



# FINAL PUBLISHABLE REPORT

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## 1 Overview

Radiological emergencies involving an accidental or deliberate dispersion of alpha emitting radionuclides in the environment can cause significant damage to humans and societies in general. A detection system to measure large-scale contamination of these radionuclides was not available and new remote detection techniques which overcome shortcomings of traditional detectors were needed. This project has developed novel instrumentation and methods and a sustainable metrological infrastructure for outdoor-detection systems, which can detect remotely alpha-emitting radionuclides in the environment. This includes two lens-based radioluminescence detection systems, a novel calibration methodology based on radiance standards, environmental standards, and an unmanned aerial monitoring system. This will lead to real-time collection of traceable radiological data and faster, more reliable information for the decision-making authorities.

# 2 Need

Alpha particles represent the biggest risk to soft biological tissues compared to all nuclear decay products due to their high energy, large mass and high linear energy transfer. The amount of deposited energy is about 2 000 000 to 6 000 000 times higher than that of an ordinary chemical reaction (ordinary chemical energy used by the cells in the body), thus implying that a single alpha particle has the ability to severely damage or kill all cells within its range (typically, two to four cells). Therefore, the release of alpha emitting radionuclides in the environment, such as by nuclear terroristic attacks or transportation accidents, as well as by severe emergencies in nuclear installations, represents the greatest radiological threat for human beings if they enter the human body.

A detection system to measure large-scale contamination of these radionuclides was not available. In case of an emergency, the only option is to evacuate the population from the affected areas and then run diagnostics by hand, thus exposing the emergency teams to considerable risk. Even then, the results of emergency field applications are notoriously ambiguous, time consuming and tedious due to the centimetre range of the alpha particles in air.

Instrumentation and methods that overcome the disadvantages of existing detectors and allow remote detection of alpha particles in the environment were thus required to be developed, lowering personnel risk, detection costs, and time. Two radioluminescence detection systems were developed to establish the metrological basis for the optical detection of alpha-emitting radionuclides. One detection system is based on a high-quality UV fused silica lens (UVFS), while the other uses a PMMA Fresnel lens. Both systems operate as mapping systems by generating the radioluminescence image of alpha radiation sources by remotely scanning a narrow field of view over the user-defined region of interest while recording the photon count rate. While the UVFS system was optimized for use as a scanning telescope on a tripod due to limitations in its weight and mechanical stability, the Fresnel lens-based lens system was optimized for use as an unmanned airborne monitoring system (UAMS) for mapping alpha contamination in the environment. The UAMS is based on the unmanned aerial vehicle (UAV) DJI Matrice 600 Pro and uses the RIMASpec software architecture which allows the real-time viewing of alpha contaminations. The techniques aim at ensuring an adequate level of preparedness and response, and assist on-site incident management, creation of evacuation plans as well as in developing strategies for protecting public from harm. These measures are required by the European Union (EU) legislations defined in the Council Directive 2013/59/EURATOM and are compulsory for all EU Member States.

# 3 Objectives

The overall objective of this project is to develop novel optical systems for the remote detection and quantification of large-scale contamination with alpha emitters in the outdoor environment for the first time, allowing sound and quick countermeasures in the case of a radiological emergency.

The specific objectives of the project are:

1. To develop a new method and instrumentation for the optical detection of alpha particle emitters in the environment by air radioluminescence over a detection range of more than two metres. This includes the development of the first prototype of a mobile-outdoor optical detection system for real-time radioluminescence mapping of alpha sources in the environment.



- 2. To develop and establish a calibration system for the novel-type radioluminescence detector systems. This includes a new metrological infrastructure with a dedicated UV radiance standard, well characterised alpha-active environmental sample (mineral-phase, soil, organic and plant specimen spiked with alpha emitters) and a validated calibration scheme for the remote detection of optical system.
- 3. To extend the optical detection system to an imaging functionality for mapping of alpha contaminations in the environment. This includes the development of an unmanned airborne monitoring system (UAMS) that will integrate the unmanned aerial vehicle (UAV) and the novel alpha-radioluminescence detection system developed in the objective 1 to scan and obtain an image of the contaminated area.
- 4. To prepare and run a feasibility study for a laser-induced fluorescence spectroscopic method for the detection of alpha emitters. This method complements alpha-radioluminescence and, depending on laser parameters such as pulse power, photon wavelength and pulse duration, can enhance the detectable activity limit to below 1 kBq/cm<sup>2</sup>.
- 5. To facilitate the take up of the results by stakeholders and provide input to relevant standardisation bodies and radiation protection authorities. Information on the project research results will be disseminated by the partners to standards committees, technical committees and working groups such as EURADOS, ISO, IEC, IAEA, BIPM CCRI (I)-(II), ICRM and EURAMET TC-IR. In addition, knowledge will be transferred to the nuclear industry sector.

# 4 Results

**Objective 1:** New instrumentation for the optical detection of alpha particle emitters in the environment **Lead:** IFIN-HH

#### Detailed description of project developments against objective 1:

Radioluminescence mapping using well-characterised and optimized optical systems is an effective method for localizing contamination with alpha-emitting radionuclides. In the framework of the EMPIR project 19ENV02 RemoteALPHA, PTB with the help of IFIN-HH, LUH, UPC, TAU, ALFA RIFT and MATE has developed two radioluminescence detection systems to establish the metrological basis for the optical detection of alpha-emitting radionuclides. One detection system is based on a high-quality UV fused silica lens (UVFS), while the other uses a PMMA Fresnel lens. Both systems operate as mapping systems by generating the radioluminescence image of alpha radiation sources by remotely scanning a narrow field of view over the user-defined region of interest while recording the photon count rate. While the UVFS system was optimized for use as a scanning telescope on a tripod due to limitations in its weight and mechanical stability, the Fresnel lens-based lens system was optimized for use as an unmanned airborne monitoring system for mapping alpha contamination in the environment. These optical detection systems are aimed to facilitate a rapid, coordinated, and effective response in emergency situations involving the release of alpha-emitting radionuclides, nuclear safeguards, nuclear decommissioning and nuclear forensics.

#### Conception of optical detection systems

The successful detection of spectral fingerprints due to alpha radioluminescence in the environment requires optical systems which efficiently detect light in the characteristic wavelengths of radioluminescence photons, but at the same time stay as insensitive as possible to the ambient light. A high radioluminescence light throughput for the optical detection system requires a compromise between the diameter of the receiving optics, *D*, and the focal length of the system, *f*, because the overall efficiency of the detection system depends on the f-number N = f/D.

The diameter of the receiving optics D determines the so-called geometrical efficiency, which represents the solid angle subtended by the receiving optics and thus directly affects the number of photons entering the detection system. The focal length f, on the other hand, determines the angle of view, which in turn affects both the number of detected photons and filtering [see Fig. 1.1 (a)]. Interference filters should transmit only the selected radioluminescence band. Since the transmission band of these filters is subject to a blue shift at non-normal light incidence, optics with a long focal length are required to ensure a narrow angular distribution of the radioluminescence light on the filter without the need for additional optical elements which would cause additional light losses.



When considering the contaminated area as an ensemble of point sources, the f-number must be chosen to maximise geometric efficiency while maintaining an acceptable field of view that does not significantly blur the scanned radioluminescence image. To illustrate this point, geometrical efficiency and field-of-view (FOV) are plotted as a function of source-to-detector distance in Fig. 1.1 (b). While the light collection efficiency scales with  $r^{-2}$ , with r being the source-to-detector distance, the FOV is proportional to r:



**Fig. 1.1 (a)** Schematic illustration of the field-of-view (FOV) in a radioluminescence detection setup composed of a lens and a photomultiplier (PMT). The focal length of a lens is denoted by *f* while  $\theta$  is the angle of view. The FOV at the object distance *s* is  $y_{FOV} = \Delta y$  (*s/s'*), with  $\Delta y$  being the size of the detector sensitive area (diameter of the PMT photocathode), *s* and *s'* the object and image distance. (b) Geometrical factor  $\Omega_{nor} = \pi D^2/(4 r^2)$  with *D* being the diameter of the receiving optics and *r* the distance between source and receiving optics, normalised to the value for *D* = 240 mm and *r* = 1 m. The right side plots the field of view  $y_{FOV}$  with *s* = *r* and  $\Delta y = 20$  mm.

#### Design of the optical detection system

The lens-based optical detection prototypes developed as part of the RemoteALPHA project were designed to comply with the requirements stated in the previous section. They share the same configuration, see Fig. 1.2: an objective lens, a filter set to select the operating wavelength range (UV-A or UV-C) and a photomultiplier tube (PMT) with a cathode material (bialkali or cesium telluride) according to the wavelength range selected by the filter set.

Figure 1.3 shows the two lens-based radioluminescence detection systems developed, characterised and optimized un the framework of RemoteALPHA. Figure 1.3(a) shows the radioluminescence system based on the UV grade fused silica (UVFS) lens with a diameter  $D_{UVFS}=240$  mm, while Fig. 1.3(b) the one based on Poly(methyl 2-methylpropenoate) (PMMA) Fresnel lens with a diameter  $D_{Fresnel}=452.9$  mm. Both systems can be operated in the UV-A and UV-C spectral region, depending on the central wavelength and bandwidth of the interference filters used:

- in UV-A spectral range, a bialkali photocathode PMT (H10682-210, Hamamtsu) is used with a 2-filter assembly consisting of Edmund Optics #65-189 and Semrock FF01-340/12-25 centered at 337 nm and 340 nm, respectively; The system can also be used with 2 Edmund Optics filters, without Semrock filters, or vice versa. The number of filters in the setup can be adapted as needed. More than two filters can also be used, depending on the background level.
- in UV-C spectral range, a cesium telluride photocathode PMT (H11870-09, Hamamatsu) is used with one or more Semrock FF01-260/16-25 filter centered at 260 nm.





