Note

Metrology for the mobile detection of ionising radiation following a nuclear or radiological incident – The EMPIR project "Preparedness"

Stefan Neumaier[1], Harald Dombrowski[1], Patrick Kessler[1], Maksym Luchkov[1], Arturo Vargas[2], Steven Bell[3], Konstantins Bogucarskis[4], and Petr Kovář[5]

[1] *Physikalisch-Technische Bundesanstalt (PTB), Germany*
[2] *Universitat Politècnica de Catalunya (UPC), Spain*
[3] *National Physical Laboratory (NPL), United Kingdom*
[4] *Joint Research Centre – European Commission (JRC), Italy*
[5] *Cesky Metrologicky Institut (CMI), Czech Republic*

In cases of nuclear or other radiologically relevant incidents or accidents ("radiological event"), including terrorist attacks, appropriate protection of the public against ionising radiation and radioactive contamination is of major importance. In such scenarios, radiation protection authorities and other decision-makers quickly need reliable information based on sound radiological data in order to determine and optimize countermeasures. The nuclear accidents in Chernobyl (1986) and Fukushima (2011) are major examples where radiation protection measures were crucial for preserving a tremendous number of human lives. However, certain smaller events have also caused severe problems, e.g., the Tokaimura nuclear criticality accident (1999). According to the IAEA Safety Standard No. GSR Part 7, "Preparedness and Response for a Nuclear or Radiological Emergency" (1), safety and security measures have the shared aim of protecting human life and health as well as protecting the environment. This document also emphasises the importance of adequate protective measures following nuclear and radiological emergencies. Reliable radiological data, available at the earliest possible stage, are a prerequisite for effectively protecting people from such unexpected but potentially highly dangerous events.

Therefore, the European joint research project 16ENV04 named "Preparedness", funded by the European Metrology Programme for Innovation and Research (EMPIR), is meant to develop reliable instrumentation and methods needed in the field of radiation protection in the aftermath of a nuclear or radiological emergency. The goal is to quickly gather quantitative data on the activity concentrations of contaminated areas and dose rate levels by aerial measurements, and analyse these air contaminations by flexible and transportable air sampling systems.

Corresponding author: Stefan Neumaier, PhD, Physikalisch-Technische Bundesanstalt, Braunschweig, Germany, email: *Stefan.Neumaier@ptb.de*

For large-area ground contaminations, surveillance by unmanned airborne monitoring systems (UAMSs), specifically unmanned aerial vehicles (UAVs) equipped with spectrometric detectors, is the best solution to protect first responders and other task forces against contaminations and hazards due to ionising radiation. 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 air sampling field stations equipped with high-resolution spectrometric detectors and appropriate shielding is needed to allow the measurement of radioactivity concentration levels in the air of affected areas. After the release of a radioactive plume to the atmosphere, the levels of the ambient dose equivalent rate and activity concentrations in air provide essential information about the progression of the radioactive cloud. This information is important for decision-makers to be able 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, short-term decontamination may not always be possible. Hence, concepts for long-term measurements have to be developed. Metrologically sound data is needed in this field as well, because decisions on e.g. decontamination measures or release of restricted areas are of vital importance. Passive dosimeters must therefore be studied with regard to their applicability for this purpose. Furthermore, the "Preparedness" project addresses the question whether non-governmental networks could support official dose rate data or undermine them because of insufficient quality.

Objectives and Work Package structure

The overall objective of this project is 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 are (8):

- To develop unmanned aerial detection systems installed on aerial vehicles[1] 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 for the determination of ground surface activities and interpretation methodologies for Rotary-Wing Unmanned Airborne Monitoring System (RWUAMS)-based radiological measurements.
- To develop transportable air-sampling systems for immediate information on radioactive contamination levels in air. This also includes 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.
- 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.
- 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.
- To facilitate the take up of the technology and measurement infrastructure developed in the project by a measurement-supply chain (instrument manufacturers, accredited laboratories), organisations that develop standards (ISO, IEC), and end-users (national nuclear regulatory bodies, decision/policy makers e.g. the International Atomic Energy Agency (IAEA), the European Community Urgent Radiological Information Exchange system (ECURIE), the OECD, the European Radiation Dosimetry group (EURADOS), the United Nations and the World Health Organization (WHO).

