considers all relevant aspects such as range and payload limitations, communications, the challenges of making autonomous flight safe, and security issues associated with maintaining control of UAVs. There is discussion throughout about flight endurance limitations and how they are dominated by the present capability of battery technology. Possible solutions are discussed, such as transmitting power from a ground-based laser to photovoltaic cells on the UAV. Unfortunately, as is implied by the section on ‘future research directions,’ none of these solutions appear to have serious prospects for use in commercially available systems. At least for general use in the short term. There may be specialist applications where extended ranges can be obtained, such as high-altitude UAVs by using lightweight photovoltaic cells on the wings. Another may be the use of the strong electric field around electricity transmission systems in UAVs that are tasked specifically with inspecting the power lines. As radiation monitoring is likely to require flying comparatively near to the ground in diverse areas, it seems that self-powered UAVs are all that would be deployable in the immediate future. The prospects for extended range UAVs are considered further in the horizon scanning section of this report.

A recent IAEA meeting in Brno (IAEA, 2022a; IAEA, 2022b) considered the relative advantages and disadvantages of single-rotor, multi-rotor, and fixed-wing UAV systems. Although the dominant technology appears to be that of multi-rotor electrically powered systems e.g. ‘quadcopters,’ it is prudent to consider the advantages and disadvantages of other designs first. Some monitoring requirements may be more suited to fixed-wing or single-rotor systems.

4.1.1 Fixed-wing UAVs

Fixed-wing systems have advantages in terms of range because the aircraft design is aerodynamically the most efficient method of flight. However, they are less manoeuvrable than multi-rotor systems and need to constantly maintain or exceed a minimum airspeed to avoid stalling. This has the knock-on effect of requiring the UAV to fly higher above the ground than its multi-rotor counterparts. Typically, the lowest safe survey height for a fixed-wing system would be around 50-70 m over relatively flat terrain. Such craft also typically require a higher degree of operator skill than is needed for multi-rotor systems and are also more adversely influenced by wind. For example, the operator needs to understand flight dynamics to fly a fixed-wing vehicle over a particular path and to avoid stalling it at slow speeds, for example when landing. One major limitation for fixed-wing UAVs relates to take-off and landing, where a runway strip is ideally needed. This is especially the case for larger fixed-wing UAVs, whilst some smaller craft can use parachutes to enable runway-free landings. Fixed-wing UAVs are much more likely to suffer damage than their multi-rotor counterparts due to their relative instability for take-off and landing, especially in inclement weather.

Generally, fixed-wing systems may be considered as best suited for large area survey applications. They may also be less prone to vibration, a potential advantage when used with some types of radiation detector. There are however some developments that may remove the requirements for a large support infrastructure such as landing strips. One relevant example is the fixed-wing UAV system produced by Wingtra, that takes off vertically before flying horizontally (Woodbrige, 2023) as shown in Figure 1.

Figure 1: Wingtra vertical take-off and landing (VTOL) fixed-wing UAV (reproduced from Woodbridge et al., 2023).

The application of such systems may be limited by legal requirements (see Appendix A for further details). Whilst these VTOL fixed-wing UAVs are capable of long-range flight, there may still be a need for an operator to retain a visual line of sight (VLOS).

Published examples of radiation surveillance tasks using fixed-wing UAVs tend to be at heights over 70 m for safety reasons. The safe height is likely to depend on the ground topography, with greater heights necessary over mountainous regions. Flying at such a height may restrict the radiation detection capability for all applications apart from detection of severe contamination. Even at a height which is well clear of all obstructions, there will be a need for the operator to be able to control the UAV safely.

Nevertheless, fixed-wing systems such as the Belgian developed ‘Penguin C’ (Geelen et al., 2022), shown in Figure 2, may have a role in environmental radioactivity monitoring. This is particularly the case following major nuclear accidents. This system is hydrocarbon-powered and launched by catapult, landing using a parachute onto an airbag for landing. It can cruise at about 20 m/s and has a flight endurance of up to 12 h with a payload of 2 kg. The extended flight times over those achievable with battery powered systems may be important following wide-area accidental releases from nuclear facilities. It might even be prudent to plan for a scenario where the UAV becomes contaminated from a plume of radioactivity. In such an event, the UAV would likely need to be decontaminated before it can be reused. Severe contamination levels may make reuse impossible, and the UAV must then be managed and disposed as a radioactive waste.

The authors of the ‘Penguin C’ study managed to use their UAV to measure the variation of naturally occurring ^{40}K in the soil. Their measurements complied within 30% of the soil sampling results. This result demonstrates that there will be a greater uncertainty from a UAV measurement taken at height compared to a value derived from a ground sample analysis. The researchers used caesium iodide (CsI) scintillator detectors, a selection based on a theoretical analysis of the best type of detector, given the weight limitations and other characteristics of their system.

Figure 2: Penguin C fixed-wing UAV on launch catapult (reproduced from Geelen et al., 2022).

A considerably larger fixed-wing system using a ‘Ranger’ UAV was developed in Finland and used as early as 2005 (Kurvinen et al., 2005). The Ranger is a multi-use hydrocarbon powered UAV, again launched from a catapult, and has a payload of up to 45 kg. With a wingspan of 5.7 m, it has much greater ground-based requirements and may have been developed primarily as an alternative to the use of manned fixed-wing aircraft. The authors managed to combine GM, sodium iodide (NaI) and cadmium zinc telluride (CZT) detectors into their monitoring package.

However, a more recent UK developed system has attempted to address the challenges of safely operating fixed-wing systems at low altitudes by minimising the weight of the vehicle (Connor et al., 2020). The UAV system uses a ‘Titan’ airframe, shown in Figure 3, and has a take-off weight of 8.5 kg including a 1 kg payload, allowing dual CsI scintillation detectors to be fitted. With a lithium polymer (LiPol) battery, this allows a 50–70-minute flight time with a speed between 14 and 18 m/s. The Titan fixed-wing UAV system has notably been used in the Chornobyl exclusion zone (CEZ).

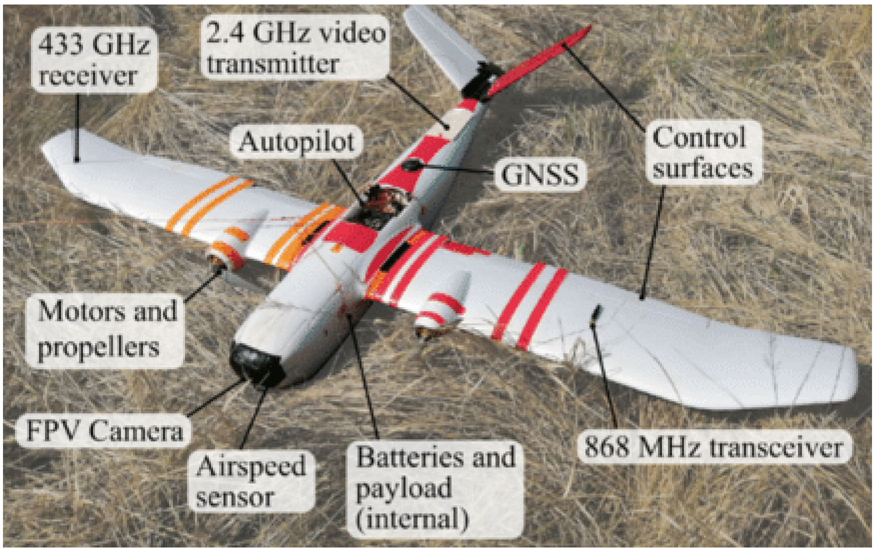


Figure 3: Titan Fixed-wing UAV system (reproduced from Connor et al., 2020).

With a comparatively small system, it was deemed safe to fly the Titan at a height between 40 and 60 m above ground level over very flat terrain. Nevertheless, the demonstration at Chornobyl was only performed after a multi-rotor UAV was used initially to check for obstacles and adequate radio reception. The minimum altitude was subsequently set to be 15 m higher than that of the tallest potential obstruction. The use of this system demonstrates that with modern electrically powered UAVs, weight can be reduced to the point that the consequences of a crash can be minimised, allowing safe flight at low levels.

The detector system on Titan was able to record signals with a caesium-137 (^{137}Cs) equivalent dose rate at levels down to 0.01 μSv/hr and up to 10 μSv/hr. Saturation of the detector at higher levels occurred, such as when the system flew over the Red Forest. It therefore appears that fixed-wing UAV systems are usable for wide area monitoring, their greater range currently providing an advantage over rotary-winged UAVs. These features may outweigh the disadvantages of lower manoeuvrability and more complicated take-off and landing arrangements, that necessitate a greater degree of pilot training.

4.1.2 Single-rotor systems

Single lift rotor systems operating with tail rotors i.e. remote-controlled helicopters, were originally developed as manned systems. When remotely controlled, they have potential advantages over multi-rotor systems, as they are more efficient and would therefore have range advantages. These UAVs are typically much larger than multi-rotor systems and tend to be fuel-powered, which enables larger payloads as well as extended flight times and range for survey missions. In general, single lift rotor helicopters are mechanically complex and are often the most difficult type of UAV to fly. This is because the tilt angle of the rotor 'disk' must be adjusted to balance the requirements of lift and forward movement, and the angle of attack of the rotor blades must also be controlled at the same time.

The difficult physical geography of some parts of Japan provided an incentive for single-rotor UAV development to facilitate agricultural tasks. This utilisation predates the Fukushima Daiichi nuclear power plant accident in 2011, with some experience of radiological monitoring occurring before then as well. For these reasons, these systems appear to have been the first types of UAV to be deployed following the accident (Furutani et al., 2013), with one type named the 'Robin-PARS', shown in Figure 4.

Figure 4: Robin-Pars remote controlled helicopter UAV (reproduced from Furutani et al., 2013).

Flying at heights between 50 and 250 m, the survey results are comparable to those obtained by ground-based monitors. Indeed, it is claimed that hot spot areas were detectable using the NaI scintillation detectors employed. Measurements were made showing radiation levels of up to values slightly in excess of 1 μSv/hr, presumably due to radioactive Cs contamination.

4.1.3 Multi-rotor systems

Multi-rotor UAVs seem to form the majority of UAV radiation monitoring systems. The other types discussed above are not mentioned as frequently in the available literature. For example, in (IAEA, 2022b), the authors describe the use of fixed-wing systems as 'generally rarer' (see page 13 of that Reference).

Multi-rotor UAVs are available in numerous different configurations, but the most common is the four arm 'quadcopter.' These have proved amenable to remote control, as functions such as level flight and stable hovering are easily achievable. As a result, they offer advantages in terms of ease of precision control compared to fixed-wing and single-rotor UAVs.

The ability to provide a stable horizontal platform is useful in environmental radioactivity monitoring applications, as the payload can be fixed underneath, sometimes alongside other sensors. An example of a commercially available quadcopter UAV system which uses plastic radiation detector materials (from Arktis, 2025) is shown in Figure 5.

Figure 5: Commercially available multi-rotor UAV with radiation monitoring payload from Arktis (reproduced from Arktis, 2025).

There is, however, a penalty associated with the benefits of multi-rotor UAVs. They are not as efficient as the other main types of UAVs, which translates to a more limited flight duration. Most multi-rotor UAVs are lithium battery powered, although some have been produced with power provided via a tethered cable.

There are already many examples of the use of multi-rotor UAV systems for radiation monitoring in the environment. Specific applications are referred in this section as well as in Section 5. One example (Connor et al., 2018) is of a system shown in Figure 6, which was used to monitor a Fukushima waste storage site during and after its construction. This simple quadcopter arrangement had a total mass of only 5 kg including a CsI scintillator detector. Radiation levels of up to 5 μSv/hr were measurable.

Figure 6: Quadcopter UAV with attached radiation monitoring package as used in Fukushima related monitoring activities (reproduced from Connor et al., 2018).

The system was used to survey at a height of only 5 m and a comparatively slow speed of 1.5 m/s. This was sufficient to allow a high spatial resolution for mapping several storage sites, and in one case showed that contamination was leaking out of some of the storage containers. Subsequent measurements, made after remediation had taken place, confirmed that the leaks had been stopped. This is illustrated in Figure 7 which show the reduction in intensity between measurements taken 9 months apart (Connor et al., 2018).

The authors used UAV systems with a photogrammetry capability and were first able to produce 3D renderings of the ground. The radiation measurements were then superimposed on the image of the ground. The three images in Figure 7a are perspective views of the same data but looked at from different angles. Rows of trees can be seen at the edges. The store is in the middle of the image but is somewhat obscured by the superimposed radiation data. As shown in Figure 7b, absolute measurement of radiation intensity on the site were made of up to nearly 5 µSv/hr.

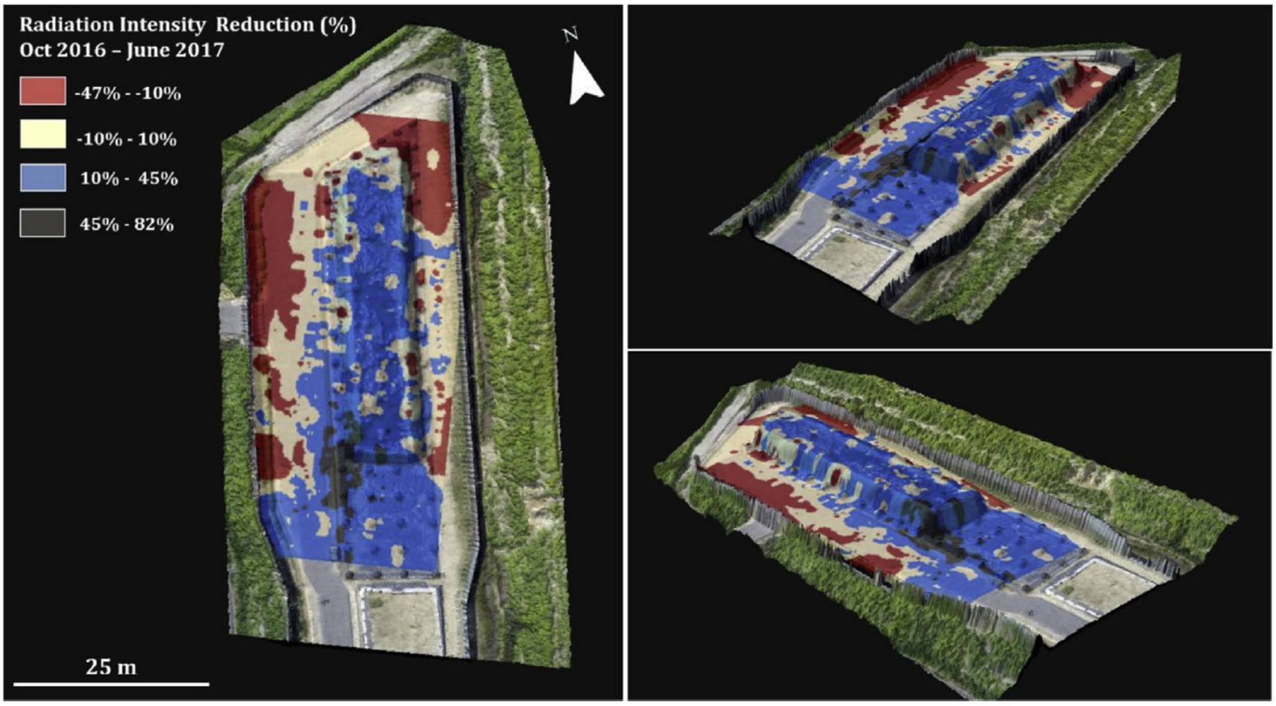


Figure 7a: Radiation intensity plots detailing the change in contamination across a Fukushima waste storage site between October 2016 and June 2017. Remediation occurred between the two surveys. 3D rendering of the site is presented from different angles using the aerial photographs taken by the UAV (reproduced from Connor et al., 2018).

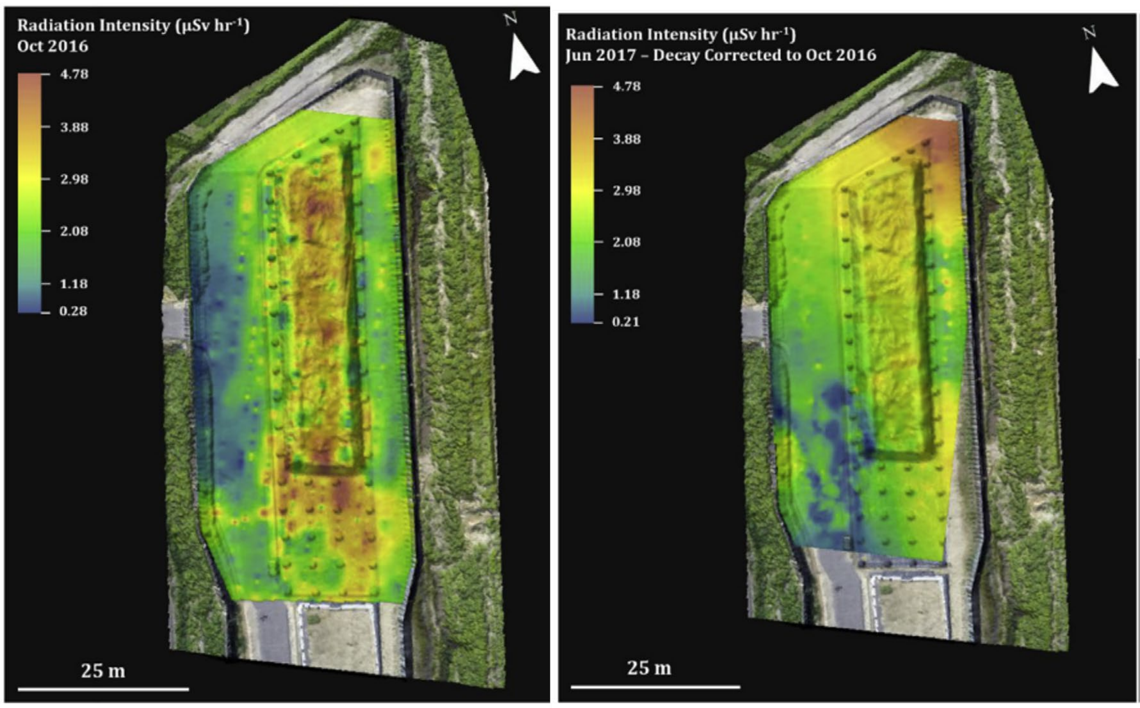


Figure 7b: Radiation intensity plot detailing the absolute radiation intensity across a Fukushima waste storage site in October 2016 (left) and June 2017 (right). 3D rendering of the site was created from the aerial photographs collected by the UAV (reproduced from Connor et al., 2018).

This example is illustrative that repeat measurements over time may be useful when monitoring waste storage and disposal sites where factors apart from normal radioactive decay may be affecting the radiation levels. This includes leaks, wash-out, run-off, remediation processes etc. The availability of UAVs for repeating radiation measurements in an area also provides an opportunity to characterise the environment around potential nuclear new build sites before activities involving radioactive materials commence. That is, UAVs could be an effective means for conducting pre-construction characterisation of a nuclear site, to establish a radiological baseline and inform future remediation.

Another study was conducted by a Ukrainian team on some of the heavily contaminated areas in the CEZ (Burtniak et al., 2018). A comparison is made with earlier manned flights performed in the 1990s. A noteworthy improvement is the reduction in the cost per hour of flight, which has reduced by a factor of 100 in moving from manned aircraft to UAVs. This is an important result because cost often influences how much environmental monitoring can be performed. Overall, this study illustrates the potential benefits that can be achieved with modern multi-rotor UAVs compared to manned flights.

Within the CEZ, one of the major radiation monitoring tasks has been the identification of ‘hot spots,’ i.e. potential areas of high contamination where radioactive items were buried, or possibly thrown, in the immediate aftermath of the disaster, without the relevant information being adequately recorded. Using a commercial UAV, mounted with NaI detectors and High Purity Germanium (HPGe) spectrometers, researchers achieved a spatial resolution of 0.5 m and a surface contamination sensitivity of 0.5 kBq/m^2 (Burtniak et al., 2018). The authors of the study reported a sensitivity of 0.8 µSv/hr by flying at heights of only 5 to 30 m and at a speed of 2.8 m/s. This contrasts with the earlier use of manned aerial vehicles that needed to travel at heights of over 200 m.

A more recent study by the University of Bristol in the CEZ used a DJI M600 quadrotor UAV with the Imitec AARM radiation mapping system containing CsI spectrometers (Scott, 2024). The team conducted radiation mapping of a hot spot in the Kopachi area that had been previously located by one of their large area fixed-wing UAV surveys. The multi-rotor UAV was used to provide a high spatial resolution map of the hot spot which pinpointed its location. The aerial system was also used to hover directly over the hotspot for several minutes to capture a detailed spectral fingerprint to identify the responsible gamma-emitting radionuclides responsible. Figure 8 shows comparable radiation maps between the fixed-wing and multi-rotor surveys conducted at 50 m and 15 m, respectively. This work showed a comparable spatial resolution and sensitivity to the Burtniak study as well as the complementary use of fixed-wing and multi-rotor UAVs.

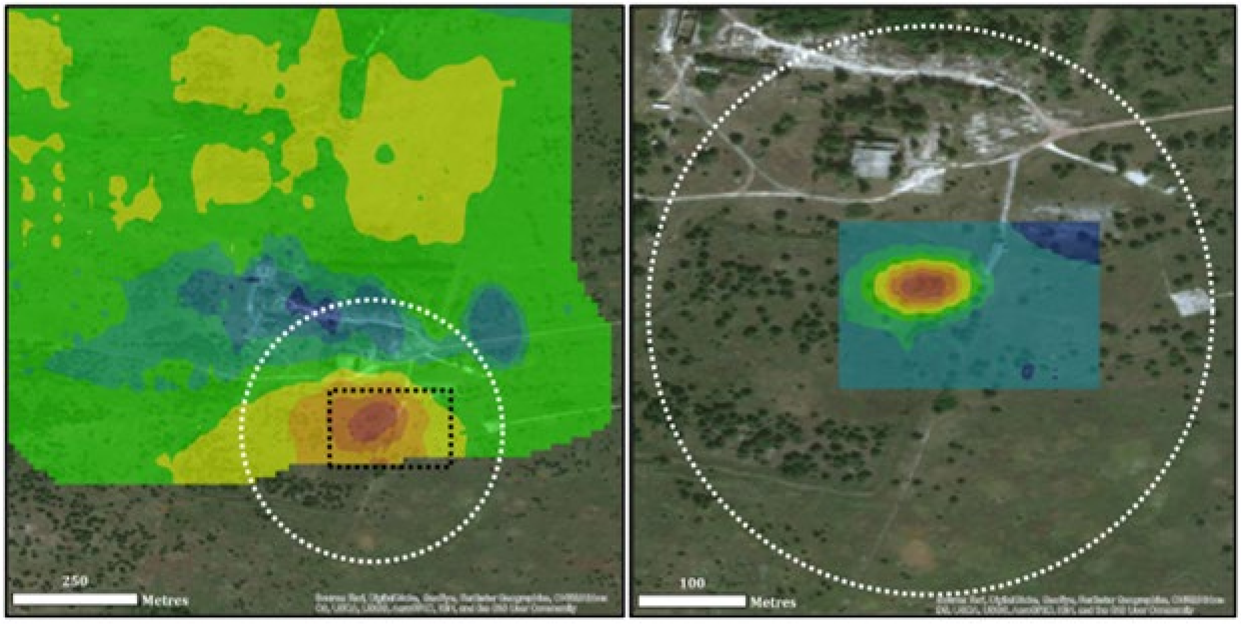


Figure 8: Radiation map recorded by a fixed-wing UAV over Kopachi, south of the Chornobyl nuclear site (left). The dashed white circle and black rectangle highlight the location of a radiation hot spot; and a multi-rotor UAV map pinpointing the same hotspot area (right) (reproduced from Scott, 2024).

These examples collectively show that multi-rotor UAVs have advantages in terms of manoeuvrability that allow them to fly safely close to the ground and to hover, an important consideration in achieving the desired sensitivity. It is for such reasons that multi-rotor UAVs will most likely dominate in terms of their use for radiation monitoring.

