JRP EMPIR 16ENV04: Preparedness

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

Good practice guide on measurement of dose rates and radioactivity concentrations using rotary-wing unmanned aerial detection systems (RWUAS)

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1. Introduction

This guide has been mainly developed based on the experiences gained during the performance of the European EMPIR "Preparedness" project. The guide is focussing on the use by stakeholders and end-users to carry out good practices for mapping dose rates, to localize point sources and to determine specific activity concentrations using airborne detectors mounted on Rotary-Wing Unmanned Aerial Systems (RWUAS).

In order to carry out good practices when performing such measurements, the end-user should take into account different topics that will be discussed in the next sections: i) detector-RWUAS configuration, ii) national regulations and licensed pilots, iii) detector characteristics, iv) RWUAS – ground station data transmission, v) on-line analysis and visualization, vi) post-processing analysis. Activity concentrations and point source localization, vii) flight plans and viii) maintenance and calibration.

2. Detector-RWUAS configuration

It has to be said, there is no optimal detector-RWUAS configuration. A specific configuration has to be customised for each scenario and situation. The end-user should analyse the most probable expected radiological situation in terms of type of radionuclides and dose rates, in order to select the most convenient detector-RWUAS configuration.

In this context, weight and size of the detector should be chosen carefully and mounted properly on a RWUAS, in order to have sufficient endurance to carry out the planned measurements. Since the radionuclides in the scenario are usually unknown, spectrometric detectors that can identify radionuclides are recommended to be mounted on the RWUAS. "Classical" dose rate monitors such as Geiger-Muller (GM) tubes can be used for a fast screening to evaluate the dose rate map for further analysis with spectrometric detectors.

The end-user should be aware that RWUAS with a weight under 25 kg have much less legal restrictions than RWUAS over this weight. However, common RWUAS mainly have a weight under 25 kg.

One important issue of concern is the flight endurance. Based on current RWUAS technology, a flight time of at least 15 minutes is recommended when investigating a certain area. The end-user should consider the characteristics of the batteries, i.e, their capacity, weight and the influence of meteorological conditions such as temperature and humidity. Furthermore, due to the application of RWUAS in emergency situations, the batteries have to be easily replaced with a minimum loss of time between flights and fast recharged in-situ. Therefore, the time needed to recharge the batteries and the number of batteries needed for the surveillance, should also be studied. Finally, the end-user should look into the manufacturer specifications and should verify if the dependence of the RWUAS endurance on the payload is clearly specified.

The RWUAS flight altitude above ground level (a.g.l.) is an important parameter that should be measured with high precision in order to carry out radiological analysis of the soil and ground contaminations and dose rates. The common GPS installed in the RWUAS have not enough precision for a detailed radiological analysis. Therefore, it is strongly recommended to install a system to measure the height precisely. In the EMPIR Preparedness project most of the teams installed a laser altimeter, however other options are also available such as the use of pressure sensors. It should be pointed out that laser altimeters are highly sensitive to obstacles (e.g. trees, bushes,…), present on the ground, which will interfere with the height measurements.

Latitude and longitude are measured by a GPS sensor installed on the RWUAS. The detector can be equipped with its own GPS sensor in order to increase the autonomy of the detection system on the carrier. Furthermore, several GPS sensors can be used simultaneously to increase the precision of the position determination.

The detector, the RWUAS and all auxiliary components are very delicate, so in case flights have to be performed during rainy periods both, the detector and RWUAS should be waterproof.

The use of the RWUAS in extreme meteorological conditions (e.g. high wind speed) are also an important criterion for its selection. Big drones usually can resist stronger winds than smaller ones. The end-user should look at the manufacturer performance specifications and verify which is the maximum wind speed in which the drone is still able to operate properly.

Furthermore, regarding meteorological conditions, the end-user should analyse the operating temperature range at which instruments, batteries and other components, such as the laser, work properly. A good option is to verify that all components perform optimally the range from -10 ^{o}C to +40 ^{o}C.

It is possible to adapt a RWUAS for flying Beyond Visual Line of Sight (BVLOS) by installing collision avoidance systems, either based on computer vision or radar, to avoid any conflict or even worse, a collision by the use. BVLOS are only permitted under special deviation and training of the pilots following the rules specify in each country.

During the EMPIR Preparedness project different detector-RWUAS configurations have been developed and tested:

i) big fuel powered (petrol) RWUAS carrying a HPGe detector (more than 20 kg), which can identify precisely the released radionuclides,
ii) medium size, battery powered RWUAS carrying a 2”x2” NaI scintillator detector of 1.5 kg,
iii) medium size, battery powered RWUAS carrying a 1.5”x1.5” $CeBr_3$ scintillator detector of 1.5 kg,
iv) small size, battery powered RWUAS, carrying a 1”x 1”x 2” CsI scintillator of less than 1 kg,
v) small RWUAS with a light CZT detector and electronics of less than about half a kg for high contaminated areas and complex geometries, e.g. urban area,
vi) small surveillance RWUAS with a light Geiger Muller detector and electronics of approximately half a kg.

A novel configuration that has also been developed in the EMPIR Preparedness project is the installation of a “localizator” detector on the RWUAS. This detector is able to indicate the source position providing the azimuthal and the polar angle. In this case, a gimbal is installed in order to maintain the “localizator” in the vertical position independently of the drone tilt.

Different configurations developed in the EMPIR Preparedness project are shown in fig.1.

Figure 1. Top left: Huge SWISSDRONES SDO 50 drone with an HPGe detector; middle left: small DJI F550 with a CZT 1.5 cm^3 detector; top right: medium DJI Matrice 600 with a NaI 2”x2”; middle center: Medium DJI Matrice 600 UAS and gimbal with a “localizator detector” bottom left: DJI M100 with a 1”x1”x2” CsI (left) and the DJI F550 with a Geiger Muller (right) and bottom right: DJI Matrice 600 with a $CeBr_3$ 1.5”x1.5” detector.

