

Metrology for mobile detection of ionising radiation following a nuclear or radiological incident.



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Metrology for mobile detection of ionising radiation following a nuclear or radiological incident

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1 Overview

The protection of the public against ionising radiation and radioactive contaminations caused by nuclear or other radiologically relevant incidents or accidents (i.e. events), including terrorist attacks, is of major importance and may affect thousands of people. Following a radiological event, radiation protection authorities and other decision makers need quick and credible information on affected areas. Therefore, this project has developed reliable instrumentation and methods needed in the field of preparedness, so that correct decisions on countermeasures will be possible. New measuring devices and methods have been developed to quickly gather quantitative data on contaminated areas and dose rate levels by aerial measurements, and to analyse contamination of the air by flexible transportable systems. In addition, improved methods for long-term monitoring of contaminated areas using passive dosimetry systems were investigated. Finally, the feasibility to use dose rate values provided by non-governmental dosimetry networks has been studied. The results of this project are relevant for the protection of the public against dangers arising from ionising radiation during and in the aftermath of a nuclear or radiological event.

2 Need

Following a nuclear or radiological event, fast and appropriate radiation protection measures, based on reliable radiological data, are of high priority for decision makers worldwide. The nuclear accidents in Chernobyl (1986) and Fukushima (2011) are major examples where such protection measures were crucial. But also, several minor accidents and incidents caused severe problems, e.g. the Tokaimura accident (1999). According to the IAEA Safety Standard No. GSR Part 7 'Preparedness and Response for a Nuclear or Radiological Emergency', all safety and security measures have one common aim: to protect human life and health, and the environment. It also emphasises the importance of adequate protective measures in the aftermath of nuclear and radiological emergencies. Reliable radiological data, available at the earliest possible stage, are a prerequisite for protecting people effectively from such unexpected but potentially highly dangerous events.

In the immediate vicinity of a nuclear or radiological accident, as well as in case of large-area ground contaminations, monitoring by unmanned airborne monitoring systems, consisting of unmanned aerial vehicles (UAVs) with spectrometric detectors, are the best solution to protect operators and early responders against contaminations and irradiation. However, advanced calibration procedures based on reference materials and standard radionuclide sources must be elaborated for these systems and verified by Monte Carlo simulations. For airborne radioactivity monitoring, transportable field stations equipped with high-resolution spectrometric detectors and appropriate shielding are needed to allow the measurement of radioactivity concentration levels in affected areas.

During a large-scale nuclear or radiological emergency with the release of a radioactive plume to the atmosphere, the levels of ambient dose equivalent rate and activity concentrations provide essential information about the progression of the radioactive cloud. This information is important for decision makers to take timely and adequate countermeasures to protect the members of the public against the dangers of ionising radiation.

After a major release of radionuclides, a short-term decontamination may not be possible. Hence, concepts for long-term measurements needed to be developed. Metrologically sound data was needed in this field too because decisions on e.g. decontamination measures or the re-opening of restricted areas are of crucial importance. Therefore, passive dosemeters were studied in terms of their suitability for this purpose.

3 Objectives

The overall objective of this project was the establishment of a metrological basis to support adequate protective measures in the aftermath of nuclear and radiological emergencies. To achieve this, the specific objectives of this project were:

 To develop unmanned aerial detection systems installed on aerial vehicles¹ and helicopters for the remote measurement of dose rates and radioactivity concentrations. In addition, to establish novel methods applicable to core and remote areas of a nuclear or radiological incident for air-based radiological measurements including dose rates, radioactivity concentrations, traceable calibrations

¹ In the public, multi-rotor aerial vehicles are often called 'drones'.



for the determination of ground surface activities and interpretation methodologies for rotary-wing unmanned airborne monitoring system or helicopter based radiological measurements.

- To develop transportable air-sampling systems for immediate information on radioactive contamination levels in air. This included generating industry appropriate pre-production models of modular and portable air-sampling systems based on gamma spectrometric detectors that can be quickly transported to places of interest.
- 3. To investigate the metrological relevance of 'crowd sourced monitoring' data on dose rates and provide recommendations on the usability of such data. In addition, to develop handy detector systems with the potential to be used as dose rate measuring instruments in governmental and non-governmental applications.
- 4. To establish stable and reproducible procedures to measure ambient dose equivalent rates using passive dosimetry in order to harmonise passive dosimetry for environmental radiation monitoring across Europe.
- 5. To facilitate the take-up of the technology and measurement infrastructure developed in the project by the measurement supply chain (instrument manufacturers, accredited laboratories), standards developing organisations (ISO, IEC) and end users (national nuclear regulatory bodies, decision/policy makers e.g. IAEA, European Community Urgent Radiological Information Exchange (ECURIE), OECD/NEA, EURADOS, UNEP, WHO, WMO).

4 Results

In the following, the results of this joint research project "Preparedness" are summarized and presented against each of the project's objectives.

To identify the state-of-the-art at the start of the project, web and literature studies, as well as the analysis of different questionnaires were performed, including consultations of various stakeholder communities. Based on those investigations, novel and SI-traceable methods for the mobile detection of ionising radiation following a nuclear or radiological incident were developed and validated in concerted actions by the project partners. In the meantime, the most important results achieved have been published in peer-reviewed journals. Some of these results are described in the following sections according to the four technical objectives of the project: i) development of unmanned aerial detection systems installed on aerial vehicles for the remote measurement of dose rates and ground contamination levels, ii) development of transportable air-sampling systems, iii) monitoring of ionising radiation by non-governmental networks and iv) the use of passive dosimetry for environmental radiation monitoring.

4.1 Unmanned aerial detection of radiological data

Several spectrometric detectors were adapted and mounted on selected UAVs (Unmanned Aerial Vehicles)^{*} based on their flight capabilities. The airborne detectors mounted on the UAVs were tested and calibrated in measurement campaigns. In addition, a measurement campaign was carried out in the former uranium mine of Seelingstädt to test the developed systems in operational conditions. The data acquired by the airborne detectors was processed and compared. *Note: In the public, UAVs and especially multi-rotor aerial vehicles are often called "drones".

A video of the results obtained by a Nal spectrometer and a source-localising detector mounted on a DJI Matrice pro 600 UAV can be accessed using the following link:

https://www.youtube.com/watch?v=IV45uvionKI&t=46s.

A description of the developed systems, including the data transmission, software visualization in real-time and data analysis to calculate $H^*(10)$ rates, radioactivity in the ground and source localization is summarized in the following sections.

4.1.1 Unmanned aerial spectrometric detector systems

The Unmanned Airborne Monitoring Systems (UAMS) for the spectrometric measurement of radiological data in the aftermath of a nuclear or radiological event were developed by equipping Rotary-Wing Unmanned Aerial Monitoring Systems (RWUAMS) with modern radiation detector systems. In addition, new software tools for data acquisition (DAQ), processing, transmission and analysis have been developed.



Based on the size of the carrier and the detector, the developed UAMS can be divided into three categories: small, medium and big. Seven different rotary-wing unmanned airborne radiation monitoring systems have been developed within this project. A wide range of spectrometric detectors was used, each of them having its specific advantages and disadvantages. Six systems use small or medium commercially available RWUAMS as a carrier, thus making the system easily adjustable and affordable for the trade-off between limited flight range and low payload capacity. A different approach was chosen for the seventh system, developed by CMI, NUVIA and MTI, which uses a large petrol engine helicopter to carry the heavy HPGe spectrometric detector for the best energy resolution available. MTI integrated the upgraded HPGe detector with telemetry devices and tested the airborne monitoring system on a piloted helicopter. MTI adapted the successfully tested airborne spectrometric monitoring system for integration into an unmanned helicopter and prepared the system for the measurement campaigns. The long flight range makes the system suitable for deployment during a serious accident, however the costs of such a system are significantly higher and dedicated pilots with special licences are needed. It should also be pointed out that one of the medium-sized RWUAMS is mounted with an angular sensitivity detector ("gamma-source locator") that can significantly optimize the method to scan an area with localized radioactive contaminations. In Fig. 4.1-1, pictures of the different UAMS (i.e. the various radiation detectors carried by the respective UAV) developed within the project, are shown.



Figure 4.1-1. Top left: medium DJI Matrice 600 with a Nal detector ("5 cm x 5 cm")** underneath; **Top right:** Huge SWISSDRONES SDO 50 UAV with a HPGe detector underneath. **Bottom left**: DJI Matrice 600 Pro with a CeBr3 detector ("3.8 cm x 3.8 cm"). **Bottom middle:** small DJI F550 with a CZT 1.5 cm3 detector (mounted on top). **Bottom right**: Medium DJI Matrice 600 Pro UAV and gimbal with a source locator detector underneath. "Note: For cylindrical detectors, the dimensions of the crystals are given in "diameter x height".

4.1.2 DAQ system, telemetry and data transmission

An airborne radiation detection system is usually designed as a stand-alone device that can be mounted onto any UAV with sufficient payload capacity. Thus, being independent of the carrier, the airborne detector is accompanied by positioning GPS modules and an extra altitude sensor, based usually on laser altimeter or barometer, because it is crucial to know exactly the height above ground level (a.g.l.) to calculate properly the dose rate and other measurement quantities. The user should be aware that GPS and barometer do not give information about the local terrain changes which can be quite significant along the course of the flight.

Fig. 4.1-2 demonstrates the terrain profile for a single flight during the measurement campaign carried out in the former uranium mine in Seelingstädt (Germany) for a nominal altitude of 25 m a.g.l.; the actual height ranges from 7 m to 70 m. On the other hand, lasers measure the distance very precisely towards a reflecting surface, but that surface might not always be the one we want to know the distance to. For example, the laser might measure the distance to a rooftop or a treetop instead of the distance to the ground and, therefore, a



combination of different altitude sensors is the most suitable solution for a redundant (quality controlled) measurement of the flight altitude.