**Fig. 1.2** Schematic drawing of optical systems developed in the framework of RemoteALPHA project. Both, the UVFS- and PMMA Fresnel-lens systems share the same configuration: they utilize large receiving optics to maximise the geometrical factor, and the focal lengths have been chosen such that the radioluminescence image is not blurred substantially by the overlapping FOVs between adjacent scanning points.



**Fig. 1.3** Lens-based radioluminescence detection systems developed within the RemoteALPHA. By using the appropriate interference filters and PMTs, they can operate in both the UV-A and UV-C spectral regions. The lens diameters and focal lengths for UV-A and UV-C operation are listed in Table 1. The UVFS system was optimized for use as a tripod telescope due to weight and mechanical stability constraints, while the Fresnel lens-based system was optimized as an unmanned airborne mapping system due to its light weight (less than 5 kg).

The focal lengths f of both systems depends on the wavelength (spectral range) the system operates, see Table 1.1.

 Table 1: The focal lengths of UVFS and PMMA Fresnel lenses at the UV-A and UV-C operating spectral regions.

Lens	Focal length <i>f</i> in the UV-A: $\lambda = 337$ nm	Focal length $f$ in the UV-C: $\lambda$ = 260 nm
UVFS ( <i>D</i> <sub>UVFS</sub> =240 mm)	615.6 mm	587.2 mm
PMMA ( <i>D</i> <sub>Fresnel</sub> =452.9 mm)	391.5 mm	424.5 mm

The transmittance spectra of the lenses, together with the count sensitivities of the used PMTs, are shown in the joint paper by PTB, IFIN-HH, LUH and TAU [5]. While the Fresnel lens systems exploit the full advantage of their large diameters in the UV-A region, their use in the UV-C spectral region is less efficient due to the transmission cutoff at 260 nm. The fused silica lens, on the other hand, has high transmission in both the UV-A and UV-C spectral regions. Both systems operate as mapping systems by producing the radioluminescence image of the alpha-emitting sources through remote scanning of narrow FOV over the user-defined region of



interest while recording the photon count rate. In contrast to imaging mode which requires additional optical elements to correct image distortions and aberrations, these configurations are designed for a minimum number of refractive elements in order to reduce unnecessary light losses.

#### Performance of the optical detection systems

The performance of the developed radioluminescence detection systems has been tested at the microbeam facility of the PTB Ion Accelerator Facility (PIAF) [5], with extended <sup>241</sup>Am sources, with environmental standards (see objective 2), with activity standard (see objective 2), with radiant standard (see objective 2) and in field tests with Unmanned Aerial Monitoring System (see objective 3). In this section (Objective 1), only results related to PIAF experiments and extended <sup>241</sup>Am sources are shown. The performance with other samples is shown in Objectives 2 and 3.



**Fig. 1.4** Left panel shows the photograph of the experimental setup at the PIAF. All optical detection systems were positioned 2 m away from the alpha particle source. In imaging mode, the UVFS system mounted on two motorised stages (Newport goniometer M-BGM160PE and rotation stage RVS80CC) was scanning the area around the alpha source. The right panel shows the photo of the alpha particle interaction region at the PIAF. The PIAF microbeam was focused into a quartz cuvette (Hellma Analytics, cylindrical quartz cuvette with two tubes, wavelength range 200 nm–2500 nm, 100 mm path length) which could be filled with different gases (air,  $N_2$ ,  $N_2$ +NO mixture).

In PIAF experiments (see Fig. 1.4), a compact cyclotron and microbeam system was used to provide a narrowly focused alpha beam with a size of about 100  $\mu$ m × 100  $\mu$ m at the entrance of the cuvette and a tunable particle rate from 5 × 10<sup>4</sup> s<sup>-1</sup> to about 4.5 × 10<sup>7</sup> s<sup>-1</sup> with an entrance energy of 8.3 MeV. Accelerated alpha particles pass through an exit window (1 mm diameter) fitted with a foil stack consisting of a 10  $\mu$ m thick scintillator (for online rate monitoring), a 3  $\mu$ m thick AI foil and a 5  $\mu$ m thick Mylar foil, sealing the high vacuum of the beam tube to the atmospheric air. Then, after a short air gap of 1 mm to 2 mm, the ion beam enters a 100 mm long cylindrical cuvette through a thin entrance window made of Mylar, 1.2  $\mu$ m thick. The cuvette is made of synthetic quartz with good optical transparency (transmission above 90%) in the wavelength range from 200 nm to 2500 nm (Hellma Analytics). The cuvette is either filled with atmospheric gas or permanently flushed at predefined flow rates of up to 5 L min<sup>-1</sup> with selected gases at atmospheric pressure, using a gas mixing and supply system based on mass flow controllers (see Fig. 5). Alpha particles with energies below 8.3 MeV were generated by inserting AI foils with a thickness of less than 26  $\mu$ m as an energy attenuator in the air gap between the beam exit window and the quartz cuvette.

Figure 1.5 shows the UV-C radioluminescence count rate measured at PIAF by UVFS and Fresnel systems as a function of alpha particle rate. The cuvette where alpha particles were stopped was filled with air at atmospheric pressure. All lens systems were positioned 2 m from the cuvette and oriented so that the location where the alpha particle energy loss is greatest (the Bragg peak) was on the optical axis.

With a field of view larger than the range of alpha particles in air (~38 mm), they capture about the same radioluminescence light as if it would be emitted from a point alpha source. In this context, rates in particles per second will be expressed hereafter in becquerels (Bq), which is a more practical unit to explain the performance of optical detection systems. With the UVFS and the Fresnel lens system anticipated for the UAV use ( $D_1 = D_{\text{Fresnel}} = 452.9 \text{ mm}$ ) radioluminescence was measured in the UV-C (solar blind region), while another Fresnel lens system with a smaller diameter ( $D_2 = 257.6 \text{ mm}$ ) lens operated in the UV-A spectral region simultaneously. Having a similar f-number, the results of Fresnel 1 lens system can be mapped into Fresnel 2 system using the factor ( $D_2 / D_1$ )<sup>2</sup>, and vice versa. The background count rate with room lighting switched off, but surrounding control lights of electronics and monitors still on was around 1 s<sup>-1</sup> in the UV-C (for both UVFS- and Fresnel lens), and around 600 s<sup>-1</sup> in the UV-A (measured with smaller diameter Fresnel lens).



With the light in the accelerator hall switched on, the background count rate was about 3 s<sup>-1</sup> in the UV-C and  $2 \times 10^6$  s<sup>-1</sup> in the UV-A. In all cases, the radioluminescence count rate is linearly proportional to the alpha particle rate.



**Fig. 1.5** Comparison of UV-C radioluminescence sensitivities in air measured at the PIAF at a reference distance of 2 m between the radioluminescence source and lens. The slopes of linear fits are 34(6) s<sup>-1</sup> MBq<sup>-1</sup> for the UVFS and 17(3) s<sup>-1</sup> MBq<sup>-1</sup> for the Fresnel lens systems at a background rate of 0.7(27) s<sup>-1</sup> MBq<sup>-1</sup> for both systems. Due to the finite FOV of both systems, the sensitivities for alpha particle energies of 5 MeV and 6.9 MeV are similar. These results have been published in [5].

Uncertainties reported in this section, including Fig. 6, correspond to standard deviations given with a 95% confidence interval (k = 2). Comparison of the measured sensitivities at the PIAF is shown in Table 2.

Detection system	Lens material	Filters	РМТ	Measured sensitivity
				(s <sup>-1</sup> MBq <sup>-1</sup> )
UVFS in UV-C	UV fused silica	2 filters (FF01- 260/16–25, Semrock Inc.)	Hamamtsu H11870-09	$34\pm 6$
Fresnel 1 (D1=452.9 mm) in UV-C	PMMA	2 filters (FF01- 260/16–25, Semrock Inc.)	Hamamtsu H11870-09	17 ± 3
Fresnel 2 (D1=257.6 mm) in UV-A	PMMA	2 filters (65–128, Edmund Optics)	Hamamtsu H10682-210	$3400\pm500$

Table 2: Measured sensitivities in units of s<sup>-1</sup> MBq<sup>-1</sup> (alias cps/MBq). These results have been published in [5].

Laboratory tests have demonstrated that lens systems with large diameter and long focal length enhance the detection limit while keeping the background signal low. In the air, the UV-C sensitivity at 2 m detection distance is 34(6) s-1 MBq-1 for the UVFS and 17(3) s-1 MBq-1 for the large diameter (D1 = 452.9 mm) Fresnel lens system. The sensitivity is expressed in terms of the count rate per activity measured by the detection system in its field of view while the detection limits are expressed in terms of the measured activity. In the air, therefore, an ISO 11929-4 [30] detection limit of 270 kBq could be achieved with the UVFS lens system and 540 kBq with a Fresnel lens system using 1 s PMT integration time. For samples with thick deposition layer, the self-absorption of the material impairs the detection limit. The Fresnel lens system is less sensitive (about a factor of 2) in the UV-C spectral range due to the transmission limit at 260 nm, but very efficient in the UV-A spectral range due to its high transmission and large geometric efficiency. In UV-A, a detection limit of 4 kBq is achieved with the UVFS system at 1 s PMT integration time, and about 1.4 kBq is expected with the large diameter Fresnel lens system. Being lightweight, the Fresnel lens system can be easily integrated in a UAV with moderate payloads (less than 5 kg). The detection limit in the UV-C can be enhanced up to about four orders of magnitude by applying a N2 + NO purge. This allows detection limits of as low as 70 Bq.