According to these objectives, the project is structured into four technical work packages (WPs):

WP1. Unmanned aerial detection systems: To obtain fast and detailed information on contaminations in vast or inaccessible areas, which is needed for making decisions regarding appropriate countermeasures, mobile detector systems for area and air monitoring should be further developed and tested in realistic field conditions. For these systems, advanced calibration procedures, based on reference materials and standard radionuclide sources, must be elaborated and verified by Monte Carlo simulations. For large-area ground contaminations, monitoring by unmanned aerial vehicles accompanied by spectrometric detectors is the best solution to protect operators against undesirable contaminations or irradiation.

WP2. Transportable air-sampling systems: Transportable systems offer flexibility for rapid redeployment should conditions change and thus provide a cost-effective solution for post-incident monitoring, a goal which is in line with (2) of the European Community Directorate-General Energy (EC DG ENER). For airborne radioactivity monitoring, transportable field stations do not yet exist. They will be developed in this project, allowing the flexible measurement of radioactivity concentration levels in affected areas. The importance of this research field is emphasised in EC Report EUR 27224 EN (3). An on-site comparison exercise for the new transportable systems will be carried out to test their properties in-field and to check the whole measurement chain. Finally, rapid radiochemical separation and analysis methods for the determination of airborne alpha and beta emitting radionuclides will be optimised and further developed as a useful complement of airborne radioactivity measurements.

WP3. Non-governmental networks: For several decades, radiological monitoring information has been provided only by national monitoring networks. In the last few years, in addition, non-governmental monitoring networks disseminating crowd-sourced data have developed rapidly after the disaster at Fukushima. This trend may continue in line with the expansion of personal networked electronics. Although the active involvement of the public should be encouraged, one should be also confident that the results measured in this way will not conflict with the official measured dose rate values that have established traceability to national standards. Metrologically unreliable data of simple electronic devices provided by non-officials to the general public and to the media may result in unnecessary concern or raise questions about the validity of the regular monitoring networks. It is equally possible that the large datasets produced through these citizen science initiatives can complement official data and provide extra insight or early warning of an incident. Hence, non-governmental monitoring requires a detailed investigation of its metrological relevance.

WP4. Passive dosimetry for environmental radiation monitoring: In routine monitoring, many national measuring bodies in Europe and worldwide use passive dosimetry systems to survey nuclear installations at the borders of the restricted territories in order to protect the public from dangers arising from ionising radiation. If passive dosimetry systems are used for environmental radiation monitoring in the aftermath of a radiological event, the reliability of the measured data is of key importance. Hence, harmonised methods are necessary and a detailed knowledge of the performance of passive dosimetry systems is required in order to allow reliable measurements even at low dose levels (a goal in line with (2) of EC DG ENER).

[1] Multi-rotor aerial vehicles are commonly known as *drones*.

Furthermore, there is a work package dealing with the dissemination of the results of the "Preparedness" project (WP5: "Impact") and a work package "Management and Coordination" (WP6).

"Preparedness" consortium

The "Preparedness" consortium comprises 17 institutions from 11 European countries and the Joint Research Centre of the European Commission, including:

- 3 National Metrology Institutes (NMIs): Physikalisch-Technische Bundesanstalt (PTB, Germany), Cesky Metrologicky Institut (CMI, Czech Republic), NPL Management Limited (NPL, UK),
- 3 Designated Institutions (DIs): Ruđer Bošković Institute (IRB, Croatia), Institut Jožef Stefan (JSI, Slovenia), Institut za nuklearne nauke Vinča (VINCA, Serbia) and
- 11 scientific and technological institutions as well as private enterprises: Aristotelio Panepistimio Thessalonikis (AUTH, Greece), Bundesamt für Strahlenschutz (BfS, Germany), Centralne Laboratorium Ochrony Radiologicznej (CLOR, Poland), Universidad del Pais Vasco / Euskal Herriko Unibertsitatea (EHU, Spain), Agenzia Nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile (ENEA, Italy), Joint Research Centre - European Commission (JRC, EC), Kromek Limited (Kromek, UK), Vojensky Technicky Ustav SP (MTI, Czech Republic), NUVIA a.s. (NUVIA, Czech Republic), Universitat Politècnica de Catalunya (UPC, Spain) and Studiecentrum voor Kernenergie, Centre d'Etude de l'Energie Nucléaire, Fondation d'Utilité Publique (SCK•CEN, Belgium).

In addition, about 10 further institutions officially collaborate with the "Preparedness" consortium and exchange know-how and scientific and technological results.

FIRST RESULTS AND DISCUSSION

As a follow-up of the European Joint Research Project "Metrology for radiological early warning networks in Europe" (MetroERM), the Preparedness project started with a considerable background of results achieved by MetroERM and published in about 20 peer-reviewed publications and numerous conference proceedings.

In the framework of Work Package 1, several detector systems were customised for the use on UAV. They are based on NaI, $CeBr_3$ and CdZnTe detectors. The systems had to be made of lightweight components including electronics and control systems. For this purpose, novel microelectronics and apt software for the recording of spectra and transmission of data had to be developed. The simultaneous wireless control of the UAV and the wireless transfer of a big amount of measured data are a challenge even for modern communication systems. Within the next years of the Preparedness project, intercomparison exercises with UAV-based spectrometry systems at flight centers in Spain, in the Czech Republic and in Germany will be performed to test measuring systems developed within this project and to elaborate calibration procedures which are needed for quantitative dose rate and activity concentration measurements.

In the following, some preliminary results of the ongoing work are described. One example is the equipment of a UAV with a spectrometer with a $CeBr_3$ scintillation crystal with the dimensions of 3.81 cm in diameter and 3.81 cm in length. This detector was characterized so that the measured spectra can directly be converted to dose rates in terms of ambient dose equivalent, $H^*(10)$. In addition to measurements in photon fields of calibration facilities, Monte Carlo simulations were performed by using the codes GEANT4 (4) (with the EMLivermore physics list), MCNP and Penelope. In Figure 1, the simulated conversion function from incidents (counts in the detector's pulse height spectrum) to dose (in pSv; pSv = picosievert) is shown for the two different $CeBr_3$ detectors. The conversion function of the larger crystal is smaller due to the larger volume and hence the higher photon detection efficiency. The detailed description of the used method to convert counts to dose and the performance of the detector system can be found in (5). The inherent background spectra of both detectors were measured at PTB's low background underground laboratory UDO II (6) within a lead castle which reduces the already very low background radiation level of UDO II (1.4 nSv/h) by more than an order of magnitude.

These measurements proved that the inherent background of the $CeBr_3$ crystal is negligible if environmental measurements are performed. With respect to weight (payload) limitations of the small UAV available at PTB, a light-weight photo-multiplier base from Bridgeport was used, including a readout electronics with digital pulse processing. In combination with a Raspberry Pi 3B for the detector control and a "power bar" a continuous operation of the detector system of 6 h is possible. The recorded gamma spectra are stored in an on-board database which facilitates working with the data and allows the retrospective analysis of time series.

In another approach, a rather heavy HPGe detector with electrical cooling system is adapted to a big helicopter drone (maximum payload of about 100 kg). Another group is responsible for equipping a UAV with a source localisation system.