Figure 4.1-2. The difference between the altitude measurements provided by the laser altimeter (black), barometer (red) and global navigation satellite system (GNSS) positioning device for PTB UAMS for the span of a single flight (take-off to landing). Note: as explained in the text, the GPS and barometer measurements do not give information about the local terrain profile, which is quite pronounced at this location (hills and valleys cause height variations of up to 70 m). Only the laser altimeter is able to follow this profile.

The installed computer chosen for low and medium-sized systems was a Raspberry Pi microcontroller. For the large helicopter a PC was installed. The systems are powered mainly with Li-ion batteries which gives a few hours of operational time.

The communication between the on-board computer and the ground control station is performed through different technologies. The most common is the communication of private radio networks using serial radio modems. However, this system has a low throughput and low latency communications. High throughput short-range communications can be performed through the Wi-Fi network. The recommended system, if there is internet coverage, for high/medium throughput and long-range communications is a 3G/4G compatible modem. The system can measure no matter where the ground control station is located.

4.1.3 Control software

The ground station (control) software displays real-time telemetry, dose rates, detector spectra and waterfall plots (i.e. time series of gamma-ray spectra). The different teams developed their own control software. As an example, in Fig. 4.1-3 the RIMA-spec software (Royo et al., 2018), developed by UPC, is shown. The information about the aerial vehicle parameters, spectrum information, the heat map and the waterfall plot are identified.



Figure 4.1-3. RIMA-Spec software toolkit which integrates flight control and online analysis of the measured radiological data. Figure taken from (Royo et al., 2018).



In case of the source locator detector, by using a special GUI, the RIMASpec software can display the directional vector towards the hotspot with respect to the UAV-position as it is described in section 4.1.5.4.

4.1.4 Data analysis

Despite previous considerations to use also digital real-time data acquisition e.g. in "list-mode" (JRC had provided the relevant procedures according to IEC63047) it was decided for this project to use only the conventional collation of gamma-spectrometric data by MCA pulse height spectra. The use of list-mode data acquisition could be advantages in case of very high count-rates or strong spatial (hence timely) variations of the source strength of gamma radiation. Both was not the case in the studies described in the following sections. The acquired data (in form of pulse height spectra) together with the position of the UAV and timestamp was processed to calculate $H^*(10)$ rates, determine the presence of artificial radionuclides, calculate the activity concentrations distributed in soil and to determine the source position.

4.1.4.1 Conversion from a spectrum to ambient dose equivalent H*(10)

There are three basic approaches to the derivation of a dose rate from a spectrum: photo-peaks evaluation, spectrum unfolding and conversion coefficients (also known as a band method). The latter has been mostly implemented in the analysis of the UAMS acquired spectra because the coefficients can be obtained by both, measurements in reference irradiation fields using (quasi-) monoenergetic γ -ray sources and MC simulations. The deterministic nature also facilitates the estimation of the dose rate uncertainty which is proven to be difficult with unfolding methods.

To project the measured dose rate to the reference height (usually 1 m a.g.l.), the altitude profiles of the background and the artificial (net) dose rate need to be considered. For the case of homogeneous area contamination (natural radioactivity), the dose rate behaviour with altitude follows the exponential integral profile and for a point source it follows the inverse of the square distance as it is illustrated in Fig. 4.1-4 for the PTB UAMS.



Figure 4.1-4. Altitude profiles of the background $H^*(10)$ rate (left) and the net dose rate (right) of a ¹³⁷Cs source located on the ground (right), measured with PTB's UAMS at the Mollerussa aerial site in Spain. The heights (in meters) refer to the flight altitudes above ground. Uncertainties are displayed with k=1.

4.1.4.2 Man-made gross count (MMGC) method

The man-made count rate algorithm, commonly referred to as the man-made gross count (MMGC), is a simple method to improve the detection of artificial sources by suppressing the influence of variations in the concentration of the natural radionuclides. This method is based on the fact that even if the natural radioactivity varies, the shape of the produced background spectrum remains almost constant. Therefore, the ratio of the count rate in the natural energy region (cps_{high}) to the count rate in the artificial plus natural energy region (cps_{low}) is essentially constant in cases where there are no artificial radionuclides. The high energy region is defined from 1360 keV to 3000 keV, with everything above 3000 keV considered to be of cosmic origin. This ratio (r_{art}) is calculated using Eq. (1) by carrying out measurements when no artificial radionuclides are present, i.e. cps_{art} is zero. The r_{art} has been calculated for different altitudes from the aggregated 2-second spectra, measured at each altitude, and then fitted by a linear function. The derived altitude dependent r_{art} was then applied to each measured spectrum to determine the man-made count rates:



$cps_{art} = cps_{low} - r_{art} \cdot cps_{high}$

(1)

Fig. 4.1-5 demonstrates the application of the MMGC method: a single flight during the measurement campaign carried out in the former uranium mine in Seelingstädt (Germany). The variations of the total count rate and $H^*(10)$ are due to both, the significantly heterogeneous natural radionuclide concentrations in the uranium piles and the presence of hidden artificial point sources. However, the variations of the MMGC are only appreciable when the artificial source is measured.



Figure 4.1-5. A single flight during the measurement campaign carried out in the former uranium mine in Seelingstädt (Germany). Right: temporal plot of total count rate in the 430-1360 keV (green line) and MMGC rate (blue line). In red circle the measurements when the UAV is flying over the source which is clearly identified by the MMGC method. Left: heat map of the $H^*(10)$ at 1 m a.g.l.

4.1.4.3 Measurement of radioactivity ground concentrations

The determination of radioactivity ground concentrations, or specific activities, is trickier than it seems at first glance: while there is an enduring legacy from naturally occurring radioactive material (NORM) mapping techniques developed for manned airborne gamma spectrometry, there is an issue of applicability of these methods in post-accident airborne monitoring using UAV.

Apart from the IAEA spectral window method recommended for NORM mapping that can be extended in case of ¹³⁷Cs contamination, the full spectrum analysis (FSA) method seems to be promising to be implemented for airborne measurements. Using this method, the measured gamma spectrum was reconstructed by several so-called reference spectra that were previously calculated by using Monte Carlo simulations for any radionuclide and source geometry. As an example, in Fig. 4.1-6 the FSA developed by UPC was applied to a spectrum measured when the UAV was flying over the ¹³⁷Cs source at a nominal altitude of 20 m in the campaign carried out at the former uranium mine in Seelingstädt (Germany). The user can select point, uniform or surface source geometries of different radionuclides and at several altitudes a.g.l. In this example, the selected geometries were uniform source of ²¹⁴Pb, ²¹⁴Bi, ⁴⁰K and ²⁰⁸TI natural radionuclides and a point source of ¹³⁷Cs.



Figure 4.1-6. The FSA result for a measured spectrum at the former uranium mines of Seelingstädt with a ¹³⁷Cs point source. Top: measured spectrum (black line) and reconstructed spectrum by FSA (blue line).



4.1.4.4 Source location

The methodologies used to localize a point source by spectrometric detectors share the common idea of mapping the area and then deducing from measured spectra, via various algorithms, the position of the radioactive source. These methodologies present reliable results (Vargas et al., 2021) but they are usually time-consuming, being in conflict with the autonomy of a UAV that needs spectrum integration times of only a few seconds.

A more efficient method of locating the radioactive hotspots was developed that uses data of the locator detector developed by IJS and UPC. With this method, the UAV computer acquires the angular radiation vector information from the locator at its 10 Hz refresh rate (i.e.in real-time). At the same pace, the on-board computer executes calculations of the anisotropy of the vector directions to judge the possible presence of a radioactive source in the vicinity and, if the anisotropy criterion is reached, the UAV will automatically stop and start collecting more angular data to better estimate the position of the radioactive source. These results will then be shown to the pilot in the remote graphical interface of the RIMA-spec software to decide on further actions, i.e. to send the UAV to a new location possibly closer to the radiation source or to continue the pre-planned path. Within a few such consecutive source position estimations, the UAV should arrive on top of the radioactive source location.

4.1.5 Measurement campaigns

4.1.5.1 Campaign in Mollerussa (Spain)

UPC, PTB and BfS compared the response of a 50 mm × 50 mm (diameter × height) Nal, a 38 mm × 38 mm CeBr₃ scintillator and a 1500 mm³ CZT semi-conductor airborne spectrometric detector mounted on the DJI Matrice 600 Pro in a weeklong comparison campaign carried out at the aerial site of Mollerussa (Spain) in September 2019. The decision thresholds that indicated the presence of artificial radioactivity were calculated for the count rates in the low energy region of the spectra, the man-made count rates and the ambient dose equivalent rates from the background flights performed at altitudes ranging between 10 m and 60 m. The capability of the different airborne systems to detect and determine the activity of a ¹³⁷Cs point source (model A3011 from Eckert & Ziegler company) with a certified activity of 346 MBq (referenced on May 27th, 2019) at different flight altitudes were compared. Finally, the airborne systems showed the ability to localize the ¹³⁷Cs point source by flying in parallel lines at 10 m, 20 m and 40 m heights. The results of the comparison have been published (Vargas et al., 2021).

As an example of the results, Fig. 4.1-7 shows the distribution of $H^*(10)$ rate for a background flight at a nominal altitude of 20 m. Following the ISO11929-4, with the standard deviation of background measurements $\tilde{u}(0)$, the decision threshold a^* for a measurand with a 95 % confidence level can be calculated as





Figure 4.1-7. *H**(10) rate histogram distribution (left) and time series (right) for a 20 m a.g.l. background flight measured with PTB system at Mollerussa aerial site in Spain.