There is no optimal drone-detector configuration. A configuration has to be customised based on each scenario. Therefore, the configuration choice should fit the most common scenarios that are predicted by the (end-) user.

3. Regulations and licensed pilots

Licenced pilots and authorized RWUAS are required for flying drones in European countries, however, at this moment, there are differences in the national regulations. In the EMPIR Preparedness project a table with the main points of the licence requirements for different countries was elaborated and can be consulted. The end-users should have available pilots with the corresponding license and authorized RWUAS in order to guarantee that in an emergency situation the response will be fast enough. In addition, some of the EU member states, for instance Spain, include in their regulatory framework different conditions and limitations on UAS flights in the event of a serious risk, disaster, public calamity or in some emergency operations.

On the other hand, Europe is currently in a period of transition between the regulatory framework of each EU member state and a common European legislation. The European legislation will allow a harmonization of the legislation of the different national regulations and therefore, there will not be these incompatibility situations mentioned above. This process is expected to be carried out during the next year.

The end-users should have available pilots with the corresponding license and authorized RWUAS in order to guarantee that in an emergency situation the response will be fast enough.

4. Detector characteristics

Dose rate monitors and spectrometric detectors that can determine *H**(10) rates are options that are commonly installed on RWUAS. Currently, the recommended option to mount on the RWUAS is a spectrometric detector that can both, calculate the *H**(10) rate and identify radionuclides. Besides the guidelines provided in section 1 regarding size and weight of the detectors, the end-user should consider at least the following characteristics while selecting the most convenient detector: i) spectrum integration time, including dead time, ii) *H**(10) rate calculation, iii) angular response, iv) energy resolution, v) energy calibration, vi) output data and data formats.

Furthermore, as mentioned in section 2, the end-user should take into account the ambient conditions under which the detector should operate, such as temperature, humidity, pressure and, in case of flights during rainy conditions, waterproofness. Furthermore, due to the movements and turbulences during the flights the resistance to vibrations and mechanical shocks should also be considered.

4.1. Spectrum Integration time

In order to carry out airborne measurements using RWUAS, the detector should be able to continuously register spectra at an acquisition rate of at least every 2 seconds, avoiding time between acquired spectra and providing the dead time correction.

4.2 H(10) rate*

The spectrometric detector output should provide the *H**(10) rate. The end-user should have the knowledge on the *H**(10) rate range that the detector is able to provide based on the short integration time of about 2 s and, on the other side when contamination is high, due to detector saturation. Different methods can be used to calculate the *H**(10) rate such as the stripping method and the conversion coefficient method. The manufacturer should provide information on the implemented method, the measured range and the calibration data.

4.3 Angular response

The angular response of the detector should be isotropic, at least in the hemisphere pointing to the ground. It has to be noted that, if the detector response depends on the incident gamma photon angles, the methods to calculate $H^*(10)$ rate will fail. Therefore, it should be verified that the angular response of the detector provided by the manufacturer is isotropic, at least in the mentioned hemisphere.

The angular response can be determined by irradiations in a reference laboratory at different incident angles of gamma photons of different energies. In Fig. 2, the angular response for the NaI 2”x 2” irradiated at the reference laboratory of the Technical University of Catalonia (UPC) is shown. The measurements indicate that the response for the incident gamma photons coming from the front part of the detector is isotropic. However, the response for photons coming from the back is not isotropic (not shown in Fig. 2). This is usually because of shielding caused by the photomultiplier tube and the electronics located in the back compartment. Therefore, it is strongly recommended to point the vertical axes of the detector to the ground.

Figure 2. Experimental relative response of a NaI 2”x2” scintillator at different angles and ^{137}Cs source (90º incident gamma photons in the direction of the vertical axes of the detector)

4.4 Energy resolution

The energy resolution of a detector is usually characterized by the Full Width at Half Maximum (FWHM). The better the resolution of the detector the most suitable it is to identify different radionuclides. Detectors with high resolution such as the HPGe detectors have a very good capacity for radionuclide identification. However, they are very expensive, are heavy in weight and display different operational issues due to the effect of vibrations. These constraints led this type of detectors to have more difficulties to be mounted on a RWUAS than scintillators and Cadmium Zinc Telluride (CZT) semiconductor detectors. On the other hand, scintillators with poor resolution are quite cheap, easy to mount, robust and big enough to have a good photon detection efficiency. Semiconductor detectors made of CZT material have an intermediate resolution, but the manufacturing process of the crystal does not allow to have big crystals and, hence, its detection efficiency is low. A solution that can be adopted is to mount a small CZT semiconductor with a good energy resolution that can work at ambient temperature in order to identify as much radionuclides as possible and a scintillator with a good detection efficiency to quantify them. Both detectors are robust enough to be mounted in a RWUAS.

4.5 Energy calibration

One of the most important issues of concern is the detector energy stabilization due to possible temperature fluctuations during the flight. The fact that the energy calibration changes during the flight would complicate the spectra analysis and, therefore, can lead to mistakes in the radionuclide identification and dose rate calculations. This problem of temperature variation is more significant in scintillators than in semiconductor detectors. Methods to correct the temperature effect should be provided by the manufacturer or developed by the end-user.

During the EMPIR Preparedness project different methods to stabilize the energy have been studied, such as temperature compensation, internal LED, isothermal material covering the detector and the use of known photon energy lines of naturally abundant radionuclides. The experience gained in the project showed that for such relatively short flights and relatively low altitudes, the best option is to cover the detector with isothermal material and to calibrate the detector using at least the 1460 keV gamma line of ^{40}K and the 609 keV of ^{214}Bi in the acquired spectra. If other gamma lines are clearly shown in the summed spectra, such as the 2615 keV from ^{208}Tl or even from artificial radionuclides (e.g. ^{60}Co, ^{137}Cs,…), they can also be used for the determination of the coefficients of the energy calibration curve.