Mapping tests with the UVFS system



The UVFS radioluminescence detection system operates as mapping systems by producing the radioluminescence image of the alpha-emitting sources through remote scanning of narrow FOV (of about 1°) over the user-defined region of interest while recording the photon count rate. Scanning is performed in a serpentine pattern from the lower left corner, traversing the entire yaw area at each pitch step. The scanning speed is typically set to 10 degrees per second and 0.5 degrees per second for the yaw and pitch steps, respectively. In all cases, the optical detection systems were set up at a distance of 2 m from the source, see Figs. 1.6 and 1.7.



**Fig. 1.6** UV-C radioluminescence image of 8.3 MeV alpha particles exiting the PIAF and stopping in the nitrogen filled quartz cuvette. This image shows the mapping capability of the UVFS lens system and has been measured at an alpha particle rate higher than  $5 \times 10^7 \text{ s}^{-1}$ , which is above the counting capacity of the online mirobeam monitoring system. The radioluminescence image has been superimposed on a conventional photograph, with the coordinates of both images correlated by ray tracing. These results have been published in [1].



**Fig. 1.7** UV-C radioluminescence image of the <sup>241</sup>Am source. The radioluminescence image has been obtained by scanning the area around the sample with the UVFS system from a distance of 2 m with a 2 s counting time per scan pixel. The radioluminescence image has been superimposed on a conventional photograph, with the coordinates of both images correlated by ray tracing. These results have been published in [5].

The experiments at PIAF, including the radioluminescence mapping of accelerated alpha particles in Fig. 1.6, were supported by an IFIN-HH research mobility fellow (19ENV02-RMG1) who was a guest scientist at PTB for six months to explore the optimisation of radioluminescence detection using Monte Carlo simulations [10].

*Summary*: Two mobile outdoor optical detection systems for real-time radioluminescence mapping of alpha sources in the environment were developed and characterized. One detection system is based on a high-quality UV fused silica (UVFS) lens while the other one uses a PMMA Fresnel lens. Both systems were designed from their inception to facilitate emergency management by maximizing radioluminescence throughput using large receiving optics and keeping the background signal low through efficient wavelength filtering and low noise photomultipliers (PMT). Both systems can be operated as scanning telescopes, with the Fresnel lens systems also being suitable to be used in UAVs as unmanned aerial monitoring systems. The methodology for radioluminescence mapping of the contaminated area and the derivation of activity was



established. In addition, the prerequisites (purging conditions and gas composition) under which the radioluminescence signal is amplified by more than three orders of magnitude were determined. With these developments, objective 1 was fully achieved.

**Objective 2:** Calibration system for the novel-type radioluminescence detector systems

#### Lead: PTB

#### Detailed description of project developments against objective 2:

To facilitate the deployment of radioluminescence systems developed in the framework of objective 1, SI traceable calibration schemes and standards have been developed. The developed calibration schemes are source-based and rely on two complementary approaches. The first calibration method comprises the application of a dedicated activity standard and environmental samples with deposited alpha emitting radionuclides, whereas the second method uses two purely optical radiation-based devices which simulate the radioluminescence in air induced by an alpha emitting source.

#### Environmental samples: pitchblende minerals

Pitchblende mineral samples were prepared and characterised by LUH. Pitchblende is a naturally occurring mineral which contains uranium and its radioactive daughters, most of them alpha emitters. Stones from Puy de Dôme in France, Uranium City in Canada and Wölsendorf in Germany with an estimated high amount of uranium were selected and cut into 5 mm thick slices with a micro-waterjet. The resulting surface is flat but not polished. Ten slices which have the largest amount of alpha emitters, distributed quite homogeneously over the entire sample area, were selected for the optimisation and characterization of the radioluminescence detection setup developed in the framework of RemoteALPHA. These ten slices were grouped to five samples, each with a surface alpha activity of 1000 Bq to 1500 Bq, see Fig. 2.1.



**Fig. 2.1** Grouping of ten slices to five samples for measurements at PTB. Sample "Mix" consists of slices A, B, E, F, G, and S (see Table 2).

Since pitchblende is an environmental sample, the alpha-emitters are not necessarily distributed homogenously over the surface. For estimation of the extent of this inhomogeneity, alpha track detection (ATD) was used. In this detection method, the alpha particles generate holes in a plastic foil, which can be observed and analyzed by microscope after chemical etching. Alpha-spectroscopy was performed using a grid ionisation chamber (GIC). The alpha energy spectra measured by the GIC range from 1 MeV to 9 MeV and yield information on the number of alpha particles per energy range. Figure 2.2 shows a typical GIC spectrum measured on sample L; similar spectra were measured for all samples.





**Fig. 2.2** GIC spectra of pitchblende sample L (c.f. Fig. 2.1). The measurement time was normalized to 3000 s for each spectrum. Spectra measured from all 10 pitchblende minerals in Fig. 1 show a large amount of low energy alpha particles due to self-absorption. Identified nuclides are written over the corresponding peak or edge.

Radioluminescence detection and mapping of all samples listed in Fig. 2.1 using the UVFS-lens system developed in objective 1 was performed in joint experiments between LUH and PTB. The radioluminescence signal was measured in UV-C and UV-A spectral ranges. While UV-C measurements were conducted only in N<sub>2</sub>+NO atmosphere, those in UV-A were conducted in air. The locations of the samples and even their shape were well recognisable in the radioluminescence images, see Fig. 2.3.



**Fig. 2.3** Arrangement of pitchblende samples in the 'mix' configuration and UV-A radioluminescence image measured using a UV-fused silica lens system.

These measurements, including a description of the preparation and characterisation of the pitchblende mineral samples, were published in [4].



#### Environmental samples: <sup>241</sup>Am-doped soil, sand and leaf samples

IFIN-HH prepared and characterised 6 environmental samples consisting of leaves, sand, and soil matrices spiked with <sup>241</sup>Am solution. These samples were selected to test the feasibility of radioluminescence instrumentation and methods for scenarios encountered when fallout containing alpha emitters (in the form of radioactive dust or washout during rain) is deposited in common environmental materials such as soil, sand, concrete, leaves, etc.

Environmental samples were prepared by distributing a gravimetrically determined amount of liquid <sup>241</sup>Am standard solution over the material surface, with the deposited activity between 0.6 kBq and 12 kBq (see Table 2.1). The composition of these samples was chosen to represent a continental European environment with leaves of the plan tree, loam soil for soil samples, and quartz sand for sand samples. Sample containers are made of plexiglass and designed as equilateral prisms with 45 mm side length and 12 mm height required to fit inside an optical chamber of IFIN-HH Liquid Scintillation Counter (LSC) for sample evaluation using the triple-to-double coincidence ratio (TDCR) technique. In the TDCR technique, radioluminescence from the low-activity samples is measured in a triangular UV tight box (i.e., no external UV light can penetrate the box) containing three PMT arranged in each box face (120° to each other), placed very near to the sample (ca. 10 cm). The activity of the sample is then determined from the double- and triple- coincidence-counting rates.

Table 2.1. The deposited activity and the mass of the environmental samples. The background values refer to the bare samples without americium solution.

Sample	Sand 1	Sand 2	Soil 1	Soil 2	Leaves 1	Leaves 2
Activity (Bq)	9510(100)	1258(13)	11370(110)	1284(13)	11370(110)	669(7)
Matrix mass (g)	10.627	10.669	7.250	7.391	1.437	1.208

The environment samples were placed in an airtight enclosure to enable optical measurements of environmental samples while conforming to the radiation protection rules concerning the handling of open sources and chemical safety due to NO.

Radioluminescence detection and mapping of environmental samples using the UVFS-lens system developed in objective 1 was performed in joint experiments between IFIN-HH, PTB and MATE. Figure 2.4 shows radioluminescence mapping of environmental samples, while table 2.2 compares the activities deduced from radioluminescence measurement to those derived from TDCR technique.



**Fig. 2.4** Processed radioluminescence images of environmental samples of sand, soil, and leaves measured in an airtight chamber. Raw UV images are smoothed and denoised through thresholding before overlapping with the corresponding color images. Image (a4) shows a separate scan of the lower activity leaf sample (0.67 kBq).

Table 2.2 Activities of environmental samples measured gravimetrically (deposited activity) and using TDCR and radioluminescence imaging techniques. Radioluminescence technique reports the total surface activity.



Method	Sample activity (Bq)						
	Leaves 1	Soil 1	Sand 1	Leaves 2	Soil 2	Sand 2	
Gravimetric	11370(110)	11370(110)	9510(100)	669(7)	1284(13)	1258(13)	
TDCR (air <b>)</b>	1309(13)	294(3)	164.3(18)	48(3)	7.4(4)	8.2(6)	
Imaging (air)	1390(210)	290(90)					
Imaging (N <sub>2</sub> +NO)	980(110)	174(25)	186(26)	51(7)			

Radioluminescence measurements on environmental samples, including a description of the preparation and characterisation, were presented in [8].