4.2 Radiation detection systems suitable for UAV use

There are many different types of commercially available radiation detector. They fall into two main categories which are gas ionisation and solid-state detectors. Other notable instruments such as neutron bubble detectors are generally for specialist uses or are obsolescent. They all vary in terms of their ability to detect different types of radiation i.e. alpha, beta, gamma, and neutrons. Additionally, some types of detectors only measure incident radiation intensity without providing usable information about the identity of the radionuclide that has generated it. They also have distinct characteristics in terms of the ‘noise’ that they generate, the minimum and maximum energy that they can detect and the efficiency with which they do so. There are further, practical aspects to consider in making a detector choice for a particular application. This includes the maximum detector size that can be produced, the physical limitations e.g. vulnerability to external influences including vibration, magnetic fields, temperature, water, as well as cost considerations.

Although radiation detection technology is not changing as rapidly as that for UAVs, there are developments occurring, such as the production of improved scintillators. An attempt has been made here to identify what is practicable technology now. In the second half of this report (Section 7 onwards), there is a consideration of what may be available in the future.

It is not the intention of this work to provide a full explanation of every type of radiation detector; several articles are available which go into greater detail. These include a report produced by Eden Nuclear and Environment for Sellafield Ltd which addresses the technology available for land-based beach particle monitoring (Newton and Tulip, 2020), an IAEA report on occupational radiation protection (IAEA, 2018), the IAEA report of their Brno meeting (IAEA, 2022b), amongst others. The Sellafield beach particle monitoring report also mentions the prospect of UAV use. Of note, a recently republished book (Geist et al., 2024) provides a comprehensive resource that deals with the interaction of radiation with matter (chapter 3) and explains topics such as gamma ray spectra, detector technology (chapter 4) and uses of such detectors to identify specific radionuclides (chapters 7-10).

The issues to consider specifically for use within UAVs include the following:

- The weight of the detector. This must be accommodated within the maximum UAV payload lift capability.
- The volume (or sometimes area) of the detector, which will determine the overall sensitivity of the package. The sensitivity will determine the maximum flying speed that can be used to detect radiation down to the desired intensity level.
- The energy measurement range of the detector. With a range of up to 3 MeV ideally needed for distinguishing different gamma emitters of geological (natural) origin but only 2 MeV necessary for anthropogenic gamma emitters.
- The physical characteristics and whether these are amenable to UAV flight. Some detector systems are fragile, hygroscopic, or sensitive to vibration.

4.3 Radiation monitoring instruments

Detection of radiation is normally achieved by means of an electrical signal pulse. Most detectors therefore consist of a mechanism for converting incident radiation into a measurable electrical signal and the necessary electronics to process it. Other types of radiation detection are excluded from discussion here. These include photographic methods where the radiation changes the state of a sensitive chemical and devices such as bubble chambers which can show the track of a charged particle. For UAV use, almost all applications will be expected to use detectors that are amenable to producing an electrical output that can be readily transmitted to the ground station, normally in real time.

Alpha and beta radiation consists of charged particles. Some detection technologies use that charge directly, but in others, a scintillation i.e. light pulse is produced and recorded that is then turned back into an electrical signal in a photomultiplier. For gamma radiation, which is uncharged, there are three mechanisms by which the ray interacts with matter. These are the photoelectric effect at low energies, the Compton scattering effect at intermediate energies, and electron-positron pair production for energies above 1.02 MeV. In practice, the Compton effect is likely to be the main mechanism for detection of gamma radiation arising from radionuclides of relevance to the monitoring scenarios identified in Section 2.2. The incident gamma ray (i.e. a photon) interacts with and is scattered by electrons in outer valence shells of the atoms in the detection material, releasing them. Depending on the detection system, these electrons are either detected directly or detected following successive physical events, when the produced electrons themselves produce photons in the visible light region.

Because the distance range over which alpha and beta radiation can be detected is limited, it is likely that UAVs will mostly find application in the detection of gamma rays. Unless otherwise stated, it should be assumed in the literature survey of this report that the UAV applications are aimed at gamma ray detection. However, many radionuclides that decay primarily by alpha and beta emission also emit gamma or X rays and these sometimes provide a viable method of detecting such radioactive substances at a distance. The potential application of UAVs to detect radionuclides that are primarily considered alpha and beta radiation emitters is addressed in the horizon scanning section of this report. This section examines likely improved capabilities that may emerge because of technological developments.

4.3.1 Gas ionisation detectors

Gas ionisation detectors work by detecting the ionisation of a gas within an electric field. When the applied voltage is high enough, a cascade occurs making the radiation easily detectable. Operated in this high voltage region, ionisation detectors are known as GM tubes. GM tubes are simple, lightweight, and low cost. They are also comparatively insensitive to vibration, can operate in high dose rate areas and require relatively simple control circuitry. However, they have limited lifetimes, are less efficient at detection, and provide no information on the energy of the incident radiation and by extension the source identity. Their response is also energy dependent. For these reasons they are sometimes considered outdated for UAV use, compared to other types of radiation detectors (Borbinha, 2020). Ionisation detectors used with lower voltages outside the GM region can provide more information. However, all the applications of ionisation detectors found in this review were for operation in the GM region.

4.3.2 Scintillation detectors

As a type of solid-state detector, scintillation detectors use a transparent medium in which an incident gamma photon interacts and causes a flash of light which is detected by a photomultiplier. There are several distinct types of scintillators available, with the dominant type made from thallium doped sodium iodide (NaI:Tl). Of note, doping of the basic scintillator is performed to produce light that matches the detection capabilities of the photomultiplier. CsI also doped with thallium or sodium has some advantages as it is less fragile, has higher density and slightly improved energy resolution. Other inorganic types also exist such as Cerium Bromide ($CeBr_3$) and Lanthanum Bromide ($LaBr_3$:Ce). Plastic scintillators (i.e. organic scintillators) are also usable but have extremely limited spectroscopy capability. Plastic scintillators do however facilitate the detection of neutrons, should that be a requirement. Additional information about many types of scintillators and semiconductor detectors is available elsewhere (e.g. Advatech, 2025).

There are two main types of photomultipliers, tube (PMT) and silicon (SiPM). The latter appears better suited for UAV applications because of their lower weight. Unlike tube types, SiPM does not require high voltages, and their performance is less sensitive to magnetic fields. Some early disadvantages associated with photomultipliers, such as noise production and temperature sensitivity, often made it difficult to accurately determine the true radiation level, particularly at low intensity levels. These issues have since been addressed by signal processing of the detected signal.

4.3.3 Semiconductor detectors

Semiconductor detectors are another type of solid-state device. Here, incident gamma rays cause electrons around atoms in the semiconductor detector material to be ejected from valence bands into the conduction band. This allows a pulse of current to flow that can be measured by electrodes placed across the semiconductor.

The most practicable semiconductor type for deployment on UAVs seems to be CZT as these have a high efficiency, counting speed, and good energy resolution, better than can be achieved with scintillators. However, detectors are yet, only available in small sizes of about 15 mm x 15 mm x 15 mm due to difficulties with growing larger defect-free detection crystals. Their small size and low detection efficiency limits the use of CZT for detecting environmental radioactivity as part of a UAV system, although that capability can in principle be improved using an array of crystals. At present, it therefore seems likely that their main UAV application would be for characterisation of radiation that had been detected by other means (e.g. a scintillator). Additionally, semiconductors on UAVs could also be used in high dose areas, as their rapid counting capability makes them less prone to saturation, compared to scintillators.

Another type of solid-state semiconductor detector uses High Purity Germanium (HPGe) transducers. HPGe detectors are more commonly found in analytical radiochemistry laboratories due to their very impressive energy resolution, which is far superior to most all other spectrometer materials. HPGe detectors have been demonstrated previously on UAVs (Rusňák et al., 2023). However, unlike CZT detectors, the germanium detection crystals require active cooling to operate. The associated mechanism to provide this cooling, whether by use of liquid nitrogen or other means, detracts from the available payload weight. It is understood that any use is likely to amount to a minimum payload of 20 kg. As such, they should probably be seen as unsuited (i.e., impractical) for UAV use, especially now that CZT devices have become available. It appears that CZT detectors are likely to be improved in the future, so can be considered a developing technology that will find increasing use in UAV applications. This is discussed further in Section 9.

4.4 The choice of detector for UAV based systems

Given that many different types of radiation detection device are available, it is reasonable to consider which is most suitable for deployment on a UAV. The final choice will depend on the application, but many applications, including those likely to be of relevance to environmental radioactivity monitoring, require detection of gamma rays at a distance. This can be best achieved with the use of large efficient detectors. Ideally these detectors will also be robust i.e. they should not suffer from temperature or vibration sensitivity, mechanical weaknesses, or be made from hygroscopic materials.

As they also provide a spectroscopic capability in addition to basic detection, inorganic scintillators combined with silicon photomultipliers seem to be finding the most applications on UAV systems. They appear to be of more general applicability than GM systems. The optimum type of inorganic scintillator is less clear, as cost issues may determine the choice. Of note, the effectiveness of the various types of inorganic scintillators has been studied (Lowdon et al., 2019). After considering a wide variety of scintillating materials, the authors modelled the capability of four different types, CsI:Na, thallium doped caesium iodide (CsI:Tl), $LaBr_3$, and cerium doped lutetium yttrium orthosilicate (LYSO:Ce). They took account of the efficiency of gamma ray detection, the wavelength, the energy resolution (to allow identification of the radionuclides of interest), and the efficiency with which the light can be detected by an associated photomultiplier. The authors concluded that $LaBr_3$ was one of the better choices for environmental monitoring, although one isotope of lanthanum, lanthanum-138 (^{138}La), is slightly radioactive and generates a background noise signal. Although the researchers did not model it, they stated that $CeBr_3$ was potentially preferable, unless it becomes possible to produce isotopically pure lanthanum that does not contain ^{138}La. Both materials are currently more expensive than NaI or CsI scintillators. Potentially for this reason, many of the articles in the published literature have used NaI or CsI scintillators. Their use may predominate in the near future. The subject of more advanced scintillator materials is discussed further in Section 10.

As well as inorganic scintillator and SiPM detectors, there is likely a role for semiconductor CZT systems. These have a high spectrographic resolution for radionuclide identification and are less prone to saturation in high-dose environments. For example, the surrounding areas of major nuclear accident. Hence, in the future radiation mapping payloads may commonly contain more than one radiation detector, to ensure that mission effectiveness is always maintained.

4.5 Non-radiological measurement systems

4.5.1 Positional measurements

Positional information, both in terms of latitude and longitude as well as height above ground, is likely to be important for UAV measurements for several reasons:

- The control and safety of the UAV flight.

- For use with the radiation detection system to identify the position of any detected areas of elevated radiation.

- A measurement of the UAV's height above the ground allows an accurate correction to the radiation intensity measured at the UAV, so that the likely intensity at ground level can be calculated.

A common feature of all UAV system measurements is positional information, as obtained from a global navigation satellite system (GNSS) (noting that the common term GPS is strictly the US operated system). There are other GNSSs. A separate GNSS may be incorporated into the radiation monitoring package to make it easier to interface with the radiation measurements. This also makes such systems easier to upgrade, because they are independent of the UAV and because data inputs can be temporally synchronised more easily.

The US government publishes data on the positional accuracy of GPS measurements (National Coordination Office for Space-Based Positioning, Navigation, and Timing, 2025). A simple GPS recorder may have an absolute lateral positional accuracy of only 5 m, although more sophisticated systems can achieve cm levels of accuracy. This higher accuracy is achieved with a technique known as differential GPS. It uses a base station at a known location nearby or a mobile phone mast. In general, height measurements are less accurate than ground measurements because of the high angle between a detector and the transmitting satellites. In some cases, the accuracy can be as poor as 25 m and no better than a measurement taken using the variation in barometric pressure. It is also worthwhile to note the performance of GNSS (including GPS) can deteriorate near reflectors such as buildings, cliff faces or trees, although that would not affect a UAV flying above those features. Absolute measurements of height i.e. altitude above sea level may not be essential for UAV radiation monitoring, instead it is the height above the ground immediately beneath which is significant to understand.

Although probably less relevant to environmental radioactivity monitoring, other positional measurement systems exist, such as those that use inertial measurements and dead reckoning to establish relative positions. They are sometimes referred to as inertial navigation systems (INS), which are used in GPS-denied areas e.g. inside buildings or cave systems. Systems are also available that establish their relative position with respect to a base station by measuring radio pulse transit times. Again, these systems may be more use inside buildings where there are no GNSS signals.

The development of a visual inertial odometry (VIO) system suitable for deployment on UAVs has been discussed (Bednár et al., 2022). This covers the limitations of GNSS-only position measurements, and ways in which the GNSS accuracy can be improved using position correction measurements from a base station (i.e. a reference point). The authors then describe methods of position measurement using cameras and inertial measurement units (IMUs) i.e. accelerometers. VIO uses the visual data to reduce the progressive increase in errors in IMU measurements. Both single and dual camera approaches are considered, the latter stereoscopic approach provides 3D data at the expense of an increased computational load. A similar analysis was performed by a different researcher

(Anand, 2021) who concluded that an absolute error of about 2 m might exist after a flight of 800 m. These systems are designed to provide positional information in real time and may be invaluable in locations where GNSS signals are unavailable such as within buildings. Unfortunately, the ability to recognise common features in optical images appears to be compromised by several factors such as weather induced changes in lighting conditions.

It may be worth considering the positional accuracy requirements for environmental monitoring. These may not be particularly stringent if other information is available, such as a visual recording made by the UAV that allows subsequent registration against features in the landscape. Recognition of such a feature may allow the identification of any particle or hot spot that needs to be returned to by the UAV, or by a person with ground-based equipment. Alternatively, if the need is to delimit a large area of NORM, a positional uncertainty of a few metres may be unimportant, and minor compared to that which exists because of the limited directional sensitivity of the radiation detector. Applications where accurate position measurement is necessary to ensure collisions do not occur might require specific collision avoidance technology and software. This might be preferable than relying on absolute positional measurements.

4.5.2 Proximity/distance measurement and other optical systems

Measurement systems are available to measure surface topography and the UAV's height above ground. These can be based on optical or ultrasonic sensors, but the most common appear to be scanning 'Light Detection And Ranging' (LiDAR) systems. These systems scan the area, measuring the time taken for reflected light to return to the UAV, allowing a 3D map to be constructed as a point cloud.

LiDAR systems are capable of revealing small variations in height that may not be apparent in a normal image obtained by a conventional camera. However, there will be a weight penalty with UAV use, as the systems may weigh a few kg. Prospects for lower weight LiDAR systems are covered in Section 11.1 of this report. Limitations exist with LiDAR, in that some surfaces may lead to incorrect readings, such as water, partial vegetation cover etc. Hence, some knowledge is needed of surface features to correctly interpret the measurement data. The need for a LiDAR system may depend on how accurate a measurement is needed. They can normally produce a substantially more accurate measurement of height above ground than a GNSS, minimising uncertainty in the reported radiation intensity. As reported by van der Veeke (2023), standard GPS typically has small error in comparison to the ground area covered when mapping radioactivity in the environment. Other options should be considered in instances where higher accuracy is needed, as can be the case for close-to-ground high-resolution measurements.

As LiDAR systems are commercially available, the capabilities are not generally the subject of review in peer-reviewed literature. However, there are examples of applications in different areas, including mine clearance and forest management. One case study details a project led by the University of Bristol to produce a radiation map of part of the CEZ, where LiDAR was needed to produce a digital terrain model (Routescene, 2020).

This allowed correction of the radiation measurements and an understanding of the mixed vegetation in the area.

Images obtained using either visible light or beyond visual e.g. infra-red systems, may also be of use to allow detailed examination of the surface, and particularly the type of vegetation present. This might be important following a contamination event when there may be a need to determine how radioactive species were being taken up by several types of vegetation.

4.6 Data processing and analysis

As a minimum, a visual presentation of the environmental monitoring results is likely to be required. One of the major advantages of the use of UAVs, is that radiation intensity maps can be produced. This can also be performed using handheld or wheeled devices, but it may then be more difficult. This is particularly the case over mixed terrain, for example, where vegetation for example makes it troublesome to access a region at a consistent scanning height above ground. Many examples from UAV surveys have been produced showing radiation intensity displayed against position, such as that shown in Figure 9 from an overseas mining area (Scott, 2024).

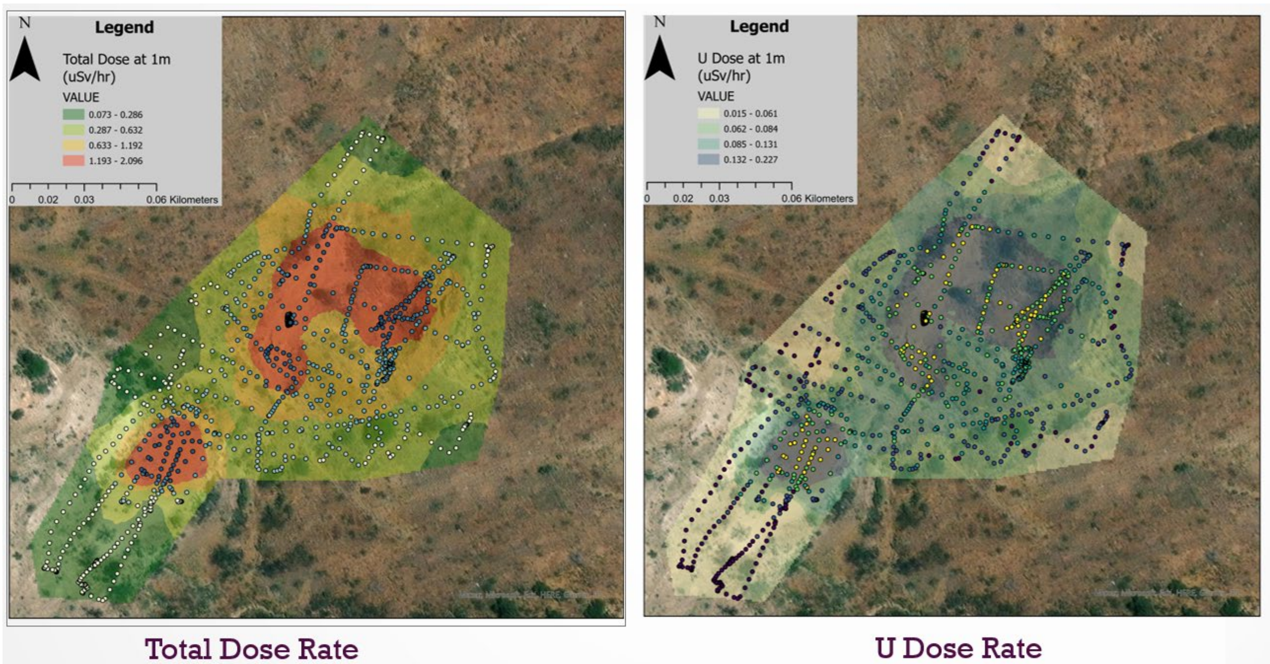


Figure 9: UAV survey data collected to assess the remediation efforts of a legacy uranium mine site in Arizona. Total dose intensity 'map' (left) and uranium dose intensity 'map' (right) (reproduced from Scott, 2024).

However, to produce a basic map of ground level radiation intensity requires corrections and interpolations to be performed. Data is nearly always corrected to a datum point (e.g. at ground level). This is so that if the survey were repeated, the UAV would not then need to record measurements from the same height. If the activity at ground level is to be determined, a calculation to allow for the height of the UAV above ground and the detection efficiency is therefore needed. To do so, necessitates provision of a range-finding capability to provide an accurate height above ground measurement.

Where the detector has the capability to determine the energy of the measured radiation (i.e. a spectrometer), processing can be performed to recognise the radionuclide involved. A further possibility is that in some cases, an analysis can be made of how deep a radioactive particle is buried (where relevant). This is because gamma rays will lose energy differently, according to their initial energy, during their passage through the ground. Such analysis is helped if there is prior knowledge of which radionuclides are present. However, identification of buried or shielded sources with UAVs may still be limited due to the aforementioned energy losses of the gamma rays. The topic of radionuclide identification is discussed further in sections below. A recent review of detection algorithms is available (Pradeep Kumar, 2020) that discusses issues related to the identification of individual radionuclides and discrimination against background noise. Signal-to-noise ratio can sometimes be improved by only considering energy deposited in a narrow range that encompasses any characteristic gamma photopeaks from the radionuclide being searched for.

As well as radiation from the intended target on the ground, gamma rays and cosmic rays originating from above the detector may be counted by the detection system. The weight limitations on a UAV generally prevent the use of shielding against cosmic rays. However, cosmic ray interactions have high energies and can often be removed by processing algorithms. Any counts produced within the detector itself from radionuclides that are naturally present, e.g. such as with ^{138}La in $LaBr_3$ scintillators, will also add to the background. Any electronic noise will likewise contribute to the background. For these reasons, although larger detectors are normally better, it is signal to noise ratio that is the more important parameter.

4.6.1 Spatial resolution

Most radiation detectors have limited directional sensitivity. This means the spatial resolution (sometimes referred to as lateral resolution or resolution in the horizontal direction) of a detection system that can be achieved, may only be comparable to the value of the UAV’s height above ground. As the UAV’s height increases, the spatial resolution of the measurements worsens. Directional sensitivity depends on numerous factors, such as the type of detector, the size and shape of the detecting medium, whether there is any shielding between the detector and the source, and the nature of the incident radiation. A detailed explanation of the sensitivity of detectors of different types is provided elsewhere and is outside the scope of this work (e.g., Newton and Tulip, 2020). In the context of environmental radioactivity monitoring, the need for a high spatial resolution may depend on the application. For an application such as identifying the boundaries of a wide area of contamination, the spatial resolution of the system may be comparatively unimportant. The same situation would apply if areas of NORM had to be delimited. However, for finding point sources, such as a lost source, it would be much more important.

A point source on the ground will be more easily detected if the detector is directly above the source, than where the UAV is not directly overhead. This is because there will be a drop off in intensity as the overall separation increases. This is a result of the inverse square law effect, together with increased attenuation in the air. Unfortunately, this inverse square effect may create a situation that will not provide much directional sensitivity (i.e. low spatial resolution). A rough criterion might be that a detector will have a spatial resolution, such that the locus of the points delineating where the intensity has fallen by half, forms a circle, with a radius equal to the height of the detector above ground. In practice the situation will be slightly better, because the detector may have some directionality, and because the above explanation is based purely on an application of the inverse square law. Attenuation of the radiation through the air will also ‘improve’ the spatial resolution. The situation is further complicated if the source of radiation is buried. In that case, ‘off-vertical axis’ paths from the source to the detector will have further to travel through the greater attenuating soil or rock, compared to gamma rays that travel straight upwards to a detector. This will improve the spatial resolution, possibly confining the detectable levels of radiation to a cone with a vertical axis, albeit the overall intensity above ground will be lower in all directions as well, because of that ground attenuation.

To improve the spatial resolution of a survey there are several possibilities. The first option is to fly the UAV lower. In the case of searches for point sources of radiation, a logical tactic may be to fly successively lower passes to pinpoint the source with increasing spatial accuracy. However, for mapping applications, improving the spatial resolution in this way will be impractical in terms of flight time, as the raster spacing of parallel flight lines also needs to be reduced to avoid missing areas. Collimators or radiation shields can also potentially improve directional sensitivity and thus spatial resolution. These add a major weight penalty, as absorption of gamma radiation requires high atomic number elements that are dense e.g. lead or tungsten. Their use is therefore perhaps at the limits of practicability for UAVs, especially if high energy gamma emitters are being searched for. However, if the task were to search for a point source of a low energy emitter, it might be viable to use a collimator. The third way to improve spatial resolution is using signal processing methods, as addressed below.

4.6.2 Signal processing to improve spatial resolution

Raw gamma survey data will typically consist of an array of point measurements, where for each measurement point there is a geospatial position (latitude and longitude), height above ground, and gamma counts, ideally as a recorded energy spectrum of counts. Systems will typically record at a rate of 1 or 10 Hz, meaning that a 30-minute survey flight would record up to 18,000 data points. These data are usually plotted as a 2D overlay on a map or satellite image, where simple linear interpolations are used to generate a coloured ‘heat’ map which shows the spatial variation in radiation measured by the mapping payload. In many cases this representation of the data can be sufficient to delineate features of interest. A more accurate representation of the true gamma field being emitted from the ground surface requires more advanced data processing techniques which can enhance the spatial resolution of the data.