4.6 Output data and data format

The acquired data by the detector are most of the time sent to a microprocessor in order to carry out the on-board data treatment and to prepare them to be sent to the ground station. The end-user should consider the compatibility between the output data from the detector with the microprocessor input throughout the corresponding cable and the installed software.

The acquired telemetry data from the RWUAS, such as timestamp, longitude, latitude and altitude should be merged with the radiological acquired data. It is also recommended that speed and the rotation angles (yaw, pitch and roll) are also merged. Longitude and latitude can be obtained from a tracking GPS system, however the altitude provided by such a system has not enough precision for performing precise radiological calculations. Therefore, an alternative system should be installed such as a laser altimeter or an altimeter base on barometric pressure, to provide a better measurement of the altitude. The acquired merged data should be provided in a standard format such as *.n42 or similar that can be used with most of the software for spectra analysis.

Besides the size and weight of the detector, the end-user should consider at least the following characteristics to select the detector: i) spectrum integration time, including dead time, ii) $H^*(10)$ rate calculation, iii) angular response, iv) energy resolution, v) energy calibration and vi) output data and data formats.

5. RWUAS – ground station data transmission

The data transmission between the aircraft and the ground station should be reliable and fast enough to get the correct information in time.

Currently the 4G/5G seems to be the easiest way for long range communications between the RWUAS and the ground station. However, the user should take into consideration that the flight surveillance area could have bad 4G/5G coverage, so the use of Wi-

Fi or point to point radiofrequency communication should also be considered as an alternative option.

The air-ground communication with the onboard computer could be performed through private radio networks using serial radio modems for low throughput and low latency communications, while high throughput short-range communications could be performed through the Wi-Fi network by means of an IEEE 802.11 compatible board. For high/medium throughput and long-range communications, a 3G/4G compatible modem which provides connectivity to the internet is commonly used.

However, in the event of an emergency situation, the 3G/4G communication network could be not operational and therefore it will be necessary to use other technologies such as private radio networks. The use of private radio networks using serial radio modems allows a communication range of a few km; the communication range depends on the use of a tracker antenna or antennas with a certain gain and the increased transmission power achieved by that.

> The user should analyse the necessities on data transmission and consider different options: 3G/4G/5G, Wi-Fi and radiofrequency.

6. On-line analysis and visualization

It is strongly recommended that the detection system mounted on the RWUAS is provided with a software that at least visualizes on-line the *H*(10)* rates map, accompanied by a “waterfall plot” (a three-dimensional diagram, containing simultaneously a time serious of spectra. The third dimension, i.e. the content of each channel of the spectrum, is achieved by visualizing different count rates by a colour code; for an example of a waterfall plot see Fig.

3) for nuclide identification. Additional information such as artificial count rate and energy spectra, can also be provided.

In order to show the $H^*(10)$ rates in a map, different options are possible such as i) map of the measured $H^*(10)$ rates, ii) map of $H^*(10)$ rates at a reference altitude of 1 m, and iii) map of the corrected background $H^*(10)$ rates. The first option has the problem that for the same contaminated area different $H^*(10)$ rates will be produce depending on the altitude a.g.l. Therefore, knowing the mathematical expression to convert the measured $H^*(10)$ rates to the reference altitude of 1 m a.g.l. would be an unambiguous and, hence, a more appropriate information for decision-makers. However, the mathematical expression to be applied depends on the geometry of the source. Because this is usually not possible a priori, the map of $H^*(10)$ rates at 1 m can be visualized assuming a homogenous surface contamination or a uniform distributed source in the ground. In case of an increase in the $H^*(10)$ rate, this will be clearly seen in the map. The actual $H^*(10)$ rates at 1 m a.g.l. should be recalculated/re-evaluated in the post-processing phase, once the geometry of the source is better defined. Regarding the third map type of corrected background $H^*(10)$ rates, it is necessary to know the background $H^*(10)$ rates in the area of investigation at different altitudes in order to subtract it from the actual measured values. Since the latter is normally not possible, measurements in a non-contaminated area close to the contaminated one can be carried out to estimate these background $H^*(10)$ rates. In the EMPIR Preparedness project a measurement campaign was carried out at the Mollerusa Aerial Site (Lleida, Spain) to evaluate the mentioned methods. The results will be described in a paper that is going to be submitted to a peer-review Journal in July 2020.

During the on-line visualization, the waterfall plot is a tool that is useful to identify gamma lines and, therefore, useful to decide rapidly if there is artificial contamination present. In the upper left part of the screenshot in Fig. 3, the on-line waterfall plot is shown. A more complete analysis of the acquired spectra is usually done in the post-processing phase.

The presence of artificial radionuclides can also be analysed by the so-called Man Made Gross Count (MMGC) method. It is a very fast and easy methodology to identify whether or not artificial radionuclides are present in the spectrum. In the above-mentioned measurement campaign results achieved by the MMGC method are analysed.

In Fig. 3 a screenshot of the on-line visualization tool provided by the RIMA-spec software developed by the UPC team in the framework of the EMPIR Preparedness project is shown. On the figure the software displays the “heat map” of the measured count rates (the conversion of count rates into a colour code: high count rates correspond to the colour red, representing a high intensity or “heat”), the waterfall plot and the energy spectra. Also, other telemetry data provided by the RWUAS, i.e., latitude, longitude, altitude, speed and rotational angles are shown.

Due to the short acquisition time of the spectra (usually about 2 seconds) it is complicated to analyse them due to the low number of counts per energy bin. Therefore, it is useful to have the possibility to visualise spectra in relation to the location in the heat maps and to sum them for a specify selected sub-region. In the summed spectrum the analysis of the radionuclide identification has much better statistics than in the 2 seconds spectra. Also, energy calibration can be done using these summed spectra.