4.1.5.2 Campaign in Seelingstädt (Germany)

The weeklong campaign was carried out at the former uranium mine area in Thuringia (Germany) in March 2020 with the participation of 5 UAMS from BfS, PTB, SCK-CEN, UPC and the German Police as invited team. Flights over covered and uncovered areas with hidden ¹³⁷Cs and ⁶⁰Co point sources and over calibrated pads



were carried out during the campaign. Results showed the complexity of analysing the data in case of a hypothetical real emergency situation. As illustrated in Fig. 4.1-8, medium-sized systems of UPC and PTB can identify the covered and uncovered zones in the $H^*(10)$ maps. However, for the small-sized UMAS of BfS such an identification is not clear. Furthermore, due to lower autonomy of the small UAV, BfS should carry out two flights for mapping 500 m x 500 m, while the medium-sized UAV only needs one flight for mapping 1200 m x 600 m.



Figure 4.1-8. *H**(10) rate maps for a 20 m a.g.l. flight measured with PTB (left), UPC (centre, units in nSv/h) and BfS (right) systems at the almost all covered area of the former uranium mines in Seelingstädt (Germany).

4.1.5.3 Campaign in Fleurus and on SCK·CEN premises (Belgium)

On November 20th, 2018, a nuclear emergency exercise took place at the IRE (Institut des Radioélements) in Fleurus. During that day at IRE, normal isotope production was ongoing which involved a routine release of Xe-isotopes through the 25 m high chimney. The release quickly varied, mostly taking place between 10h00 and 12h00, and it consisted primarily of ¹³³Xe and ¹³⁵Xe. The equipment for measuring radiation from a UAV was a 2"x1"x1" Csl detector (Kromek Sigma50) developed by SCK CEN. The two peaks of the xenon isotopes were clearly visible in the spectra. In total, during the five flights, 1,225 useful spectra were collected. From each spectrum the ambient dose rate was derived using the energy dependent calibration coefficients obtained in a previous measuring set up especially for that purpose. It was not straightforward to map the plume of an ongoing release with a source term that changes quickly in time. It would even be a huge task for a constant release under fairly stable weather conditions. As flight times of UAVs were relatively short, winds changed constantly, and the UAVs themselves caused considerable disturbance to the plume because of the large air displacements they caused for staying airborne. On the SCK premises, the BR1 reactor, when working, produced a rather constant Ar-41 source term during its operation time. Taking all the above limitations into account, Fig. 4.1-9 shows a 3D impression of the plume as it was seen by the airborne detector. Therefore, those series of flights with a still rather experimental airborne detector setup needed to be considered more as a proof of concept, or rather an attempt to understand what might be possible using that sort of equipment. To improve such 3D maps, swarm UAV can be a future solution.



Figure 4.1-9. 3D impression of the released plume. The stack is approximately indicated with a black rectangle.



4.1.5.4 Campaign in Barcelona Drone Centre (Spain)

The measurement campaign was carried out at the aerial site of the BCN Drone Centre in the town of Moia, about 80 km north of Barcelona (Spain). An area of approximately 70 m × 100 m was used for the flights to test the locator detector. The ¹³⁷Cs point source with a certified activity of 346 MBq was placed on the ground during the measurements. The flights were carried out on November 3rd, 2020.

As an illustrative result, a test flight at an altitude of 10 m and a UAV velocity of 2 m s⁻¹ is presented in Fig. 4.1-10. The UAV autonomously flew over the planned path and kept calculating, in real time, the radiation anisotropy estimator to see if the criterion of meaningful anisotropy was reached. When this criterion was met (Fig. 4.1-10-a) the UAV stopped and started accumulating more data and calculating the direction towards the radioactive source, sending to the pilot the absolute geolocation positions where the path towards the source probably was. These positions are illustrated as "x" markers in green colour in Fig. 4.1-10 under section (a) and a "+" marker in the same colour represents their centre of mass. Then, the UAV pilot flew to the next measuring point (Fig. 4.1-10-b). The same procedure was repeated until the UAV reached the position (d) where the UAV descended from the initial 10 m altitude to approximately 2 m to improve the statistics.



Figure 4.1-10. Field flight with the result of source localisation. The dots represent the position of the UAV while calculating the approached path towards the source (marked with x) and their average marked by +. The same colour represents the same group, also marked with small letters (a, b, c, d) marking the correspondence to the previous figure with chronological information.

4.1.6 Summary of key outputs and conclusions

Seven different airborne gamma spectrometry monitoring systems, carried by unmanned rotary-wing aerial vehicles ("drones"), for the remote measurement of dose rates and radioactive ground level contaminations, as needed in the aftermath of a nuclear or radiological event, were developed and carefully tested within this project. The monitoring systems used, comprise various scintillation detectors (NaI, CeBr3, CsI), CdZnTe semiconductors of different size (and sensitivity), operational at common temperatures in the environment, and an electrically cooled high resolution HPGe detector. According to the different weight of the detectors and the intended applications, mainly small and medium size UAVs were used as carrier. The considerable weight of the electrically cooled HPGe detector, however, required a large petrol engine driven unmanned helicopter (SWISSDRONES SDO 50) with a payload of up to 50 kg. In comparison campaigns in Spain and Germany, these systems and a source localizer were tested, and different data acquisition, telemetry and data transmission systems were compared under real flight conditions.

Impressive results were achieved with a source locator, able to automatically identify hotspots of radioactivity on ground. While classical spectrometers installed on UAVs need to scan the whole affected area to find hotspots (a very time consuming process), the source-localizing detector improves the scanning as it is able to identify the direction of a hotspot of radioactivity on ground in real-time and optimizes the scanning process by adjusting the flight path towards the direction with the highest photon fluence. The process is shown in the video (https://www.youtube.com/watch?v=IV45uvionKI&t=46s)



The tests of the various detector systems were essential for their appropriate calibration, the validation of data processing techniques and the comparison of the developed data evaluation methodologies for simulated emergency scenarios. The seven airborne detector systems revealed their respective advantages and disadvantages and limitations, depending on the specific characteristics of the nuclear or radiological event. The objectives of these tasks of the project are achieved, and the main results are available (A. Vargas et al., 2021).

4.2 Transportable air-sampling systems

Three new rapidly transportable instruments have been developed, calibrated and tested for the on-line monitoring of gamma-emitting radioactive aerosols. Each system comprises of an air sampler and integrated gamma-ray spectrometer. These systems were designed to be rapidly deployed / re-deployed during the immediate and long-term response to a nuclear or radiological incident in order to obtain accurate information vital for the health of first responders, recovery operatives and the local public community. A summary of each system along with key results is presented in the following sections.

4.2.1 Kromek QuantAir

The QuantAir instrument (shown in Fig. 4.2-1) comprises of a 1 cm³ coplanar-grid CdZnTe detector (Kromek GR1) and lead-shielding, packaged in a compact, hand-carriable casing. The instrument was originally designed for on-site monitoring of ¹³¹I in air by nuclear power plant (NPP) workers. An air sampler with a 'Maypack' activated charcoal filter was used to trap radioiodine for on-line measurements by the GR1. In the weeks and months that follow a nuclear incident, the relevance of radioiodine and other short-lived radionuclides will decrease as they decay away. Radionuclides with intermediate half-lives, such as ¹³⁷Cs, will grow in significance. Most of these radionuclides are less volatile than radioiodine, making the use of a standard glass fibre filter more appropriate. Glass fibre filters vary in both geometry and density compared with activated charcoal, so a new calibration is required. It is also preferential to use radionuclide-specific calibration factors when performing measurements at such close source-detector geometries.



Figure 4.2-1. Kromek QuantAir, with coplanar CdZnTe detector. A Maypack activated charcoal filter is shown installed in a socket directly below the detector.

The QuantAir has been calibrated for energy, peak-shape and ¹³⁷Cs-detection efficiency. Further, minimum detectable activity (MDA) values have been determined and translated to minimum detectable concentration (MDA) values of ¹³⁷Cs in air for a range of measurement and sampling times. ¹³⁷Cs was selected as it is a major fission product of relevance to short-, medium- and long-term monitoring following a nuclear incident.

4.2.1.1 Preparation of calibration filter

The calibration filter was prepared by first marking a uniform grid across a blank glass fibre filter. The filter used was a Whatman GF/A with a diameter of 47 mm. A hexagonal pattern was chosen as this provides good spatial uniformity and packing density within a circle. The area of each hexagon was 1 cm², with a total of 14 hexagons (drop positions) inside the 47 mm diameter filter. As the solution made contact with the filter, it was absorbed and spread, resulting in near complete surface coverage. An NPL-certified solution of ¹³⁷Cs as caesium chloride, traceable to national standards was dispensed by pycnometer to the pre-marked filter. The mass of the pycnometer was weighed before and after dispensing by a calibrated six figure balance. The activity of the calibration filter was 94.7 ± 1.7 kBq.g⁻¹. A second filter was prepared for use as a quality control (QC) source to check the detection efficiency. The activity of the QC filter was 10.43 ± 0.24 kBq.g⁻¹.



4.2.1.2 Minimum detectable concentration

The QuantAir was first calibrated for energy, peak shape and efficiency using the calibration filter. Following this, laboratory background measurements were completed for 1 min to 21 hours. With these data, and the assumption of an air sampler flow rate of 60 L min⁻¹ (3.6 m/h), it was possible to determine the minimum detectable concentration (MDC) of ¹³⁷Cs-in-air that the QuantAir could measure. The results are presented in Table 4.2-1. It was found that the QuantAir can measure an activity concentration of ¹³⁷Cs below its DAC value of 2,000 Bq.m⁻³ within 1 min following a sampling period of 10 min, or within 10 min following a sampling period of 1 min. This result provides confidence that the QuantAir instrument is suitable for use by recovery workers operating in a contaminated environment following a nuclear or radiological incident.