Processing algorithms may be able to improve the spatial resolution from survey data, thus compensating for the inherently low directionality of most radiation detectors. A variety of signal processing methods appear possible to achieve what is generally termed a deconvolution. Mathematically, there are several possible numerical techniques for achieving such a deconvolution. A method known as Kaczmarz deconvolution has been reported in a study performed on small test samples (White et al., 2021). The processing appeared to improve the resolution of the image of two-point sources considerably, as shown in Figure 10.

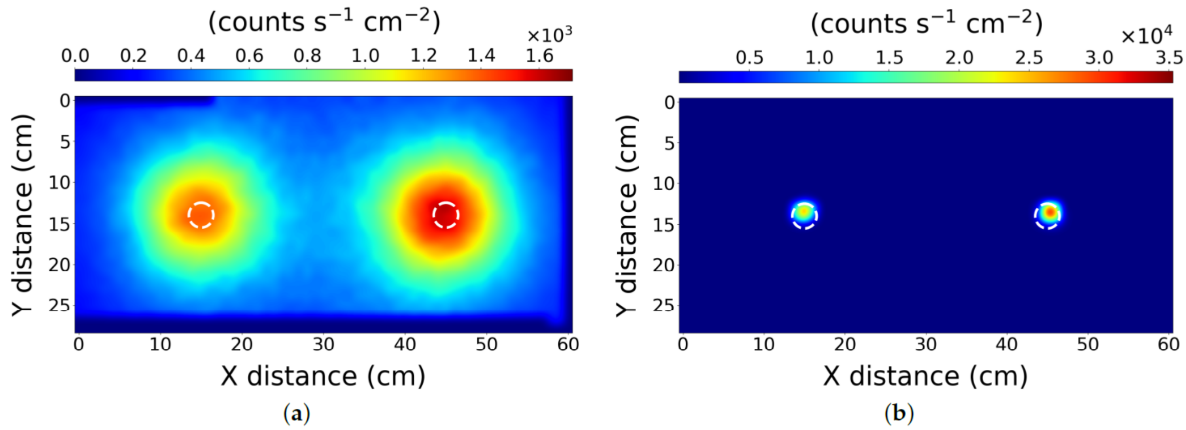


Figure 10: Intensity maps of two-point radioactive sources obtained by different data processing methods: (a) simple interpolation and (b) application of a deconvolution algorithm. The dashed white circles show the actual locations of the sources (reproduced from White et al., 2021).

It can be seen that the processing improves the resolution considerably. However, deconvolution generally requires a good signal to noise ratio to exist in the dataset to be processed. The example shown was obtained with test sources placed 30 cm apart and presumably a comparable distance away, scanned with a detector mounted on a robot arm. The authors suggest that the technique could be used on a UAV system, although this was not assessed in their study. The signal to noise ratio may not be as good in a map obtained from a UAV operating at a height, because of the low number of counts received by the detectors from the source compared to the measured background signal.

A further example of processing to improve spatial resolution has been demonstrated (Goren, 2019). This was a study over Chornobyl contaminated land and involved a UAV flight at several different altitudes. Figure 11 shows the radiation maps obtained at four different heights for the Kobachi weighbridge.

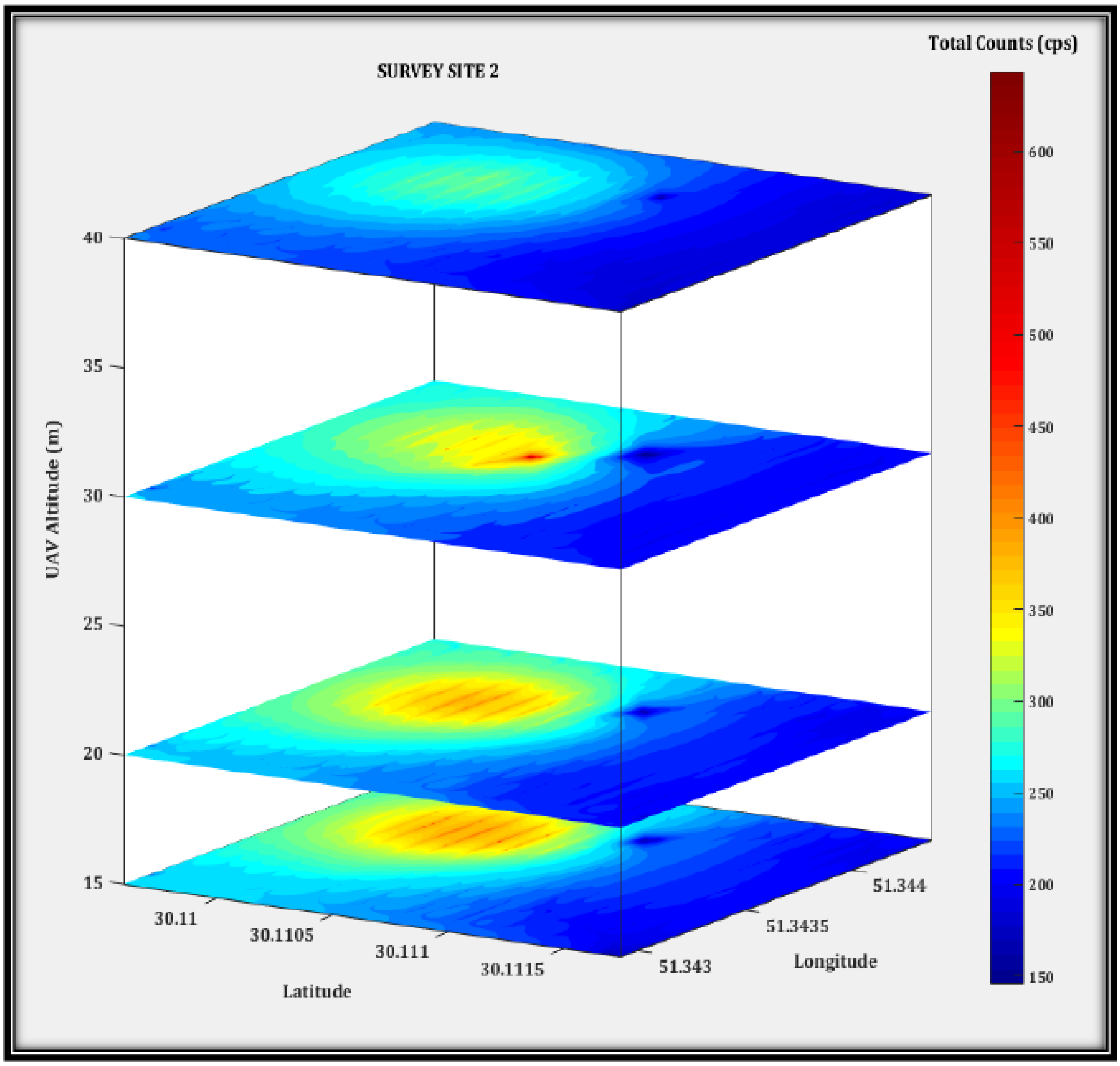


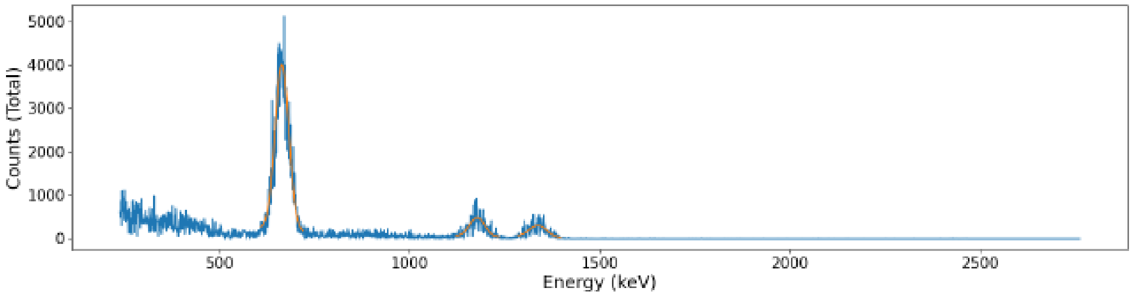
Figure 11: Radiation maps obtained at different heights with a fixed-wing UAV for Kobachi weighbridge in Chornobyl (reproduced from Goren, 2019).

The extra information available from flying at different heights provides a greater depth of data that allows more advanced processing to be performed. The author describes this as a mathematical 'inversion,' although the Kaczmarz algorithm was again used. Improvements in resolution were obtained, although some of the data collected suffered from detector saturation effects because the hot spot source was so intense. Use of these advanced data processing approaches promotes the collection of UAV data at numerous different heights above the ground. This represents a departure from standard methodologies for aerial data collection where surveys are usually conducted at a single fixed height. Whilst such new methodologies will require a greater amount of data and survey flight time, it may be justified by the substantial enhancement in the spatial resolution of the data. Such processing is computer intensive and not yet possible in near-real time. However further development and testing can be anticipated in the future.

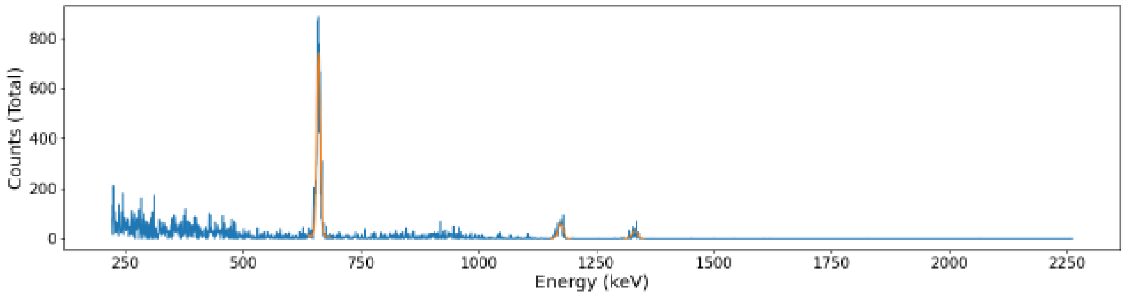
4.6.3 Application of signal processing to identify specific radionuclides

In many of the environmental monitoring scenarios considered in this report, it would be desirable to identify which radionuclides are generating the detected signals. This is not possible with GM detectors, but it can be achieved with both scintillators and semiconductor detectors. This is because they allow a measurement of the energy of each incident gamma ray photon. By recording many thousands of photons, a gamma energy spectrum can be recorded, which will typically contain several photopeaks imposed at different energies on a continuous but varying background signal. Each gamma-active radionuclide has one or more characteristic photopeaks in its emission spectrum, essentially like a fingerprint. By determining the energies of any recorded photopeaks, the radionuclides present in a survey area, or locality, can be determined.

The energy spectra from different radionuclides sometimes overlap, making discrimination between them challenging. There are two commonly used analysis approaches to extract concentrations of individual radionuclides from the measured spectra: the Windows Analysis method and the Full Spectrum Analysis approach (van der Veeke, 2023). The two methods take different approaches to extracting the contributions of overlapping radionuclides. Example spectra of a mixed radioactive source are shown below in Figure 12 and were taken from (Fearn et al., 2022).



Isotope	Energy (keV)	RI (%)	$\bar{R}^2$ of fit	CPS	ACF
Cs-137 (IND)	663.61	20.95±0.1	0.9002	144.5	2
Co-60 (IND)	1177.4	100.0±0.22	0.5705	689.69	3
Co-60 (IND)	1337.82	5.096±0.05	0.4593	35.15	3



Isotope	Energy (keV)	RI (%)	$\bar{R}^2$ of fit	CPS	ACF
Cs-137 (IND)	660.93	21.85±0.46	0.8887	7.57	2
Co-60 (IND)	1175.02	23.35±0.47	0.7105	8.09	3
Co-60 (IND)	1332.83	18.98±0.43	0.4972	6.58	3

Figure 12: Gamma spectrum from a mixed ^{137}Cs and ^{60}Co source produced with a CsI(Tl) scintillator (top) and with a CZT detector (bottom). In both cases, the three peaks are easily distinguished allowing ^{137}Cs and ^{60}Co to be identified. The energy resolution is greater in the case of the CZT detector (bottom), and the recorded count rate is greater for the scintillator (top) (reproduced from Fearn et al., 2022).

Researchers at the University of Bristol have published an open-source module to facilitate the automated identification of photopeaks in gamma spectra, to assist with rapid attribution of radionuclides in field applications (Fearn et al., 2022). Rapid identification of the radionuclides present in the environment is desirable as it may help to establish its origin and may be useful in determining the level of hazard present. This knowledge can also help inform the nature of any remedial measures (if required), which would be partly dependent on the abundance and half-life of the radionuclides as well as their radiochemical toxicity. The reference also contains a useful summary of radionuclides that might be expected to be found together according to their possible origin, including the 'early' and 'late' stages of major radiation incidents.

5 Current applications of UAVs for radiation monitoring

Applications and proposed applications for UAV radiation monitoring systems have been widely discussed in the literature. It has not been the intention here to identify and comment on every use (or intended use) that has been identified. In this section, reviewed articles have been grouped into seven different themes. While these themes show dependencies, they have been selected to help explore the key applications of UAVs reported in the published literature.

The seven themes are:

- IAEA activities.
- Case studies reported at the IAEA Brno meeting.
- Fukushima related radiation mapping activities.
- NORM identification and mapping.
- Perspectives from Portugal.
- Monitoring after nuclear power plant accidents.
- Detection of lost or maliciously placed sources.

It is unlikely that a UAV radiation monitoring package of universal applicability can be identified. Perspectives on the requirements will differ according to the authors' views, their specific monitoring application, and perhaps the location of use i.e. environment. For example, someone in a country without a domestic nuclear power industry may assign more importance to being able to find lost industrial radiation sources.

In this section, the work of the IAEA is detailed first. This is appropriate; the IAEA is the world's centre for cooperation in the nuclear field. It therefore undoubtedly has a role in coordinating, encouraging, and disseminating information in new technological developments. Further examples of applications (i.e. themes) are then presented.

5.1 IAEA's activities

The IAEA has performed activities relevant to UAVs at least as far back as 2012 via the Nuclear Science and Instrumentation Laboratory (as described in IAEA, 2021a). One driver for UAV development was the Fukushima nuclear power plant accident in Japan in 2011. The IAEA developed and tested instrumentation and methodologies for characterising the contaminated regions. This was part of the IAEA's action plan on nuclear safety, which has been intended to strengthen safety in many technical areas, not just in Japan. Specifically for Fukushima, the IAEA provided a complete UAV system for radiation measurements together with associated training for deployment within the Fukushima Prefecture. In the absence of fixed-wing UAVs with sufficiently long flight durations, the early UAV flights were made using uncrewed helicopters (Sanada and Torii, 2015). Of note, these aircrafts were previously used for spraying agricultural chemicals and the familiarity with this technology may have influenced decision makers. The radiation surveys provided useful information on the accident situation in the initial aftermath and the spread of radioactive material in the years that followed.

Although IAEA documents sometimes only emerge on a protracted timescale, the IAEA has an extensive set of publications and is a comprehensive resource of information on the present topic. Their activities have not been confined to post-accident activities such as those conducted around the Fukushima Prefecture. There has also been consideration of the use of UAVs to investigate uranium legacy sites, particularly in former Soviet Republics such as Kazakhstan (IAEA, 2021b). IAEA's training activities continue with at least one workshop held each year since 2022 (IAEA, 2022b; IAEA, 2023a; IAEA, 2024a). IAEA's work with UAVs is not confined to radiation monitoring activities. For example, they have also organised activities related to nuclear security. Given these capabilities may be of relevance in the localisation of missing sources/heterogenous radioactive particles, applications of this nature are considered further in Section 5.5.

5.1.1 IAEA's Fukushima Prefecture monitoring activities

The IAEA's final report about the radiation monitoring and remediation performed in the Fukushima Prefecture provides a useful explanation of the UAV work performed (IAEA, 2023b). It is particularly useful, as other sections place the monitoring in the context of all the necessary activities associated with the response and recovery from a major nuclear contamination event. That is, the UAV monitoring was an element of the overall monitoring programme which used 3500 fixed monitoring locations, car borne surveys, and sampling and analysis of foodstuffs and drinking water. In some cases, it proved practicable for the UAV to fly over the area to be monitored at a height of only 10 m. Comparisons were made between UAVs fitted with GM detectors and backpack systems operating at 1m height using NaI spectrometers, with correction factors being derived so that the measured dose rates could be extrapolated to ground level values., It appears this approach was designed to allow for an exponential dependence of the dose equivalent rate with height, as would occur with the attenuation of gamma rays with increasing distance. Presumably, this was because the Fukushima contamination was so extensive that the ground could be considered as an extended source.

Measurements of radiation must eventually be usable by those providing practical advice or instructions. The changes in radiation as contaminants are taken up by vegetation and are eventually washed out into water courses are important parameters to understand in the aftermath of the Fukushima accident.

UAVs appear to have been successfully tested in many of the environments that were affected by the Fukushima accident. This includes monitoring the activity of temporary storage sites containing contaminated soil, as well as monitoring areas of agricultural farmland (bounded by irrigation channels), steep-sided woodland and villages (Martin, 2018). Measurements using handheld devices might have been difficult to perform safely or effectively over wide areas of unconsolidated material or vegetation. UAV monitoring is well suited for the measurement of ^{137}Cs in these environments. It is a critical point that in any area, whether following an accident or a permitted release, there are likely to be several distinct types of surface topography that need monitoring. It would be incorrect to conceptualise the likely general monitoring task to a single category e.g. a flat beach.

Other reports dealing with IAEA's assistance on monitoring activities within the Fukushima Prefecture are available (IAEA, 2024b), although they do not necessarily focus on the use of UAVs.

5.1.2 Other (non-Fukushima related) IAEA activities involving UAVs for radiation monitoring

Other notable IAEA activities have included a four-day meeting in Brno in 2022 (IAEA, 2022a). This meeting focused on the use of UAVs for radiation detection and surveillance, and the technical output is now available (IAEA, 2022b). As this is a comparatively recent meeting and of direct relevance to the subject of this report, it will be considered in greater detail in Section 5.2. The document is more than a series of individuals' contributions; it has been edited to provide a coherent description of the aerial detection of radiation and surveillance topic. Albeit some of the applications are outside those likely to be of relevance to environmental radioactivity monitoring. There are also several case studies.

The Brno meeting report deals with different types of UAVs, categorising them according to size and likely payload. For example, they identified medium and small sized UAV systems are the most commonly used (i.e. those with a maximum payload of 10 kg). These are comparatively easy to transport (e.g. in a standard road vehicle). Larger systems are also considered, either uncrewed helicopters, or uncrewed fixed-wing aircraft. They normally require specialist ground support and transport.

The authors broadly consider that the rotary-wing UAVs will become the dominant technology for many reasons related to its minimum permissible operational height. Multi-rotors are typically operated with a lower minimum height which offers increased safety as well as greater spatial resolution and convenience (easier to control mid-flight and during take-off/landing). They note that such UAVs are finding applications precisely because they represent a good compromise between the use of crewed aircraft systems and the alternative of ground-based monitoring.

5.2 Case studies reported at the IAEA Brno meeting

5.2.1 Airborne HPGE gamma spectroscopy

A Czech institute has studied the use of HPGe detectors on uncrewed helicopter UAVs (Rusňák, 2022). This work discusses the difficulties and limitations of using heavy HPGe detectors. Nevertheless, the author regards them as useful both for radionuclide identification following an accident and for geological surveying and environmental monitoring. Furthermore, the author provides an example of use following development as part of a European research project (EURAMET) (Euramet, 2021). The Euramet project investigated seven different UAV systems, and it is possible that the HPGe systems was used as an example to show what was necessary to deploy an HPGe detector system with a weight of nearly 50 kg. Although the energy resolution of the system was particularly good, the only advantage over a manned helicopter appeared to be the potential benefit of avoiding a pilot having to fly into a contaminated area.

5.2.2 Norwegian UAVs for maritime monitoring

The Norwegian government has explored the implications of incidents involving nuclear powered vessels and materials in their coastal waters. The coastguard may have to respond to an incident with potential radiological impact. They have therefore developed UAV systems (Aas-Hansen, 2022) capable of flying in a marine environment and transferring data directly to their nuclear safety authority. They used a Teledyne FLIR Skyranger R70 with optical and infra-red cameras apparently capable of operating in Arctic conditions. The radiation detection module has sensors for gamma dose rate and spectrometry and neutron detection. The weather limitations of their system are not stated but it would be useful to know these. This application could be seen as one of the more limiting, due to the very harsh environment involved. Harsh operational conditions over North Sea marine environments may constrain potential uses in the UK.

5.3 Other Fukushima related mapping activities

Following a major nuclear accident such as the one that occurred at Fukushima in 2011, several radiological monitoring activities became important. Apart from those covered above, monitoring is needed to understand the way in which radioactivity is being transported though the environment by natural processes such as rainfall and run-off. Monitoring can also provide crucial insights into the efficacy of remediation measures such as the removal of topsoil. This knowledge may help return contaminated areas to agricultural production if residual contamination levels can be shown to be sufficiently low.

One priority after the Fukushima accident was the need to determine the movement of radionuclides, predominantly caesium-134 (^{134}Cs) and ^{137}Cs. One research team studied the problem of radionuclide transport on a typical farm with multiple stepped paddy fields and associated drainage systems (Martin et al., 2016a). This produced a need for accurate and detailed mapping as well as radiation level measurements. The measurements also had to be corrected to allow for attenuation in water. They used a comparatively small drone with a CZT detector, that was flown at the lowest possible safe height of 1-10 m over a farmstead to study an area 200 x 50 m. The UAV was also equipped with a LiDAR system enabling accurate mapping. An example is shown in Figure 13.

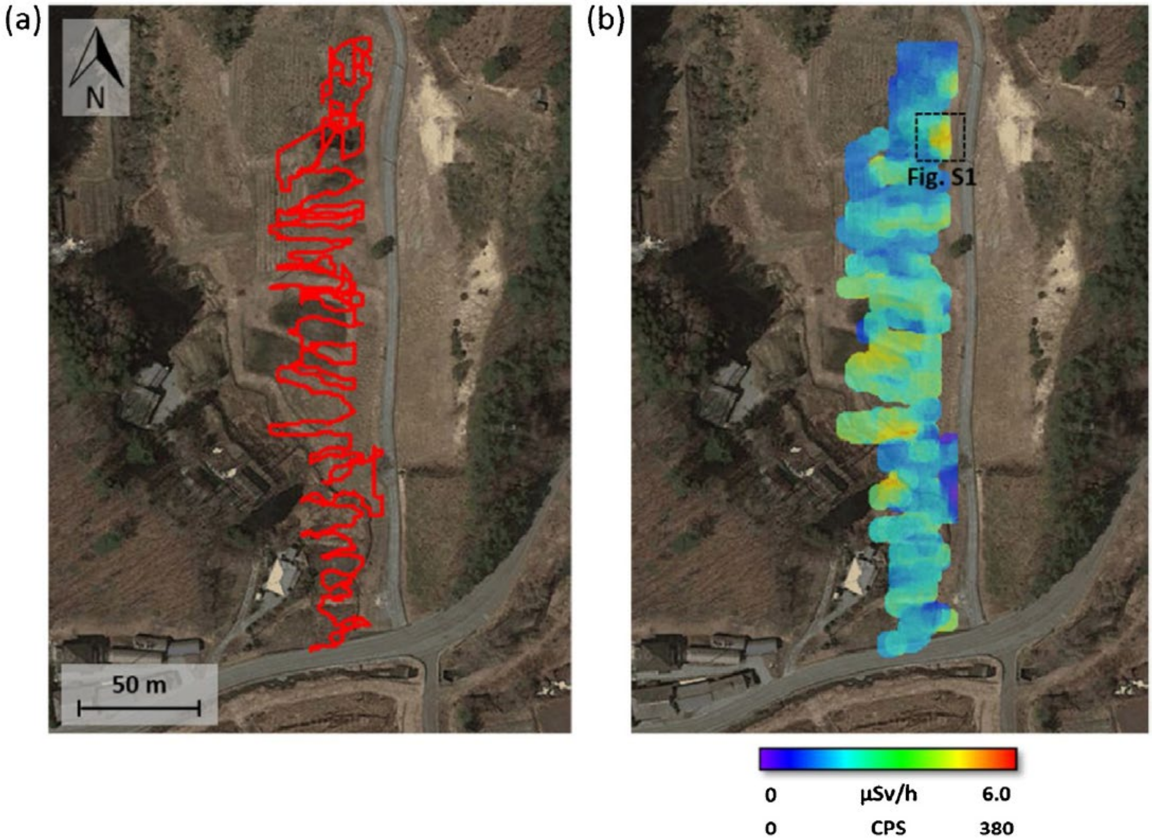


Figure 13: (a) Flight path of the UAV undertaken during a site survey of a farm in the Fukushima Prefecture and (b) corresponding radiation distribution map with values normalised to 1 m above the ground (reproduced from Martin et al., 2016a).