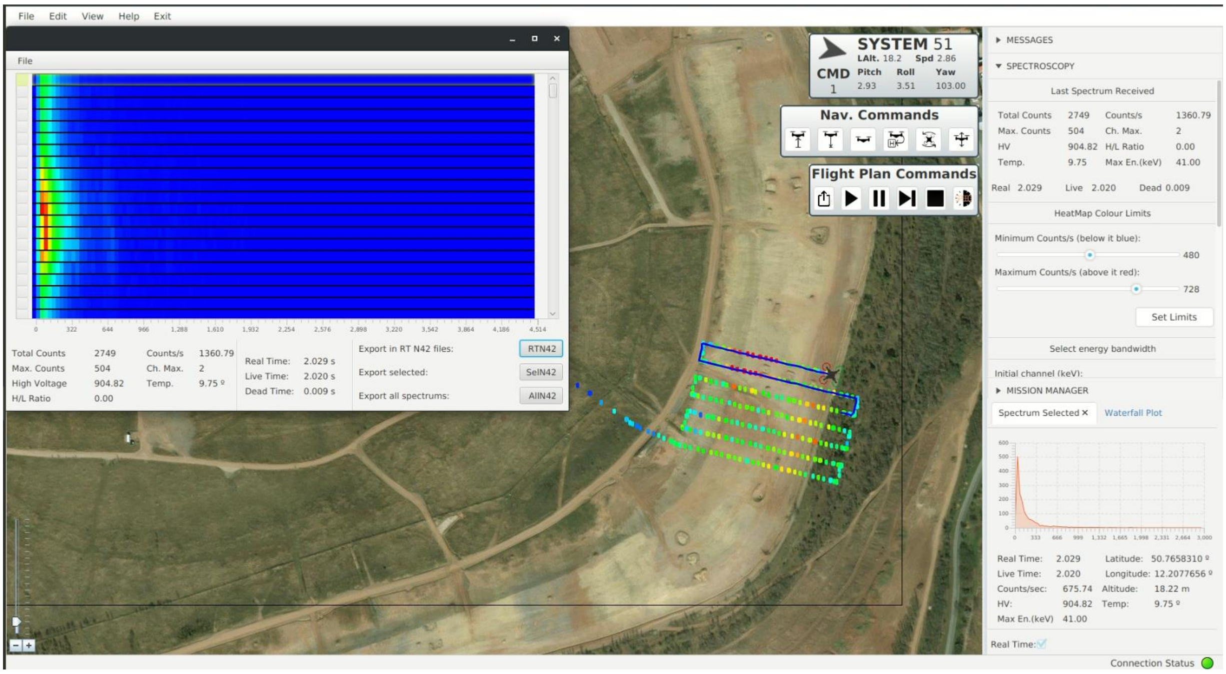

Figure 3. RIMA-spec software ground station visualization.

The detection system should be provided with a software to visualize timely *H*(10)* rates map at a reference altitude of 1 m or background subtracted, preferably combined with a waterfall plot. Additional information can also be provided such as artificial count rate and energy spectra.

7. Post-processing analysis. Activity concentrations and point source localization

A more detailed analysis of the acquired data can be carried out after the flight using more complex algorithms. For instance, one easy option to improve the radionuclide analysis is to sum spectra of a selected region of an area of interest to have better statistics and, then, carry out the analysis of this spectrum with common gamma-spectrum analysis codes.

In the EMPIR Preparedness project, it was pointed out that the Full Spectra Analysis (FSA) is a promising technique for the spectra analysis in airborne measurements using RWUAS due to the low number of counts. Fig. 4 displays an example of a measurement in the former Uranium mine at Seelingstädt (Germany) in combination with ^{137}Cs and ^{60}Co measurements originating from hidden artificial sources. The spectrum from both natural and artificial radionuclides is compared with a simulated spectrum from a uniform radionuclide distribution of ^{214}Bi, ^{214}Pb, ^{40}K and ^{208}Tl in the soil, and point sources for ^{137}Cs and ^{60}Co.

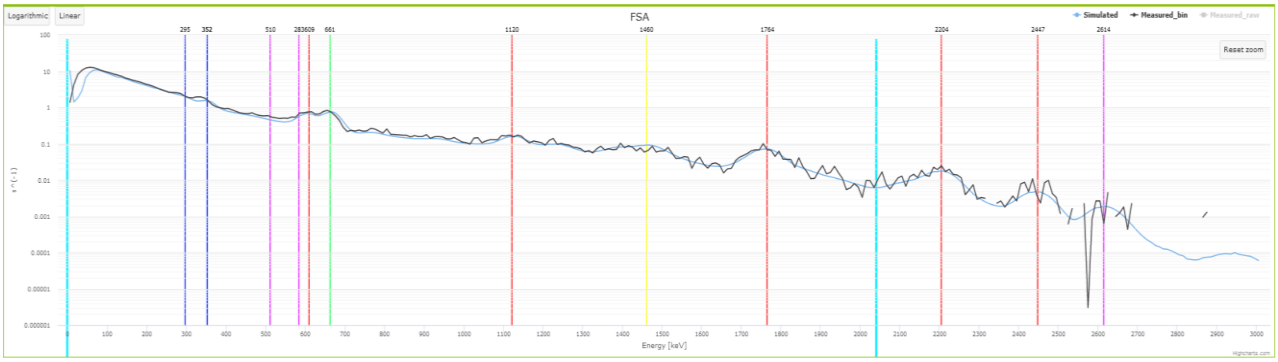

Figure 4. Measured count rate in former Uranium mines at Seelingstädt (Germany) and simulated spectra to determine the radionuclide activities using FSA. The altitude of the measurements was 20 m a.g.l., the speed of the drone 2.8 m s^{-1} and the spectrum the total integration time was 44 s.