#### Alpha activity standard

For traceable calibration of radioluminescence detector systems, it is necessary to use an alpha particle emitting source whose characteristics are traceable to national standards. The source should have as little angular dependence as possible, with the alpha particles emitted at their peak energy in a large solid angle close to  $2\pi$ . Since alpha particles in air must first generate radioluminescent light and this signal is then used to calibrate optical systems at some distance, the source of alpha radiation must be of appropriate strength to also achieve sufficient statistical uncertainty. Preliminary estimations based on tests with accelerated alpha particles at the PTB Ion Accelerator Facility indicated that an alpha activity between 500 kBq and 1 MBq would be well suited for calibration. This alternative is the <sup>210</sup>Po radionuclide. With a half-life of  $T_{1/2}^{Po-210} = 138.3763(17)$  d, the required film thickness is a factor of 1000 less than that of <sup>241</sup>Am for the same activity. Only 10 ng of <sup>210</sup>Po already correspond to an activity of 1.66 MBq. Moreover, <sup>210</sup>Po has only 2 alpha transitions, of which the higher energy one at 5.30433(7) MeV has a transition probability of 99.99876(4) % and a single gamma transition at 0.803052(24) MeV which is practically negligible with a transition probability of only 0.00123(4) %. Since <sup>210</sup>Po decays directly into the stable <sup>206</sup>Pb, no other radiation from the <sup>238</sup>U decay chain affects the measurement. Thus, the emission spectrum of a <sup>210</sup>Po source has the nearly ideal properties for traceable calibration of radioluminescence detector systems.

PTB developed the alpha activity standard by dissolving <sup>210</sup>Po in dilute nitric acid from a silver and gold composite. A total of 840 kBq of <sup>210</sup>Po was deposited on the silver target with an active area of 12 mm. The <sup>210</sup>Po activity standard was hardened at 250° and subsequently analysed using the defined angle alpha spectrometry as the PTB alpha-activity national standard. The solid angle from the source to the detector is defined by an aperture system which is measured traceable to the national length. This defines the traceable solid angle and the PIPS detector has an efficiency of 1 for the alpha-particles in the regarded alpha-energy range. A comparison of the alpha spectra measured at different angles relative to the surface normal is shown in Fig. 2.5. Although some asymmetry in the measured spectra is still evident at low energies-mainly due to solution impurities deposited in the substrate-all spectra show a sharp peak at 5.30(1) MeV, with an FWHM of only 26.8(7) keV at 69° to 31.9(16) keV measured at 0° relative to the surface normal.





**Fig. 2.5** Relative alpha emission measured with a 25 mm<sup>2</sup> silicon surface barrier detector behind a 3.2 mm aperture and a distance from the source surface of 15 mm. The spectra have been measured at 0°, 42° and 69° relative to the surface normal. The inset shows the <sup>210</sup>Po sample with a diameter of 12 mm (central part) deposited on the silver substrate.

The <sup>210</sup>Po alpha activity standard has been developed and used to characterise the UVFS lens-based radioluminescence detection system developed in objective 1 in terms of its sensitivity to alpha-induced radioluminescence in different atmospheres (air,  $N_2$ ,  $N_2$  + NO mixture) in the UV-A and UV-C (solar blind) spectral regions, see Fig. 2.6. This detection system was used as an intermediary transfer device to cross-calibrate two portable integrating sphere-based radiance standards designed to simulate radioluminescence in the UV-A and UV-C spectral regions.



**Fig. 2.6** UV-A radioluminescence image of a <sup>210</sup>Po activity standard in the experimental chamber filled with air at atmospheric pressure.

Calibration of the UVFS-lens system with <sup>210</sup>Po activity standard, including the development and characterisation of the <sup>210</sup>Po source has been presented in [9].

#### Radiance standards

To implement the optical radiation calibration scheme, PTB with the help of BFKH has designed, manufactured and radiometrically characterised two dedicated variable low-photon flux, UV-C and UV-A radiance standards. These radiation standards are portable and intended for use in the calibration of radioluminescence instruments without the need to relay in open alpha sources and stringent radiation protection protocols. Both radiance standards rely on integrating spheres as optical diffusors and share the same design concept (see Fig. 2.7):

- main integrating sphere diameter of 150 mm, radiating port of 25 mm diameter and two additional ports with 12.5 mm diameter,
- up to four orders of magnitude variable radiance via the application of a precision, µm-gauge variable slit and a satellite integrating sphere (50 mm diameter),
- aluminum spheres with high-purity alumina (Al<sub>2</sub>O<sub>3</sub>) blasted, diffusely reflecting surface for enhanced stability in the UV spectral range,
- modular radiation sources port concept for UV-LED single/dual wavelength operation mode and additional continuum sources for spectral straylight simulation,
- monitor detector for radiance control and monitoring, and
- rigid aluminum rail framing for transportation and structural stability.





**Fig. 2.7 (a)** Sectional schematic representation of the variable radiance, satellite integrating sphere-based configuration of the low photon flux UV radiance standard. **(b)** Realised prototypes of the variable low-photon flux UV-C (260 nm; left) and UV-A (340 nm; right) spectral range radiance standards for the calibration of the radioluminescence detector systems.

Radiance standards based on integrating spheres have the advantage that they represent a realisation of a homogeneous Lambert radiator and are therefore a suitable transfer standard for the optical simulation of the radioluminescence radiation of an isotropic alpha particle radiator. UV LEDs with central wavelengths at 260 nm (UV-C; OPTAN-260J-BL) and 340 nm (UV-A; DUV340-HL18W), a spectral bandwidth (FWHM) of 11 nm and 8 nm, respectively, and an average radiant power of 1 mW are used as optical radiation sources. Their emission spectrum overlaps with the N<sub>2</sub> + NO radioluminescence emission lines at 259.1 nm and the 337.1 nm line of N<sub>2</sub>, respectively, which are selected by the interference filters for detection, allowing thus radiometric characterisation of the radioluminescence detection systems in the respective spectral regions specified by their interference filters.

The low-photon flux radiance standards developed in the framework of RemoteALPHA were calibrated with the PTB transfer standards which consist of integrating sphere-based spectral radiance standards with 10 W tungsten halogen lamps as radiation sources, well characterised in terms of radiance stability and calibrated in terms of the absolute spectral radiance by direct comparison to the PTB primary radiance standard, the high-temperature blackbody HTBB3200pg at the PTB Spectral Radiance Comparator Facility. Both low-photon flux radiance standards were calibrated with their variable slit setting fully open (7.5 mm) i.e., the setting with the maximum photon flux output [4,5]. The results for the calibrated spectral photon radiance of the UV-A and UV-C low-photon flux radiance standards are shown in Figure 2.8.



**Fig. 2.8** Calibrated spectral photon radiance of the UV-C / UV-A spectral range low-photon flux radiance standards (filled squares/circles). The uncertainty bars denote the type A standard uncertainty. Solid lines represent the manufacturer specified transmittances of the interference filters applied in the radioluminescence detectors.

The stability of the UV low photon flux radiance standards prototypes was examined for a period of 12 hours of continuous operation by measuring the output voltage of the monitor detectors. For the duration of the measurement, the radiance standards were installed inside a climatic chamber. A temperature cycle from 19



°C to 27 °C was conducted simultaneously to investigate the effect of environmental temperature change on the stability. Both radiance standards are stable within 0.1 % for an observation period of 12 hours and an environmental temperature change of  $\pm 4$  °C. The day-to-day variation lies within 0.03 %. If a warming-up time of approximately 1 hour is respected, the stability is within 0.02 %.

#### Environmental samples: <sup>241</sup>Am-spiked concrete samples

Since concrete is a wide spread material in urban areas, LUH manufactured concrete samples spiked with <sup>241</sup>Am. These sample would simulate a scenario of deliberate of accidental dispersion of alpha emitting radionuclides in urban areas. The concrete samples were manufactured by using a commercial concrete mixture for tinkering for home use. It already contains cement and aggregate in a balanced mixing ratio only water needed to be added. The mixing ratio between concrete mixture and water is called water-to-cement-ratio and as a high impact on the sample properties. For our samples, two different ratios 13:90 and 1:4 were used. The 1:4 ratio is so liquid that it could be poured into ice cube trays, which allows manufacturing of very smooth concrete surfaces. For a variation in surface roughness, the samples were roughened with sandpaper. The well-known surface was then spiked with <sup>241</sup>Am solutions of different activity and molarity. A high molarity of 1 mol/l HNO<sub>3</sub> caused a significant reaction of the acid with the basic concrete, visible by gas bubbles and a destruction of the concrete surface. The activity of each concrete sample was investigated by using a grid ionisation chamber (GIC).

In total, 18 <sup>241</sup>Am-spiked concrete samples were produced with surface activities ranging from 0.161 MBq to 18.44 MBq. The topography of the concrete surface has a significant influence on the recovery parameter because alpha particles from the deposited <sup>241</sup>Am solution that spreads in the interior concrete layers may be shielded or lose some energy relative to those emitted from the surface. The recovery is defined by the ratio of the applied activity of the solution over the measured activity calculated from the alpha spectrum. Due to the geometry, it can be 50% at maximum. The surface roughness is defined by the "arithmetic mean of the absolute height"- parameter *S*<sub>A</sub> in µm. It was determined by using an optical microscope and measuring the depth of the craters and holes. The samples were grouped by roughness in three categories: (*i*) smooth: *S*<sub>A</sub> < 5 µm, (*ii*) rough: 5 µm≤ *S*<sub>A</sub>< 25 µm, and (*iii*) very rough: 25 µm ≤ *S*<sub>A</sub>. Figure 2.9 shows the influence of surface roughness on the surface activity of the concrete sample spiked with <sup>241</sup>Am standard solution, while table 2.3 shows the dependence of recovery on the surface roughness.



Fig. 2.9 Alpha-spectra for different sample roughness

Table 2.3: Recovery of concrete samples with different surface roughness.

Sample	Recovery
Smooth	51.43 %
Rough	36.47 %
Very rough	38.77 %

The radioluminescence mapping of <sup>241</sup>Am-spiked concrete samples using the UVFS lens system developed in objective 1 is shown in Fig. 2.10. Radioluminescence mapping was performed in joint experiments conducted by LUH and PTB using the same techniques as for other environmental samples.