In a later stage of the project, the airborne mapping of activity concentrations using UAV-based light-weight spectrometry systems will be possible. There is a trade-off between measuring time and measuring precision. To be able to map an area with significant spatial resolution, a measuring interval of a few seconds has to be realised. This means that the efficiency of the detector system has to be

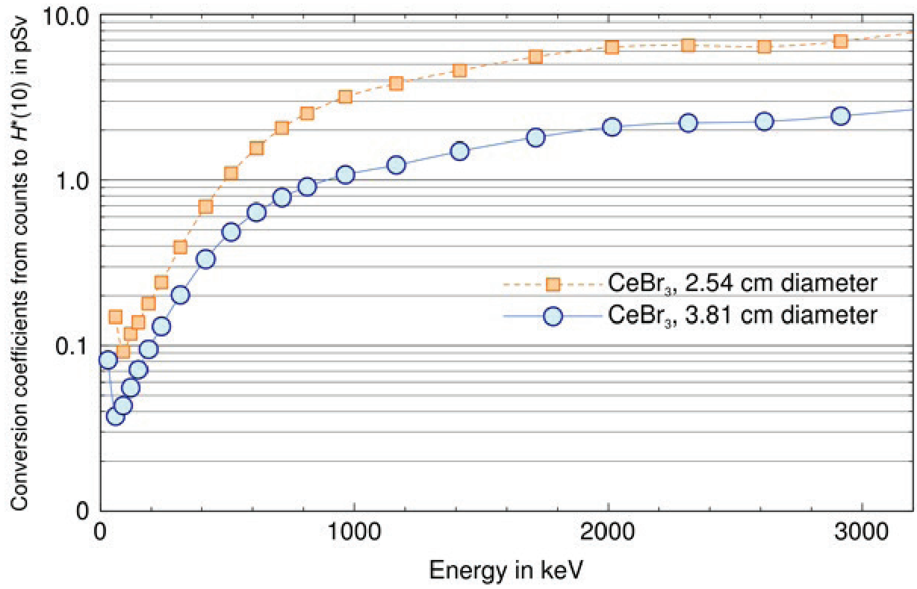

Figure 1 Comparison of the energy-dependent conversion functions of two $CeBr_3$ detector systems comprising of a 2.54 cm x 2.54 cm and a 3.81 cm x 3.82 cm scintillation crystal, respectively, based on simulated spectra calculated with the MC code GEANT 4, including the low-energy Library of EM-Livermore

sufficiently high. Figure 2 shows the results of a test measurement where a detector with a 3.81 x 3.81 cm $CeBr_3$ crystal was irradiated by an uncollimated ^{137}Cs-source. The measuring time of each spectrum was 2 s. In this case of an artificial dose rate of 260 nSv/h, corresponding to a ^{137}Cs-contamination level of about 70 kBq/m^2, the 662 keV line of ^{137}Cs can be easily identified (inset) and the dose rate reference value (red line) can be reproduced well within a range of ±10% as indicated by the red dashed lines. The standard deviation of the mean value of 252 nSv/h is 8%.

Addressing the problems of data acquisition on-board of a UAV, data transmission between the UAV and the ground station and swift and clear data visualisation at the ground station, new software was developed which includes modules for different spectrometry detection systems. The software is called RIMASpec. A proof of concept of this software has been carried out by investigating the ability