		Sampling time (min)									
		1	10	30	60	120	180	360	720	1440	
	1	9500	950	320	160	79	53	26	13	6.6	
ime	10	1100	110	37	18	9.1	6.1	3.0	1.5	0.76	
) ut t	31	600	60	20	10	5.0	3.3	1.7	0.84	0.42	MDC > 100% DAC
eme	60	370	37	12	6.1	3.0	2.0	1.0	0.51	0.25	100% DAC > MDC > 10% DAC
(1	120	200	20	6.7	3.4	1.7	1.1	0.56	0.28	0.14	10% DAC > MDC > 1% DAC
Aea	720	76	7.6	2.5	1.3	0.63	0.42	0.21	0.11	0.053	1% DAC > MDC > 0.1% DAC
4	1278	61	6.1	2.0	1.0	0.51	0.34	0.17	0.085	0.043	MDC < 0.1% DAC

Table 4.2-1. MDC values (Bq/m³) for a range of sampling and measurement times, with colour coding to indicate how MDC values compares to the ¹³⁷Cs DAC value of 2,000 Bq/m³.

4.2.2 JSI MARE

A rapidly deployable spectrometric air-sampling system, first developed in EMRP project ENV57 MetroERM, has been upgraded and tested by JSI. The device, MARE, has been upgraded to allow for easy control from a remote location to perform real-time analyses of the measured data and to determine the absolute activity concentrations for the radioisotopes in air at the sampled locations. The device firmware has been upgraded with a radionuclide identification algorithm so that the device is able to perform analyses of the data on its own and report results to a remote location/laboratory for further and more precise analyses. The pre-production model has been tested and validated in the laboratory by JSI with spiked filters provided by NPL.

4.2.2.1 Nuclide identification algorithm

The nuclide identification algorithm (NID) code is based on the classical inverse linear problem approach. Explained simply, pre-recorded gamma-ray energy spectra of *n* various radionuclides can be thought of as a collection of *n* column-vectors of dimensionality *m*, constituting a matrix *A* (NID library), while the degree of presence of each radionuclide is encoded as an element of a column-vector *b* with *n* elements. Applying the linear operator *A* onto *b*, then yields Ab = c, with *c* representing the experimental gamma-ray spectrum to be analysed. The formal solution *b*, coding in individual vector elements the abundance of each radionuclide contributing to the gamma-ray energy spectrum, to this linear problem is then *A*⁻¹. The strength of this approach is that the radionuclide spectral library *A* can be prepared beforehand, and so can *A*⁻¹. As this is typically an overdetermined problem, singular value decomposition (SVD) is used to find a pseudo-inverse *A*'=*A*⁻¹ beforehand for a given spectral library *A*. In typical use, only *A*' needs to be calculated once in a given setting, keeping the computational cost at $O(n \cdot m)$. The approach is then enhanced by specific checks and corrections regarding temperature compensation etc., moderately adding to complexity.

Nuclide identification algorithm was implemented on the MARE device so the user can perform analysis directly on the spot of the measurement. Gamma spectra of several nuclides were obtained in the laboratory to serve as a library for nuclide identification. These nuclides presently are Ba-133, Cd-109, Eu-152, Cs-137 and Co-60. Regions of interest, spectra and their pseudo-inverses are saved in a binary file on the SD card of the MARE device. The algorithm has been designed so that it tries to regenerate a spectrum from the spectra of nuclides in the library to match the currently measured spectrum. When the user initiates nuclide identification, the report is displayed on the touch screen and also saved in a file in ASCII format (.txt) on the SD card. An on-screen report shows which nuclides were identified, the presence percentage of their spectra in the regenerated spectrum and the trust level of the regenerated spectrum in per cent. The report in the .txt file is more detailed, also including metadata about the measurement (date, life-time, real-time, total counts) and the data of all nuclides in the library that were used in the process of nuclide identification (nuclides and their regions of interest for the trust level calculations).



4.2.2.2 Server implementation

To implement remote communication, a GSM daughterboard from MikroElektronika with a Telit GL865-QUAD module, which can be connected to a GSM/GPRS network, was used. Mikromedia 5 for Tiva microcontroller communicates with the module via UART by sending it AT commands. As the module is used for a server application, it is essential that a SIM card with a static IP is used in this module.

According to the instructions made by the vendor, AT commands were sent to configure the connection to GPRS network of the mobile operator to establish a TCP/IP socket server with an enabled firewall. The firewall was configured to drop all incoming connections, except those from IPs that are listed in the configuration file on the microcontroller's SD card.



Figure 4.2-2. Remote communication via GPRS.

When the MARE device is turned on, the server immediately starts listening on a specified port. To control and get data from the MARE device via the GPRS network TCP/IP, the client socket (socket) must be created on a remote computer and connected to the internet. If the computer has a public IP allowed by the firewall, it can connect to the server and start communication.

4.2.2.3 Validation

For an independent control and validation of the performance of the MARE system and its newly developed software for spectral analysis, measurements were made of a reference filter prepared by NPL. Further, a Monte Carlo model of the MARE system was produced by EHU and used to predict the response of the system to the reference filter. The result of the test (presented in Table 4.2-2) shows that all results are acceptable using both the experimental and Monte Carlo efficiency curves.

Radionuclide	Gamma Energy [keV]	Reference values (NPL)		Measured activity on reference date, calculated with experimental efficiency curve		Measured activity on reference date, calculated with Monte Carlo code		Relative bias Reference values / Measured	Relative bias Reference values / Measured	ζ-score Reference values / Measured	ζ-score Reference values / Measured
		Activity [Bq]	Uncertainty [Bq]	Activity [Bq]	Uncertainty [Bq]	Activity [Bq]	Uncertainty [Bq]	values (exp. eff.)	values (MC)	(exp. eff.)	(MC)
Cd-109	88,0	14670	240	13942	10737	17188	13236	-4,96	17,16	-0,07	0,19
Co-57	122,1	576	10	515	153	541	161	-10,67	-6,07	-0,40	-0,22
Ce-139	165,9	578	11	467	205	489	215	-19,13	-15,47	-0,54	-0,42
Cr-51	320,1	9460	170	13885	13224	15170	14448	46,78	60,36	0,33	0,40
Sn-113	391,7	2095	53	1926	587	1935	590	-8,09	-7,63	-0,29	-0,27
Sr-85	514,0	2077	36	1809	520	1973	567	-12,92	-5,03	-0,51	-0,18
Cs-137	661,7	2570	46	2674	779	2774	808	4,04	7,94	0,13	0,25
Mn-54	834,8	2327	29	1827	285	2115	330	-21,50	-9,11	-1,74	-0,64
Y-88	898,0	4362	54	5364	837	6143	958	22,96	40,82	1,19	1,86
Zn-65	1115,5	5677	96	6765	1957	6795	1966	19,16	19,70	0,56	0,57
Co-60	1173,2	3211	39	2314	692	2177	651	-27,93	-32,21	-1,29	-1,58
Co-60	1332,5	3211	39	2543	753	2571	762	-20,80	-19,94	-0,89	-0,84
Y-88	1836,1	4362	54	4008	1138	3714	1055	-8,11	-14,87	-0,31	-0,61

Table 4.2-2. Results of the measurements of the reference filter and comparisons of results obtained with an experimentally determined efficiency curve and with Monte Carlo method, with NPL reference values.



4.2.3 Nuvia/CMI CEGAM

The system designed and built by CMI and NUVIA is capable of producing traceable measurements of radioactivity-in-air, i.e. activity concentration of artificial radionuclides. The usability and communication capability of the system to a remote station was tested to ensure the system is ready for deployment in an emergency. The pre-production automated transportable air-sampling system based on an advanced mechanically cooled HPGe detector was designed for medium to long-term monitoring of a site once the location of an incident is confirmed. Special software was developed for the fully automatic operation, calibration and spectral evaluation. This includes the implementation of a sub-software for the subtraction of natural radionuclides contribution from measured gamma spectra. The system was tested in-situ at a collaborating laboratory site responsible for monitoring the surroundings of the NPP Dukovany (CZ) and detection limits and uncertainties were determined. The system will be offered to the Preparedness end-user community as a NUVIA's catalogue product called CEGAM (Continuous Environmental Gas Aerosol Monitor). The system is shown in Fig.4.2-3.



Figure 4.2-3. Measuring system CEGAM and the container.

4.2.3.1 Calibration

The full-energy peak calibration was performed for filter (type GA-100 made from glass microfiber, outer diameter 10 cm, active part diameter 8.2 cm) measuring geometry using standard sources traceable to the National standard for the activity of radionuclides (primary method) and Monte Carlo (MC) calculations using MCNP code.

The calibration curves were constructed for the full-energy peak efficiency as a function of photon energy in the energy range of 20 keV to 2 MeV. For the construction of the calibration curves, the MCNP code was used and the calibration was validated using the standard radionuclide sources traceable to the National standard. The MC model was considered validated when the maximum difference between calculated and experimental full-energy peak efficiencies is lower than ± 5 %. The calibration curves for 3.0, 3.5, 4.0, and 5.0 mm distance of the filter from the detector end cap are shown in Fig. 4.2-4. Finally, position 4.0 mm was chosen for the on-site measurement. The calibration assumed a filter type of GA-100, made from glass microfiber, outer diameter 10 cm, active part diameter 8.2 cm.







4.2.3.2 In-field testing

The system CEGAM for the measurement of the concentration of radionuclides in air after a nuclear or radiological incident was transported to the station monitoring the surroundings of the NPP Dukovany (CZ) for a long-term testing. The over one-year on-site testing was aimed at (i) the stability of trouble-free remote-controlled automatic operations of the system, (ii) the long-term stability of the measuring part parameters, (iii) the long-term stability of the sampling parts and (iv) the background measurement and detection limits determination. During the testing, hundreds of samples were collected, measured and evaluated.