*Summary*: A <sup>210</sup>Po activity standard was developed to establish the relationship between alpha activity and radioluminescence intensity. Environmental standards based on pitchblende minerals and <sup>241</sup>Am-spiked sand, soil, leaf and concrete samples were developed and characterized. Two radiation standards (UV-A and UV-C) simulating alpha emitters were developed and characterized. A new calibration methodology has been developed that provides valuable information on the performance of radioluminescence detection systems and provides confidence in these systems. This calibration method is based on two complementary approaches: (a) application of a well-characterized <sup>210</sup>Po standard and (b) use of all-optical radiation-based devices that, when calibrated against an alpha activity standard, simulate the radioluminescence induced in nitrogen (N<sub>2</sub>) and nitric oxide (NO) by alpha particles in specific spectral regions. With these developments, objective 2 was fully achieved.

#### **Objective 3:** Mapping of alpha contaminations in the environment using UAVs

Lead: UPC

#### Detailed description of project developments against objective 3:

#### Unmanned Aerial Monitoring System (UAMS)

UPC with the help of PTB has developed an UAMS which integrates an unmanned aircraft system (UAS) from the UPC fleet with a novel alpha-radioluminescence detection system developed in the framework of objective 1 to scan and obtain a map of the contaminated area. The UAMS hardware uses the RIMASpec software architecture developed by the UPC, which allows the real-time viewing of alpha contaminations.

The optical detection system integrated in the UAMS is based on a light weight Poly(methyl methacrylate) (PMMA) Fresnel (Orafol Fresnel Optics) having a diameter of 452.9 mm (SC 2045) and nominal focal lengths of 391.5 mm at 546 nm. The photon filtering is done with 3 Semrock FF01-260/16-25 interference bandpass filters centered at 260 nm with a bandwidth of 16 nm. At this operation wavelength selected by the interference filters, the focal length of the Fresnel lens is 424.5 mm. To achieve the best UV-C band filtering, a set of two corrective fused silica lenses (Thorlabs LC4252 and LA4052) were installed to parallelise the collimated photon beam. An additional filtering performance was achieved by tilting two filters in the set by 3 degrees relative to the optical axis.

Photon counting is performed with a PMT detector that converts incident light into an electrical signal that is analysed by a digital pulse processing unit. The detection system uses the solar-blind Hamamatsu H11870-09 photomultiplier tube with transistor-transistor logic (TTL) output and the GBS Elektronik MCA527 OEM+ multichannel analyser (MCA) working in the scaler (gating) mode to translate these TTL signals into the timestamped count rate.

A carbon fiber-reinforced cone-shaped polymer frame has been built to hold the lens and the detection system. The frame materials were chosen to provide the necessary stability for the system while keeping it lightweight. The detector has a height of 790 mm and a diameter of 520 mm at the base. Given the dimensions of the detector, no commercial UAS was tall enough to natively integrate the detector under its belly, since the height



of the detector is larger than UAS legs. This made it difficult to integrate the detector into a commercial UAS unless the detector itself acted as a landing gear. Therefore, the structure of the Fresnel lens has been designed such that it can be used as a landing gear of the unmanned aircraft. The alpha radioluminescence detector with the landing legs, the MCA counter, the laser altimeter, and the onboard computer with a 4G/LTE modem were integrated with the DJI Matrice 600 Pro (M600P) UAS as shown in Figure 3.1.



Fig. 3.1 Radioluminescence detection system integrated with the DJI Matrice 600 Pro and ready to fly.

#### Characterisation of the radioluminescence detector for flight missions

To validate the operation of the UAMS, the detection system mounted on a UAS must be tested in the environment using alpha radiation sources. The problem with using alpha radiation sources is the strict radiation protection measures for both the airfield and travel to the test site, which limits the flexibility of outdoor testing. Although alpha radiation sources were used in the final flights, they were replaced in several preliminary tests by UV-C LED sources that simulate the air radioluminescence produced by alpha particles.

Investigation of the detector response was first performed under light-controlled conditions with UV LEDs to determine the field of view (FOV) and the best focusing configuration for the flights. In addition, the change in efficiency as a function of the angle of incidence and the power of the LED lamp was also investigated. The UV-C LED lamp used to test and optimise the optical system had a 5 mm thick Teflon disc at the exit aperture and was calibrated with a <sup>210</sup>Po activity standard. The LED lamp allows 12 different power modes, from number 0 to 11, simulating alpha sources with energy 5.4 MeV and activities up to 7.3 GBq (setting Nr. 11).

The optical system has a sliding detector design which allows adjusting the focus according to the object distance. The efficiency of each focusing configuration, represented by detector position F (protrusion from the frame in centimeters) was tested with the LED source placed at the optical axis at various distances as illustrated in Fig. 3.2.



Fig. 3.2 Scheme representation of the optical system focus configuration and field of view tests.

The field of view is defined as the diameter of the spot that can be seen by the optical detection system. It depends on the focal length of the used receiving optics and the object distance. While in the simple lens-PMT case, the FOV can be estimated with a formula, the use of corrective lenses and non-trivial filter allocation required experimental evaluation. To determine the field of view, the LED source was moved perpendicularly to the optical axis. The FOV is calculated then by fitting the experimental data to a Gaussian function.





**Fig. 3.3** Count rate measured at different source-lens distances and different focus configurations F. Uncertainties in the figure correspond to standard deviations given with a 68% confidence interval (k = 1) and are attributed to the counting statistics of the detection system.

To assess how the tilt of the UAS can affect the light collection efficiency, the radio-luminescence signal has been measured as a function of the angle between the Fresnel lens optical axis and UV LED axis using a rotation platform with 1° precision.

In order to characterise the detection system two parameters are crucial, i.e., the FOV and the detection efficiency. In Fig. 3.3, the LED source was placed at a distance *d* ranging from 2 to five meters from the Fresnel lens. The position of the focus, *F*, was varied in the range from 1 cm to 10 cm during the tests. The results of the count rates measured at constant LED power simulating 7.3 GBq are shown in Fig. 3.3 with the measured most effective detector position marked with a red circle.





In order to determine the FOV, Fig. 3.4 shows the count rates measured for every lateral position h (i.e., perpendicular to the optical axis) of the LED source at different distances to the source and focus configurations F. These parameters were estimated from the Gaussian fits of corresponding lateral profiles (see Table 3.1). From Table 3.1 it is apparent that FoV is relatively small: for a distance of 5 m and a focus configuration at 3 cm, the FoV is 10.7 centimeters.

Table 3.1: FOV and AFOV (angel of view) estimated for different F positions and source-lens distances.

	$F(cm)$ $d(m)$ $n(s^{-1})$	FOV (cm)	AFOV (°)
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3	2	2240	9.6	2.75	
3	3	2510	7.5	1.44	
3*	4	1550	8.6	1.24	
3*	5	811	10.7	1.22	
7*	2	6070	4.1	1.17	
4*	3	2770	6.4	1.23	

\* Indicates case for F of maximum measured count rate

With a field of view on the order of 10 cm, it is obvious that in scenarios with point alpha sources, the flight tracks should be very close together, the speed of the UAS should be very low, and the integration time should be short to maximise the probability of their detection. Another concern with this type of scenario is that the UAS is not always completely perpendicular to the ground due to variations in wind and UAS speed resulting thus in changes in the roll and pitch of the whole flying system. These variations in the roll and pitch of the UAS reduce the number of counts acquired compared to a vertical position that is completely aligned with the ground. But on the other hand, this variation in roll and pitch increases the probability of detecting the source because the area covered by the detector is larger than when the UAS is in constant vertical alignment.

#### Software architecture

The UAMS hardware uses the RIMASpec software architecture already successfully used in the previous gamma detection projects (e.g., EMPIR project 16ENV04 Preparedness). For the RemoteALPHA project, the software was upgraded to visualise a map of alpha-emitting radionuclides in the environment in real time. To visualise the count rate on a map in real time, a web application was developed. This web application has a backend and a frontend as shown in Fig. 3.5. The backend has been developed using the Apache Tomcat Server (https://tomcat.apache.org/). Apache Tomcat is a popular open-source web server and Servlet container for Java code. For this work, this server was hosted on the same machine as the MQTT server. The backend is subscribed to the MQTT data through which all the information from the air segment arrives. The air segment information is processed and ready to be displayed on the different web browser clients (frontend). The communication between the backend and the frontend is done through web sockets and HTTP queries.



Fig. 3.5 RIMASpec ground segment software architecture.

Web application allows any computer with an Internet connection and a browser to access the application using a username and a password requiring no additional software installation to run the RIMASpec ground control station. The web application has a database (MongoDB) where the users are created and where all the measurements with the drone are stored. The application has three user types: the administrator, the operator, and the viewer. The viewer type is intended for users who are only interested in radiological information. Under the role of operator, the user has control over the UAS. The administrator can manage user profiles on top of the previously described functionality.

Once logged in, the screen shown in Figure 3.6 appears with three panels representing application options.





Fig. 3.6 RIMASpec UAS control tab.

Panel 1 has the tools needed to create and edit a flight plan for the UAS. Through this panel, the user can create or edit an operation area and save it in a file. Then, the software can generate a flight plan over that area: for example, a random flight plan, or a flight plan with different parallel tracks, see Fig. 3.7. Panel 2 presents the tools to work with the map. This panel allows zooming in and out on the map or centering the map at the UAS location. Finally, Panel 3 alerts the user when it detects a UAS that wants to connect to RIMASpec.