Determination of the point source location is a specific topic in radiological airborne measurements. The process to locate a source, using airborne spectrometric detectors, is based on the measured radiation intensity at different positions of the detector relative to the source. Some methods to locate point sources are: recursive non-linear least squares optimization algorithms, maximum likelihood estimator algorithms and the mapping localization method. In the EMPIR Preparedness project a method based on an evolution algorithm has been developed and tested in real flights with a ^{137}Cs point source in the measurement campaign at Mollerussa aerial site. The method takes only a few seconds to calculate the position of the source with an uncertainty of about half a meter for a flight at 20 m altitude, speed of 2 m s^{-1} and a point source activity of 346 MBq. The description of the methods will be shown in the publication of the results of the measurement campaign carried out in the framework of the EMPIR project. In case that more than one point source is present, the end-user should take into account that the detected photons are originating from different sources. Consequently, the location methodology becomes more complex. Another issue that complicates the localization of a source is the variation of the natural background activity. This has been observed in the EMPIR Preparedness project during the measurement campaign carried out in former Uranium mines.

As described in the “detector-RWUAS configuration” section, a “localizator” detector was mounted on a RWUAS using a gimbal. The detector can localize the position of a source when the increment of the $H^*(10)$ rate is about 20 % over the background. The detector provides the azimuthal and polar angles of the direction where the source is located. In combination with the yaw of the RWUAS and the measured altitude, this enables to calculate the position of the source. Once the source is detected, the flight plan of the RWUAS is modified in order to go to the source position. The procedure has been implemented in the Rima-Spec software developed by the UPC in collaboration with IJS. The system has been tested in real flights with a point ^{137}Cs source of 346 MBq. In figure 5, a screenshot of Rima-Spec using the “localizator” is shown.

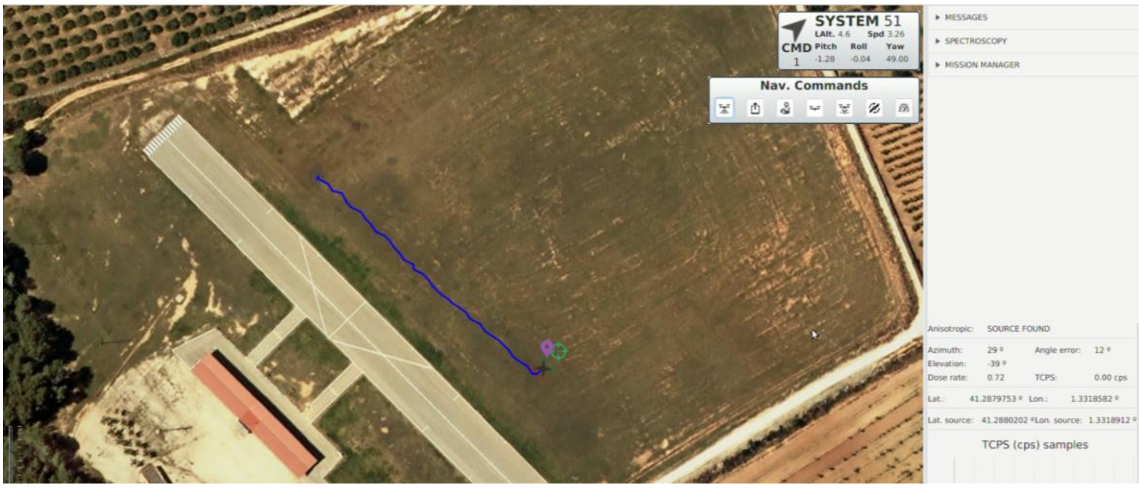

Figure 5. Screenshot of Rima-Spec on-line visualization used with a localizator detector. Violet dot is where the detection system locates the source and the green dot is where the RWUAS goes to.

A more detailed analysis of the acquired data can be carried out after the flight with more complex algorithms. For instance, Full Spectra Analysis (FSA) is a promising technique for spectra analysis in airborne measurements using RUWAS. For point source location also post-processing analysis is needed, unless a "localizator" detector is mounted on the RWUAS.

8. Flight Plans

Before starting a flight, the main objective of the mission should be clearly defined. Two main objectives can be identified: i) *H**(10) rates and radionuclide activity mapping and ii) source localization. During mapping *H**(10) rates and radionuclide activities one tries to find out areas with radiological risk. In case the objective is source localization one intends to localise and identify an individual radioactive source, including its activity.

Once the objective is defined, a flight plan is designed in order to cover the area of investigation. The flight plan could be composed of parallel, spiral or even random trajectories. For mapping dose rates or the determination of soil activities, parallel or spiral trajectories are recommended. For source location, random trajectories can also be used.

The altitude a.g.l. of the flight is an important parameter that should be measured with precision to calculate the dose rates and activities concentrations. We recommend an altitude a.g.l. of about 40 m, to avoid crashes with obstacle such as electric lines and trees. However, the selected altitude is highly dependent on the complexity of the zones. In urban or industrial areas higher altitudes are recommended, where above meadows lower altitudes can be used. Therefore, the end-user should decide if the altitude should be higher to avoid obstacles or even to have a wider study area or decide to fly at lower altitudes to have a better resolution and to detect sources with lower activities. As a rule of thumb, the distance between lines for parallel trajectories could be about 1 to 2 times the altitude.

The flight plan has to be introduced in the auto pilot system of the RWUAS. Recommended speed velocities of RWUAS are between 2 $m\ s^{-1}$ and 10 $m\ s^{-1}$ and altitudes from 10 m to 100 m (depending on the regulations in each country).

In order to carry out a flight, at least a RWUAS pilot in command and a radiological expert for the first analysis of the results are at least needed. Furthermore, it is also useful that after evaluation data are sent on-line to the decision-makers centre to follow the radiological status. This can be easily done by sending the information to a server.

> The flight plan should be clearly defined by the end-user according to the scenario. For the flights it is recommended that at least a RWUAS pilot and a radiological expert for the first analysis is available on site. After evaluation data are sent to the decision-makers centre to follow the radiological status on-line.