During the over one-year testing, hundreds of filters were deposited and evaluated. Only natural radionuclides from uranium and thorium decay series and Be-7 as a cosmogenic radionuclide were identified in the spectra, with no artificial radionuclide being found. As only artificial radionuclides are of interest after a nuclear or radiological incident, we considered the spectra without artificial radionuclides as the background. This background is unstable throughout the year and so are the minimum detectable activities for radionuclides of interest. The minimum detectable activities were calculated using the standard ISO 11929 and are shown in the Table 4.2-3 for different radionuclides. The background measurement led to the following upgrades of the measuring and evaluation software:

- The live measuring time is changed in dependence on the background, so that minimum detectable activities for key radionuclides remain almost the same.
- The sampling time is changed in dependence on the concentration of radionuclides in air so that the dead time of the measuring part is lower than 30 % (otherwise the resolution of the HPGe detector gets worse and so gets the identification of artificial radionuclides in the gamma-ray spectrum).

Radionuclide	MDA _v , mBq/m ³	Radionuclide	MDA _v , mBq/m ³
Na-24	0.8	Y-88	0.6
Sc-46	0.6	Zr-95	1.0
Cr-51	4.9	Ru-103	0.6
Mn-54	0.6	Ag-110m	0.6
Co-57	0.4	Sb-124	0.6
Co-58	0.6	Cs-134	0.6
Fe-59	1.1	Cs-137	0.6
Co-60	0.6	Eu-154	0.8
Zn-65	1.3	Am-241	3.6
Se-75	0.6	U-238	2027
As-76	1.3	U-235	3.2
Sr-85	0.8	Np-239	1.4

Table 4.2-3. Minimum detectable volume activities for selected radionuclides (sampling time 24 hours, measuring time 12 hours, air volume 240 m³).



4.2.4 Procedures and Guidance

In addition to developing new transportable systems for measuring radioactivity in air, a short guide has been produced for their use in the laboratory and in-field. The guide provides advice and procedures for the calibration, validation and operation of gamma-ray spectrometers integrated into air-monitoring systems in routine and emergency scenarios. Recommendations were provided for establishing a QA/QC programme, the preparation of calibration/QC sources and other factors to consider when undertaking an in-field measurement campaign. The guide will shortly be published on the project website.

4.2.5 Summary of key outputs and conclusions

Modular and portable air-sampling systems, based on gamma spectrometric detectors, were further developed to commercially available industrial prototypes. Three different air-sampling systems (two developed in the EMRP project ENV57 MetroERM and one commercially available from Kromek) have been upgraded, calibrated with various spiked filters and partly tested under real field conditions. The CEGAM system of NUVIA/CMI was tested in-situ in the surroundings of the NPP Dukovany (CZ) and detection limits and uncertainties were determined. All three systems allow the quick transportation to any place of interest. This will support the collation of reliable information on radioactive releases immediately after a real emergency. Procedures for the in-field use of these systems, including calibration, validation and operation were described and are summarised in a deliverable report. An on-site comparison exercise of transportable air sampling monitors at Chernobyl had to be cancelled, due to the Covid-19 pandemic. Part of the investigations into faster radiochemical methods for the assessment of pure alpha and beta emitters in air also suffered by Coronarestrictions (long-term closure of technical infrastructure). However, in parallel, mass spectrometric (MS) methods, able to replace radiochemical methods, have been further developed and showed that MS is a very promising approach, especially for the detection of actinides. Despite the mentioned shortcomings, the objective as a whole has been satisfactorily achieved. Part of the results are publicly available at the project's website (www.preparedness-empir.eu).

4.3 Monitoring of ionising radiation by non-governmental networks

After the Fukushima NPP accident, a high number of non-governmental dosimetry networks appeared worldwide in the internet (e.g. Safecast.org). These networks publish data which are collected by laypersons under uncontrolled measuring conditions. The number of these networks may increase in case of a future NPP accident or any other serious radiological event. The easy access to these networks as well as the high availability of the measured data may then have a strong political impact. Therefore, the metrological possibilities and limitations of such systems were carefully evaluated by JRC, ENEA, NPL, PTB and VINS. For this purpose, numerous measurements in reference facilities (ENEA, NPL, PTB and VINS) and methodological investigations were performed, to investigate whether such networks could serve as a reasonable source of useful information for the support of decision makers (e.g. the EURDEP system operated by JRC), or how such data could be judged in the future.

Especially, the most comprehensive study ever on the basic performance parameters of such relatively simple, lightweight and cheap dose rate Measurement Instruments used in Non-governmental dosimetry Networks (MINNs) was performed in an intercomparison exercise at the reference sites for environmental dosimetry of PTB (Morosh et al. 2021). In addition, two novel MINNs have been developed by the project partner Kromek Limited in cooperation with NPL and tested during the intercomparison campaign at PTB.

4.3.1 Evaluation of existing MINNs

The total amount of 68 detectors were tested in four dosimetry laboratories: the two national metrology institutes PTB and NPL and the two designated institutions ENEA and VINCA. These labs provided irradiation facilities with dose rate values traceable to primary standards which allowed testing at low dose rates and assessing the most relevant performance parameters: detector's inherent background (measured at the PTB low dose rate underground laboratory UDO II), energy dependence and linearity of the response (Fig. 4.3.1), sensitivity to secondary cosmic radiation (Fig. 4.3.2), response to small changes of the dose rate (Fig. 4.3.3), stability of the detector's reading at various climatic conditions).

The results of these investigations reveal that the most serious problem of dose rate measurements using these MINNs is their very strong energy dependence, found with all tested types. In some cases, an over-response that exceeds the acceptable upper limits as defined in IEC 60846-1 by up to a factor of 6.7 was found. The cause of this problem is the use of non-compensated GM tubes with a bad inherent energy dependence. In principle, this problem could be solved by using appropriate energy compensation filters. The



latter could only be done by the MINN-manufacturers themselves but certainly not by the laypersons that typically own and operate such simple devices. The results of this intercomparison exercise show that the calibration factors applied by the manufacturers can deviate significantly for some of the systems. Both, the introduction of energy compensation filters and correct (traceable) calibrations by the manufacturers are strongly recommended, but this would probably lead to a price increase of such systems dedicated to citizen science networks.

Concerning the other basic performance parameters, all MINNs showed satisfactory inherent background values of the order of a few tens of nSv/h, and most of them also showed a satisfactory linearity of the response for dose rates of up to 100 μ Sv/h and above. An over-response to secondary cosmic radiation was found (about 50 %), which is typical of GM counters. Finally, in a climate cabinet, the dependence of the dose rate indication of the MINNs under different climate conditions was studied. Concerning their use within the temperature and humidity range specified by the manufacturers (typically -20 °C to +40 °C and a relative humidity between 50 % and 95 %), with exception of the systems of one manufacturer, all other systems showed no readings at all (0 cpm) and therefore should not be used for measurements in the natural environment.

In order to study the sensitivity of the systems to small artificial increases of the dose rate (as caused by a radioactive plume that passes by or by contaminations due to a radioactive fallout), the MINNs were exposed to a natural radiation environment at PTB, superimposed by weak radiation fields, generated by various radioactive sources. All MINN types, except for one, showed a statistically significant increase of the count rates, even for a moderate increase of 60 nSv/h (i.e. about the same order of magnitude as the natural background radiation at sea level). This means, that MINNs would be able to detect relevant dose rate increases, typical of accidents with a massive release of radioactivity. The MINNs investigated typically comprise GM tubes, featuring small dimensions which means that longer integrations times are necessary for reasonable statistics, but, on the other hand, lead to a less pronounced angular dependence of the response. Nevertheless, inappropriate location or orientation of the MINNs (e.g. indoors or near buildings or inside cars) may significantly influence their dose rate readings.

None of the tested MINN types fully conforms with the relevant dosimetric standards and they all show inferior performance when compared with dedicated dosimeters used by governmental networks. Nevertheless, in case of a nuclear or radiological emergency, the possibly large amount of data obtained by non-governmental radiological monitoring networks (NRMNs) using MINNs could presumably be used to track radioactive plumes and to detect and quantify radioactive contaminations. Both are extremely relevant information for radiation protection measures of the local authorities, national governments and the European Commission. However, such information based on non-governmental measurements using MINNs should be used with great precautions, considering the possibility of reporting faked data or of malfunctioning MINNs. In addition, the NRMNs are sometimes not able to keep the data up to date, due to manual data upload.

Therefore, the comparison with other nearby MINNs and with data from stationary or mobile governmental detector systems will be a prerequisite for an appropriate quality assurance.



Figure 4.3-1: 400kV X Ray with a MINN placed for the test and gamma ray irradiation equipment used at PTB for MINN energy response tests.





Figure 4.3-2. Floating platform and plastic boxes with MINNs positioned on them for testing of their response to Secondary Cosmic Radiation.



Figure 4.3-3. Plume simulation setup.

4.3.2 Development of novel MINNs

Two medium-cost, low-power compact gamma-ray detector systems with the potential to be used as doserate measuring instruments in non-governmental applications have been developed. The first instrument, developed by Kromek and based on an existing device (D3S), utilises a CsI(TI) detector with a silicon photomultiplier (SiPM) readout. The detector response to radiation has been characterised by NPL and PTB in terms of linearity, from ~1.5 nSv/h to ~1 Sv/h, for a range of gamma-ray energies (²⁴¹Am, ¹³⁷Cs and ⁶⁰Co etc). Further, device-to-device variability and possible failure modes have been investigated.

The CsI(TI)-SiPM detector calculates the ambient dose equivalent rate $H^*(10)$ using an on-board spectral fluence algorithm, similar to that employed in the Kromek RayMon10 hand-held detector. The algorithm converts a measured gamma-ray energy spectrum from fluence to $H^*(10)$ by assigning each event with a dose according to the channel it is recorded in. The channel-to-dose conversion factors have previously been calibrated with traceability to national standards of absorbed dose. The total dose is determined by integrating across the spectrum from 30 keV to 3 MeV. The dose rate is determined by dividing the total dose by the measured real time. For the silicon photodiode, the $H^*(10)$ dose rate is determined from the count rate by a

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simple conversion factor. Dead time corrections are applied on an event-by-event basis for both detectors assuming a non-paralyzable model.