**Fig. 3.7** Screenshot of RIMASpec during a test flight around an <sup>241</sup>Am source. For the test flights, a back-and-forth scan pattern was chosen to cover the whole area and to have a certain repeatability in the flight execution that the random algorithm does not offer. To cover the complete area, a distance between parallel lines of 10 cm needs to be used. However, the UAS does not permit placing waypoints in such close proximity, therefore the shortest distance allowed by the UAS, approximately 70 cm, was selected. Given the manufacturer-specified horizontal positioning error of 1.5 m, it will be necessary to perform several iterations of the parallel line scan pattern with a small offset to ensure that the UAS passes through areas it omitted in the previous iteration.

#### Flight test with LEDs and <sup>241</sup>Am source

As mentioned above, all flight and detector data are stored in the database, and RIMASpec can replay previous flights as shown in Fig. 3.7 which displays a screenshot of a flight performed in December 2022. The color and height of the cylinders indicate the counts measured in 0.1 seconds. The color range and height of the cylinders can be modified to optimise the visualisation of the source detection. The detected counts can be also read numerically in the right-hand data box. In this data box, the UAS telemetry is also displayed: speed, pitch, roll, yaw, longitude, latitude, and altitude. Behind the telemetry box, the commands box is placed which contains the dialog for each possible command that can be sent to the UAS. The visualisation software also shows the UAS position and the location on the ground where the detector is pointed (violet line). RIMASpec software has more extensive functionality beyond the application-related features shown here, such as user management tools, layer visualisation, and flight plan editing.





**Fig. 3.8** Flight performed with 5 LEDs and an americium source. **a)** UAMS during the flight at the Drone Research Laboratory (DroneLab) of the Technical University of Catalonia (UPC). **b)** Radioluminescence mapping via RIMASpec. The color map is set such as the yellow color (background) is set to 20 s<sup>-1</sup> and the red color shows the count rate of  $50 \text{ s}^{-1}$  or more, with intermediate count rate values having a color between yellow and red. **c)** 241Am source in the dedicated chamber. **d)** UV-C LEDs used to simulate radioluminescence from alpha sources.

Figure 3.8 shows a flight example with 5 LEDs surrounding the americium source in the middle. The 100 MBq <sup>241</sup>Am source with an active area of 20 mm x 100 mm, specifically designed for the project, was manufactured by Eckert & Ziegler Cesio s.r.o (Czech Republic). To fulfil the radiation source handling requirements, the <sup>241</sup>Am foil was mounted on an aluminum base plate and covered with a quartz dome optically transparent to the radioluminescence produced by alpha particles in the air. The chamber design allows it to be evacuated to approximately 1 hPa and purged with gas at pressures up to 1000 hPa (environmental pressure). The 241 Am source was purged with N2+NO (5 ppm) gas mixture to amplify the UV-C radioluminescence. The UV-C LED sources used in the flights are commercially available and commonly used for water purification, disinfection, and sterilization of home aquariums. The LED has a peak wavelength between 270 nm and 280 nm and a radiant flux of 8 mW. Teflon sheets of a few millimeters are used to moderate the radiant flux to the level representative of radioactive sources that could be found in an emergency scenario. Following the choice of the optimum height of 5 m, the flight speed is primarily determined by the field of view of the detector. With the FOV of about 10 cm, the measurement time of 100 ms necessitates flying at a speed of 1 m s<sup>-1</sup>. The flight planner software module of the RIMASpec ground control station can generate flight plans for a UAS that cover an area with a back-and-forth pattern which allowed detection of all sources. The results of the laboratory characterisation of the detector, as well as the various flights performed on UV LEDs and a 100 MBg <sup>241</sup>Am source to demonstrate the system's feasibility in a realistic scenario, are presented in [7].

The main conclusion from the results presented in Fig. 3.8 is that alpha particles can be detected remotely from an unmanned aircraft system (UAS) by using optical detectors. To the best of authors' knowledge, this results demonstrates for the first time remote detection of alpha particles from an UAS. The described prototype system, with certain operational improvements, can be used to assess contaminated areas without the need to put first responders at risk.

As mentioned before, due to GPS uncertainties and the wind effects (roll and pitch variations), the same flight plan repeated many times does not cause UAS to fly exactly over the same place and, therefore, the measurements are scattered between consecutive runs. For instance, during experiments with five LEDs placed in random positions, not all of them were detected during the same iteration. During the first flight, three of the five LEDs were detected. Using the same flight plan in the following flights, either no LEDs or all of them



were detected. Concluding the flight results, the probability of detecting a point source constitutes approximately 60%. This probability can be boosted by increasing the field of view of the detection system. However, increasing the FOV also has some other consequences such as the reduction of the detector efficiency and background light leakage. Extended sources with larger lateral dimensions (e.g., on the order of GPS uncertainty), on the other hand, would not be susceptible to difficulties encountered in the case of point sources.

Another important conclusion of this work is that the operational experience gathered with the novel radioluminescence detection system can be readily applied to the extended alpha source detection (spread over the area), while the point source localisation needs further hardware improvements. All test flights carried out during this study were performed using point sources – LEDs or the americium source – due to the difficulty of simulating an extended source. Even though point sources are difficult to detect given the optical constraints, the prototype system was able to detect them with a reasonable probability of about 60%. Extended sources are far less dependent on alignment stability and are therefore much easier to detect.

The major limiting factor of the developed detection system towards the localisation of point sources is its small field of view. Since the FOV of the detection system (up to 10 cm) is smaller than the uncertainty of the UAS GPS (about a meter), the detection of point sources becomes more difficult. To mitigate this issue, two clear operational improvements are therefore proposed: i) Equipping the UAS with Real-Time Kinematic (RTK) system to achieve centimeter-level navigation accuracy, and ii) Increase the FOV of the detector. The last point would require enlarging the PMT surface, reducing the focal length of the objective, or using mirrors with shorter focal lengths. However, this option would require a tradeoff with background light leakage. An improved FOV would open the possibility of increasing the speed of the UAS and the distance between flight tracks, thus increasing the size of the area scanned with a single flight.

The Fresnel-lens detection system used to measure the alpha-induced radioluminescence was relatively large. This is because maximising radioluminescence throughput while minimising background signal requires a compromise between the diameter of the receiving optics (which determines the geometric efficiency of the system) and the focal length (which determines the FOV, that subsequently affects both the number of detected photons and filtering. The detector's size makes the drone integration difficult which means it can only be integrated into medium- and large-sized UASs, with the sensor itself acting as a landing gear. The lens, located at the aircraft's underbelly deep below its center of gravity, resists UAS movement. Flight tests conducted in windy conditions revealed significant instabilities in UAS flight. It is not advisable to exchange the landing gear supplied by the manufacturers for incorporating the detector. Therefore, in future iterations, the compact detector design must be implemented.

Summary: A light weight Fresnel lens-based optical detection system developed in objective 1 has been extended to an imaging functionality for mapping of alpha contaminations in the environment. This includes the development of an unmanned airborne monitoring system (UAMS) that integrates the optical detection system and the unmanned aerial vehicle (UAV) DJI Matrice 600 Pro. The UAMS hardware uses the RIMASpec software architecture which allows the real-time viewing of alpha contaminations. With these developments, objective 3 was fully achieved.

**Objective 4:** Feasibility study of laser-based techniques for detection of alpha emitters

Lead: TAU

#### Detailed description of project developments against objective 4:

#### Radioluminescence in atmospheric gases

Radioluminescence is created when an alpha particle is released in the air. The alpha particle ionizes molecules and causes electronic excitations for molecules, which then relaxes as luminescence transitions. The wavelength of radioluminescence is gas dependent and in the normal atmosphere, the strongest transition can be seen at 337 nm and is a result of nitrogen's second positive system relaxation **Error! Reference source not found.**, where the detectable radioluminescence is created only by  $N_2$  and  $N_2^+$ . Other major species in air are oxygen and argon. Oxygen has no strong identified emission peaks, so utilisation of oxygen as the radioluminescence source can be excluded. Argon does produce radioluminescence **Error! Reference source source not found.**, but only in pure argon. In presence of nitrogen, electronic excitations of argon are efficiently transferred to nitrogen.



Nitric oxide (NO) has been shown to be able to drastically enhance the radioluminescence signal in nitrogen atmosphere (T. Kerst, https://urn.fi/URN:ISBN:978-952-03-1247-3). Unfortunately, the same enhancement is not present in normal atmosphere due to oxygen quenching of N<sub>2</sub> and NO. For these reasons we have focused on nitrogen transitions in this work, as those are the most prominent in normal atmosphere as also shown by Brett et al. (doi: 10.1016/j.nima.2017.08.056).

Nitrogen has radiative transitions from deep UV to far infrared region. There are three main regions for feasible measurements. First, in dark environments all transitions. This includes the main transition of  $N_2$  at 337 nm and the main transition of  $N_2^+$  at 391 nm, and yields to detection limit of 1 kBq for alpha active point sources (J. Sand, https://urn.fi/URN:ISBN:978-952-15-3889-6). If the lighting consists only of LED lights, the  $N_2$  transitions are feasible, but the  $N_2^+$  transition interferes and is dominated by typical LED spectrum. In full daylight conditions, the measurement must be limited to UVC region (< 280 nm), which means to measure very weak N<sub>2</sub> emission lines. The measurement has shown to be feasible in full daylight for point sources with surface alpha activity more than 1 MBq.