Early monitoring after the Fukushima accident indicated that that the caesium deposited was largely uniform with a covering of 1-2 MBq/m^2 (MEXT, 2011). At the time of the study in 2014 (i.e. over three years after the accident), it was possible to discern that regions of different radioactivity contamination levels were developing, with a variation of approximately a factor of 3 (Martin et al., 2016a). This indicates that certain types of radioactive contamination can under some circumstances become mobile within the environment e.g. due to the action of rainwater and other weathering effects. The work indicates that for some monitoring applications, it is important to combine radiation measurements with a detailed assessment of the topography and hydrology. Without that, conclusions about radionuclide mobility in the environment, which have long term consequences for the potential reuse of the land, cannot be reliably made.

5.4 NORM identification and mapping

UAVs with radiation monitoring equipment may have value in the identification of NORM. In areas of the UK known to contain NORM, airborne aerial measurements (from a fixed-wing crewed aircraft) have been made in the past between 1998 and 2013 with the aim of detecting and mapping ^{40}K, uranium, and thorium deposits (Beamish, 2014). Flying at heights of about 80 m over countryside and 250 m over urban areas the ground spatial resolution was about 100 m in the former case. Aerial measurements were obtained that correlated well with ground-based measurements. It is noted that the detectors used were large with a volume of 32 L of NaI:Tl. Figure 14 shows a map of the total dose recorded during a crewed airborne flight over part of the Southwest England. This work is sometimes referred to as the Tellus SW surveys.

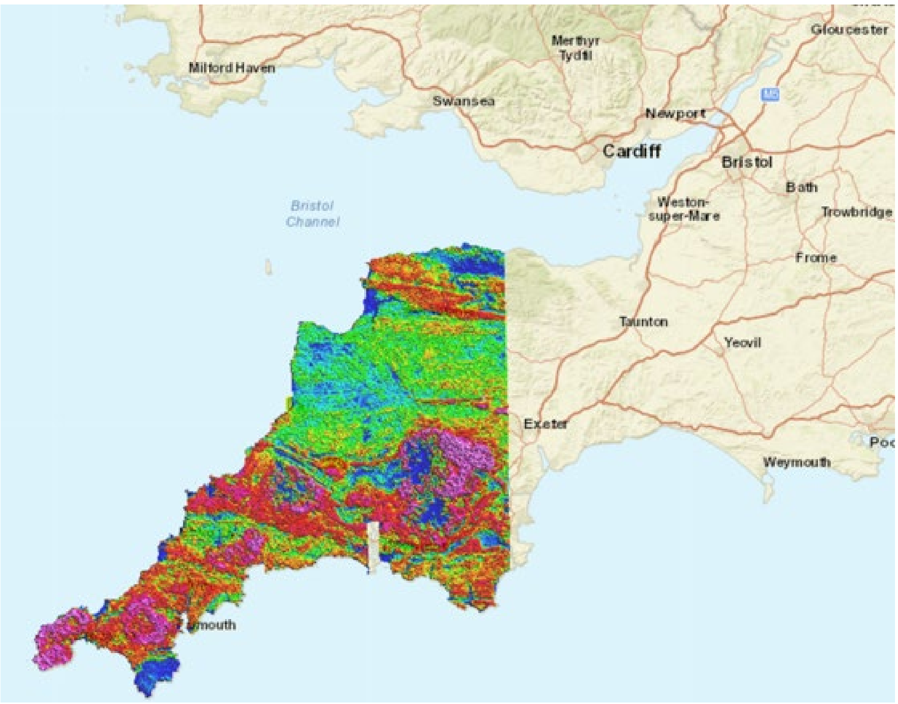


Figure 14: Radiation map of the south-west of England produced during the Tellus SW surveys (reproduced from Tellus Southwest, 2025).

Covering such large areas would require beyond visual line of sight (BVLOS) flights (BVLOS capabilities are discussed further in Appendix A), and a large UAV would be needed to carry such a detector array. On that basis, manned systems may be better suited for identifying NORM deposits or land contaminated with NORM after industry operations. An additional point is that as this is NORM, and the level of such a background is generally deemed acceptable for human habitation, there is unlikely to be concern about the radiation exposure to the human operators of manned vehicles.

Advantages of aerial technologies for monitoring NORM may lie in the higher precision that a UAV can achieve flying closer to the ground. Future developments may allow greater autonomy, thus increasing the potential advantages of UAVs. Smaller UAVs can also safely fly lower to the ground than a larger manned aircraft, allowing greater lateral precision. This may be important when identifying deposits that need to be sampled later in NORM investigations. As an example, a UAV system with a CZT detector was deployed in a legacy uranium mine (South Terras mine) in Cornwall in Southwest England (Martin et al., 2015). The mine ceased operations before 1930 but is understood to be a source of high-grade ore. In the absence of radiological control measures at the time, the site was left without significant remediation. The authors found that the overgrown state of the land meant that ground-based investigations were difficult to perform. Their UAV was flown at a height of 5-15 m and at a speed of 1.5 m/s. This provided enough sensitivity to map the radiation profile, as shown in Figure 15 and Figure 16. It is also important this exercise could achieve sufficient spatial resolution to be able to delineate regions of higher activity. This is so that either remediation can be performed, or boundaries can be marked, to protect members of the public and wildlife.

It is productive to consider the Beamish and Martin monitoring activities above as potentially being complementary with one another. That is, extensive, low-resolution monitoring (typically upwards of 300 m (Beamish, 2014)), could be used to initially identify potential areas of interest for further investigation with much higher resolution. The Beamish investigation (i.e. monitoring from a crewed fixed-wing aircraft) was an extensive exercise over Southwest England which likely detected radiation from the mine workings discussed in the Martin report, although as it happens, the existence of the NORM was known beforehand. The Martin exercise, using a UAV, allowed better spatial resolution scans to be performed. This collective information was needed to provide accurate enough positional data to inform decisions about potential remediation.

Figure 15: Satellite image overlain with the flight path of a UAV during a survey of the former South Terras mine in Southwest England (reproduced from Martin et al., 2015).

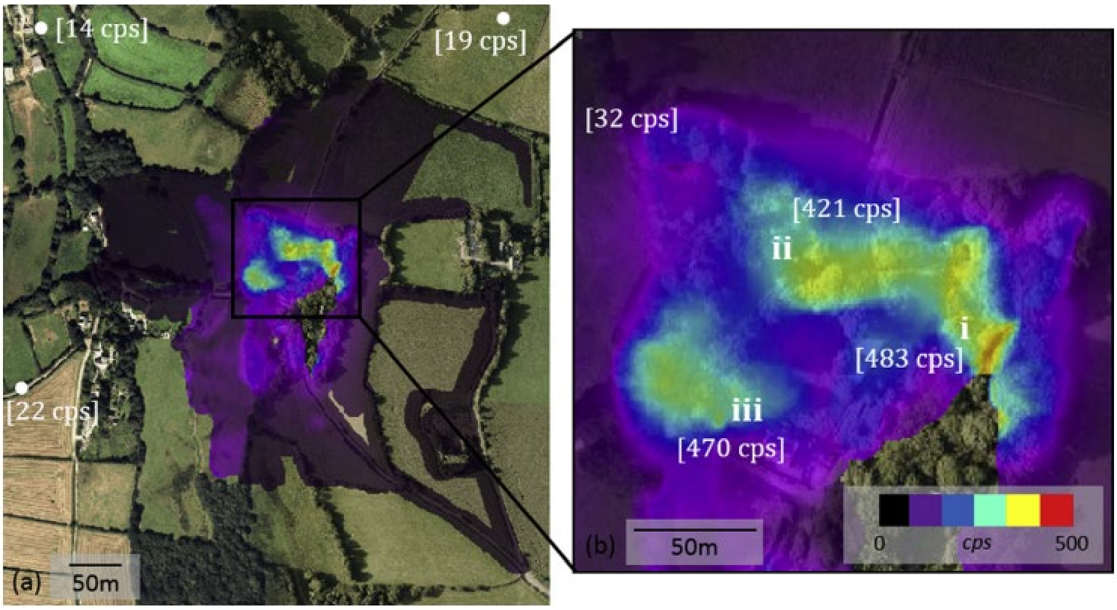


Figure 16: Radiological map for the survey region as shown in Figure 15. (a) Measured at a height of 5-15 m and (b) enlarged version of the central area comprising three main hotspots (reproduced from Martin et al., 2015).

An abandoned copper mine in Arizona in the United States (Wooley Mine site) was scanned with an Imitec Ltd. AARM system (shown below in Figure 17) carried by a DJI M100 multi-rotor UAV (Martin et al., 2020). The mine was known to have trace uranium mineralisation before this UAV monitoring investigation. Using a control system, scans at heights of 35 m over areas of 200 x 150 m were performed autonomously.

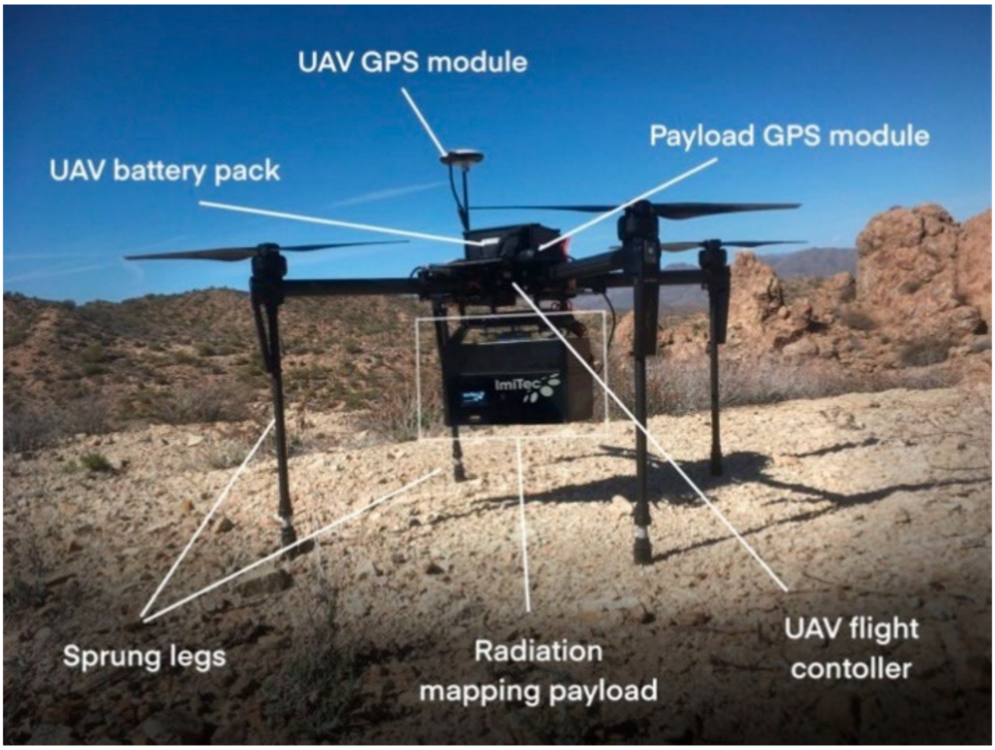


Figure 17: DJI Multi-rotor UAV used with Imitec system for monitoring the former Wooley Mine site in Arizona (reproduced from Martin et al., 2020).

Radiation maps such as the one shown in Figure 18 were obtained.

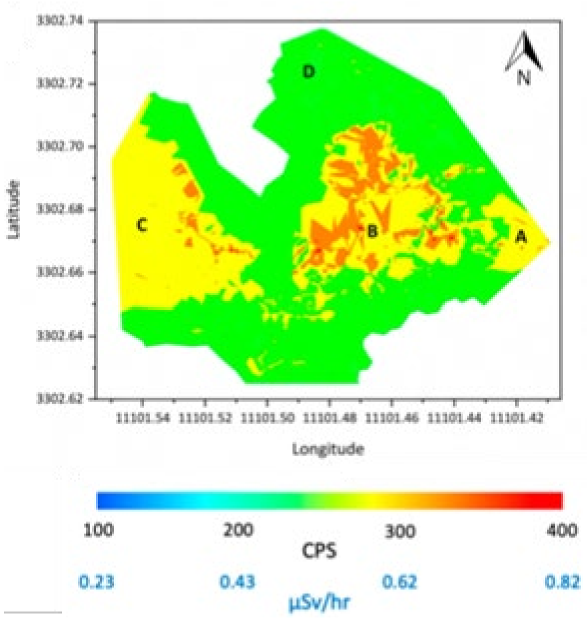


Figure 18: Example radiation intensity contour plot obtained during a UAV survey of the former Wooley Mine site in Arizona (reproduced from Martin et al., 2020).

Radiation maps were subsequently combined with 3D photogrammetry images obtained from the UAV as shown in Figure 19. This was done to allow a better understanding of the distribution of radioactive elements in the mine. In this case, the authors were able to determine that the higher areas of radioactivity were associated with spoil heaps containing discarded material. This may have been dumped as it did not contain enough copper to be economically viable to recover. A natural vein of radioactive material was also identified, showing the run of the copper ore.

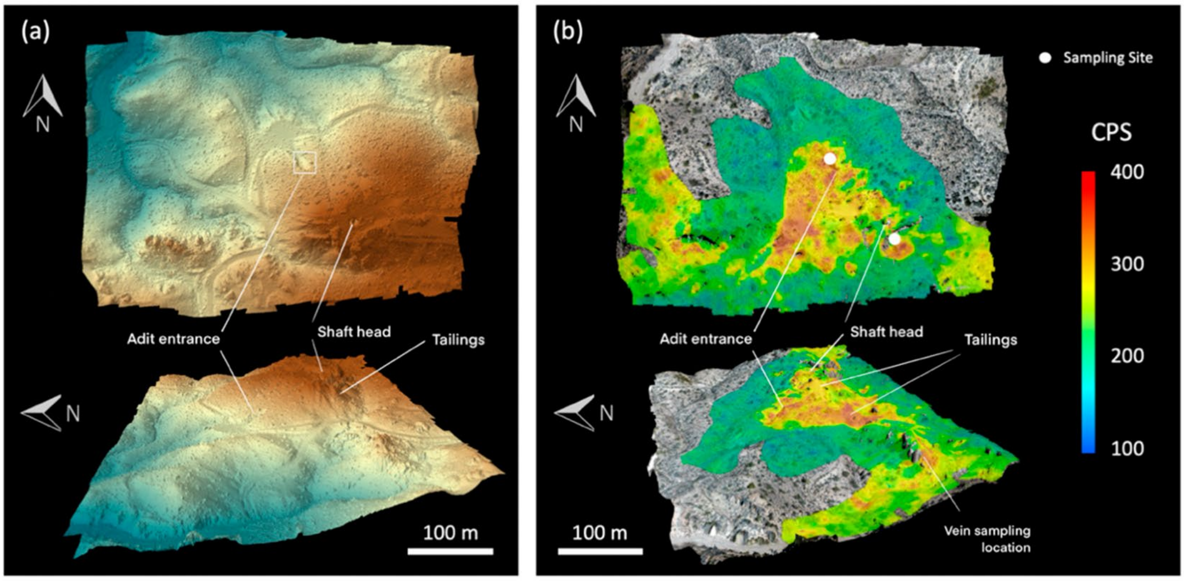


Figure 19: Photogrammetry (left) combined with radiation maps (right) to show the relationship between ground topography and the spatial distribution of radioactivity for the former Wooley Mine site in Arizona. The top and bottom images show plan and oblique aerial views of the site, respectively (reproduced from Martin et al., 2020).

These maps have enough detail to be able to direct people on the ground to regions for further investigation. It is therefore evident that a small UAV system with a weight of 3.6 kg can produce useful information and of a quality sufficient for site investigations on areas of around 1 km^2.

5.5 Marques et al., 2021 review

A comprehensive review article was undertaken by Portuguese researchers on the capabilities of different radiation monitoring instruments (Marques et al., 2021). Since Portugal does not have a domestic nuclear power industry, the motivation of this research was to support national bodies with responsibilities for radiological protection. Of note, the review identifies four scenarios for monitoring which overlap with those identified for this project (as outlined in Section 2.2). The review considers:

- Radiological and nuclear accidents and emergencies.
- Illicit trafficking of Special Nuclear Materials (SNM).
- Nuclear, accelerator, targets, and irradiation facilities.
- Detection, monitoring, and identification of NORM.

The article is not specifically dedicated to UAV monitoring, but they consider UAVs in considerable detail. One reason for doing so is that the article has a security focus, and they foresee the potential need for rapid deployment of mobile systems to areas of security concern. The authors also note that during the Fukushima nuclear power plant accident in Japan, some of the fixed monitoring stations failed or were otherwise unusable. Of note, 23 of the 24 fixed monitoring points at the Fukushima power station were destroyed by the Tsunami which caused the nuclear accident.

There is an analysis of the most likely radionuclides that may be associated with each of the scenarios in the Marques study. For example, in a nuclear accident from an operating power station the fission products of ^{137}Cs and ^{134}Cs are significant contaminants due to their high yield coupled with high solubility and rate of uptake in the body. Iodine-131 (^{131}I) and iodine-133 (^{133}I) also tend to be of immediate concern, although their short half-lives (approximately 8 days and 1 day, respectively) mean they are unimportant in the longer term (Martin, 2018). For malicious incidents involving radiation e.g. a 'dirty bomb' event, it is considered that industrial sources such as for radiography or medical use are the more likely to be released. This could include a wide range of radionuclides such as cobalt-60 (^{60}Co), ^{137}Cs, and iridium-192 (^{192}Ir), or the pure beta emitter strontium-90 (^{90}Sr) (Gonzalez, 2003; Holbrook, 2005).

In their review of detection systems, Marques et al. (2021) note the difficulty in detecting illicitly trafficked SNM such as plutonium and enriched uranium because of the weak gamma and neutron emissions, and the comparative ease with which the gamma emissions can be shielded or masked by NORM. Identification of such materials in transit is a challenging task and one where UAVs may only have a limited role, as large detectors may be needed to achieve high sensitivity e.g. portal monitors at ports. However, the Norwegian case study discussed above aimed to establish a capability to provide radiation monitoring of cargo ships ahead of them arriving in port. This could be possible if the UAVs were able to fly at the speed of the cargo vessel and monitor for sufficient time.

The article also considers the more likely radionuclides to be found as NORM (e.g. uranium and thorium decay series) and in the decommissioning of nuclear facilities. Several of these radionuclides do not possess significant gamma emissions and would therefore be difficult to detect with current UAV systems. The potential of future UAV systems to monitor alpha and beta radiation is discussed in Section 8 of this report.

Finally, the Marques study provides a useful review of mobile platforms for radiation monitoring comparing ground based wheeled/tracked vehicles, person-carried equipment, UAV technology and the potential for 'walking' robotic vehicles. Their conclusions about the different facets of UAV and radiation detection technology are not significantly different to those detailed in this report and elsewhere. It is nevertheless a major review, with 232 references and provides further background on many related topics.

5.6 Accidental releases from nuclear power stations

A radiation monitoring system called RMS-00x has been developed and is used in standard emergency planning exercises at the nuclear power plant Bohunice (EBO) in Slovakia (Lüley et al., 2020). It was specifically designed to reduce the radiation burden on the workforce, including those responding to an uncontrolled release of radioactivity to the environment. A commercially available DJI Matrice 600 UAV was used with a modular sensor system. The modular system consists of a communication and control unit, a radiation measurement unit, an air sampler unit, and a GPS tracker. A GM tube detector was used, and reported to have an operating range of between 50 nSv/h to 277 µSv/h. The Lüley study states an upgrade may be in prospect to allow the upper dose limit reading to be raised to 2 Sv/h. The air sampler is only measured upon return to the base station.

The system was calibrated and deployed in an exercise, producing a radiation map. The design intent was therefore met i.e. a system was developed and capable of being deployed to monitor an airborne release of radioactivity to the environment. However, there was no discussion as to the resilience of the UAV in an intense radiation field. This should perhaps be a consideration for operation as a monitoring system, following severe accidents. Furthermore, it is understood most UAVs are not sealed units but have air intakes to cool the motors. This could severely detract from their utility where there is a plume of radioactive material, as any airborne contamination could be taken in, affecting the integrity of the radiation measurements thereafter. This is in addition to contaminating interior UAV surfaces and potentially creating challenges with system decontamination.

5.7 Sellafield on-site monitoring

Whilst monitoring on licensed nuclear sites is outside of the scope of this project, it is nonetheless important to capture transferable learning that may arise. In particular, where UAVs have found a role in routine operations to characterise areas difficult for human workers to physically access or to reduce worker doses. An early (2014) deployment at the Sellafield site in West Cumbria demonstrated the potential usefulness of UAV technologies (Martin et al., 2016b). This was the first use of a UAV on a nuclear site in the UK, involving 15 flights conducted by the University of Bristol with a bespoke octocopter X-configuration UAV. The aircraft was fitted with a gimbal-mounted CZT spectrometer detector, a GPS and a simple downwards pointing laser range finder. Scans were performed over surface storage containers, as shown in Figure 20. This allowed both maps of the emitted radiation to be made and the radionuclides within to be confirmed.