9. Maintenance and calibration

The end user should calibrate the detector mounted on the RWUAS periodically and keep the system operational so it can be deployed in case of an emergency. Furthermore, the pilot, radiological experts and decision makers should be involved in periodical exercises and measurement campaigns to be prepared in case of a radiological accident.

9.1. Detector calibration

9.1.1. *Internal background*

It is recommended to determine the internal contamination of both, the detector and the RWUAS. The influence of the RWUAS internal contamination to the detector measurements is usually not significant due to the low inherent radioactivity of the construction material and its small size. However, care should be taken if the RWUAS flight into a radioactive cloud since it can be contaminated by deposited radioactive particles that can lead to incorrect contamination results. In the same context, in order to protect the detector from being contaminated it is recommended to cover it with a thin plastic foil or similar material and replace it in case the RWUAS has flown through a radioactive cloud.

Some detection material of some devices have a significant internal background. This is for instance the case for $LaBr_3$ scintillators. Due to the fact that the background contribution in the measured spectra is constant, and independent on the altitude, it has the advantage that it can be used to determine the energy calibration curve of the detector. However, this high internal background has a negative effect on the detection limit of the detector.

The internal background can be determined by carrying out measurements in underground laboratories with very low background radiation, e.g. the low-dose rate underground laboratory UDO of PTB. The manufacturer should provide information about the internal background of the detector. No information is available on the possible influence of the RWUAS internal background to the detector measurements. However, as mentioned previously, it is expected that common RWUAS will have no significant influence on the spectra measured by the detector as has been shown in the EMPIR Preparedness project using Monte Carlo simulations.

9.1.2. *Response to secondary cosmic radiation and to radiation originating from radon progeny*

It is recommended to characterize the response of the detector due to secondary cosmic radiation (mainly high energetic muons and electrons). This can be done by measurements over a water area far away of the coast to avoid the influence of the terrestrial component and the radon progeny concentration in air. It has been determined that influence of the cosmic radiation to common spectrometric detectors of 2”x 2” and 3”x 3” size, and for an altitude close to the see water level is between 5 nSv h^{-1} and 10 nSv h^{-1}. In Fig. 6, a spectrum acquired by a NaI 2”x2” above a lake is shown. The peak in the 609 keV could be due to the radon concentration in air. The $H^*(10)$ value calculated from this spectrum corresponds to 7 nSv/h.

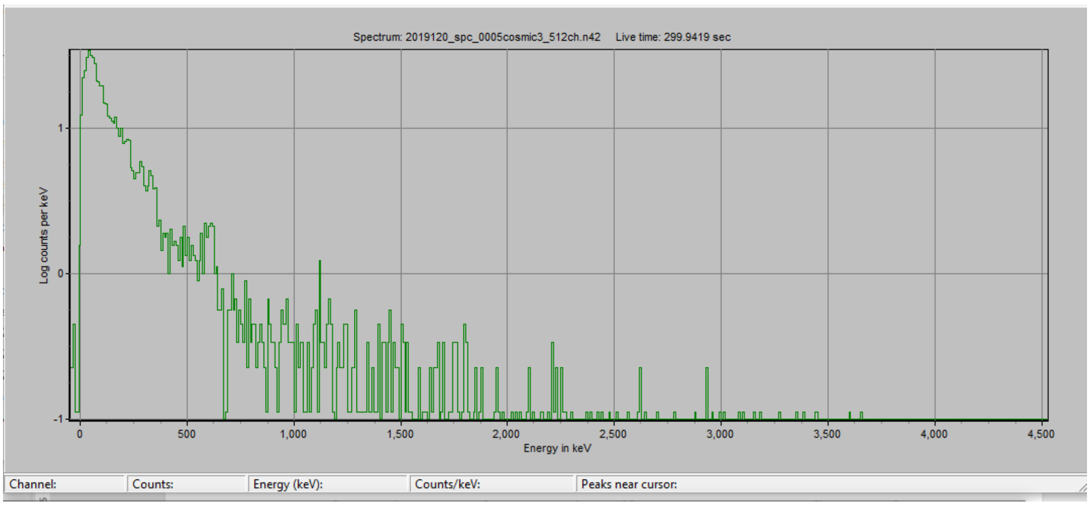

Figure 6. Spectrum acquired by a NaI 2”x2” at Banyoles lake (Barcelona, Spain).

Since the flight altitude using RWUAS is between 10 m and a maximum of about 100 m, the contribution of the secondary cosmic radiation on the detector will be practically constant during the flight. An easy way to estimate the terrestrial *H**(10) rate is to subtract this constant value caused by cosmic radiation from the measured *H**(10) rate.

The radon progeny concentration in air can have some influence on the measured spectra as can be seen in Fig. 6. As a rule of thumb, a radon concentration in air in equilibrium with its progeny (i.e. the daughter nuclides in the radon decay chain) of 10 Bq m^{-3} leads to an increase in the *H**(10) rate of about 2 nSv h^{-1}. This is not a crucial issue, but the end-user should know that the *H*(10)* rate can change by a few $nSvh^{-1}$ due to the influence of radon progeny concentrations in air. The response of the detector to radon progeny concentrations can be determined by Monte Carlo simulations. If radon concentrations need to be considered in the data analysis, it is recommended that also radon measurements are carried out at the ground level close of the measured area. A study of the influence of radon progeny to a 2”x2” NaI detector has been carried out in the EMPIR Preparedness project.

As indicated above, the contribution to *H**(10) rates due to typical concentrations of radon progeny in air are only a few nSv h^{-1} and, therefore, usually not important to be considered for these calculations. However, radon progeny concentrations can interfere with the measurements, when natural activity concentrations in soil are calculated. For instance, the determination of uranium concentration can be compromised when calculations are based on equilibrium conditions of ^{214}Bi concentration in the soil.