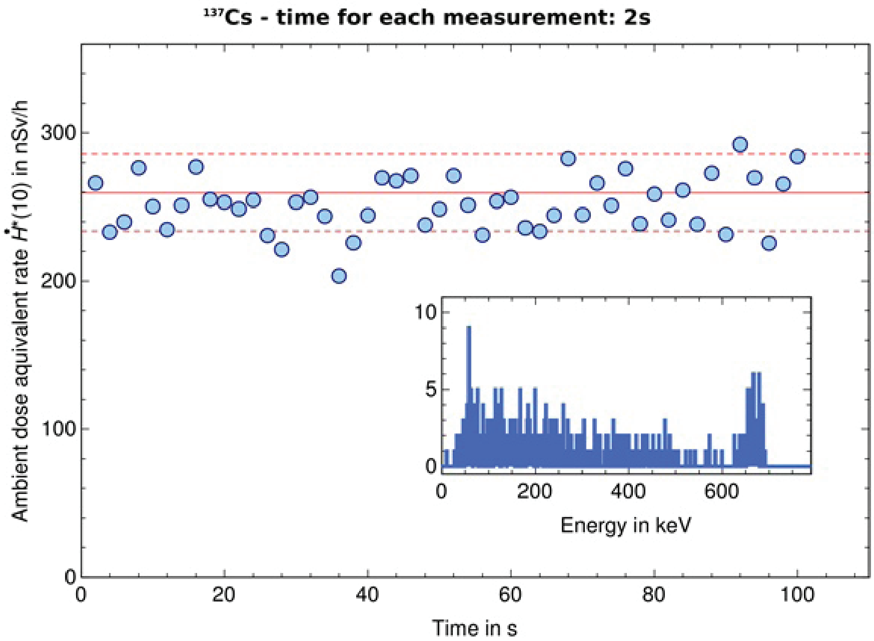

Figure 2 Test results from a measuring campaign on PTB's premises, where an uncollimated free field irradiation facility was operated. This facility can also be used for the simulation of a by-passing radioactive plume (6). The spectra (inset) are recorded every 2 s and the average dose rate during these 2 s is calculated for each spectrum individually. Most measured dose rate values lie in a 10% range around the reference value of 259 nSv/h indicated by the dashed lines

of a CdZnTe detector mounted on a DJI 550 multirotor to detect a ^{99m}Tc source, which was positioned at an aerial site. A complete description of the RIMA-spec software and the results of the test measurement has been compiled and published in (7).

These first results of activities within WP1 "Unmanned aerial detection systems" are very promising. Even a 2 second integration time is sufficient to identify ^{137}Cs as the source of an additional dose rates of 260 nSv/h and the dose rate values derived from the pulse height spectra show only small statistical variations (less than ±10%).

The development of transportable air-sampling systems within WP2 has started only recently. A summary of the previous achievements, within the MetroERM project, is given in (8).

In order to investigate the performance of measuring instruments used in non-governmental dosimetry networks (MINNs), as a central activity of WP3, PTB, ENEA, NPL and VINCA have selected and commissioned a representative variety of MINNs for test purposes and for systematic metrological investigations. The first results of these studies will become available next year and will be published elsewhere. A summary of a first analysis within WP3 was presented during the 3rd European Radiological Protection Research Week by G. Iurlaro et. al.

To analyse the most widespread MINNs in Europe, as a first step, several private companies and non-profit organisations were selected. The techniques used to measure radioactivity and convert raw data to values were investigated. Furthermore, a representative variety of measuring instruments used in each network were selected for test purposes at metrological reference facilities within the consortium. Table 1 shows the selected measuring instruments used in non-governmental networks in Europe.

Within Work Package 4 "Passive dosimetry for environmental radiation monitoring", passive detector systems intended to be deployed for long-term monitoring of contaminated areas in the aftermath of a radiological accident were studied. As a first step, the status of radiation monitoring in Europe using passive detectors was investigated. Within an intercomparison exercise at PTB, basic properties of 38 passive dosimetry systems were tested using different measuring sites. For this purpose, passive area dosimeters were supplied by European measuring services or bodies to be tested under the same irradiation conditions. Four dosemeters of each participant were exposed for 6 months at the reference site for ambient radiation, four other dosimeters were exposed for 6 months at the reference site for cosmic radiation and eight dosimeters were irradiated in a primary ^{137}Cs-photon field of the PTB at two angles. Four transport dosimeters were

Figure 3 Passive dosimeters exposed at the PTB reference site for environmental radiation. Active reference dosimeters are visible in the middle of the site

Table 1 Instruments used in non-governmental networks in Europe selected for test purposes at metrological reference facilities within the consortium