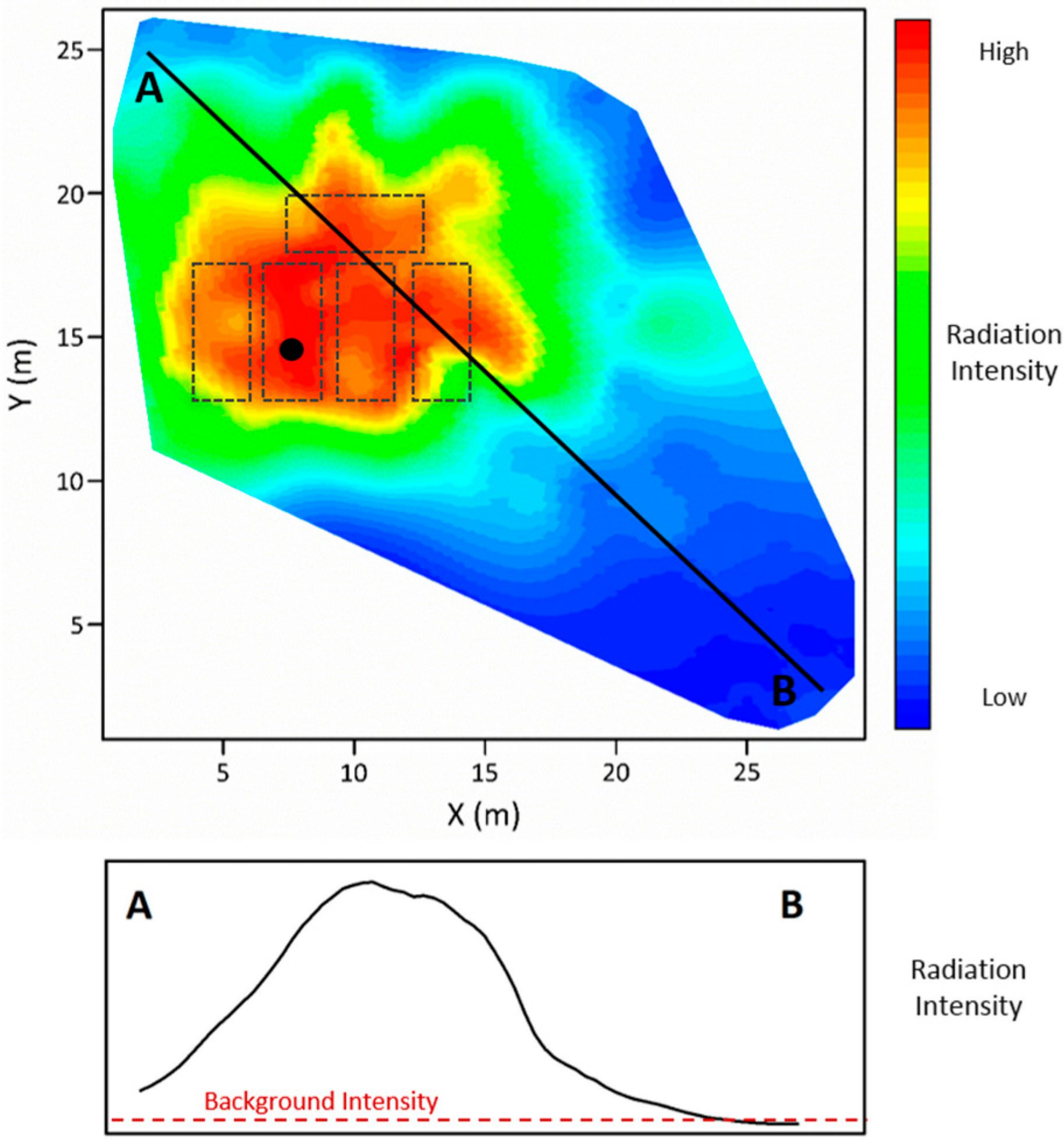


Figure 20: Radiation intensity map obtained by a UAV flying the transect line A-B over a secure freight storage container compound at the Sellafield nuclear site (top). A sharp rise in detected radiation is readily apparent (bottom) (reproduced from Martin et al., 2016b).

The authors state that some metres away from the containers, the detected level has fallen to that of a typical background level. As an observation, this fall-off (as measured by a small detector flying in close proximity to the containers) suggests that any subsequent leakage of contaminants might be detectable, assuming that repeat measurements were performed. The study also highlighted how UAVs flying low and slow over structures containing gamma-emitting nuclear materials can be used to obtain high lateral spatial resolution radiation maps. Inclusion of spectrometers on the UAV system also permits identification of the contents of buildings or containers where the radioactive contents is initially unknown. The concept of flying at a low speed and altitude is equally applicable to obtaining high resolution surveys of the open environment as it is a nuclear power plant.

Following from this survey work, use of UAVs on the Sellafield site has now become relatively common and the site now has a UAV team. The UAV programme was reported to have saved over £4 million in 2022/23 by using UAVs to complete inspections which would otherwise have been undertaken using traditional methods (Sellafield Ltd, 2023). It appears that many of the UAV initiatives on the Sellafield site have focussed on remote inspection of hazardous environments (e.g. assets at height) and not radiation monitoring.

5.8 Detection of lost or maliciously placed radiation sources

Radiation sources are used in many industrial, educational, and medical applications around the globe (IAEA, 2024c). Examples include (but are not limited to) radiography, level meters, sterilisation units and various therapies. Despite robust regulatory controls around the world, these sources do occasionally go missing. One paper noted that there had been 253 radiation accidents in China over an 11-year period, most of which involved lost or stolen sources (Gong et al., 2019). In the UK, such incidents are rare but nonetheless possible. Lost or stolen radioactive sources have the potential to generate significant amounts of environmental contamination and lead to high levels of exposure to members of the public (IAEA, 1988). There is also a possibility of malicious use of radioactive sources. The use of UAVs to assist with finding such lost sources in the environment has thus been considered.

In contrast to malicious radiological events, one potential advantage in the case of a lost source here is that the type, size, and form of the source is likely to be known. This may assist with detection of the source, as the energy spectrum is predictable. Signal processing software could be used to search specifically for the spectrum of interest, which may enable a better signal to noise ratio over the background level to be obtained. However, sources such as those used for radiography are supplied in shielded containers. This may make their detection by searching for their radiation problematic, whether with a UAV or another monitoring method. Any shielding between the source and a potential detector will reduce the signal and modify the gamma spectrum. Therefore, in conducting a search, all available information about the likely disposition will be useful.

In the case of malicious use of radioactive sources, several credible situations are possible. These range from a source being mostly left in its shielded container, to its complete dispersal by chemical explosives or another type of dispersal device. It is possible that a major terrorist event conducted by capable personnel might lead to wide area contamination, as might a major fire or accidental explosion, in which case the situation might resemble the characteristics of a nuclear accident. On the other hand, a malicious radiological incident could also lead to a situation where the environmental radioactivity is coming from one or more-point sources. It is therefore useful to consider the search for something expected to be a single or small number of point sources.

Radiation from a point source measured at a distance will decline according to both the inverse square law as it spreads out, and due to attenuation by the air it passes through. A

UAV scanning in a raster pattern over the search area may therefore find a region with a higher count rate. The operators then have the task of investigating further to determine the position of the lost source. Some strategies may involve further UAV scanning at successively lower heights to localise the source position directly. In some cases, speed will be of the essence, such as if multiple point sources need to be found, so signal processing algorithms may be of value.

One investigation used 25 mm x 25 mm NaI:Tl detectors as well as a GM tube detector in an exercise to find a 3.7×10^7 Bq ^{131}I source in the environment (Gong et al., 2019). Using a statistical source location technique, they found that with a search area of 100 m^2, a survey flight time of 5 minutes was sufficient to obtain the necessary data to locate the source, which was identified with an accuracy of approximately 30 cm. This was successful for sources positioned variously near a tree, in grass and in a puddle. The authors also review other signal localisation approaches and methods designed to achieve the same ends such as the use of multiple detectors. The report appears to be a useful demonstration of the capability that can be achieved with standard detection technology.

Another study addresses the same theme of point source detection (Brouwer, 2020). They reviewed various source localisation approaches to address the general problem of having several point sources within the area of concern. These approaches include standard mathematical prediction methods, such as maximum likelihood and Bayesian. They also use a method that they term ‘robust localisation with clustering’ based on a Monte Carlo method of updating an initial assumption through successive iterations, and a least square error method. They performed both simulations and experimental trials with multiple point sources that included americium-241 (^{241}Am) and ^{40}K. Their system used GM tubes, but they also modelled and conducted limited experimental work with the use of a collimator to improve spatial resolution. Their conclusion was that the maximum likelihood technique was the most effective. This is a method based on estimating the source position and intensity which best explain the observed data. The mathematical description can be found in an article published by Morelande et al. (2007).

Collimation offers benefits for point source localisation. There are only limited references in the published literature to the use of collimators with UAVs, probably because the weight penalty is sufficient to make them a difficult feature to incorporate. Indeed, in the Brouwer et al. (2020) paper, the authors were unable to fly their UAV with the collimator attached; they only worked with simulated results and those that used handheld detectors. Nevertheless, if the weight penalty can be managed by available UAV technologies, it may be worth considering for equipment that is specifically intended for that application.

6 Assessment of current UAV systems for environmental radioactivity monitoring

In this section, the information within the literature review and the observations that have been made are used. Five generic monitoring scenarios are considered in turn, to see how existing UAV technology might be deployable. These scenarios were derived from the different types of environmental radioactivity monitoring identified in Section 2.2, together with discussions between the authors and Environment Agency representatives. The inclusion of monitoring scenarios in this report does not necessarily reflect a high likelihood of their occurrence. Rather, the scenarios identified are generic and not a specific or an exhaustive set of monitoring requirements. The scenarios are:

1. To inform the environmental remediation of a legacy industrial site.
2. A routine survey close to a permitted discharge from a licensed nuclear site.
3. Localisation of point sources (e.g. heterogeneous 'hot' radioactive particles arising from authorised discharges to the environment or lost radioactive sources).
4. Mapping widespread contamination in the environment following a nuclear accident.
5. Mapping a contamination in the urban environment following a radiological terrorist incident.

Collectively, these scenarios are intended to cover a range of monitoring requirements and environments that could potentially be encountered in the context of radioactive substances regulation. The likely advantages and disadvantages of using a UAV system, compared to the deployment of currently used technologies for each scenario are considered.

6.1 Informing remediation requirements of a legacy industrial site

6.1.1 Typical situation

This application is limited to survey areas of at most a few km^2. A typical site might be an abandoned mine with a known extent, perhaps marked on existing maps and/or with a boundary fence. There may be concerns that contaminated material extended beyond that boundary, but that would be a limited, rather than widespread, issue.

This scenario does not consider a search for previously undiscovered NORM or mine deposits that exist over large areas. Such large area searches would need to approach the extent of the activities performed in the Tellus SW surveys (Beamish, 2014). This type of monitoring objective would require fixed-wing aircraft to fly at a safe height (>60 m), necessitating large arrays of detectors, almost certainly scintillator types (for reasons described in Section 4.3.2). Even then they would have low spatial resolution because of the high flight altitude and speed needed.

6.1.2 Topography

Topographic features may include undergrowth along with varied natural and man-made features such as spoil heaps. There could possibly be streams originating within mine shafts and pools of water. Bodies of water, due to its attenuation efficiency, will typically represent as areas of extremely low radioactivity versus average terrestrial gamma background. The whole area may have been excavated i.e. the entire site might be in the form of a depression of some type.

6.1.3 Radioactive elements of interest

Typical radioactive elements of interest associated with NORM are uranium, thorium, and potassium. The Tellus surveys estimated ^{238}U through bismuth-214 (^{214}Bi), thorium-232 (^{232}Th) through thalium-208 (^{208}Tl) and ^{40}K directly. As these radionuclides are of geological origin, they can be assumed to be in equilibrium with the daughter radionuclides, enabling a subsequent calculation of the ^{238}U or ^{232}Th concentration. This is possible even if the ^{238}U or ^{232}Th are not easily detectable directly. The daughters are readily detectable from photopeaks in the MeV range according to the following table from (Beamish 2014). Of note, other photopeaks are also usable.

Table 1: Spectral ranges used to detect U, Th and K present in NORM (reproduced from Beamish, 2014).

Window	Radionuclide	Energy Range (MeV)
Thorium (eTh)	^{208}Ti (2.61 MeV)	2.41-2.81
Uranium (eU)	^{214}Bi (1.76 MeV)	1.66-1.86
% (%K)	^{40}K (1.46 MeV)	1.37-1.57

6.1.4 Likely monitoring objective

The monitoring objective may involve identifying the radionuclides present and producing a radiation intensity map or ideally a radiation dose map of the area. A more detailed characterisation could be needed of higher activity regions (e.g. spoil heaps) to understand the contaminants present and inform any decisions on subsequent remediation. The spatial resolution of the survey is at the meter-scale.

6.1.5 Subsidiary objectives

Monitoring may also be needed to establish whether contamination is spreading off the site (or not) e.g. by runoff.

6.1.6 Suitability of UAV systems

UAV systems are eminently suitable. Scanning using a UAV would potentially be faster than hand-held systems or other ground level activities because they are uninhibited by a challenging terrain or ground obstacles such as fences or walls. There are existing examples of such monitoring (Martin et al., 2015; 2020). Furthermore, the area is small enough for a multi-rotor UAV to be usable. The flight height and radiation intensity mean that use of both scintillators and CZT detectors is practicable, allowing intensity measurements and characterisation in one pass.

6.1.7 Other considerations

The expected radiation intensity of NORM sites is comparatively low, so there may be value in characterising the background level nearby. A low level of radiation has the advantage of imposing limited restrictions on personnel access. Such sites are unlikely to require frequent monitoring, although if remediation is needed, the site might be monitored afterwards to prove the efficacy of the remedial works.

6.2 A routine environmental survey close to a nuclear site

6.2.1 Typical situation

This scenario focuses on monitoring the environment in the vicinity of permitted discharges from licensed nuclear sites. It does not consider monitoring following accidental or malicious discharges that are beyond the authorised limits. This possibility is covered in a later scenario. Typical monitoring operations can be considered to encompass a medium sized survey area i.e. 1-10 km^2, but not necessarily a rectilinear one. Example areas would be a beach or foreshore of around 100 m width over an extended distance of some kilometres such as the Esk estuary at Ravenglass near the Sellafield nuclear site. Offshore sandbanks and sea-washed turf might also be in scope. Inland, fields, nature reserves, and semi urban environments might also be monitored.

6.2.2 Topography

Some areas might be difficult or dangerous to access on foot or in a wheeled vehicle. Examples of these areas might include muddy ploughed fields, natural bogs, and overgrown land such as occurs in many nature reserves. Some beach and sandbank areas may be dangerous to visit because of fast tidal movement and sinking sands. Vertical obstructions might also need consideration e.g. tree cover, edges of buildings.

6.2.3 Radioactive elements of interest

The radionuclides of concern will depend on the activities that take took place on the site and possibly the history of accidental releases. As an example, for Sellafield this will include radionuclides that include alpha, beta, and gamma emitters. For example, it is understood that ^{241}Am and ^{137}Cs account for most of the previous finds of heterogeneous particles in the vicinity of Sellafield (Harrison et al., 2023). The other main radionuclides detected were ^{60}Co, ^{90}Sr, and Pu isotopes (Environment Agency, 2021). Environmental monitoring near other nuclear sites may require a greater focus on gamma emitters.

Potential target radionuclides of interest include ^{137}Cs, ^{60}Co, ^{90}Sr+^{90}Y, and ^{241}Am. Although ^{241}Pu is of interest, it is a very weak gamma emitter and detection at distance (such as could be most easily achieved from a UAV) would probably be primarily by finding the ^{241}Am daughter. ^{241}Am is a weak gamma emitter (with a gamma emission at approximately 59.54 keV) and is therefore easily attenuated (especially if buried at any depth), which in turn increases the lower limit of detection. ^{90}Sr does not emit gamma radiation but the decay product ytrrium-90 (^{90}Y) produces high energy beta particles that are detectable at short range in air (approximately 1 m) (Newton and Tulip, 2020). ^{60}Co, which occurs when metal structures are exposed to neutron radiation (and become neutron activated), is also of potential interest (EPA, 2025). It is readily detectable from the associated strong gamma emissions. There may be other monitoring requirements e.g. for tritium (^{3}H), but these are difficult to detect without sampling and laboratory analysis i.e. they are not easy to detect with handheld or wheeled vehicles either. For that reason, they are not treated further here. Typical emissions of target radionuclides of interest are shown in the following table.

Table 2: Radioactive emissions for the likely radionuclides of interest, reproduced from (Newton and Tulip, 2020).

Isotope	Emissions (keV)			
	alpha	beta$^-$ (E_{max})	gamma	x-ray (mean)
^{241}Am	5485 (85.2%) 5443 (12.8%) 5388 (1.4%)	N/A	59.54 (35.9%) 26.34 (2.4%)	16.6 (37.7%)
^{137}Cs	N/A	514 (94.4%) 1170 (5.6%)	662 (84.99%)	N/A
^{90}Sr	N/A	546 (100%)	N/A	N/A
^{90}Y	N/A	2279 (99.98%) 518 (0.02%)	1760 (0.02%)	N/A
^{241}Pu	N/A	20.8 (99.99%)	N/A	N/A
^{60}Co	N/A	317 (99.88%) 1490 (0.12%)	1170 (99.85%) 1330 (99.99%)	N/A

In general, ^{241}Am, ^{137}Cs, and ^{60}Co are detectable as gamma emitters. However, detection of ^{241}Am is complicated by the fact that it is only a weak gamma emitter. Measurement may necessitate the use of detectors without a metallic covering and for the UAV to fly at a low altitude to minimise gamma ray attenuation in air. ^{90}Sr presents more of a radiometric detection problem, but a detector suitable for detecting and quantifying the daughter radionuclide yttrium-90 (^{90}Y) beta radiation may be possible on a UAV. While laboratory-based gamma spectrometry can be used to identify ^{241}Pu, the most probable gamma emission occurs for 0.0002% of decays. As such, it is not practical for detection in the context of aerial monitoring of environmental radioactivity, because the gamma signal would be too infrequent for representative sampling by a moving UAV.

6.2.4 Likely monitoring objective

This scenario would primarily provide reassurance monitoring of radionuclide distribution in the environment, as part of a standard environmental monitoring programme. Areas around licensed nuclear sites which generally have low liquid and solids-in-liquid discharges would be considered. Historical discharges from the site may have led to the accumulation of low levels of anthropogenic radioactivity in the immediate environment. These areas may also be candidates for environmental monitoring.

The intention of this scenario would be to produce a radiation map of the area, with a sensitivity that went down to a level consistent with what would be judged as the background. This would allow anthropogenic radioactivity in the environment to be distinguished from that derived from natural radionuclides. The radionuclide distribution would probably be more dispersed than in the case of the remediation of a legacy industrial site, requiring a lower spatial resolution (e.g. 10 m resolution). Although, this would depend on the specifics of the site and the goal of the survey. Such baseline maps would also provide an ongoing reference for comparison against in case of any future inadvertent or accidental radiological release event. These maps would prove useful for determining where anthropogenic radioactivity had spread and for identifying any areas requiring remediation.

Determining an appropriate background level of radiation is not always a trivial task. There is a wide natural variation in the UK due to differences in geology. There has also been contamination of some parts of the UK from overseas sources e.g. Chornobyl nuclear power plant accident in 1986. If there is substantial preexisting contamination, it may be sufficient to take the 'natural' background level from measurements made some distance from the nuclear site, but with the same geology. Baselining of background radiation in the vicinity of nuclear sites and other sites with significant radioactive inventories could be of strategic value. Where signals that are significantly greater than the background are measured, it would be an intention to identify the radionuclides present. The data obtained could be used for the purpose of providing an attribution of the source of material. It could also aid public reassurance that nuclear sites were being managed correctly.

6.2.5 Subsidiary objectives

Repeated monitoring over time may also help establish how radionuclides are being transported through the environment e.g. by determining if concentrations on the ground surface are uniform, being taken up by vegetation or being flushed into the sea by rainfall. Segregation of particles by depth is predicable, for example movement through sediments due to tidal action. There may be a need to measure radiation from such buried particles.

6.2.6 Suitability of UAV systems

UAVs could more easily access some areas that are difficult for a person or ground vehicle to reach. The need to measure low levels of radiation and discern natural radionuclides from anthropogenic material mean that large detectors (such as scintillators) would be desirable. As the levels of anthropogenic radiation are expected to be low, accurate characterisation of the natural background is increasingly important and approximation is probably not appropriate. For the detection of low intensity radiation, a low scanning speed may be needed to achieve the necessary sensitivity. However, it may be unduly time consuming to monitor large areas (in excess of 1 km^2) at low scanning speeds. For reference, multi-rotor UAVs typically have a flight time of about one hour.

Searching for alpha and beta emitters (such as ^{90}Sr) with UAVs may not be entirely satisfactory if they are only fitted with detectors optimised for gamma detection. The prospects of using UAVs for detecting alpha and beta emitters are discussed in Section 8. As such, it may be that UAVs could not presently provide a full solution to the environmental monitoring task for this scenario. Their deployment may be ideal on some terrain that is otherwise difficult or unsafe to access, but elsewhere they may not offer capability or speed advantages over hand-held or wheeled detectors. Additionally, routine discharges that have been occurring for many years may be accumulating below the surface. For example, there is evidence to suggest this phenomenon is occurring in the Esk Estuary, where contaminated sediments are buried by deposits of uncontaminated sediments transported by tidal processes e.g., bioturbation, sediment movement etc. (Wood and Copplestone, 2011). A full radiological characterisation of these types of environments would likely require samples to be taken and analysed in a laboratory. Nevertheless, UAVs could partially automate what would otherwise be a time-consuming task if undertaken purely manually. Automation facilitates repeat surveys, and hence the use of UAVs to provide trending of key radionuclides such as ^{137}Cs may be valuable.

6.2.7 Other considerations

If there is a natural variation in radiation background intensity, it may be difficult to separate this from anthropogenically induced variations. Repeat monitoring would presumably be necessary to determine if the situation is changing.

6.3 Localisation of point sources (e.g. heterogeneous particles or lost radioactive sources)

Two exemplars are considered in one scenario here, as they share characteristics in terms of the environmental monitoring and searching tasks. These exemplars are:

- Localisation and identification of contaminated items or heterogeneous particles such as those previously found on beaches e.g. near the Sellafield and Dounreay nuclear sites (Harrison et al., 2023), as well as Dalgety Bay (SEPA, 2024). The main radionuclides of concern in these areas include ^{90}Sr, ^{137}Cs, radium-226 (^{226}Ra), ^{241}Am, as well as Pu isotopes. In other areas, there may be contamination with depleted uranium from munitions. This latter material becomes easier to detect with the passage of time as gamma emitting daughter products start to accumulate.

- Localisation of lost (i.e., orphan) radioactive sources in the environment such as radiography sources including (but not limited to) ^{60}Co and ^{192}Ir.

In the first case, the application is detecting and quantifying potential historic contamination and unauthorised and/or accidental discharges that may be counter to current permit requirements (Environment Agency, 2021).

The second case might typically be a lost industrial radiography or irradiation source. This would be a larger emitter than a beach particle but may be held within a shielded container. There have been examples of unshielded sources being lost and there are scenarios, for example transport accidents, where an unshielded source could be created. For example, a 20 GBq ^{137}Cs source was lost in Western Australia in 2023 and was subsequently found 2 m from the road by a vehicle-based scanning system that was moving at 70 km/h (~43 mph) (ANSTO, 2023). Although not a UAV application, this is a useful example of how radioactive sources can be lost and recovered.

6.3.1 Typical situation

For beach particles, the situation has similarities with the second scenario (monitoring in the vicinity of a permitted discharge); a medium sized beach/foreshore search area of 1-10 km^2. Searching may be confined to regions where high activity particles have previously been found and where ongoing monitoring is required to provide public reassurance that no additional particles remain.

It is difficult to be specific about lost radiography or irradiation sources. Their original use may have been within an industrial or urban environment and at some point, they fell out of regulatory control. There have been cases where sources were found in (non-nuclear) waste e.g. from legacy armaments facilities. A source that has been accidentally consigned as industrial waste may also need to be located and retrieved.

6.3.2 Topography

Beaches and foreshores tend to be flat, although there may be cliffs to consider which may make GNSS signals less reliable. The public normally has access to the foreshore, which may raise a safety concern with UAVs if they need to fly at very low heights.

A credible lost source scenario may require searches over a large distance, but a reasonable assumption is that the item will be somewhere along (or near) a known route. For the lost source in Western Australia mentioned above, the location could have been anywhere along a 1400 km transport route.

6.3.3 Radioactive elements of interest

For beach particles, the radionuclides of concern are normally the same as those detailed in scenario 2 (a routine environmental survey close to a nuclear site). However, the Dalgety Bay contamination was with legacy industrial contamination from luminous paint, the radionuclide being ^{226}Ra. Furthermore, the potential contamination will depend on the activities that take took place on the site and possibly the history of accidental releases. It is understood that ^{241}Am and ^{137}Cs have accounted for most previous finds in the Sellafield area (Newton and Tulip, 2020).

Typical radiography sources, (e.g. ^{60}Co, ^{137}Cs and ^{192}Ir), are strong gamma emitters. If unshielded, they would be comparatively easy to detect. Am-Be sources are used as neutron emitters in the oil and gas industry, and fast neutrons are also produced when the decay alpha particles interact with beryllium-9 (^{9}Be) (Scherzinger, 2015). Provided the

^{241}Am source is used in conjunction with ^{9}Be, a UAV with a neutron detection capability could potentially be used to detect sources of this type.

6.3.4 Likely monitoring objective

For beach particles, the intention would be to find areas of elevated radiation, possibly indicating the presence of radioactive particulate material, for further investigation and remediation. It is assumed that depth information is not important. A threshold for further investigation or removal could be set that was higher than with the standard monitoring detection level.