 $N_2$  and  $N_2^+$ energy states have been studied extensively and reported with good accuracy as reviewed by Lofthus and Krupenie **Error! Reference source not found.** Our target is to construct a model with enough accuracy to replicate measurement results and see if there are any possible transitions for re-excitation. In practice we have selected the most suitable and probable energy states that couple together. Based on literature (J. Sand, <u>https://urn.fi/URN:ISBN:978-952-15-3889-6</u>; T. Kerst, <u>https://urn.fi/URN:ISBN:978-952-03-1247-3</u>; A. Lofthus and P. H. Krupenie, doi: 10.1063/1.555546; S. Chung and C. C. Lin, doi: 10.1103/PhysRevA.6.988; Y. Itikava, doi: 10.1063/1.1937426), following triplet states can be used as a starting point  $C^3\Pi_u$ ,  $A^3\Sigma_u^+$ ,  $B^3\Sigma_g$ ,  $B'^3\Sigma_g^+$ ,  $W^3\Delta_u$  and  $E^3\Pi_g^+$ .

The most studied transition of nitrogen is the C -> B transition, which called the second positive band. The emission peaks from 260 nm to 385 nm are created by the same electronic transition from C to B state. The first positive band of nitrogen is from state B to state A, which gives luminescence at 600 nm - 1200 nm wavelengths. That is rarely utilised, as it is weaker luminescence, and the wavelength region is more difficult for the sensors in terms of sensitivity and background filtering. All the excited states have a lifetime in order of nanoseconds, except the transition from A state to ground state X.

Another set of transitions identified for nitrogen molecule at around 400 nm wavelength are the electronic transitions of nitrogen ion. The most utilised transition is from the B state of the ion to the ground state X of the ion. This transition is called the first negative band of nitrogen and is has emission peaks at wavelengths from 390 nm to 440 nm. The ionic excited states have short lifetimes in nanoseconds, but the ground state X is a stable state as long as the ion exists. Thus, we have initially two long-lived states for nitrogen: the state A of the neutral nitrogen molecule and the state X of nitrogen ion. Long lived states are needed if we want to perform efficient laser re-excitation of the transitions.

#### Population Dynamics of $N_2$ in air

Laser re-excitation fluorescence yield is directly proportional to the population of re-excitable states. Ideally,  $N_2$  would have some semi-stable excited state that is generated in the alpha decay process. Suitable laser could then be used to electronically excite molecules to highly radiative state for enhanced radioluminescence signal after the laser pulse.

The population dynamics of different electronics states can be simulated by using the rate equation model. The simulation was carried out using standard atmospheric temperature and pressure.

Oxygen has major effects on  $N_2$  excited states. Lifetimes of B, B', E and W-states have natural lifetimes in microseconds, but oxygen quenches these states and the lifetime is reduced to few nanoseconds. A-state has been considered as a metastable state with natural lifetime in the range of 2 s, however oxygen reduces the lifetime to 42 ns.

As an example, for 1 kBq alpha radiation source there is in average 1 decay for every 1 millisecond. When compared to nanosecond level decay times of  $N_2$  it can be concluded that there is no build-up of population in any excited state. That is true for alpha sources with surface activity up to 10 MBq or so. The decay events are individual events that create some hundreds of excited molecules at the time of the event. That is not enough to make any feasible laser re-excitation arrangement in case of neutral nitrogen molecules in air. Some build-up of excited states is assumed in case of nitrogen flush, where oxygen is removed and the nitrogen A state lifetime get longer (2 s). However, the laser pumping of the A state back to C state is difficult to arrange with two lasers. Thus, this option was left out from the experimental part, especially because the build-up of the excited states is even better with the nitrogen ions handled in the next chapter. Further, we have introduced



a powerful passive radioluminescence scheme for the nitrogen flushed closed volumes showing about 100 times intensified radioluminescence for trace amount of nitric oxide compared to nitrogen radioluminescence in air (T. Kerst, https://urn.fi/URN:ISBN:978-952-03-1247-3).

#### Population dynamics of $N_2^+$ in air

Literature provides little to no data for distribution of electronically excited  $N_2^+$  states. The simulations assume uniform population to all states as the lifetime and dynamics are more important for possible build-up of population. The simulation was carried out using standard atmospheric temperature and pressure.

Oxygen quenching plays again a role in  $N_2^+$  dynamics. Natural lifetimes of excited states range from microseconds of state A to tens of nanoseconds of other excited states. The long intrinsic lifetime of state A tells that it is not very efficient source of luminescence. Thus, the main interest in nitrogen ion is the state B, and transition from state B to the ground state X. In normal atmosphere the lifetimes are reduced to less than nanosecond because of oxygen, which also reduces then the luminescence efficiency. The ground state of  $N_2^+$  has strong potential for laser re-excitation when the lifetime is considered. The re-excitation can be arranged between states X and B e.g. by pumping with 391 nm ((0,0)-vibrational transition) laser wavelength. The resulted fluorescence can be monitored at another vibrational transition at 428 nm ((0,1)-vibrational transition), so that the laser and the fluorescence are possible to separate at the detection due to different wavelengths.

The major effects in N<sub>2</sub><sup>+</sup> ground state concentration build-up are ion creation rate Q, diffusion rate D and ion re-combination factor  $\alpha$ . When a steady state is considered, we can write following differential equation for ground state population N

$$\frac{dN}{dt} = -\alpha N^2 - \frac{3D}{2R^2} N + Q = 0 \tag{1}$$

The recombination factor  $\alpha$  has reported values of  $2.9 \times 10^{-13} \frac{m^3}{s}$  **Error! Reference source not found.** The diffusion constant of air is  $0.2 \frac{cm^2}{s}$  (J. Brett et al., doi: 10.1016/j.nima.2017.08.056). Ion production rate of alpha radiation source can be estimated by considering the alpha particle energy loss as it travels in air. Based on the Bragg curve (J. Sand, https://urn.fi/URN:ISBN:978-952-15-3889-6) and 1 cm radius above the radioactive target 0.9 MeV energy loss can be calculated. Figure 6 shows the geometry used in the ion density estimation. The ion production by alpha particle has been estimated to be 35.5 eV/ion pair (W. P. Jesse and J. Sadauskis, doi: 10.1103/PhysRev.90.1120). Using the alpha activity of 1 kBq that is mainly considered in this deliverable, we can estimate ion production rate in the volume as

$$Q = \frac{0.9 \frac{MeV}{particle}}{35.5 \frac{ev}{ton \, pair}} \times 0.78 \times 1000 \ \frac{particles}{s} \times \frac{3}{2\pi \ (0.01m)^3} = 9.4 \times 10^{12} \ \frac{ion \, pairs}{m^3}$$
(2)

The equation 1 can be solved and assuming no other losses of nitrogen ions, the steady state concentration for 1 kBq source is about  $5 \cdot 10^6$  ions / cm<sup>3</sup>. This is estimated density in the half sphere having the radius of 1 cm. Using the same estimation, we get about  $10^8$  ions / cm<sup>3</sup> for a 1 MBq point source and about  $5 \cdot 10^9$  ions / cm<sup>3</sup> for 1 GBq point source of alpha particles. The ion concentration increases in square root of the activity, as can be seen from the Equation 1. As other loss mechanisms like effect of surfaces and separation of charges have not been considered, these values can be used as upper limit values for the ion concentration.

#### Laser re-excitation experiments

We performed the laser re-excitation measurement with a wavelength tunable Optical-Parametric-Oscillator (OPO) -laser (Expla NT342) after a consideration of different laser options. We needed a powerful and wavelength tunable laser, so a nanosecond pulse OPO-laser was a good option for the experiments. Figure 4.1 shows how the laser with a pulse width of 4 ns and energy of 1 mJ is directed 4 mm over americium alpha source that has total activity of 32 MBq. The source is a 60 mm long and 3 mm wide stripe, and the laser beam was aligned along the stripe. Luminescence light is collected with a UV-lens, wavelength filtered (Semrock FF01-433/24-25) to remove laser light, and directed to the spectrograph with another UV-lens. Output of the spectrograph is connected to a gated ICCD camera (Andor iXon Ultra 897) to make low-noise and highly sensitive spectral measurements. The camera is synchronised with the laser to integrate only 50 ns after the laser pulse to reduce noise, as luminescence is expected to follow the laser excitation rapidly. The ICCD camera is used with high gain settings to be sensitive for single photons. The slit width of the spectrometer is 1 mm which limits the area that the spectrograph sees from the alpha source. Effectively we only measure



signal from 1 mm length of the 60 mm long stripe. This is clearly not optimal, but the available radioactive sources and spectrometers did not allow better configuration.



Figure 4.1. Experimental arrangement for laser re-excitation of radioluminescence.

P. Rousselot et al. (doi: 10.1051/0004-6361/202142829) shows a high-resolution space telescope data of emission peaks of nitrogen ions at 391 nm (0,0)-vibrational peak. The "peak" actually consists of multiple rotational lines of the nitrogen ion, and thus the effective spectral cross-section is spread over a spectral range from 389 nm to 391.5 nm. However, the band edge structure of the rotational peaks creates there a high density of peaks, and that can be found at 391.4 nm wavelength. The laser wavelength tuning measurements were planned based on the data of nitrogen ion peak positions. The laser linewidth is according to manufacturer less than 0.12 nm. For single peaks it is not very good, but it should work fine at the band edge area of the spectrum, where the density of the peaks is high. The laser wavelength tuning measurement was performed with a 0.05 nm steps from 389.35 nm to 391.60 nm. To collect good statistics of 10000 pulses per measurement with 10 Hz repetition rate of the OPO-laser, one single measurement needs 1000 seconds, i.e. about 17 minutes of averaging.