Example of MINN	Supplier	Networks
uRAD Monitor Model A	Magna SCI	uRad Monitor
GMC-600	GQ Electronics	GMC map
bGaiger Nano	Safecast	Safecast
Radalert 100	International Medcom	Radiation Network/Safecast
GMC-320 Plus	GQ Electronics	GMC map / Radmon
GMC-500 Plus	GQ Electronics	GMC map / Radmon
uRAD Monitor model KIT1	Magna SCI	uRad Monitor
Monitor 4 Geiger Count KIT	S.E. International Inc.	Radiation Network
GMC-300 Plus	GQ Electronics	GMC map
RADEX 1212	Quarta-RAD Inc.	GMC map/ RadexRead Radiation Mapping
PMR 7000	Mazur	Radiation Network
Monitor 200	S.E. International Inc.	Radiation Network
uRAD Monitor Model D	Magna SCI	uRad Monitor
MyGeiger ver.3 PRO DIY	RH Electronics	Radmon
Inspector Alert	International Medcom	Radiation Network
Rad 100	International Medcom	Radiation Network/Safecast

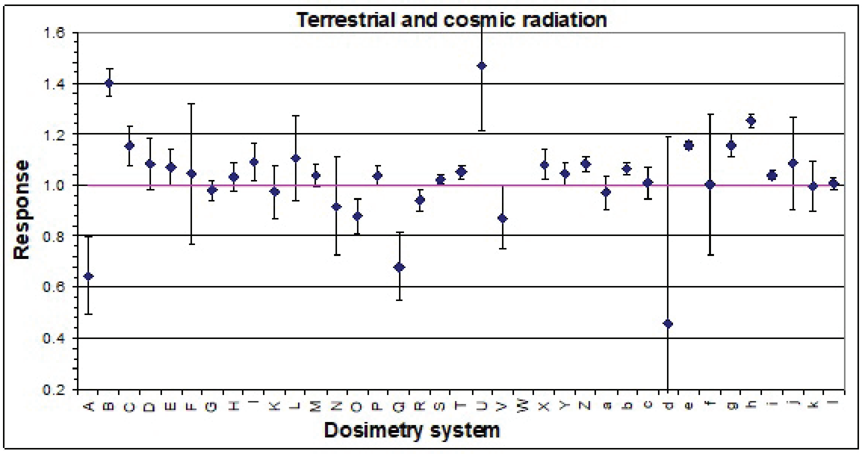

Figure 4 Response of European dosimetry systems to combined terrestrial and cosmic radiation. The ideal response is exactly 1. The dosimeters were exposed for 6 months on the PTB reference measuring site for environmental radiation as shown in Figure 3. The systems (participants) are anonymised. Most systems are based on TLD detectors

stored at UDO II, the underground laboratory of PTB, while the other dosimeters were exposed above ground. In total, 760 passive dosimeters were exposed. PTB supplied reference values independently, which are traceable to the primary standards and which are derived from a set of active detectors permanently run on the free-field site.

Most of the passive dosimetry systems showed results, which are in agreement with the reference values within a ratio of 0.77 to 1.43 (the inverse of a corrections factor of ±30%). In many cases, even a better agreement was found, as shown in Figure 4. However, some systems clearly failed. The results obtained in the PTB irradiation facility reveal information on the home calibration of the participants and the angular dependence of the detector systems. Flat detector holders, actually constructed for personal monitoring, often have a pronounced angular dependence, when exposed in the environment. This may lead to a high uncertainty, when measurements are performed in a surrounding with an inhomogeneous radiation field. A tendency was found to overestimate the contribution of the secondary cosmic radiation to the total dose. This has to be taken into account when the terrestrial component and contamination levels are derived.

All participating institutions were informed about the complete results. If measured data showed significant deviations from the reference values, the involved institutions were notified, in order to allow them to investigate the reasons for their poor results. This intercomparison is 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 reduce their measurement uncertainties.

CONCLUSION

A brief description of the “Preparedness” project and first results are given and regularly updated in its Publishable summary (9). Further information, especially for collaborators and stakeholders, can be found on the project’s website (10).

After the first year of the “Preparedness” project, the first results became available. This paper presents the project, its background, and the main objectives as well as a selection of first and promising results, especially concerning the operation of scintillator-based spectrometry systems on unmanned aerial vehicles in case of a nuclear or radiological event.

Acknowledgements

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