For a lost radioactive source, the initial objective would be to locate it. It is likely that some information would be available about the source characteristics (size and radionuclide), and whether it was in a shielded container. If it was, then finding it might be difficult by searching for radiation emission. The more hazardous situation is if the source is exposed, which would likely make it more detectable. Knowledge of the radionuclide and size of the source should allow a calculation of the maximum height that a UAV could be flown at, to enable detection of the lost item.

6.3.5 Subsidiary objectives

For a lost radioactive source, there may be a secondary objective after the source has been found and retrieved, to determine if there is any residual contamination in the area. Once a shielded or unshielded source is found, it is probable that a person would need to approach to secure it. Measurement of the radiation intensity would be necessary beforehand to ensure their exposure is within acceptable limits.

6.3.6 Suitability of UAV systems

The considerations here are not significantly different from those for the 'a routine environmental survey close to a nuclear site' scenario considered earlier. Higher levels of contamination would be expected to be easier to find than lower levels.

Examples of areas where searches have previously taken place for beach particles include regions near the Sellafield and Dounreay nuclear sites, and at Dalgety Bay. At Dalgety Bay, a substantial amount of the beach top layer was removed and scanned using fixed detectors mounted over conveyor belts. For the Sellafield beaches, it is understood that detected particles over a certain activity are removed.

The use of UAVs would be to identify areas of elevated activity, for further investigation either by UAV or more traditional techniques (i.e. a handheld detector or remote operating vehicle). Possible advantages of UAVs for beach monitoring include: a reduction in transportation/set-up times (compared to the use of a wheeled vehicle), a reduction in cost (due to a fewer number of people required as opposed to handheld monitoring or the use of a wheeled vehicle), and a potential reduction in the total survey time. However, on initial investigation, there is some uncertainty as to how effective UAVs would be for this application, especially for the low energy gamma emitters (e.g. ^{241}Am) or for buried particles. The current system employed by Sellafield uses an array of scintillator detectors (deployed using a wheeled vehicle) at a height of 150 mm above the surface. The Maximum Missable Activity (MMA) of a UAV mounted detector will be higher than a ground-vehicle mounted device if there is a need to scan from greater heights (e.g. to minimise the collision risk) and with a smaller detector (e.g. due to payload restrictions) (Newton and Tulip, 2020). A Beach Particle Detection Technology Review conducted on behalf of Sellafield Ltd (Newton and Tulip, 2020) concluded that the role of UAVs in beach particle monitoring would likely be hotspot detection (as opposed to accurate localisation).

For a lost gamma emitting source, prior knowledge of the source size and radionuclide should enable a calculation of the expected gamma intensity at different heights. That would allow the necessary altitude for a UAV search to be determined with whatever detection systems are available. If an extended area needed to be searched, a fixed-wing UAV may be more suitable or potentially a manned aircraft. If the sensitivity is adequate, flying high enables a wide ‘corridor’ to be searched in a single flight line. If such a search were successful in identifying the approximate location, the strategy would be to perform further scans at lower altitudes to enable a more precise location to be identified. This might be suitable for a multi-rotor UAV, perhaps equipped with a CZT detector. This would have the advantage that it would not saturate at a high intensity, thus enabling a precise (i.e. metre-scale) position to be determined.

6.3.7 Other considerations

Lost sources can be sufficiently large that it is dangerous to approach them unless they are within their container. Should an event of this type occur, the recovery task might be assisted by a UAV leading the ground team to the source and thereafter providing visual monitoring for remote observers.

6.4 Mapping widespread contamination in the environment following a nuclear accident

Major releases of radioactive material have occurred several times around the world, including the Windscale fire in 1957, the Chornobyl accident in 1986, and the Fukushima Daiichi accident in 2011. These all involved the release of fission products that were initially contained within the fuel in operating reactors. Other accident scenarios are possible, such as fires in fuel manufacturing facilities or storage sites.

Any major release would necessitate urgent action to protect the workforce and public. In the short term, it would be vital to understand the extent and movement of the radioactive plume and the nature of environmental contamination so to inform the selection of protective measures. One immediate concern would be the airborne release of volatile elements, but contamination of critical infrastructure may also become problematic. In the longer term, it would be necessary to map and quantify the extent of environmental contamination. Regular monitoring of the contaminated area would be necessary to inform decisions about whether the land was safe for agriculture, habitation etc.

6.4.1 Typical situation

There is no typical situation with nuclear accidents; but several scenarios are foreseeable based on previous accidents.

One of the more serious scenarios is an accident in which fuel failures occur, releasing iodine (^{131}I and ^{133}I), strontium (^{89}Sr and ^{90}Sr) and caesium isotopes (primarily, ^{134}Cs and ^{137}Cs) which are contained within a plume that moves away from the site under the action of wind. The radionuclides may then deposit on the land or sea depending on winds, rainfall, and other meteorological conditions. Less impactful events could lead to similar qualitative outcomes. For example, accidental liquid effluent discharges, which are then washed back onto beaches. These types of radiation incidents might also require rapid assessment of environmental contamination and its impacts.

6.4.2 Topography

The topography is likely to vary considerably across the survey area. The survey area would be large, at worst with linear dimensions of hundreds of km. Agricultural and urban lands could both be affected.

6.4.3 Radioactive elements of interest

For releases from reactors where the fuel is damaged, the elements of concern include ^{137}Cs, ^{90}Sr, and ^{131}I. The UK has graphite moderated reactors, so a major accident might involve releases of carbon-14 (^{14}C), and other elements present in the graphite core such as ^{3}H, ^{60}Co, and chlorine-36 (^{36}Cl).

6.4.4 Likely monitoring objective

In the short term (e.g. the first few days after the initial release), it would be desirable to understand the extent of the plume of contaminated material and how it was behaving. On a longer timescale (e.g., weeks-months to potentially years after the initial release) the need would be to map the extent of ground and marine contamination and to identify regions in need of remediation. On a much longer timescale possibly continuing for decades, it might be necessary to remap the residual contamination to understand radionuclide fate and transport through the environment (e.g. for public reassurance purposes). With longer half-lives and high capacity for bodily uptake, ^{90}Sr and ^{137}Cs are of longer-term concern for an environmental monitoring programme. In this scenario, activity concentration variation is expected to occur slowly. A spatial resolution of 20 m represents a compromise between resolution and total coverage (and survey time) for widespread mapping applications (Connor et al., 2020). The primary objective would be identification of high levels of radiation i.e. ones that posed a significant risk to human health.

6.4.5 Subsidiary objectives

At the edges of the contaminated region, there would be a need to determine safe boundaries, possibly delineating areas of restricted access such as no personnel to enter at all, only personnel to enter involved in remediation activities, limited occasional public access, public habitation allowed, agriculture allowed etc.

6.4.6 Suitability of UAV systems

When dealing with high levels of radioactive contamination in the environment, there are many issues to consider, such as that:

- People operating the UAV may be at risk unless they can be located in a safe area.
- The UAV may become contaminated and need decontamination.
- Operations such as changing UAV batteries might be hazardous as people would need to touch a UAV that had travelled through the plume.
- There may be other aerial traffic to consider e.g. ambulances, evacuation flights, and movement of emergency personnel.
- Data communication through public networks may be compromised.
- At extremely high levels of radiation, the UAVs may be susceptible to damage such that they fail.

An initial concern may be whether there is radioactivity being released at all. This might apply should there be a fire near a facility such as a waste store. Here there may be a role for UAVs flying over the facility or around the site boundary to determine if there is any increase in environmental radioactivity. It is noted that the Slovakian system discussed earlier (Lüley et al., 2020) was designed for such a scenario (i.e. for use close to the site and to help protect its operators by being easily decontaminated).

In such a scenario it is readily conceivable that the UAV might be flying with a thermal camera as well as a radiation mapping capability. This system has been demonstrated in work at the University of Bristol, where thermal imaging and gamma mapping have been undertaken on the same UAV platform, as shown in Figure 21.

Figure 21: A DJI M300 UAV mounted with an Imitec AARM radiation monitor and a DJI H20t thermal camera (image supplied by the University of Bristol).

For accidents where an airborne release has been confirmed, it is necessary to distinguish situations where there is still a plume in the air, versus events where all the released radioactive material has deposited onto the ground. For the former, it would be a challenging task to monitor the radiation. The contamination plume will be moving, possibly in high winds and at high altitude and it will have a three-dimensional shape. Modelling tools, fixed monitoring sites, and meteorological advice should be available to determine the most useful flight path, which may be a series of transepts across the predicted path of the plume.

For plume tracking applications, a fixed-wing UAV seems to be preferable. If hydrocarbon powered, it might have an extended flight time and range compared to a battery powered multi-rotor type. It would therefore not need to return for battery changes. The radiation detection task is comparatively simple and a small detector of almost any type could find the plume. However, given that some quantification is needed and that there would be no prior knowledge of the intensity, a detector such as CZT would be useful as it could cope with a large variation of incident gamma intensities. Contamination of the UAV system represents a significant risk for plume tracking operations. Overall, making measurements within a plume is a challenging task and technologically may be beyond small-scale UAVs, due to the possible flight altitudes required and the need for high levels of ingress protection/contamination control. It is possible that military grade UAVs would be needed.

Once the source of the release has been curtailed and the contamination has reached the ground or water bodies, the monitoring task focuses on characterising the ground and water body activity. As noted previously, if the area of contaminated land is large, a fixed-wing UAV may be more suitable. Due to the attenuation of water, the background count rate during monitoring will be high for radionuclides in water bodies (in relative terms). Hence, physical sampling may be a more suitable approach. There is a greater level of dispersion in water bodies as opposed to land which can also be difficult to measure.

6.4.7 Other considerations

Every type of UAV will have a weather window within which it is safe to operate. For some UAV types (such as multi-rotor UAVs), the window can be limited in terms of wind speed. Similarly, it may not be considered safe to fly when it is dark, even assuming legal restrictions have been surmounted. A technology that can only be deployed a proportion of the time could not be relied upon to be the sole monitoring method in the period immediately following a major radiation incident. As previously noted, the RREMS capability represents a key source of monitoring resource across the UK and also possesses a mapping functionality for the display of plume models. The decision to deploy a UAV after a nuclear accident would probably follow, and be informed, by these alternative types of monitoring and modelling tools. UAVs will therefore inevitably exist in a 'toolkit' of techniques for monitoring environmental radioactivity after a nuclear accident, irrespective of weather conditions. That is, nuclear emergency planners are likely to explore a wide range of technology options for monitoring environmental contamination.

6.5 Mapping contamination in an urban environment following a malicious radiation incident

For this scenario, the possible distribution of radiation following a terrorist incident is considered, together with how UAVs might assist in the activities necessary to monitor it. The remediation necessary after a large-scale attack by a hostile state is not dealt with in this report. Rather, only relatively unsophisticated events are discussed here, such as the use of a chemical explosives to disperse stolen radioactive material (i.e., a so-called dirty bomb), disruption of nuclear fuel in transport, or a release that did not involve an explosion, such as the deliberate contamination of a water course. Similarly, the radionuclides likely to be available are ones that could potentially be stolen from UK licensed users of radioactive substances, such as medical or industrial organisations.

A hostile state might have access to Pu or polonium-210 (^{210}Po), the latter being used in the poisoning of Alexander Litvinenko in 2006. These radionuclides are extremely difficult to detect (due to their low probability of gamma emission) and represent a significant monitoring challenge (Owen, 2016). The detection of alpha emitters with UAV systems is considered in Section 8 of this report.

6.5.1 Typical situation

Credible scenarios include attempts to disperse radioactive material, such as a stolen radiography source. Disruption of nuclear fuel transport is also a conceivable event, but even then, the fuel flasks are designed to be capable of withstanding train crashes. Something akin to an armour piercing weapon would be needed to penetrate them. These are beyond what can be made outside industrial facilities. Even if a fuel flask were disrupted, the fuel would be expected to be comparatively stable. This is because the decay heat in used fuel is low by the time the fuel is moved. Contamination of the drinking water supply could potentially lead to ingestion of radionuclides. However, such an event seems unlikely to lead to contamination of urban spaces, of the type where wide area monitoring would be beneficial.

Many scenarios therefore seem to be those in which the spread of radioactive material is limited initially, perhaps to the immediate blast area of a bomb. However, the unintentional spreading of contamination by people or vehicles moving away from the affected area may be a factor that also needs to be dealt with (as it would exacerbate the monitoring challenge during emergency response and recovery). The key monitoring task is likely to determine the extent of environmental contamination and its level of dispersion. Taking the above considerations into account, this scenario focuses on the malicious dispersal of a single radionuclide (sourced from a medical or industrial device) in an urban environment. The expected spatial extent of contamination of up to approximately 10 km^2 for such an incident is much smaller than the nuclear accident scenarios described above.

6.5.2 Topography

It is assumed that a hostile actor would commit an act of radiological terrorism in an urban area to maximise economic and social disruption. Monitoring would be required in an outdoors urban environment, most likely a densely populated area (e.g. a city centre).

6.5.3 Radioactive elements of interest

^{60}Co and other elements used in radiography are of interest, as are ones used in industrial meters such as ^{137}Cs. Medical radionuclides are also potentially relevant but generally have short half-lives (e.g. ^{131}I). This means that if such a source were stolen and then used in a dirty bomb, the radiological consequences would be short-term.

6.5.4 Likely monitoring objective

The immediate objective would be to map the extent of the contaminated area and depending on the degree of dispersion achieved, to find any large radioactive particles. This information would be used to manage the situation i.e. whether to abandon the area for a period or to attempt to remediate it.

6.5.5 Subsidiary objectives

It seems possible that people and vehicles near the site of the explosion will have been contaminated and that this may have led to the spread of contamination. There may therefore be other areas where the radiation needs to be monitored e.g. hospitals and the routes to them. Later, drains, sewers and watercourses would need to be monitored.

6.5.6 Suitability of UAV systems

Depending on the size of the event, multi-rotor UAVs may have a significant role to play. Rapid identification of the contaminated area and characterisation of the contamination footprint would be vital in the immediate aftermath of the incident, where the goal is to protect the public. There is a possibility that this can be done without an operator needing to be nearby, should a UAV with First Person View (FPV) capability be available (see Appendix A for further information).

A later stage in the incident management timeline is the recovery phase, which would likely involve decontamination. Whilst there may be a need for handheld monitors and other ground-based equipment, UAVs are still likely to be useful. This is especially the case if contamination is present at height and not easily accessible by humans. Multi-rotor UAVs with scintillators and CZT detectors may both be useful. The former would achieve the maximum sensitivity, whereas the CZT detectors would have the maximum diagnostic capability and the ability to approach high intensity objects closely without saturating.

It is plausible that the radioactive material has only been locally dispersed, even if there has been an explosion. The task might then be one of finding the few particles that were produced. In this case, monitoring requirements would be comparable to those described for the 'localisation of point sources' scenario discussed above, with similar advantages and limitations of UAVs. The overall monitoring objective would be to pinpoint the locations, such that the particles could be identified and recovered.

6.5.7 Other considerations

Managing the aftermath of such an event would also require visual monitoring, possibly with UAVs. Significant coordination would be necessary with the emergency services, especially if recovery of casualties were required. Because of the possibility that people or vehicles might inadvertently spread contamination, monitoring technology would ideally need to be deployed quickly. Therefore, numbers of UAVs would need to be available as a resource for the emergency services in the UK's major urban centres. However, there may be an increased UAV collision risk (e.g. with urban infrastructure).

7 Potential Improvements to UAV technology

The horizon scanning section of this report begins with a discussion of emerging UAV technology components and opportunities that have the potential to improve capabilities relevant to aerial monitoring of environmental radioactivity (Section 7). A discussion of novel radiation detection capabilities is then presented (Sections 8-11).

7.1 Improvements in flight duration (use of fuel cells)

Whilst UAVs have many advantages over larger manned aircraft (e.g. safety, flexibility), there are disadvantages. One such limitation of UAVs is their reduced flight time and range due to the smaller size and therefore fuelling capacity. This was recognised in a previous study and note that this is especially the case for multi-rotor aircraft, where flight times are reduced further as the payload increases (Woodbridge et al., 2023). The authors explain that for very heavy sensor payloads, the flight time for some multi-rotor aircraft can be less than 20 minutes. The fixed-wing craft compared in this study had flight times between 50 and 120 minutes.

One option is to reduce the mass of the payload as this will increase the range of the UAV. However, this is not always practicable, especially where large volume scintillators are required to provide high detection sensitivity. Another option is to have several batteries: either two batteries (operational and standby) or multiple (possibly charging between cycles). However, batteries for larger UAVs cost approximately £1000 and, with a flight time of less than an hour, the use of multiple batteries to support continuous survey work over the course of a day can be expensive (DJI, 2023). The UAV must also ‘return to base’ each time, limiting the total area surveyed. Battery technology may advance and as discussed previously, the weight of detectors may reduce. Hence, improvements in UAVs for environmental radioactivity monitoring can be expected. The use of solar power as a continuous source of power during UAV flights has previously been investigated (Khan et al., 2021). Due to the weight of the solar photovoltaic cells, significant improvements in flight time were not possible.

An alternative fuel source is hydrogen. The use of hydrogen fuel cells to power UAVs is a capability which is being more widely used to power commercial UAVs (Intelligent Energy, 2025). Hydrogen fuel cells, designed as modular systems for UAV compatibility, are now available commercially, with flight times which exceed those typically available from battery-powered systems. For example, Intelligent Energy quote flight times of between 2.6 and 15.6 hours for one product, with a system mass (the fuel cell power module and hydrogen regulator) of between 4 and 7.4 kg (Intelligent Energy, 2025). Similar flight times were reported in a 2013 study, where prototype fuel cell systems were compared (Dudek et al., 2013). These types of examples in the literature collectively suggest that there are potential benefits for flight time. However, it should be recognised that there are risks and challenges with the use of high-pressure hydrogen in the field. Hydrogen is a highly flammable gas and there are risks of explosion and fire if hydrogen were to leak under high pressure. Specialist equipment (e.g. compressors, pipework, external power source) is needed to fill hydrogen canisters and coupled with the bulk hydrogen cylinder, this presents practical challenges for certain UAV deployment scenarios. Figure 22 shows a hydrogen fuel cell and cylinder attached to an example of a commercially available UAV.

Figure 22: Hydrogen fuel cell and cylinder attached to a commercially available UAV (reproduced from Intelligent Energy, 2025).

The capital expenditure for the infrastructure is likely to mean that hydrogen fuel cell usage is not a practical solution unless routine monitoring of a large area is required. For surveying a smaller area, or for scenarios where the monitoring can be split across several days, battery power seems likely to remain the more practical choice.

7.2 Lighter-than-air UAVs

A lighter-than-air system, also referred to as a non-rigid airship (NRA), consists of a buoyant gas-filled balloon (such as helium or hydrogen) that supports sensors. ‘Balloon’ is used to describe a system which is tethered/towed, whereas ‘blimps’ implies a dirigible which is capable of independent flight (Verfuss et al., 2019). Lighter-than-air UAVs are a type of UAV platform commonly used for marine fauna monitoring applications. Due to the buoyancy provided by the gas-filled balloon, the UAV has an extended flight time (up to 40 hours (Verfuss et al., 2019). There is one recorded use within the nuclear industry; a helium blimp designed for indoor use (NDA, 2019). The prototype blimp was designed for applications within contaminated facilities where an extended flight time is necessary and where loose contamination was a key risk (hence downdraught must be minimised) (Sellafield Ltd, 2019). Figure 23 shows such a lighter-than-air inspection vehicle.

Figure 23: Demonstration of the lighter-than-air inspection vehicle at a facility on the Sellafield nuclear site (image supplied by Sellafield Ltd).

Whilst extended flight time is advantageous, there are several overriding issues for environmental monitoring. The physical size of the vehicle increases their sensitivity to wind (the prototype trialled at Sellafield had a volume of 1.5 m^3 and length of approximately 2.5 m). They are understood to be difficult to control as the propellors are typically small and have a low power output. Their purpose is to provide limited movement in the horizontal plane. Coupled with their profile and susceptibility to wind, realistically, their application is limited to indoor use in the UK and are therefore poorly suited to the environmental monitoring applications considered in this report.

The payload capacity of lighter-than-air UAVs is also extremely low (approximately 200 g) and capable of deploying only a small scintillator detector. For example, the GR1 SIGMA-25 from Kromek Ltd, which has a mass of 56 g (Mirion Technologies, 2019). The low downdraught could be advantageous where it is beneficial to conduct monitoring close to the target and where disturbance must be avoided e.g. detecting loose alpha contamination. However, payload constraints currently make this unfeasible, as batteries, transmitter and possibly other instrumentation would add to the payload.

8 Detection of alpha and beta emitting radionuclides by future UAV systems

The detection and measurement of alpha and beta radiation was not considered in detail in the literature review, with the focus mainly on the monitoring of gamma radiation. The detection of alpha and beta emitting radionuclides is revisited here.

For certain situations, there may be an opportunity to detect beta radiation with a gamma spectrometer that is sensitive to both gamma and beta radiation (e.g. the GR1 from Kromek Ltd, mentioned previously). It would be necessary for the gamma detector to be close to the source (e.g. within approximately 1.5 m). This would require either the detector to be within that distance of the ground, or for the source of beta radiation to be in the air around the UAV (e.g. during plume tracking operations). For both cases, the beta particle would need to pass through the front window of the detector and interact with the detection crystal. This is observed as a characteristically broad photopeak at two thirds of the average peak energy of the incident beta radiation.

Whilst most alpha and beta emitters also emit gamma radiation, the probability of gamma emission can be low. For example, ^{210}Po is almost a pure alpha emitter and more than 99% of decays from the radionuclides ^{239}Pu, ^{238}Pu and ^{238}U proceed through alpha emission. Further, even minor alpha emitters that exhibit high rates of gamma emission, such as the low gamma energy emitter ^{241}Am, can be difficult to detect using gamma detection capabilities (Kong et al., 2024a). This is due to the comparatively high gamma background. Given that many industrial applications involve the processing of actinides, it is recognised that an improved detection of alpha particles could offer significant benefit to the following scenarios:

- A radiological terrorist incident involving an alpha source (see scenario 5 ‘mapping contamination in the urban environment following a malicious radiation incident’). In the case of the poisoning of Alexander Litvinenko in 2006 (Harrison et al., 2017), it was necessary to evaluate the spread of alpha contamination (^{210}Po) across a wide area in Greater London. A remote detection capability would increase the speed of the survey (minimising health risk to the public) and remove the operator from the scenario. Of note, a small proportion of alpha emissions from ^{210}Po are accompanied by an 882 keV gamma emission. It is this gamma emission that led to the discovery of the use of ^{210}Po in the Litvinenko poisoning.

- Managing the clean-up of legacy radiological contamination released from industrial applications or locating lost alpha and beta sources (see scenario 3 ‘localisation of point sources’). Extensive on-ground monitoring has been required for the clean-up of heterogenous alpha-emitting (^{226}Ra) sources at Dalgety Bay with activities ranging from 1 kBq to 76 MBq (SEPA, 2024). Despite remediation work being complete, there is a role for aerial monitoring as part of future monitoring plans to provide public reassurance. Worldwide, uranium hotspots in the environment can be partly traced to industrial activity (e.g. mining), applications relating to nuclear power, and the detonation of uranium-containing munitions (Nelson, 2009).

Alpha detection is an area where rapid advancements have been made in recent years, because of improvements in the sensitivity of camera technology. Two methods are considered here for the indirect measurement of alpha radiation: light-induced fluorescence and alpha induced fluorescence imaging. The former method is typically limited to uranyl (i.e., uranium (VI)) compounds.

- Light-induced fluorescence. Some radioactive compounds (such as uranyl compounds) will fluoresce when ultraviolet (UV) light is shone on them. The light which is induced by the UV is then detected and measured by a standard red, green, and blue (RGB) camera unit.

- Alpha-induced fluorescence imaging. This approach uses the emission of photons from radio-ionised excited nitrogen molecules in the air to observe alpha emitters from a distance.