9.1.3. *Response to gamma fluence rate*

The response of the detector to incident gamma photons per unit area should be provided by the manufacturer at different energies, i.e., the detected counts per second (cps) per unit fluence rate or detector efficiency at different energies (unit: cm^2). In order to determine this efficiency, the detector is exposed to different gamma sources in a reference laboratory. Furthermore, these measured spectra can be used as bench mark experiments to validate Monte Carlo simulations. The efficiency curve for all energies can then be completed by Monte Carlo simulations. In Fig. 7 the efficiency curve obtained with Monte Carlo simulations for a NaI 2”x2” detector is shown.

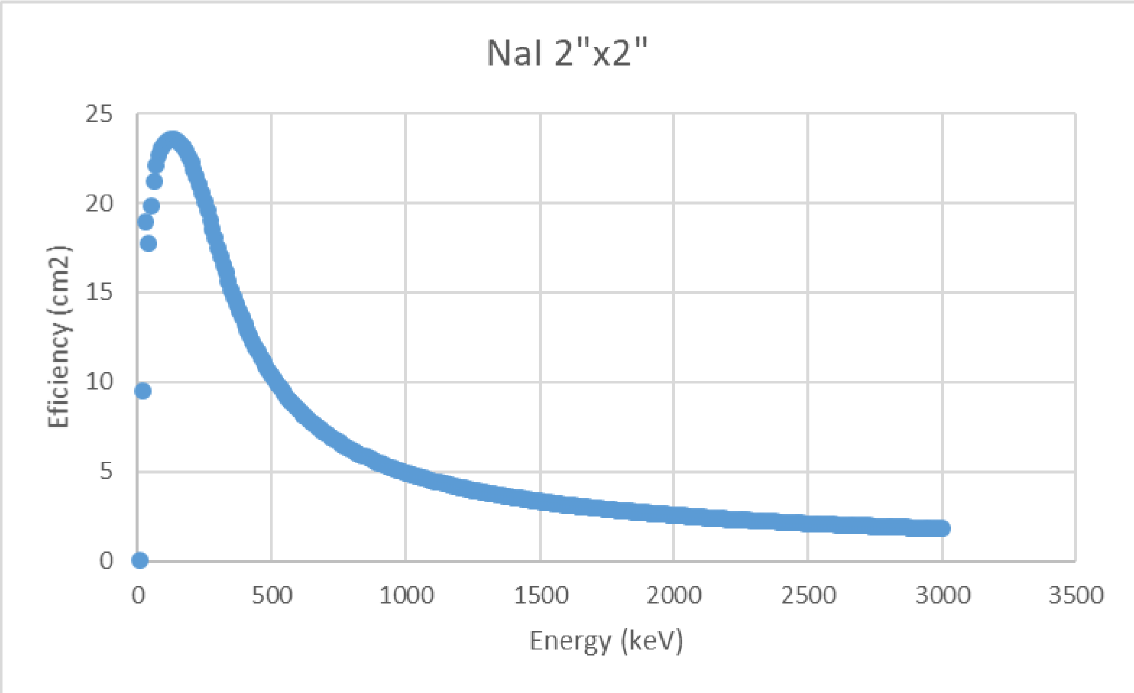

Figure 7. Efficiency per unit fluence rate obtained with Monte Carlo simulations for a NaI 2”x2” expressed in cm^2.

9.2. Background response during flights

Measurements at different altitudes from 10 m to 100 m are recommended close to the area of interest in order to determine the detector response to background and its dependence with the altitude. For instance, in Fig. 8, the dependence with altitude during the measurement campaign in the EMPIR Preparedness project carried out at Mollerussa Aerial Site (Lleida, Spain) for different scintillator detectors is shown. *H**(10) rates were calculated conversion coefficient method. Corrections due to secondary cosmic radiation and radon progeny concentrations were not taken into account in these calculations.

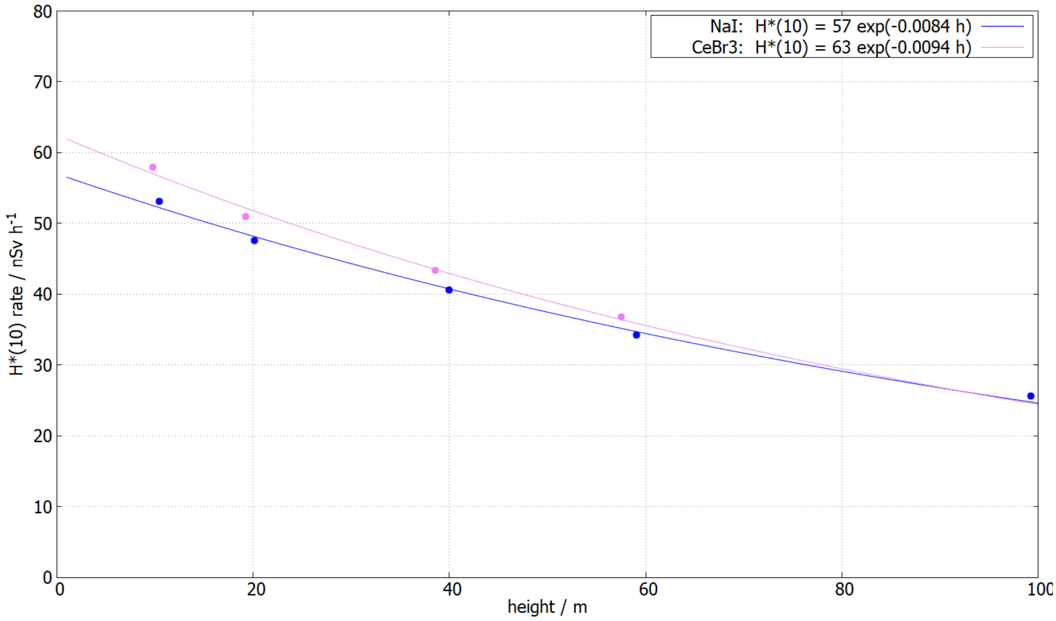

Figure 8. H(10)* rate at different altitudes using the summed spectra. Exponential functions are fitted for the different scintillator detectors.