The compact, wearable device is intended for use by public agencies for homeland security applications. However, with the removal of the LiF:ZnS-SiPM sensor, the device has the potential for the application within non-governmental monitoring networks. The Kromek D3M is shown in Fig. 4.3-4.



Figure 4.3-4. Kromek D3M Gamma-ray and neutron detector.

The second instrument (Fig. 4.3-6), developed by BfS, also utilises a CsI(TI) detector but is read out with a silicon PIN (SiPIN) diode with a Raspberry Pi controller. The instrument's analogue and digital hardware stages and its software have been developed and tested.

Since the volume of such a diode is relatively small, the working range would not cover background radiation levels. For a detector like this to be suitable for private users or non-governmental organizations, the final product should aim for low to mid-dose-rate levels. In order to increase the overall efficiency of the detector it was decided not to use a single stand-alone Si PIN photodiode but a photodiode coupled with a scintillator (CsI(TI)).

To get an estimate of the detector response, a simple measurement with a Cs-137 source has been made. In this test, only one channel (two comparators) has been used and the voltage thresholds have been set so that only pulses in the range from 10 mV to 300 mV are counted. The activity of the source is approximately 300 kBq. Fig. 4.3-5 shows the measurement data of various distances between the source and the detector. The distance on the x-axis still has an offset to the active detector unit which can be estimated from the fit parameters (2.738 cm) and thus the actual distance can be corrected. Measurement time for each point is one minute. A background measurement was made beforehand, resulting in 38 counts per minute.





Figure 4.3-5. Measurement data of various distances between source and detector.

At a distance of 5.74 cm, the calculated dose rate is $6.96 \,\mu$ Sv/h. With 6,011 registered counts per minute, this results in a count rate of 14.4 Hz at 1 μ Sv/h This is a bit lower than expected. The reason could be that the lower threshold has been set relatively high to make sure not to count any events triggered by noise. Spectral analysis shows that in the low energy region a lot of additional counts are to be expected. They could make up for the difference of theoretical and measured count rate.



Figure 4.3-6. The dosimeter developed by BfS utilises a CsI(TI) detector, but it is read out with a silicon PIN (SiPIN) diode with a Raspberry Pi controller.

4.3.3 Summary of key outputs and conclusions

The metrological quality of dose rate monitoring data provided by Measuring Instruments used in Nongovernmental dosimetry Networks (MINNs) was investigated for 18 different MINNs under laboratory as well as under in-field conditions. To check the reproducibility of the results, for almost all of the systems (16 out of 18) 4 identical detectors were purchased and tested. In an intercomparison exercise for almost all of these 68 detectors (16 systems x 4 detectors + 2 additional systems x 2 detectors) the basic metrological parameters were determined: inherent background reading, response to secondary cosmic radiation, energy and dose rate dependence of the response, sensitivity of the systems to small dose rate variation (produced by artificial gamma ray photon sources; i.e. the simulation of a radioactive plume passing by) on top of the natural environmental radiation level and climatic tests, studying the influence of air temperature and humidity on the dose rate readings. Only for a few detectors not all these tests could be performed, due to technical or logistical problems (especially climatic tests were not possible for some systems).

This intercomparison of 18 different MINN systems is the most comprehensive one ever performed, and it revealed a few but important limitations of such systems, like e.g. the very strong energy dependence of the response, caused by the use of non-compensated Geiger-Muller tubes. The results of this intercomparison as well as first recommendations on the usability of MINN data are published (Morosh et al., 2021). In addition,



two handy detector systems with the potential to be used as dose rate measuring instruments in governmental and non-governmental applications were developed. The objective to investigate the metrological relevance of 'crowd sourced monitoring' data (dose rate data from MINNs) was fully achieved.

4.4 Passive dosimetry

In the aftermath of a nuclear or radiological accident, accompanied by a major release of radioactivity in the environment, a short-term decontamination of the affected areas may not be feasible. Hence, concepts for long-term monitoring of radioactivity concentrations in contaminated areas are essential for the proper protection of the public against dangers arising from ionizing radiation and the related governmental counter-measures.

A cost-effective way for the long-term monitoring of the ambient dose equivalent rate in extended areas is the use of a large quantity of passive dosimetry systems. However, metrologically sound data are of crucial importance for the reliable control of the fading of radioactivity concentrations and especially for decisions on the re-opening of restricted areas. Therefore, in this project, passive dosemeters were studied in terms of their suitability for this purpose. The basic technical properties of various passive dosimetry systems, used in environmental radiation monitoring, as well as different methodologies in passive area dosimetry were systematically investigated. These efforts were also intended to establish stable and reproducible procedures to measure ambient dose equivalent rates and to harmonise passive dosimetry for Environmental Radiation Monitoring (ERM) across Europe.

In addition to the additional dose caused by contaminations (artificial radionuclides), in ERM the natural background dose needs to be quantified. For this purpose, IRB in collaboration with CLOR, ENEA, VINS and PTB, investigated the technical properties of various passive dosimetry systems used by several European institutions in ERM, including dose response, energy response, angular response and the response to a natural radiation spectrum (i.e. terrestrial and secondary cosmic radiation).

Within this project, these dependencies were studied for 12 different passive dosimetry systems from 9 institutions. These nine institutions are: the Central Laboratory of Radiological Protection (CLOR), Poland; ENEA-Radiation Protection Institute, Italy; Institute for Occupational Health (IMI), Croatia; Jožef Stefan Institute (JSI), Slovenia; L.B. Servizi per le Aziende SRI (LBSA), Italy; Politecnico di Milano (POLIMI), Italy; Ruđer Bošković Institute (IRB), Croatia; Universitat Politècnica de Catalunya (UPC), Spain and the Vinca Institute of Nuclear Sciences (VINS), Serbia. Nine out of 12 systems used different types of TLDs and the remaining three were based on RPL, OSL and film dosemeters. Irradiations of the various passive dosimetry systems were carried out in four Standard Dosimetry Laboratories (SDL) using their respective irradiation facilities in S-Cs, S-Co and Ra-226 radiation qualities and also at 8 different narrow series radiation qualities (N60, N80, N100, N120, N150, N200, N250 N300).



Figure 4.4-1. Various passive dosimetry systems in their respective casings.

Of all passive dosimetry systems tested within this study, OSL and RPL based systems showed excellent performance in all tests.



The holders and the holder-filter combination, together with the detectors, can have an important influence on the energy and angular response of the systems and currently there is no standard or recommendation about holders for the use in environmental radiation monitoring. Therefore, investigations and tests of the whole system before their use in case of a nuclear and radiological event are needed.

As the use of different detectors, holders, calibrations, measurement procedures and uncertainties, leads to differences in the measured data, prior investigations and harmonization of passive dosimetry systems are necessary to achieve reliable and comparable dose measurement results.

4.4.1 Preparedness Intercomparison of passive H*(10) area dosimetry systems

The aim of this intercomparison was to study the long-term behavior of passive area dosemeters (for the monitoring of artificial radiation) in the natural environment. From October 2017 to April 2018, photon dosemeters of 38 dosimetry systems were exposed to environmental radiation at three dosimetric reference sites, operated by PTB. In addition to the measurements under natural conditions, a number of dosemeters were also subject of an additional irradiation at two angles in PTB's photon fields. 34 measuring bodies and institutions, which are mainly involved in ambient monitoring in Europe, took part in this intercomparison.

At each of the three PTB measuring sites, 4 dosemeters of each dosimetry system were exposed for six months. The used measuring sites were: a free-field reference dosimetry site for environmental radiation, a dosimetry site for cosmic radiation and a low-level underground laboratory for dosimetry and spectrometry (UDO). In addition, 8 of the dosemeters were irradiated in PTB's primary photon fields (4 dosemeters under an incident angle of 0° and 4 under 90°). All measured data, as well as the reference values, were provided in terms of ambient dose equivalent, $H^*(10)$, which is the appropriate quantity for area dosimetry, according to EU Directive 2013/59.



Figure 4.4-2. PTB reference measuring site for environmental radiation ("free-field" measuring site) with the exposed passive dosimetry systems of the intercomparison exercise suspended at horizontal metallic rods.

The results of this intercomparison (i.e. the use of passive dosemeters for environmental monitoring of gamma radiation), showed for many of the systems a very good agreement with reference values (statistical variances higher than 30 % were not accepted) whereas some measuring bodies clearly failed to reproduce the reference values. Some dosimetry systems showed values outside the limits (IEC60846, IEC 62387), due to poor measured values and/or high uncertainties. An over-response to cosmic radiation was observed (in some cases more than 40 %). This effect needs to be taken into account if measurements in the natural environment are compared with reference values. The systems should be calibrated in photon fields, preferably in the gamma radiation of a sealed ²²⁶Ra source (which resembles natural terrestrial radiation very much), so that



additional gamma radiation could be quantified correctly in the natural environment. A strong dependence of the response to the angle of incident was observed for some systems. In area dosimetry and radiation monitoring, a better agreement of measurements of different systems and dosimetry services is highly desirable. Measuring procedures should be harmonized on a European level and best practices should be recommended. Up to now, only a DIN standard has been published in this field, being published in German only and from today's view, it is partly outdated.

This intercomparison was an important contribution to the quality assurance of dosimetry services dealing with passive dosimetry and will help the services to improve their performance and finally to reduce their measurement uncertainties (Dombrowski, 2019).

4.4.2 Uncertainties of passive area dosimetry systems

ENEA, in collaboration with CLOR, VINS, IRB and PTB, investigated the parameters which may affect the results of a passive dosimetry system used in environmental radiation monitoring with the aim of quantitatively evaluating the uncertainty of the measurement of $H^*(10)$.