8.1 Light-induced fluorescence

Light-induced fluorescence is a technique based on the fluorescent behaviour of certain compounds when excited by strong monochromatic UV light. Initially the monochromatic light source was a laser, but more recently light emitting diodes (LEDs) have been used. Fluorescence occurs when, due to the absorption of light, the electrons in a material acquire such an energy as to reach an excited state. On returning to the ground electronic state, the electrons compensate for the sudden loss of energy by emitting photons, which are detectable using optical instruments. The fluorescence spectrum is characteristic of each fluorescent component present and can therefore be used to identify those components (Lo Savio et al., 2024, Sirven et al., 2023).The intensity of fluorescence can be used to determine the concentration of the fluorescent material (Ramanna, 1989).

Of specific relevance to this study is the fluorescence of uranyl compounds. These may be present in the locations of former industrial sites (e.g. disused uranium mines) or where depleted uranium munitions have been used. In addition to radiological impacts, excess uranyl ions can affect renal function and in extreme cases cause failure (UKHSA, 2007). Uranium is commonly found in the hexavalent (i.e. uranyl) chemical form in the environment, although it can exist in the tetravalent (i.e. U(IV)) form. Studies in the US of contaminated soils from specific Department of Energy sites, have suggested that 75-95% of uranium exists in the hexavalent form (Lo Savio et al., 2024). There is therefore a potential opportunity for aerial deployment of laser induced fluorescence to provide faster and systematic detection and measurement of uranyl compounds in the environment.

There is limited published work concerning stand-off detection of uranium in the environment through this method. One study undertaken in the 1980s is of particular interest for an aerial monitoring application (Kasdan et al., 1981). This research consisted of two parts: 1) a field investigation using a system constructed to detect uranyl fluorescence from geological targets, and 2) considerations for the conceptual design of an airborne monitoring system for widespread mapping. The system used in the field investigations comprised a scanning transmitter (to excite fluorescence in the target), a receiver (an optical system and detector), and signal processing electronics. Fluorescence measurements were performed at an open pit quarry which had known surface uranyl mineralisation along its walls. Signal to noise ratios were obtained for different ranges and uranyl concentrations, under different lighting conditions and laser parameters. These considerations were then fed into the conceptual design of an airborne system. The calculations indicated that widespread mapping of uranyl fluorescence is technically feasible.

In 1996, the use of a portable laser-induced fluorescence system for the measurement of widespread uranium oxide contamination was demonstrated as part of the Fernald Environmental Management Project (FEMP) in West Virginia, sponsored by the US Department of Energy. The demonstration was performed indoors, over various man-made surfaces (e.g. steel beams, concrete walls, scabbled surfaces), and up to a range of approximately 6 m. It demonstrated successful localisation of uranium dioxide in quasi real-time with high spatial resolution (US DOE, 1999).

Recently, a team of researchers from the University of Bristol have used induced fluorescence measurements from a UAV to map uranium deposits inside an abandoned uranium mine at distances of 10 m as well as outside on the quarry face (Leach, 2024, Verbelen, 2024). In this case, a bank of LEDs was used to provide UV illumination rather than a laser system. This enabled illumination of a larger area and rapidly increased the speed of surveying. Figure 24 shows an output from the UV imaging system used to map fluorescent uranyl mineral precipitates inside an abandoned mine in Arizona (known as the Sue mine).

Figure 24: UV map of fluorescent uranyl mineral precipitates inside the former Sue mine in Arizona (reproduced from Verbelen, 2024).

Although induced fluorescence is a simple technique, which is quick to deploy and which can detect small quantities of uranium with excellent spatial resolution, there are some drawbacks which may affect a future UAV deployment. It is best performed where other light sources including daylight can be excluded. It may be possible to use the technique during the day, but to do so may require a powerful light source, and coincident hyperspectral camera. This is perhaps difficult to arrange on a UAV. Further, the uranyl surfaces must be exposed. For example, in the field investigation of the open pit quarry (Kasdan et al., 1981), it was the exposed surfaces which were selected as the target. For some survey areas, the presence of undergrowth or sediment would obscure any fluorescent surface. The fluorescence of uranium compounds is also limited to the uranyl containing phases (Sirven et al., 2023), which are often the most dominant but not the only uranium bearing phase in the environment.

There are some safety considerations to be examined for these technologies. For operation at night, obstacle avoidance (including nocturnal wildlife) is a challenge. However, clashes may be somewhat mitigated through pre-programmed flight paths, recorded during the day. Although, the need for pre-programmed missions does potentially limit its use in emergency scenarios. Power and cooling requirements are extremely high due to the intensity of UV light needed which would limit UAV flight time. Precautions must also be taken to avoid eye damage caused by scattered UV light.

8.2 Alpha-induced fluorescence

Alpha-induced fluorescence is a technique which measures the radioluminescence (RL) induced in the air immediately above an alpha radiation source. This technique could potentially enable the detection of alpha emitters at greater ranges than what can typically be achieved with conventional alpha radiation detectors (approximately a few centimetres in air). Long-range alpha detection is currently a topic of wide interest across the nuclear industry. A PhD project for example was undertaken in this area at Lancaster University (Crompton, 2019) and a joint challenge on the topic was commissioned by NNL and AWE through the Game Changers innovation programme (Game Changers, 2021). Alpha particles ionise atmospheric nitrogen molecules surrounding the source. The ionisation process produces secondary electrons which excite surrounding nitrogen molecules, emitting photons as they return to their ground state, which are detectable through optical instruments. The RL emission mainly falls within the ultraviolet A (UVA) region (wavelength range of 315-400 nm), with primary peaks at: 315.9 nm, 337.1 nm (main emission peak) and 357.7 nm (Kong et al., 2024b) which coincide with solar emissions. Whilst detection in the 300-400 nm range has been achieved under special lighting conditions, the interference with solar emissions has historically hampered detection in daylight conditions. A key challenge in detecting alpha radioluminescence is the weak emission intensity of peaks free from interference. A solar-blind emission occurs in the ultraviolet C (UVC) region (200-280 nm), as solar radiation in this range is absorbed by the ozone layer and does not reach the Earth's surface. However, RL emissions in the UVC spectrum are weak (less than 1% of the full emission).

Recent advances have been made using camera systems equipped with Charge-Coupled Devices (CCDs) which superimpose the RL signal onto a visible light image. The primary challenge with CCDs is their susceptibility to interference from visible and infrared light, and this has been investigated by the University of Bristol (Kong et al., 2024a, Kong et al., 2024b). For indoor environments, where the effects of solar background UV can be largely ignored, a series of UV transmissive filters have been used to maximise blocking efficiency and identify the main emission peak at 337.1 nm. However, for the monitoring scenarios relevant to this study (i.e. outdoor applications), the UV background cannot be neglected (even at night). In the University of Bristol research, a series of five stacked 276 nm filters were used to block the UV background and obtain only the UVC region, free from solar radiation. The filters were arranged in tilted positions and integrated with a highly UV-sensitive deep cooled CCD camera. Figure 25 shows an example of a long-range alpha detection camera, in this case patented by VisionAlpha.

Figure 25: Long-range alpha detection camera patented by VisionAlpha (reproduced from VisionAlpha, 2025a).

The present lower limit of detection (at 1 m in 10 minutes) for the alpha camera is understood to be (VisionAlpha, 2025b):

- 3 kBq in a UV-free environment (i.e. indoors or in an acrylic glovebox (Kong et al., 2024b));
- 100 kBq at night; and,
- 3 MBq under indirect sunlight.

A 3 MBq alpha source could be detected under night-time conditions, at a 1 m detection distance within one minute. However as for light induced fluorescence, the performance is evidently poorer when there is ambient light present.

As noted in one study, the system provides good spatial resolution when two sources of varying intensities are placed in proximity (Kong et al., 2024b). A 29 kBq source could be separated from a 3 MBq source at 9 cm, when placed 2 m from the camera and with an exposure time of 1 hour, as shown in Figure 26.

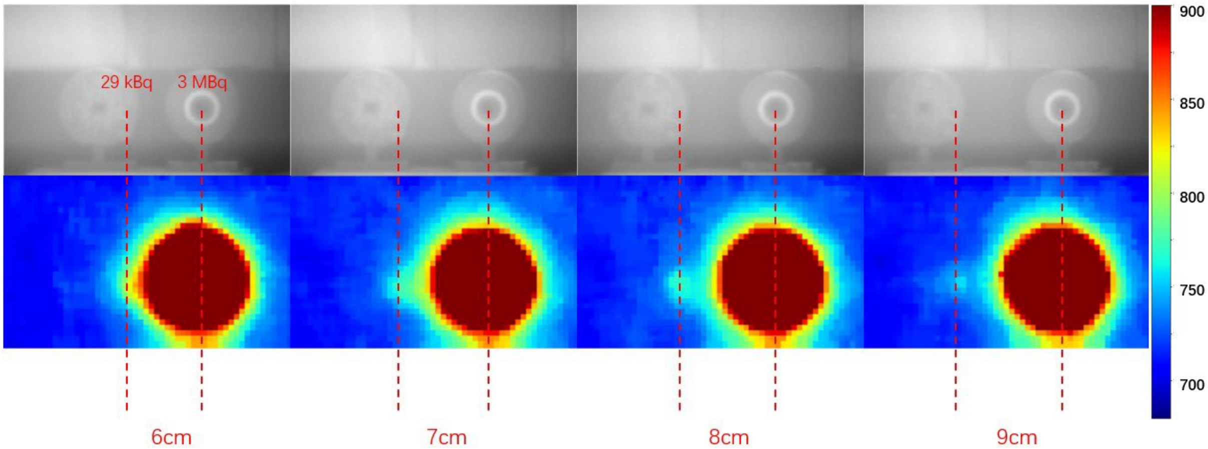


Figure 26: Visible light images (top) and alpha-induced radioluminescence images (bottom) of 29 kBq and 3 MBq alpha sources in close proximity to one another at various separations (reproduced from Kong et al., 2024b).

The alpha RL signal is proportional to the activity of the alpha source and inversely proportional to the square of the detection distance. However, a roughly proportional relationship is expected between limit of detection and distance (as the number of pixels occupied by the corona of the RL decreases proportionally with the detection distance). Hence, a limit of detection of 1 unit activity at a detection distance of 0.8 m is expected to scale to 3 units at 2.4 m. Research into the relationship between limit of detection and range is currently ongoing.

The system provides the ability to detect alpha sources at the metre range, with activities that would be typical of a lost source or heterogenous particle. However, in its current form, several challenges exist for environmental monitoring application. For the detection of sources of the order of MBq at 1 m, exposure time in the order of minutes is required. The system has an angular field of view of 7.2° resulting in a linear field of view of approximately 12 cm at 1 m. In its current form, the survey time would be impractical for all environmental monitoring scenarios. The weight is also considerable for a UAV based system (approximately 3 kg), because of the cooling system needed (VisionAlpha, 2025b), which is a further consideration for survey time. If undergrowth is present, or the alpha particles partially buried/obscured, the luminescence cannot be detected. It was also found that combinations of incandescent and fluorescent light sources, such to represent city light, overwhelmed the RL signal to the UV component of the fluorescent light. This presents an additional constraint for its use in the urban environment.

The monitoring scenario which is of most relevance to alpha-induced fluorescence capability is the detection of alpha contamination from a radiological terrorist incident/lost source. That is, where widespread detection of alpha emitters is necessary. It may therefore be beneficial to investigate increasing the field of view of the detectors. As the field of view increases, the coverage increases, and survey area decreases. Whilst increasing the field of view will decrease the spatial resolution (as the signal is focussed on fewer pixels), the signal per pixel is expected to increase and thus the detection limit may also increase.

The alpha cameras are currently being designed for use in an industrial glovebox, at a range of 2-3 m. Whilst the lens set-up is therefore comparable to that which would be used by an UAV, indoor lighting conditions are significantly different to a natural outdoor environment. Acrylic windows (as used by a glovebox) have been shown to be highly effective filters of the ambient UV background which may exist outside the glovebox. This makes gloveboxes a favourable environment for deployment of the alpha-induced fluorescence technique (Kong et al., 2024a). However, caution is required when attempting to infer the possible applications of these techniques for environmental monitoring from existing glovebox related applications.

9 Advances in CZT detector technology

9.1 Compton imaging

Cadmium zinc telluride is a valuable material for radiation detection due to its good energy resolution and the direct conversion of photon interactions to an electronic signal. This means CZT detectors can operate in high-intensity environments. In the applications of CZT detectors considered thus far, source localisation is achieved in post-processing (e.g. using deconvolution and geometry optimisation algorithms), where the detector itself does not provide any directional information. In recent years, there has been an emergence of 3D arrays of detectors, specifically CZT types, to provide directional information. Several methods have been developed; one uses two layers of detectors arranged to detect coincident events. In the first layer, the gamma ray is detected by Compton scattering and in the second, detection occurs again when the scattered gamma ray is stopped. A 3D image can be constructed by determining the path of the gamma rays through the two layers of detectors (Abraham, 2023, Myjak and Seifert, 2008).

A research team at Sandia National Laboratories trialled the use of a 3D array of CZT detectors, with the aim of tracking particles to demonstrate directionality (Mitchell et al., 2016). The detector arrangement was produced by H3D Gamma Inc, although it is not clear whether this was a commercially available system. There were two versions of the system, which consisted of two variations of modules of 18 individual CZT crystals (of dimensions 2 cm × 2 cm × 1.5 cm arranged in two planes. A gamma-ray image was superimposed over a photograph taken with an optical camera, integrated into the detector arrangement. Various sources (^{241}Am, barium-133 (^{133}Ba), ^{137}Cs, and ^{60}Co) were placed in a quadrant, at different relative positions, and the emission profiles were obtained and processed by the system software. The sensor array was positioned 1 m from the sources, whose activities ranged from 1.6 to 4 MBq. The results showed that for the high energy gamma emitters (^{137}Cs and ^{60}Co), spatial resolution was possible at separations of less than 2° (approximately 2 cm displacement in the vertical and horizonal). To resolve the lower energy gamma source (notably ^{133}Ba) spatially, a much greater separation was necessary (greater than 10°).

As an illustration of existing capabilities, H3D Gamma Inc. (the providers of the detector arrangement in the Mitchell study) have a range of Compton imagers, in different of detector sizes. They measure from 50 keV to 3 MeV, have a high energy resolution (<1.1% FWHM at 662 keV), low weight (3.5 kg) and have high ingress protection (IP67) for ease of decontamination. Real-time spectroscopy, characterisation, and visual image overlay is provided, and wireless data can be transmitted, as discussed in (H3D, 2024). More information on the systems provided offered by the company and case studies for their use is available in (H3D, 2016). H3D also produce an array detector marketed specifically for UAV applications, the M400 series, which, with a mass of approximately 0.5 kg and a robust design. The M400 series has a high spectral resolution and is capable of detecting weapons grade uranium and plutonium, as reported in (Goodman et al., 2020).

Whilst Compton imaging has many beneficial attributes, some limitations are expected. One of these relates to the detection of low energy gamma radiation. At low energies, gamma rays are more likely to interact only once in the CZT material (via the photoelectric effect) and hence, in such a case, Compton imaging cannot be performed. It has been suggested that a coded aperture mask technique can be used (Abraham, 2023). In this instance, localisation would need to be performed by changing the direction from which gamma rays are accepted (as a function of time). For a UAV deployment, this would likely be undertaken by hovering over the survey area, obtaining a measurement, before being repositioned (and this process repeated). However, this method would be onerous and impractical for wide area monitoring. Measurement time is also expected to be an issue for a UAV deployment of Compton imaging. As mentioned above, each incident photon must deposit energy in two interactions for it to be usable for source localisation. It should be noted that the use of a coded mask, typically made from tungsten, represents an increase in payload mass. This may not be easily accommodated for some UAV applications.

The use of Compton imaging is highly relevant to many of the monitoring scenarios and may be accessible in an easily deployable form with imaging available in real-time. Whilst these characteristics may support its use for applications where quick deployment is necessary, other factors need to be considered. For example, the capability of Compton imaging for environmental radioactivity monitoring involving the measurement of sources with low count rates or gamma energies is expected to be challenging. However, 3D position sensing technologies offer two significant opportunities:

- There is the opportunity to modularise detector design: through multi-detector arrays, systems can be tailored for a specific application (Streicher, 2017). This is being made possible through the advances in integrated circuitry in the consumer electronics industry. A larger detector array could be created for a low-dose application (or improving photon stopping power), overcoming some of the historic limitations associated with CZT crystal growth.

- By recording directional radiation measurements alongside a 3D point cloud (e.g. LiDAR), each radiation measurement can be placed on a 3D surface. There is no post processing (e.g. inversion) needed to obtain the location of the radiation measurement, hence this attribution can be undertaken in real-time. For teams working collaboratively (e.g., in a nuclear accident scenario), access to data is maximised.

Gamma-ray imaging is the subject of significant academic interest, with many active research areas and published studies in the literature. These include collaborations with CZT manufacturers to understand how detector growth and fabrication affect performance and how power consumption can be minimised to maximise the battery life of portable systems (Streicher, 2017). For example, the Orian Radiation Measurement Group at The University of Michigan (whose academics founded the company H3D) have published approximately 50 research papers on this topic (Michigan Engineering, 2025).

9.2 Multipixel Detectors

One area of developing CZT technology is the use of multipixel detectors, which are also able to capitalise on the opportunities for position sensing detectors discussed in Section 9.1. Multipixel detectors consist of a CZT detector that has a common cathode, but the anode is divided into pixels, as shown in Figure 27.

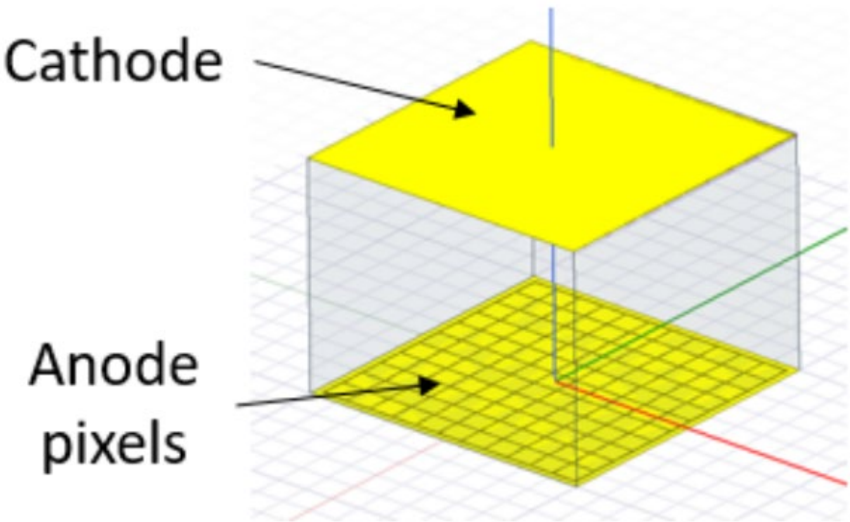


Figure 27: Multipixel CZT detector (reproduced from Petryk, 2023).

When a gamma ray interacts with CZT, electrons are released in the form of a charge cloud. A charge pulse is produced for each pixel, which is reproduced as a signal. A multipixel detector can identify events where charge is shared between pixels and enable directional information about the gamma-ray to be obtained through post processing. Pixel size and pitch can be optimised to improve the performance of the device, depending on whether the application requires either improved characterisation or positional accuracy. A smaller pixel size provides higher positional resolution but at the cost of spectroscopic performance as there is a loss of charge in the interpixel regions (Du et al., 1999, Allwork, 2013, Petryk, 2023).

The key benefits of a multipixel detector for UAV deployment are twofold. Firstly, there is an increase in the count rate for a given source. All incident photons can be detected and tracked, as opposed to only those that undergo Compton scattering. Secondly, there is no need for collimation or coded apertures, minimising the weight of the detector. The avoidance of long count times and potential for reduction in payload are significant benefits for a UAV deployment. Multipixel detector systems for source localisation are currently being developed; although only one system is known to be commercially available. This is the LAMP system from Gamma Reality Inc. (GRI, 2024). The development of multipixel detectors is one of the areas of focus of the Orian Radiation Measurement Group at The University of Michigan. The University of Bristol is also developing a multipixel system for the purpose of UAV-application. Multipixel detectors represent a potential area of future benefit, particularly for UAV applications such as source localisation where high spatial resolution is required.

10 Advances in scintillator technology

In certain areas of the UK, historic discharges of technologically enhanced naturally occurring radioactivity (TENORM) are significant contributors to public dose rates. As an example, approximately 91% of the total estimated dose (0.21 mSv out of 0.23 mSv) received by the Cumbrian coastal community near Sellafield in 2023 was due to TENORM exposure (CEFAS, 2024). In this case, TENORM originated from historical discharges from a former phosphate processing plant near Whitehaven. For in-situ detection and measurement of these radionuclides in the environment (e.g. U and Th isotopes and ^{40}K), detectors which can measure up to 3 MeV with high efficiency are necessary. Larger volume detectors provide a better detection efficiency for gamma-rays than an equivalent smaller volume detector (due to the increased stopping power) (Lowdon et al., 2019). Currently, CZT detectors are not available in large volumes. Therefore, for applications where the detection of high energy gamma radiation is necessary (or at low count rates), a scintillator is used. This is commonly NaI or CsI, with a trace amount of dopant. For example, a larger volume CsI detector (32.8 cm^3) was used in one study in preference to a CZT detector with an active volume of 1 cm^3 (Connor et al., 2018). This was despite the CZT detector having an improved energy resolution. The larger volume (higher efficiency) detector was necessary in the lower count rate regions.

The characteristics of a suitable scintillator material are discussed in earlier works (e.g., Wilkinson, 2004). It is stated that the ideal scintillator should convert all the incident photon energy into scintillation pulses, have a high stopping power, and provide fast sampling rates so that saturation of the electronics does not occur. The material should also not be hygroscopic and have no intrinsic radioactive background. Scintillators are available in a range of volumes. For a survey conducted by vehicle or large aircraft, a large volume detector system can easily be accommodated. Large volume NaI scintillators with a mass of 17.5 kg (and volume of 4 L) were deployed from a manned fixed-wing aircraft in the aftermath of the Fukushima disaster. Deployment of such a detector from a UAV is not currently practical, where the payload is limited to typically several kilograms. This system is not always necessary either, as UAVs can operate at a lower altitude and can therefore capture more of the gamma radiation. However, as flight time is related to payload, there is an inherent balance between flight time and detector capability and payload mass. A reduced mass, or an improvement in capability (for the same mass), are clear benefits.

An evaluation of alternative scintillator detection material specifically for UAV systems was undertaken in a previous work and discussed in Sections 4.3.2 and 4.4 above (Lowdon et al., 2019). In Lowdon's study, the scintillation properties of CsI(Na), CsI(Tl), $LaBr_3$, and LYSO(Ce) were modelled in software package GEANT4, with the aim of identifying whether there was a more suitable material than the more commonly used CsI detectors. It was found that $LaBr_3$ outperformed all other materials, due to its augmented detection efficiency, leading to increased count rates and energy resolution. The only shortfall associated with $LaBr_3$ was found to be the noise created by the self-reactivity. ^{138}La decays to either barium-138 (^{138}Ba) or cerium-138 (^{138}Ce) which produce peaks at 1.436 and 0.789 MeV, respectively. The former decay increases the signal-to-noise ratio when measuring the 1.461 MeV ^{40}K peak and other low energy decays. This result is a key factor when distinguishing anthropogenic from natural radiation. As ^{138}La decays to ^{138}Ce, it is possible that $CeBr_3$ could be a better scintillator option. However, further work would be required to evaluate its performance. The Lowdon study states that the intrinsic radioactivity of ^{138}La is a considerable issue, unless it can be well characterised and accounted for, work which was ongoing at the time of publication.

A common issue with NaI, CsI, and the two bromine-based crystals is their hygroscopic behaviour, which can cause degradation in performance. This issue requires mitigation for environmental monitoring applications, including UAV applications. It should also be noted that an increased count rate also improves the ability for localisation via a deconvolution algorithm. Hence, there may be further benefits from these alternative scintillator materials not yet realised. The use of $CeBr_3$ is supported by an investigation which compared its use against a HPGe detector and found its performance broadly comparable to that in a laboratory environment (Idoeta et al., 2021). Bromide-based scintillators are commercially available, but are not yet popular, as they are still relatively unproven. Field trials involving bromide-based crystals could help establish their capabilities and improve understanding on whether their hygroscopic behaviour impacts performance.