Three examples of the recorded spectra are shown in the Figure 4.2. The main features seen in the spectra are not radioluminescence or laser re-excited fluorescence lines, but Raman scattering of oxygen and nitrogen in air. Oxygen has Raman shift of 1556 cm<sup>-1</sup> from the laser line and nitrogen has the shift of 2330 cm<sup>-1</sup>. That produces peaks at 414.5 nm and 428.3 nm with the pump of 389.4 nm, which is the first out of the three spectra in Figure 2. In the second spectrum, the pump is at 390.4 nm, and the Raman peaks should be respectively shifted to 415.6 nm and 429.5 nm. The main peaks seem to follow the known Raman peak positions very accurately. In the third spectrum, the pump is at 391.4 nm, and the Raman peaks should be respectively shifted to 416.8 nm and 430.7 nm. This is exactly what can be found from the data, too. Other sharp peaks in the spectra are dark counts, as the peaks are narrower than the spectrometer resolution. So they are not physically possible, but generated by thermal excitations in the camera sensor.

Being able to detect gas phase Raman scattering from the interaction length of 1 mm shows that our experimental arrangement is in the top notch condition. The noise suppression by gating, high gain in the photomultiplier, and statistically averaging over 10000 pulses makes the measurement very sensitive, and still we cannot see laser re-excitation of radioluminescence, not even at the best pumping wavelength of 391.4 nm in the third spectrum. The position of the expected luminescence peak is marked with the orange line in the figure. The main reason for the failure is most likely our low ion concentration, which is about 10<sup>8</sup> ions / cm<sup>3</sup> at the best according to our model. The ion concentration might be even lower in reality, as our model did not take all the loss mechanisms into account.



We did try also nitrogen flushing of the chamber, where the alpha active source is located. The flushing is not affecting too much in the concentration of the ions, but it will enhance the fluorescence yield of the transitions a bit. However, that measurement was not successful either.



Figure 4.2. Laser re-excitation attempt while tuning the laser from 389.35 nm to 391.60 nm with the steps of



0.05 nm. The orange line points the spectral location where we would expect to see the 428 nm luminescence peak of nitrogen ions. No luminescence was found even at the best pumping wavelength of 391.4 nm. The two peaks shifting with the laser wavelength are Raman scattering of oxygen and nitrogen molecules.

#### Discussion

We build a model to carefully study different re-excitation possibilities. Based on the model, we picked the most promising scenario of nitrogen ions for experimental testing and made that also with nitrogen flushing. Our radioactive source is having 32 MBq surface activity of alpha particles spread over a 6-cm-long stripe. Besides of the best of our experimental trials, we could not detect any laser re-exited radioluminescence. The main obstacle here came from the low concentration of the states that the laser is about to re-excite. We did not manage to get high enough ion concentration with the 32 MBg source, so it would be quite impossible with 1 kBq source, or less active. In the study made by K. Konthasinghe et al. (doi: 10.1366/14-07696), they demonstrate weak laser-Induced fluorescence from nitrogen ions generated by a corona discharge. They had optically very similar measurement principle, and also they observed the Raman signal of nitrogen in the same wavelength range. Their data show that the fluorescence signal is very weak at the same level with Raman scattering. They did produce nitrogen ions with corona discharge and estimated the concentration of ions being at around 2 · 10<sup>9</sup> ions / cm<sup>3</sup> depending on the discharge current. Our ion concentration model predicts that we would need 100 - 200 MBg alpha activity in an area of smaller than 1 cm<sup>2</sup> to create similar concentrations of ions, most likely even more as our model does not take account all the loss mechanisms of ions. This gives an outlook that the laser-induced fluorescence will be possible also for alpha radiation generated nitrogen ions. It just requires large source activity, big laser systems and very sensitive detection, which makes it quite impossible to use for environmental screening.

The appropriate literature has been studied, models have been created and experiments to determine the feasibility of the laser-induced radioluminescence technique to enhance the detectable alpha activity limit to below 1 kBq/cm<sup>2</sup> have been conducted. The experimental setup turned to be very sensitive as we were able to detect gas phase Raman scattering of oxygen and nitrogen from 1 mm interaction length. However, no laser-induced emission of nitrogen ions was detected. A maximum nitrogen ion concentration of 10<sup>8</sup> ions/cm<sup>3</sup> was generated. This was not enough to detect laser-induced fluorescence from the ions with the selected laser and optical arrangement. The ion density was one to two orders of magnitude below the detection limit set by the laser and the used alpha source. Re-excitation and detection efficiency could be increased by one to two orders of magnitude by selecting a narrow linewidth laser with more pulse energy. Narrower linewidth laser is absorbed more efficiently by the narrow spectral lines of nitrogen ions, and more pulse energy directly increases the amount of signal. Another option would be to use a higher activity alpha point source in the measurement. However, getting to over 100 MBq activity point sources or using a high-end narrow linewidth laser system with 10-100 mJ of pulse energy is not anymore very feasible, especially for environmental sensing.

Summary: A feasibility study for a laser-induced fluorescence spectroscopic method for the detection of alpha emitters has been conducted. The rate-equation model to determine the dynamics of fluorescent transitions in different gas environments, including standard atmospheric conditions has been developed. Experiments to determine the feasibility of the laser-induced radioluminescence technique have been conducted. The experimental setup turned to be very sensitive as gas phase Raman scattering of oxygen and nitrogen from 1 mm interaction length was detected. However, laser-induced emission of nitrogen ions produced by an extended <sup>241</sup>Am source (32 MBq) was not detected as the ion density was up to two orders of magnitude below the detection limit set by the used laser and the alpha source. Re-excitation and detection efficiency could be increased up to two orders of magnitude by selecting a narrow linewidth laser with more pulse energy. The objective of this feasibility study was only partially achieved, as the detection limit below 1 kBq/cm<sup>2</sup> was not reached. Nevertheless, the models for predicting the dynamics of the excited states related to radioluminescence were developed and the experimental procedure for carrying out laser-induced radioluminescence measurements was established.



# 5 Impact

The objectives and results of the project have been presented at more than 40 conferences and workshops including national conferences on radiation protection and radiation fields, global conferences on radiation topics and standards and regulatory meetings.

The project generated two exploitable products: (a) UV fused silica lens-based radioluminescence detection system for mapping contamination with alpha emitting radionuclides, and (b) low photon flux UV radiant standards for calibrating radioluminescence detection systems. The sectors of applications include nuclear industry, radiation protection, emergency preparedness and response, and UV radiometry.

#### Impact on industrial and other user communities

The feasibility of the developed UVFS radioluminescence system to detect and map low activity environmental and uranium samples has illustrated the potential application of the system towards item (source, container) integrity checks during the transfer and storage of nuclear materials. With the optical detection method, the hotspot localisation and quantification can be done on a sample of arbitrary shape and size without limiting the inspection to flat external surfaces. The Safeguards System at IFIN-HH, Romania is planning early uptake of the alpha imaging technology developed in RemoteALPHA project. It is foreseen that the optical method will be first implemented for detecting contamination on objects that are brought under safeguards to IFIN-HH or on objects already stored there. Wider use of the developed technology for nuclear safeguards and nuclear forensics applications is also considered.

#### Impact on the metrology and scientific communities

A novel calibration methodology has been developed to provide valuable information about, and confidence in, the performance of radioluminescence detection systems. The proposed calibration methodology is based on two complementary approaches: (a) application of well-characterised activity standards (<sup>210</sup>Po source) to establish a traceable relationship between radioluminescence intensity and alpha activity, and (b) use of alloptical radiation-based devices (radiance standard) that, when calibrated against an alpha activity standard, simulate the radioluminescence induced in nitrogen (N<sub>2</sub>) and nitric oxide (NO) gases by alpha particles in specific spectral regions. These radiance standards simplify substantially routine quality control of radioluminescence detection systems by eliminating the need for open alpha sources, which are always associated with strict radiation safety precautions. Furthermore, since the intensity of radiance standards is adjustable over a very wide range, linearity and detection limits of radioluminescence detectors can be readily determined.

#### Impact on relevant standards

The project has provided guidance for stakeholders and input to international standardisation bodies such as ISO as far as nuclear and radiological emergency preparedness is concerned. The methodology developed in this project will set the basis for new standards for the remote measurement of alpha emitters. Current standards such as ISO 8769:2020 (Measurement of Radioactivity) do not include neither the radioluminescence method nor radiance standards as a means of detecting and calibrating, respectively, alpha emitters. The project will help to fulfil the IAEA requirements listed in the Convention on Early Notification of a Nuclear Accident and in the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency of the European Commission.

#### Longer-term economic, social and environmental impacts

The wider long-term impact of this project is to allow for a rapid, coordinated and effective response in emergency situations involving dispersion of alpha emitting radionuclides in the environment. The development of new calibration procedures for radiometric traceability of radioluminescence detection systems, will enable appropriate accident and post-accident radiation measurements that will lead to more effective countermeasures and better protection of people, wildlife, and the environment. The instrumentation and methodology developed in this project will assist response teams to assess the breakdown phase (i.e., the initial location of the accident and whether the cause of the accident is moving or fixed). It will help authorities take immediate targeted action for the public protection, including measures to reduce panic and prevent unnecessary chaos by providing the public with reliable data on the spread of radioactive particles. More accurate determination of the extent of land contamination will help to reduce the area designated for exclusion and evacuation zones, thereby minimising associated follow-up costs.



# 6 List of publications

[1] I. Lalau and M.-R. Ioan, Simulation of radioluminescence induced by alpha particles in the air by Monte Carlo method, Ninth International Conference on Radiation in Various Fields of Research, June 2021. <u>https://doi.org/10.21175/RadProc.2021.07</u>

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This list is also available here: <u>https://www.euramet.org/repository/research-publications-repository-link/</u>



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