9.3. Response to artificial point sources

The determination of the response of the detector due to point sources at different altitudes from 10 m to 100 m is recommended. The net count rate and also the *H**(10) rates due to the ^{137}Cs point source at different altitudes can be determined during experimental flights above a source. In table 1, the H*(10) rates in the aerial site of Mollerusa over a ^{137}Cs point source with an activity of 346 MBq for different detectors are shown.

Table 1. Measured *H**(10) rates with the ^{137}Cs point source, background *H**(10) rates and ^{137}Cs point source contribution to the *H**(10) at different altitudes a.g.l. for the three different detectors (NaI/$CeBr_3$/CZT

$h_{nominal}$ (m)	Measured *H**(10) ($nSv\ h^{-1}$)	BG *H**(10) ($nSv\ h^{-1}$)	^{137}Cs point source contribution to the *H**(10) ($nSv\ h^{-1}$)
10	364/ 439/387	53/57/69	311/382/318
20	125/144/163	48/52/63	77/92/100
40	57/64/81	41/44/52	16/20/29
60	42/45/62	35/36/43	7.2/8.7/19

Furthermore, flights over a point source according to a defined flight plan are recommended to calibrate the response of the detector. Flight altitudes can range from 10 m to 100 m depending on the intensity of the source and RWUAS speed (ranging between 2 m s^{-1} and 10 m s^{-1}). In Fig. 9, the *H**(10) rate map for a flight over a ^{137}Cs point source of 346 MBq at 20 m altitude and 3 m s^{-1} is shown.

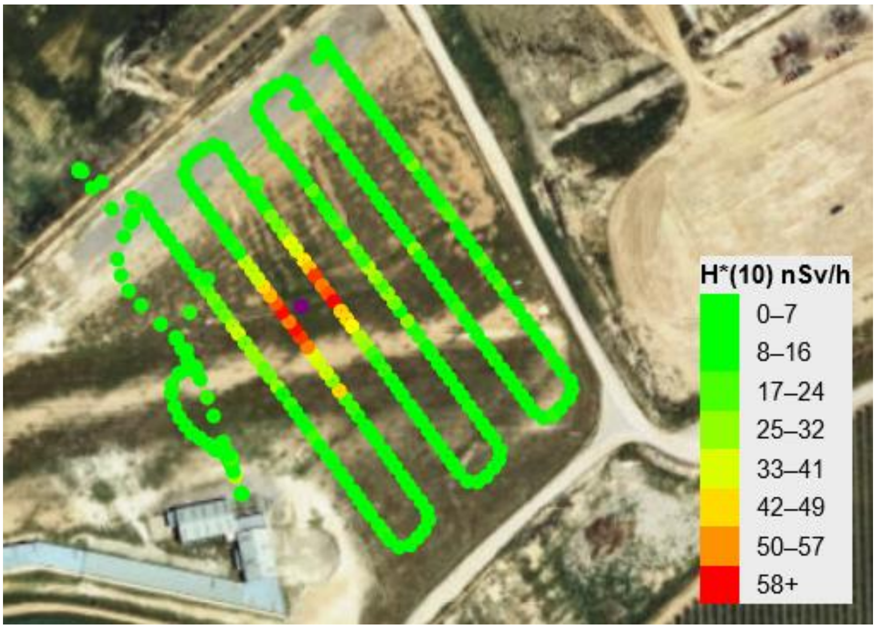

Figure 9. *H**(10) rate map of a 2"X2" NaI detector mounted on a RWUAS, flying over a ^{137}Cs point source of 346 MBq at 20 m altitude a.g.l. with a horizontal velocity of approximately 3 m s^{-1}. The calculated location of the source is indicated by a violet dot.

The pilot, radiological experts and decision makers should be involved in periodical exercises and measurements campaigns to be prepared in case of a radiological accident.

Calibration procedures should be carried out by the end user during measurement campaigns at aerial sites to validate the measurements and the calculation of dose rates at a reference altitude, the localization of a point source and of activity concentrations in the soil.

10. Summary

1. There is no optimal drone-detector configuration. The choice of a specific configuration depends on the radiological situation and the assessment of the overall scenario. Therefore, the selection of this configuration should fit the most common scenarios that are previously forecasted by the end-user.

2. The end-users should have available pilots with the corresponding license and authorized RWUAS in order to guarantee a fast response in case of a nuclear or radiological emergency.

3. Besides the size and weight of the detector, the end-user should consider at least the following characteristics to select the detector: i) spectrum integration time, including dead time, ii) $H^*(10)$ rate calculation, iii) angular response, iv) energy resolution, v) energy calibration and vi) output data and data formats.

4. The user should analyse the necessities on data transmission and consider different options such as 3G/4G/5G, Wi-Fi and radiofrequency.

5. The detection system should be provided with a software to visualize timely $H^*(10)$ rates by an appropriate mapping at a reference altitude of 1 m a.g.l. or background subtracted, preferably combined with a waterfall plot of the measured spectra. Additional information can also be provided such as artificial count rates and energy spectra.

6. A more detailed analysis of the acquired data can be carried out after the flight with software programmes with more complex algorithms. For instance, Full Spectra Analysis (FSA) is a promising technique for the spectra analysis in airborne

measurements using RWUAS. Point source location also usually needs post-processing analysis unless a “localizator” detector is mounted in the RWUAS.

7. The flight plan should be clearly defined by the end-user according to the scenario. For the flights it is recommended that at least a RWUAS pilot and a radiological expert for the first data analysis are available. After evaluation data are sent to the decision-makers centre to follow the radiological status on-line.
8. The pilot, radiological experts and decision makers should be involved in periodical exercises and measurements campaigns to be prepared in case of a radiological accident.
9. Calibration procedures should be carried out by the end user during measurement campaigns at aerial sites to validate the measurements and the calculations of dose rate at a reference altitude, localization of a point source and activity concentrations in soil.