Research is also being undertaken based on the use of Gadolinium Lutetium Oxide (‘GLO’), a novel and high-density scintillator material (UKRI, 2025). GLO is believed to offer improved hygroscopic behaviour compared to conventional scintillator materials. In addition, lead-based crystals are in an early stage of development. They are expected to exhibit good brightness (e.g. high efficiency) and high stopping power with good water resistance. However, their widespread use is currently limited by the difficulty of scaling up their synthesis (Erroi et al., 2023). Fabrication and cost issues need to be addressed before these materials can become commercially viable (Chen, 2024).

11 Advanced sensors

11.1 Solid-state LiDAR

The most basic form of range measuring technologies employed by UAV systems are (single point) laser range finders. For surveys where vegetation cover does not have a major effect on the profile of the surface (e.g. urban or arid landscapes), this technology is appropriate (Connor et al., 2020). For survey areas where the topography is affected by the presence of undergrowth, a scanning laser system is necessary (e.g. LiDAR). The LiDAR system emits and detects multiple pulses of light in an arc, enabling first returns (e.g. foliage) to be distinguished from subsequent returns (e.g. the ground) (Connor et al., 2016).

Early scanning LiDAR systems used mechanical component, typically a rotating mirror, to emit and receive the pulses of light and thereby calculate the distance to the object (via the time-of-flight principle). More recently, solid-state systems have emerged. Although the principle of operation remains unchanged, direction of the beam is achieved using electronics (an array of aligned sensors) which makes higher scanning rates possible (MacDonell et al., 2023). This technology shift has been driven by the automotive industry which has created a need for sensors with a wider field-of-view and finer angular resolution. Whilst a greater resolution at range offers benefits for UAV deployment, added benefits are expected to include a reduction in both power and weight requirements and an increase in robustness (due to the absence of sensitive mirrors).

There is little published information on the application of solid-state LiDAR for conducting aerial surveys. Of note, a consumer-grade solid-state LiDAR (DJI Zenmuse L1) was used in one study to map the dry topography of a 3 km stretch of river in the UK (MacDonell et al., 2023). Flying at an altitude of 60-80 m, the system was found to be effective over a penetrating sparse canopy-type vegetation. However, it was less capable with dense, ground-hugging vegetation (e.g. heather, thick grass). The authors suggested further research to improve vegetation penetration, such as flying lower, increasing flight overlaps, and flying after autumnal foliage dieback (the latter being species specific). It should be noted that this is one instance of solid-state LiDAR use. Additional investigation is likely needed to compare mechanical and solid-state LiDAR systems in the same environment. The DJI Zenmuse is an integrated LiDAR-camera system which creates a photorealistic point cloud as opposed to a single-colour 3D point cloud. The information obtained is similar to that of photogrammetry, obtaining the best possible information to support remedial work. It is plausible that technologies such as these may ultimately replace traditional photogrammetry techniques as described in the literature survey.

Availability of solid-state LiDAR systems is currently a limiting factor in their adoption, as there are currently few manufacturers of solid-state LiDAR sensors. However, with car manufacturers increasingly adopting driver-assist systems, and with each system requiring multiple LiDAR sensors, the market is expected to expand. Availability issues and manufacturing costs might then reduce. At that point, solid-state LiDAR could potentially represent an excellent potential translation of technology from a non-nuclear industry.

11.2 Thermal imaging

The role of UAV deployments of thermal imaging is recognised in one NDA report (NDA, 2019). Notable functions discussed include ecology monitoring or mapping of a building's thermal flux). While these applications are not relevant to this study, thermal imaging could potentially be used in an emergency scenario or to supplement environmental radioactivity measurements. For example, it may be possible to locate a lost radioactive source by using thermal imaging to observe an object which is thermally anomalous versus its surroundings. If the source is held in a metal casing which provides shielding, then the casing will likely be thermally distinct from the surrounding environment. Strong radiation sources will often be self-heating, providing itself as a thermal anomaly for detection.

12 Discussion

The results of the literature survey were summarised according to topics relevant to aerial monitoring of environmental radioactivity. The suitability of currently available UAV systems was also evaluated against five environmental monitoring scenarios. For the horizon scanning section, technological developments that can reasonably be anticipated have been identified. This is not to say that all the developments discussed will necessarily prove practicable for UAV deployment, as some may have limitations that prove insurmountable.

Radiation monitoring systems must be tailored to the application as there is no universally applicable technology. UAV based systems have some advantages for the purposes of environmental monitoring. For example, they allow scanning of an area, and the data can easily be presented as a 'radiation map.' Although this may also be the case when handheld or wheeled vehicles are used, UAVs would be able to do so more efficiently over some types of terrain. For example, when there is mixed vegetation, very overgrown land, or where access is dangerous or inconvenient for a person to attempt to reach. In other situations, such as where continuous monitoring is needed, UAVs may not be a useful tool. The current generation of multi-rotor UAVs have flight times of the order of one hour, which is too short for a situation that demands continuous monitoring. For any given monitoring task, UAVs need to be compared against alternatives that include the use of fixed monitoring stations and ground-based monitoring by a person (using either a handheld or wheeled system). This will enable the identification of the technology (or technologies) which provides the most appropriate monitoring solution. The table below shows such a comparison for some of the relevant categories.

Table 3: Comparison of the advantages and disadvantages of UAV monitoring, fixed monitoring stations, and manual monitoring capabilities. It is assumed that UAVs are used for in-situ monitoring and not to collect samples for subsequent analysis.

	UAV with radiation detectors	**Fixed monitoring points**	**Monitoring by persons using handheld or wheeled monitors**
Type of radiation	Only gamma radiation is easily detectable at height. Ground based alpha and beta may be detectable, however with difficulty. Currently, alpha radiation has not been measured with a UAV system. Beta	Gamma radiation is detectable. Alpha and beta radiation can only be detected if present in in a gaseous/vapour plume immediately	Alpha, beta, and gamma radiation are potentially detectable using handheld or wheeled monitors. However, detection of alpha and some beta emitters can be challenging. Manual monitoring also exposes the operator to radiation.

	UAV with radiation detectors	Fixed monitoring points	Monitoring by persons using handheld or wheeled monitors
	radiation may be detected using gamma spectrometry if the UAV were to pass through a gaseous beta emitting plume.	near/at the monitoring point.	
Repeatability	Exactly repeatable but continuous monitoring is not possible.	Continuous monitoring at precise static position.	Repeatable but not continuous monitoring. Repeat surveys will not be identical.
Use in high radiation fields	Yes, although electronic systems may ultimately degrade/fail in very high radiation fields.	Yes, it is comparatively easy to provide a hardened system.	Unlikely to be permissible because of operator safety aspects (or at least severely restricted).
Other monitoring capabilities	Visual (e.g. smoke) plumes identifiable, Temperature is measurable, but wind speed is difficult to measure when airborne.	Visual and wind speed measurements possible but are limited to near ground level.	Possible. An operator may notice other relevant aspects such as wildlife intrusion/pathways. They can also dig down and/or take samples for laboratory analysis.
Access	Need line of sight to operator.	Occasional personnel access e.g. for maintenance and calibration needed.	Limited by personnel safety issues e.g. working at height, working in high radiation fields etc.
Technological Limitations and Vulnerability	Limited flight time which decreases as payload increases. Minimum flight height may be adversely affected by obstacles on the ground.	Unlimited monitoring time assuming wired power connection.	Unlikely to be cost effective for continuous monitoring.

	UAV with radiation detectors	Fixed monitoring points	Monitoring by persons using handheld or wheeled monitors
	Limited weather conditions for flight but deployable quickly in emergencies.	Vulnerable to damage e.g. vandalism.	
Possible safety implications	Can cause injury if they collide with people or wildlife, or damage property if they crash. Possible other claims on airspace and communication bandwidth during emergencies.	Limited, but personnel access safety needs to be assessed.	Minimal in routine applications, personnel safety issues in accident monitoring.

Potential technological developments have been considered in the horizon scanning component of this report. UAV technology will improve, although a step change in range and mission duration is unlikely unless improved battery types are developed. As discussed earlier, lithium polymer battery technology appears to have reached a plateau in terms of its development.

The literature survey described radiation monitoring systems that were primarily aimed at the detection of gamma rays. Horizon scanning suggests detection of other types of radiation with a UAV system may be possible, e.g. the energetic beta radiation from ^{90}Y, the daughter product of ^{90}Sr. However, remote detection of alpha and beta radiation remains a challenge. The ability to detect alpha and beta radiation at a distance would be an extremely useful capability for a wide range of radiation monitoring situations. This includes UAV monitoring of environmental radioactivity. There are such prospects now (e.g. by alpha-induced fluorescence) but they need further development to be deployable from UAVs and may only be suitable for certain environments. For example, those cases where a low flight height can be maintained. These monitoring situations may be relevant, and the use of nearly-lighter-than-air reduced downdraught UAV is discussed to avoid the disturbance that may occur with conventional multi-rotor UAVs.

Advances in conventional gamma detectors will continue with improved scintillators and solid-state detectors. Better scintillators and solid-state radiation detectors do seem to be in prospect, although challenges remain in terms of cost and ease with which larger crystals can be grown. In addition, a key parameter which must always be considered for technology use on UAVs is the weight. This may act against the application of the more complex imaging techniques, at least in the near future, because of the current size and weight of these technologies.

13 Conclusions and Recommendations

Monitoring anthropogenic radioactivity in the environment is an important task that is undertaken by the operators of nuclear facilities and regulators, either directly or using specialist support. Multi-rotor UAVs have now reached a stage in their development where it is possible to mount radiation detectors and ancillary measurement devices onto them and monitor radioactivity in the environment. Other platform types, such as fixed-wing UAV systems, have also been developed and offer extended ranges for monitoring surveys, albeit at the expense of manoeuvrability.

The extensive literature review that forms the first half of this report has covered many potential applications of UAVs. These include:

- Monitoring of areas that may be contaminated by radioactive materials from mining areas.
- Monitoring to ensure compliance with permitted discharge limits from nuclear sites.
- Monitoring of radioactive contamination from historic discharges or runoffs.
- Searching for lost radioactive sources.
- Monitoring of radioactive contamination following nuclear accidents.
- Monitoring of radioactive contamination following an act of radiological terrorism.

The evidence in the published scientific literature indicates UAV radiation monitoring systems offer advantages over the use of fixed monitoring stations, hand-held instruments, or wheeled vehicles. Areas can be monitored that would be difficult, intrusive, or dangerous for a human operator to reach. Examples include sandbanks, nature reserves, fragile roofs, and heavily contaminated areas. UAVs can also potentially monitor large areas which would be extremely time intensive to monitor using handheld techniques or analyse by collecting samples for subsequent laboratory measurements. The ability to construct a map of environmental radioactivity in the target area is perhaps the most useful attribute of a UAV. A ‘radiation map’ can provide valuable information on the spatial distribution of environmental radioactivity which would be troublesome to achieve by other means.

UAV systems also possess limitations, although technological developments are underway that may allow improvements. These limitations include the maximum payload weight and flight time that is currently possible, which may detract from the potential economic and technical advantages they otherwise offer. A major constraint of current UAV systems is that they are largely limited to monitoring gamma emitters. In addition, the UAV must also be flown in sufficiently proximity to the radioactive source so that useful information can be obtained. This distance is dictated by specific monitoring scenarios such as the source properties and is limited by the allowable flight altitude. Another concern is that the ‘weather window,’ within which a UAV would be possible to operate, may be limited. As an example, UAVs will sometimes need to fly close to the ground and hover for a period, to achieve the necessary sensitivity. This may prove difficult in winds of more than a moderate nature. Furthermore, the advanced techniques for monitoring, such as induced fluorescence or radioluminescence techniques discussed in the second half of this report, will clearly be more usable at night. This may increase risks of collision with members of the public and nocturnal wildlife, as well as disruption to some habitats.

Overall, the deployment of UAVs for the characterisation of environmental radioactivity might be possible and could, for some (but not necessarily all) situations, improve environmental monitoring programmes. However, there are knowledge and evidence gaps surrounding the potential of UAVs for monitoring radioactivity in the environment. Many of these have practical implications regarding the development of regulations relating to the use of these technologies specifically for environmental radioactivity monitoring. The following recommendations for further research are made here that are intended to assist with the likely appropriate 'next steps.'

The first and second recommendations relate to the incremental advancement of UAV systems for environmental monitoring scenarios that have not been extensively studied previously. Further testing is needed to better understand if proposed weather constraints for UAV use are overly restrictive. This line of enquiry should be framed in the context of monitoring radioactivity in the environment under typical UK weather conditions.

Recommendation 1 – Field tests need to be expanded on to reduce the uncertainty in the 'weather window' of UAV systems for monitoring environmental radioactivity in the UK. New research could consider international experiences, such as those of the Norwegian radiation safety authority (DSA), to understand their experiences of UAV deployments in challenging environments. UK organisations (e.g. the Royal National Lifeboat Institution) may also be able to provide advice.

The demonstrations made over the Chornobyl and Fukushima exclusion zones have an advantage in terms of detection, in that the contamination levels are high and widespread. For applications where activity levels are lower or do not vary with the same spatial extent (hence the probability of missing radiation is higher), UAVs may not offer an advantage over more traditional, ground-based monitoring methods (e.g. handheld or wheeled vehicle). The example given in the report which had some uncertainty about its viability was the use of UAVs for detection of heterogenous particles on a beach (e.g. small contaminant items, potentially buried, emitting low energy gamma radiation).

Recommendation 2 – Conduct a desktop feasibility study for the application of UAVs for a challenging and unproven deployment (e.g. a beach monitoring exercise). The study will assess the suitability of a UAV system to meet the characterisation objectives (as defined in advance) and the expected effect of detector size and type, scanning speed, altitude etc. on meeting the objectives. A feasibility study could also inform the design of a "viability" protocol for UAV monitoring campaigns in the context of radioactive substances regulation.

The final recommendation relates to the advances in technology identified in the horizon scanning element of the study and the future potential benefits to environmental radioactivity monitoring programmes. This includes routine monitoring and incident management scenarios.

Recommendation 3 – Continued development of the enabling technologies that may enhance environmental radioactivity monitoring programmes. Several specific cases of high potential benefit could be considered: field trials for novel scintillator materials ($CeBr_3$), the development of wider FoV alpha cameras and multipixel CZT, specifically for UAV application.

As a final observation, it is noted that technological innovations are not necessarily designed to order. Often, technology and techniques emerge and find applications that were not anticipated e.g. mobile phones. It is possible that the fast-developing field of UAVs will facilitate the monitoring of environmental radioactivity in ways that have not yet been identified or fully appreciated. As an example, the development of new virtual reality and artificial reality capabilities for UAVs may aid data visualisation and analysis following an environmental radioactivity monitoring operation. It therefore seems prudent for interested organisations to keep up to date with UAV technology developments. This approach would also help the Environment Agency assess and respond appropriately to environmental monitoring data collected by citizen scientists with their own UAV systems.

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List of abbreviations and acronyms

Term	Definition
BAT	Best Available Techniques
Bq	Becquerel
BVLOS	Beyond Visual Line of Sight
CAA	Civil Aviation Authority
CEZ	Chornobyl Exclusion Zone
COMAH	Control of Major Accident Hazards regulations
CsI	Caesium Iodide
CZT	Cadmium Zinc Telluride
FWHM	Full Width at Half Maximum
GBq	Gigabecquerel; 10^9 Becquerels
GM	Geiger Muller
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HPGe	High Purity Germanium
IAEA	International Atomic Energy Agency
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
keV	Kiloelectronvolt; 10^3 electronvolts

Term	Definition
LED	Light Emitting Diode
LiDAR	Light Detection And Ranging
LiPol	Lithium Polymer
MBq	Megabecquerel; 10^6 Becquerels
mSv	Millisievert; 10^{-3} Sieverts
NaI	Sodium Iodide
nm	Nanometre; 10^{-9} metres
NORM	Naturally Occurring Radioactive Material
nSv	Nanosievert; 10^{-9} Sieverts
PMT	Photomultiplier Tube
RL	Radioluminescence
RREMS	Radiological Response and Emergency Management System
RSR	Radioactive Substances Regulation
SiPM	Silicon Photomultiplier
Sv	Sievert
TENORM	Technologically Enhanced Naturally Occurring Radioactive Material
UAV/UAS	Uncrewed Aerial Vehicle/System
VIO	Visual Inertial Odometry

Term	Definition
VLOS	Visual Line of Sight
VTOL	Vertical Take-off and Landing
μSv	Microsievert; 10^{-6} Sieverts

Glossary

Term	Definition
Becquerel (Bq)	Standard international unit of radioactivity, corresponding to one disintegration (i.e., decay) of a radioactive nuclide per second.
Best Available Techniques (BAT)	Most effective and advanced methods, processes, or technologies that are currently available for achieving a high level of environmental protection, while being economically and technically feasible in a specific context.
Beyond Visual Line of Sight (BVLOS)	UAV operations where the aircraft flies beyond the ground operator's direct visual range.
Daughter	Resulting nuclide formed after a radionuclide disintegrates e.g. ^{90}Y is the daughter of ^{90}Sr. Daughter nuclides may be stable or unstable (i.e. radioactive).
Directional sensitivity	Ability of a detector to distinguish signals (e.g. radiation) coming from different directions. Detectors with directional sensitivity are typically designed to be more responsive to signals coming from a specific direction.
Dose	Amount of ionising radiation energy absorbed by an organism such as a person, or a specific biological tissue. Often measured in terms of the unit Sievert (Sv).
First Person View (FPV)	Capability which allows the operator (on the ground) a pseudo pilot's eye view from the UAV, using a remote link to a video camera mounted on the UAV.
Global Navigation Satellite System (GNSS)	Network of satellites with global coverage. Provides global positioning, navigation, and timing data to connected sensors on the Earth. Global Positioning System (GPS) is one example of GNSS i.e. the US operated system.
Inertial measurements and dead reckoning	Process by which position can be determined using accelerometers and a known reference position. Three mutually orthogonal accelerometers allow measurement of the acceleration vector to be made, as for example, a UAV moves away from the known reference position. By

Term	Definition
	integrating the acceleration to determine distance travelled, the current position of the UAV can be determined.
Isotope	Sometimes referred to as radioisotope. Varieties of a chemical element characterised by different numbers of neutrons in the atomic nucleus. Isotopes of an element may be radioactive or non-radioactive.
Isotropic point source of radiation	Radiation source which emits radiation without preference for direction. In practice, no source can radiate energy perfectly uniformly in all directions. However, it may be useful under some circumstances to assume a source is isotropic.
Light Detection And Ranging (LiDAR)	Remote sensing technology that uses laser light to measure distances and create highly accurate, three-dimensional models of objects or environments.
Maximum Missable Activity (MMA)	The maximum amount of radioactivity which may not be detected by an instrument under normal monitoring conditions.
Naturally Occurring Radioactive Material (NORM)	Radioactive materials that naturally exist in the environment e.g. in the Earth's crust, soil, water, air etc.
Radioluminescence	Type of luminescence. Ionising radiation excites the electrons in a material which results in the emission of light as the electrons de-excite.
Radionuclide	Radioactive isotope of a chemical element.
Sievert (Sv)	Common unit of radiation dose (see dose).
Spatial resolution	Sometimes referred to as lateral resolution. Refers to the level of detail or clarity in a representation of monitoring data, particularly in terms of how small or closely spaced changes in radioactivity can be distinguished.
Special nuclear material	Category of radioactive materials which require specific regulations and controls to prevent their misuse, such as

Term	Definition
	potential use in nuclear weapons. Often includes plutonium and uranium enriched in the uranium-235 isotope.
Stopping power	Refers to the rate at which the energy of ionising radiation is lost as it travels through a material. Radiation detectors with a higher stopping power are more effective at absorbing the energy of incoming radiation, which typically results in an improved detection efficiency.
Technologically Enhanced Naturally Occurring Radioactive Material (TENORM)	NORM that has been concentrated above natural levels or potential for human exposure is higher due to human activities or industrial processes e.g. mining, oil, and gas extraction.
Uncrewed Aerial Vehicle (UAV)	Sometimes referred to as an uncrewed aerial system (UAS) or a drone. An aircraft which flies remotely by a ground operator and without a human pilot (or crew) onboard. Many UAV technology designs are known, with variations in rotor system, power source, size etc. They are all referred to as UAVs in this report.
Uranyl	Sometimes referred to as U(VI), $(UO_2)^{2+}$ or hexavalent form of uranium. A chemical form of uranium present in some compounds which contain that element.

Appendix A – Potential legal constraints

It is not the intention of this report to comment in detail on the UK's legal restrictions on UAV use. Nevertheless, the capabilities of UAVs for monitoring radioactivity in the environment must be compatible with environmental protection principles if these technologies are to be useful. Rules and regulations for UAV flying vary internationally and it seems likely that some of the overseas applications that have been discussed in this report would not necessarily be permissible currently in the UK. On that basis, it is worthwhile to briefly examine the key risks of flying UAVs to people and wildlife in the context of monitoring radioactivity in the environment. This section is not a comprehensive account of all possible risks and associated legal constraints. Of note, regulation of flight safety by crewed and uncrewed vehicles in the UK is performed by the CAA.

Environmental risks associated with UAV use

UAVs contain fast moving parts, can travel at relatively high speeds (up to 60 mph), and the batteries which power them have a high energy density. Accordingly, they are potentially hazardous if in collision with people, other aircraft, or animals (including their habitats). Owing to the typical range of UAV flight heights, flying animals are expected to be the most vulnerable species to collision risks. Noise pollution originating from UAV use may negatively harm local habitats and this must be considered as part of any proposed environmental monitoring strategy. Noise generation is likely to be most significant for single-rotor UAVs.

UAVs pose a more limited threat to ground based infrastructure such as buildings or industrial facilities, because of their limited mass and hence kinetic energy. Although collisions with urban infrastructure may cause damage to the aircraft. Fire safety issues also need to be considered if UAVs are used in areas where flammable items could be present e.g. refineries, although this seems unlikely for most types of environmental monitoring.

The manufacture of most UAVs requires the use of elements that have been linked to environmental damage, such as by the refining of cobalt, used in batteries and motors. However, radiation monitoring itself is a non-destructive technology, UAVs can be presumed to have reasonably long lifetimes and UAVs are normally of limited size. For example, it seems likely that the creation-to-disposal environmental impact of a UAV system will be lower than that of the vehicle used to transport it to the monitoring site. Additionally, the materials used in the manufacture have high value and can be expected to be recycled. Most UAVs are electrically powered and thus the energy required to operate will increasingly be from 'green' generation sources. As such, there do not appear to be any notable environmental issues with the manufacture and transport of UAVs.

Possibilities for ‘Beyond Visual Line of Sight’ operation

Present legal requirements broadly necessitate operation with a visual line of sight (VLOS) to the UAV, unless an operational authorisation has been granted by the CAA (CAA, 2024a). This policy is intended to minimise collision risks for people, other aircraft, and wildlife (as described above). In practice, VLOS means that the distance between a UAV and the operator is limited to (typically) a few hundred metres (e.g. either the UAV operator’s eyesight or the presence of obstructions). Monitoring scenarios that require much greater distances to be covered, or where the line of sight to the UAV is obstructed (e.g. in an urban environment, or industrial site after a radiation incident) represent a BVLOS requirement and CAA authorisation will likely be needed. It should be recognised that, at the time of publication of this report, BVLOS capability is not yet commonplace on or around nuclear licensed sites. However, the UK CAA has indicated (through the publishing of a roadmap to BVLOS in 2024) that it is receptive to the introduction of such technology, provided it can be demonstrated as safe (CAA, 2024b). The situation about what is permitted by the CAA should not therefore be considered static (CAA, 2025).

BVLOS operation would almost certainly require a technical capability which has been accepted as being at least equivalent to the ability of a pilot of a manned aircraft to ‘see and avoid potential conflictions.’ This may involve the use of FPV equipment, a capability which allows the pilot (on the ground) a pseudo pilot’s eve view from the UAV, using a remote link to a video camera mounted on the UAV. Even then there may be requirements depending on weight and speed, for example minimum altitude requirements. UAV users may also need a protocol to adequately address a situation where communication was lost.

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