The results of this study are used as a starting point for the quantification of the characteristic limits of the dosimetry systems by applying the ISO standard 11929 (ISO, 2019).

The studied dosimetry systems are based on thermo-luminescence (TL) detectors (four types) and radiophotoluminescence (RPL) detectors (one type).

<u>Main conclusions drawn from a questionnaire for passive area dosimetry systems for environmental</u> <u>monitoring</u>

A detailed questionnaire was distributed among the partners which included 40 questions addressing technical data of dosimetry systems, elements of dose calculation, the uncertainty budget of dose calculation and the current typical coverage factor applied to the uncertainty of dose calculation. Significant differences and some conformances were found in the answers to the questionnaire between the laboratories.

The operational quantity $H^*(10)$ for gamma radiation is measured in different rated dose ranges and rated energy ranges in all laboratories. The measuring period for environmental radiation monitoring varies from a minimum of 1 to a maximum of 6 months.

Regarding dose calculation procedures, all laboratories take the reader sensitivity factor of the dosimetry system into account and three systems consider the detector normalization factor. Two systems take the relative response due to energy and angle of the incidence into account and no one makes a correction for non-linearity and environmental influences.

The inherent background of the dosemeter reader is taken into account by three different algorithms. Furthermore, the background dose contribution is subtracted from $H^*(10)$ as a mean background dose value in standard procedure of three laboratories. Only one laboratory applies transport dose corrections for two passive dosimetry systems.

In the uncertainty budgets of dose calculation, the laboratories routinely apply the uncertainty of all parameters taken into account in their procedure.

Main conclusions drawn from a simulation of a scenario for radiation monitoring in emergency

To compare the five dosimetry systems used by four laboratories, all partners simulated the measurement of the specific low dose $H^*(10) \approx 0.165 \text{ mSv/month}$. This value corresponds to a conservatively estimated additional effective dose of 0.7 mSv/year (less than the limit on the public exposure of 1 mSv/year).

The number of days between two consecutive readings is assumed to be 50 days for a measurement period of one month. The decision thresholds (h*) and detection limits (h[#]) of the five systems for this selected measurement condition is presented in the following table.



	TLD-ENEA	TLD-CLOR	TLD-RBI	RPL-RBI	TLD-VINS
h*(µSv/period)	32	31	I:35; II:32; III:30	25	35
h [#] (µSv/period)	76	67	I:80; II:72; III:65	51	86

Table 4.4-1. Decision thresholds (h*) and detection limits (h#) of the five investigated systems.

The main conclusions of the comparison of these dosimetry systems were:

- The detection limit depends on the number of parameters taken into account in the uncertainty budget. To compare the detection limit of different systems, it is necessary to verify that the parameters used in the respective uncertainty budgets are the same.
- The five dosimetry systems studied show that the uncertainty of environmental dose determinations is relatively high at low dose rate levels (for a dose rate of 0.165 mSv/month the uncertainty is in the range of 19 % to 50 % with k=2).
- The use of more detectors for each dosemeter can help to reduce the final uncertainty, for example 22 % is the uncertainty for the mean value of three detectors with uncertainties for a single detector in the range of 33 % to 42 %.
- This study showed how important it is to analyse the factors which affect this uncertainty and several improvements are necessary in each laboratory in order to harmonize the methodologies of environmental dose measurements with passive dosimetry systems in normal as well as in emergency situations.

A detailed description of the uncertainties of ERM using passive dosimetry systems is given by (lurlaro et al., 2021).

4.4.3 Procedures to measure mean $H^*(10)$ -rates using electret ion chambers

AUTH investigated the capabilities of electret ion chambers to measure mean ambient dose equivalent rates by performing both laboratory and field studies on their properties. First, electret ion chambers were "calibrated" to measure ambient gamma dose equivalent in the Ionizing Radiation Calibration Laboratory (IRCL) of the Greek Atomic Energy Commission. The electret ion chambers were irradiated with different gamma photon energies and from different angles. Calibration factors were deduced (electret's voltage drop, due to irradiation in terms of ambient dose equivalent). In the field studies, electret ion chambers were installed at eight locations belonging to the Greek Early Warning System Network (which is based on Reuter-Stokes ionization chambers) for three periods averaging five months each. At the same locations, in-situ gamma spectrometry measurements were performed with portable germanium detectors. Gamma ambient dose equivalent rates were deduced by the in-situ gamma spectrometry measurements and by soil sample analyses. The mean daily electret potential drop (in Volts) was compared with the mean daily ambient dose equivalent, measured with a portable HPGe detector and Reuter-Stokes high pressure ionization chambers (HPIC).

Main conclusions concerning the laboratory studies are:

• The study of the Calibration Factors (electret potential drop per μ Sv) as function of the electret voltage indicates that for electret voltages above 450 V the calibration factors are constant. On the contrary, for initial electret voltage with less than 450 V the calibration factors depend on the initial electret voltage. It is therefore recommended to use EIC with relatively high initial electret voltage in case of environmental gamma monitoring measurements.

• The calibration factors as function of the irradiation photon energy (at zero-degree incidence) are clustered within 14 % around a mean value of 0.16 V/ μ Sv.

• For most incident photon energies (except gamma rays from Co-60 source) an angular dependence of the calibration factors is observed.



Main conclusions concerning the field studies are:

• A mean "field" calibration factor of 0.17 V/ μ Sv was deduced from the three time periods in good agreement with the 0.16 V/ μ Sv deduced from the Laboratory studies.

• In case of long-term environmental gamma monitoring with EIC, at least 4 EICs should be used in each location, due to the possibility of abnormal discharge of the electrets (25 electrets in a total number of 110 electrets had an abnormal discharge and were disregarded for evaluation)

• An inherent voltage loss of 0.31 V/d of the electret material (not due to ionization within the chamber) has been found in accordance with previous results (0.14 to 0.34) V/d

• The difference between the mean ambient dose equivalent rate measured by EIC detectors and portable HPGe detectors is less than 10 %. The mean ambient dose equivalent rate due to cosmic radiation deduced with the EIC detectors is 35 nSv /h, which is similar to the ambient dose equivalent rate due to cosmic radiation (excluding neutrons) at sea level (33 ± 2.6) nSv/h.

• The correlation between mean ambient dose equivalent rate measurements in the eight locations performed by portable HPGe and Reuter-Stokes HPIC indicates a difference of only 2 % between the terrestrial gamma dose rates measured by the two instruments (HPIC and HPGe). In addition, a constant value of 34 nSv/h is found between the mean values of the dose rate measurements performed by the two detectors (HPIC and HPGe). The constant value of 34 nSv/h is very similar to the ambient dose equivalent rate due to cosmic radiation (excluding neutrons) at sea level.

• Last but not least, a good agreement between direct (in situ gamma spectrometry) and indirect (from soil sample analysis) measurements of the ambient dose equivalent rates is observed. The mean difference between direct (in situ gamma spectrometry) and indirect measurements is about 6 %. For more details see (Leontaris et al., 2020).

4.4.4 Summary of key outputs and conclusions

The use of passive area dosemeters for the radiation monitoring of contaminated areas was investigated. It was supposed that passive dosimetry is a good and inexpensive alternative to the use of active electronic instruments, especially if a very large number of measuring places of interest exists, or if the use of active instruments is complicated, e.g. due to a missing infrastructure (power supply, etc.) or harsh environmental conditions. The precision of the dose measurements performed with electronic and with passive dosemeters can be similar, depending on the concrete measurement procedures and the selection of dosemeters. In this project, systematic investigations into the properties of current commercial passive area dosimetry systems revealed their properties and their performance in routine operation. Unfortunately, these investigations also showed that the use of different detectors, holders and methodical differences in the measurement procedures (due to different national traditions and experiences) lead to considerable differences in passive dosimetry in Europe. In order to achieve reliable and comparable environmental dose measurements, prior investigations of the passive dosimetry systems to be used are a necessary prerequisite. As an important deliverable of this project, recommendations on the use of passive dosimetry systems in environmental radiation monitoring were collected and the metrological properties of passive dosimetry systems were described.

An intercomparison exercise took place that included 38 measuring bodies and institutions involved in ambient radiation monitoring in Europe, which participated with 20 passive dosimetry systems each. This means that the intercomparison comprised a total of 760 dosemeters. The response of the dosemeters to terrestrial and to secondary cosmic radiation as well as the accuracy of the dose values after a free-field exposure of six months were determined. The results of these considerable efforts, including typical measurement uncertainties in passive dosimetry in the environment and basic metrological properties of the systems, were summarised and published (Knesevic et al., 2021). The recommendations will successively be made available and discussed with the major measuring bodies in Europe (under the guidance of EURADOS WG3), in order to proceed towards a European-wide harmonisation.

5 Impact

To promote the uptake of the project's outputs, this was disseminated to a network of stakeholders and endusers, formally organised with the assistance of a Stakeholder Committee. Finally, the project had 11 collaborators and 29 other stakeholders from industry, universities, public research organisations, public



bodies and NMIs/DIs. The results of this project have been disseminated to the interested community via presentations and open-access peer-reviewed publications. 56 conference papers were presented at international workshops and conferences on ionizing radiation monitoring, preparedness issues and related topics. The project's results are available on the project website. In addition, communities such as EURADOS and NERIS served as a platform to share results of this project with experts in related fields. Partners of the project are working in different advisory boards of various national radiation protection authorities, including ministries and other governmental institutions. Thereby, input has also been given directly to national governments in partnering countries.

Impact on industrial and other user communities

Reliable radiological data is of key importance for the European Data Exchange Platform (EURDEP). The feasibility to use non-governmental data, in addition to the data provided by the 5500 governmental stations, has been comprehensively investigated for the first time. Reliable radiological data will also strengthen the confidence and credibility of the public in the decisions of the legal authorities.

The development and test of radiation detection systems, together with good practice guides on the measurement of dose rates and radioactivity concentrations using measurement systems that have been developed in the project, are useful both for the metrological community working in this field and for end users (e.g. regulatory authorities, supervisory authorities, civil protection or official measuring bodies) and for manufacturers of dosemeters, contamination monitors or other radiation meters.

The two industrial partners of the project, Kromek and NUVIA, have developed UAV based spectrometry systems for the measurement of ground contaminations. In line with that, the company SwissDrones developing and producing UAVs has been adopting a method for monitoring radioactivity after a nuclear accident using HPGe detectors. Joint tests with CMI were performed in Switzerland and a joint product will be presented in the Czech Republic during an air-show, which will be organized by NUVIA and CMI as soon as reduced pandemic restrictions will allow it; presently envisaged for May 2022.

In collaboration with the Jozef Stefan Institute in Ljubljana, a real time detector for the localization of hotspots of gamma radiation (brand name "Gamma 4") has been adapted to be operated on a Matrice 600 drone. Specific software was developed for this use and preliminarily tested. The final product should have been presented during a course and demo performance at the Barcelona drone Centre in June 2020 to stakeholders like the Spanish Nuclear Safety Council, Catalan Nuclear Safety Authority, Catalan Police, operators of NPPs, fire-fighters and military services. This course had to be replaced by an online-video presentation because of the corona pandemic.

Kromek Limited produced 10 units of a newly developed version of a dose rate detector based on a simplification of the existing D3S instrument. Kromek with support of NPL determined the response of the CsI(TI)-SiPM based detector allowing spectral dose to be calculated following the same fluence algorithms employed in the Kromek RayMon10 hand-held detector. Kromek and NPL assessed the validity of crowd sourced data produced by the dose rate detectors. Kromek has developed a concept website (an HTML server software) for real-time sharing of dose rate readings. The final product will be offered for use in non-governmental radiological networks.

The NPP Dukovany (CZ) will use the data and experiences from the long-term monitoring of radioactivity in air by a modular and transportable air-sampling system developed in this project. The Slovenian NPP Krsko showed interest in the rapidly deployable spectrometric air-sampling system upgraded by JSI and NPL. The system was also presented to the US company F&J Specialty Products Inc. as a potential distributor.

Impact on the metrology and scientific communities

The progress in measurement technologies achieved in this project improved the early identification of affected areas, including identification of radionuclides, e.g. Cs-137, I-131, Ba-140, Ce-141, Ru-103 and Np-239 as well as the determination of contamination levels. The novel instrumentation is essential for a quick and adequate response from nuclear regulatory bodies and other decision makers, e.g. from local authorities or aid organisations, during and in the aftermath of a nuclear or radiological accident.

After establishing aerial calibration and test sites for airborne dosimetric and spectrometric instruments, standardised procedures became available for European measuring services and governmental bodies. In this scope of application, the verification of methods to measure absolute dose rates and activity concentrations on a metrological basis are a major step forward in quality assurance. In addition, the proposed harmonised procedures will result in a mutual recognition of calibrations, with transparency and significant cost saving for the customers. As a further direct impact of this project, more reliable dose values in routine monitoring using



passive dosimetry systems should become available on a European scale. This and other goals of the project are in line with the policy of the EC DG ENER.

An intercomparison exercise with 760 passive dosemeters from 38 different dosimetry services in Europe was performed at various reference sites of PTB. Passive dose meters were exposed for six months to natural radiation and some of these systems also to artificial radiation fields of Cs-137 as well as to pure secondary cosmic radiation in order to determine the various response factors and the sensitivity of the systems to low doses and to small dose rates variations. The information gained from the systems is of key importance for the quality assurance of various dosimetry services. The published results (Dombrowski, 2019) show that most dosimetry services are able to measure typical free field annual dose values with reasonably small uncertainties (less than 20 %). In a few cases, however, the measurements based on thermoluminescence dosimetry detectors (TLDs) failed. The intercomparison gave the operators of such TLD systems the chance of an improved understanding of their methods and thereby helped to improve their performance.

Impact on relevant standards

The project also aimed at an international harmonisation by providing guidance for stakeholders and by providing input to international standardisation bodies (ISO, IEC), as far as nuclear and radiological emergency preparedness is concerned. 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.

Members of the consortium are involved in the following committees: ISO/TC 85 (Nuclear Energy), IEC/TC 45 (Nuclear Instrumentation), EURAMET TC-IR (Technical Committee for Ionizing Radiation), ICRM (Gamma and Beta Spectrometry WG, Alpha Spectrometry WG and Low Level WG) and BIPM CCRI I and II. This enabled the direct dissemination of the harmonised procedures and methods developed in this project to European and international standardisation committees and working groups.

The project was presented to ISO/TC 147 (Water quality, radioactivity), ISO/TC 85 (Nuclear energy, nuclear technologies and radiological protection), IEC/TC 45 (Nuclear instrumentation), CENELEC/TC 45B (Radiation protection instrumentation), ICRM WG Gamma Spectrometry and EURAMET TC-IR.

Longer-term economic, social and environmental impacts

The development of radiation detection systems operated on drones and other unmanned aerial vehicles, together with good practice guides on remote measurement of dose rates and radioactivity concentrations, will be very useful for end-users and manufacturers. After establishing aerial calibration and test sites for airborne dosimetric and spectrometric instruments, standardised procedures have become available for European measuring services and governmental bodies. Metrologically sound, i.e. accurate and traceable accidental and post-accidental measurements of area contaminations, airborne radioactivity concentrations and ambient dose equivalent rates, are a major step forward in quality assurance. This will contribute to increase the competitiveness of European manufacturers. In addition, harmonised procedures will result in a mutual recognition of calibrations, with transparency and significant cost saving for the customers.

After an event, all follow-up and countermeasures, especially on the prompt determination of exclusion zones and off-site emergency zones, will depend significantly on the metrological quality of data. The total economic costs of both the Chernobyl and the Fukushima accident are estimated at hundreds of billions of euros. The adoption of the project results and recommendations by national nuclear regulators and international standard bodies will contribute to considerable cost savings in case of future nuclear or radiological emergencies.

Additionally, environmental damages will be minimised by early and correct governmental decisions. The outcomes of this project will, in the future, enable national regulators to judge emergency situations more appropriately. Therefore, the affected population will be protected more effectively against dangers arising from ionising radiation caused by a nuclear or radiological event and the public's confidence in governmental decisions will be increased. For the latter, the investigation of non-governmental dose rate monitoring networks and the feasibility study of the potential use of non-governmental dose rate data provided by such networks, is of key importance for the credibility of governmental authorities and their decision and hence has a considerable social impact.



6 List of publications

[1] P. Royo, et al.: An Unmanned Aircraft System to Detect a Radiological Point Source Using RIMA Software Architecture. Remote Sensing 10(11), 1712, (2018). <u>https://doi.org/10.3390/rs10111712</u>

[2] A. Vargas et al.: Comparison of airborne radiation detectors carried by rotary-wing unmanned aerial systems. Radiation Measurements 145, 106595, (2021). <u>https://doi.org/10.1016/j.radmeas.2021.106595</u>.

[3] M. Luchkov et al.: Unmanned aircraft-based gamma spectrometry system for radiological surveillance. SMSI 2020 peer-reviewed proceedings. <u>https://doi./10.5162/smsi.2020/E6.2</u>

[4] V. Morosh et al.: Investigation into the performance of dose rate measurement used in non-governmental networks. Radiation Measurements. <u>https://doi.org/10.1016/j.radmeas.2021.106580</u>

[5] G. lurlaro: Dose rate data of measuring instruments used in non-governmental networks in the framework of Preparedness project. EUROSAFE 2019 peer-reviewed proceedings. ISBN978-3-947685-51-6. http://www.etson.eu/sites/default/files/eurosafes/2019/EUROSAFE2019_Proceedings.pdf

[6] Z. Knezevic et al.: Investigations into the basic properties of different passive dosimetry systems used in environmental radiation monitoring in the aftermath of a nuclear or radiological event. Radiation Measurements. <u>https://doi.org/10.1016/j.radmeas.2021.106615</u>

[7] G. Iurlaro et al.: Study on the uncertainty of passive area dosimetry systems for environmental radiation monitoring in the framework of the EMPIR "Preparedness" project. Radiation Measurements. https://doi.org/10.1016/j.radmeas.2021.106543

[8] H. Dombrowski: Preparedness intercomparison of passive H*(10) area photon dosemeters in 2017/2018 (IC2017prep). Journal of Instrumentation. <u>https://doi:10.1088/1748-0221/14/10/P10008</u>

[9] F. Leontaris et al.: Procedures to measure mean ambient dose equivalent rates using electret ion chambers, Radiation Protection Dosimetry 190 (1), 6–21, (2020). <u>https://doi.org/10.1093/rpd/ncaa061</u>

The published papers are also available here: <u>https://www.euramet.org/repository/research-publications-repository-link/</u>

7 Contact details

A project public website has been created: www.preparedness-empir.eu. A partners' share point has also been created to give all the partners the possibility to share their work documents and deliverables.

The contact person for general questions about the project and its coordination is Stefan Neumaier, PTB; email: stefan.neumaier@ptb.de.

The contact persons for the technical work packages are:

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WP2 Transportable air-sampling systems: Steven Bell (NPL); email: steven.bell@npl.co.uk

WP3 Monitoring of ionising radiation by non-governmental networks: Giorgia CINELLI (JRC); email: Giorgia.CINELLI@ec.europa.eu

WP4 Passive dosimetry: Stefan Neumaier (PTB); email: stefan.neumaier@ptb.de

WP5 Creating impact: Petr Kovar (CMI); email: pkovar@cmi.cz