

ARTICLE

Use of a drone-based gamma-ray spectrometry system to assess point or extended radioactive sources

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Abstract – In recent times, the utilization of unmanned aerial vehicles (UAVs) has emerged as a novel tool for a wide range of tasks associated with radiological protection in hazardous situations. This article presents the development of a rotary-wing drone-based system equipped with a LaBr₃(Ce) detector, enabling highly accurate quantification of both point and extended radiation sources. The drone's capability to precisely measure H*(10) and the activity levels of the involved radionuclides has been assessed through real-world testing in two scenarios. The results demonstrate uncertainties of less than 20%.

Keywords: Environmental assessment / dose equivalent / scintillation detector / spectrometry gamma / TENORM

Résumé – Utilisation d'un système de spectrométrie gamma par drone pour évaluer les sources radioactives ponctuelles ou étendues. Récemment, l'utilisation de véhicules aériens sans pilote (UAV) est apparue comme un nouvel outil pour un large éventail de tâches associées à la protection radiologique dans des situations dangereuses. Cet article présente le développement d'un système basé sur un drone à voilure tournante équipé d'un détecteur LaBr₃(Ce), permettant une quantification très précise des sources de rayonnement ponctuelles et étendues. La capacité du drone à mesurer précisément H*(10) et les niveaux d'activité des radionucléides concernés a été évaluée par des essais en conditions réelles dans deux scénarios. Les résultats démontrent des incertitudes inférieures à 20 %.

Mots clés : évaluation environnementale / équivalent de dose / détecteur à scintillation / spectrométrie gamma / TENORM

1 Introduction

When working with radioactive materials, there are many planned or emergency situations in which radioactive sources, whose activities may cause high radiation doses in their surroundings, must be located, identified and characterised. These operations must be carried out with minimum exposure to the technical personnel responsible for carrying them out. Recent technological developments have made it possible to locate the radioactive source to be evaluated from a distance, so that these operations can be carried out without exposing the personnel involved to any risk of radiation. The use of remotely operated vehicles equipped with ionising radiation monitors allows many of the tasks associated with radiological protection in general and the management of radiological emergencies in particular to be carried out while ensuring the safety of the operators.

Particularly noteworthy in this context is the relatively recent use of unmanned aerial vehicles (UAVs) (Pöllänen *et al.*, 2009; Towler *et al.*, 2012; Sanada *et al.*, 2015; Vale *et al.*, 2017; Bednář *et al.*, 2021). The works of Chen *et al.* (2020) and Lee *et al.* (2019) stand out for their in-depth analysis of the state of the art in the use of UAVs and the types of detectors depending on the mission objectives for which these systems are used.

After the Fukushima accident, the usefulness of UAVs for the characterisation of areas potentially affected by the disaster was demonstrated, particularly in areas where the deposited artificial radionuclide activity significantly exceeded the environmental background (Falciglia *et al.*, 2018). However, in areas where the activity levels of the radionuclides to be studied were of the order of the environmental background, the use of UAVs and low-efficiency scintillators (CZT, CsI(Tl), etc...) was more limited (Falciglia *et al.*, 2018; Pinto *et al.*, 2021; Katreiner *et al.*, 2022). In this regard, there have been fewer works focused on mapping areas with subtle radiological anomalies. For example, the work of Šálek *et al.*, (2018)

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focused on mapping an area with significant U concentrations, using a mini-airborne equipment based on two BGO detectors. In addition, the study by Ji *et al.* (2019) focused on the use of LaBr₃(Ce) in airborne gamma-ray spectrometry using a drone to assess dose rates at diverse flight altitudes but did not provide information about the quantification of radionuclide concentration in the soil. To solve this lack of information, it is also important to highlight the recent work carried out by Rusnák *et al.* (2023) within the framework of the European Metrology Program for Innovation and Research (EMPIR), where they describe the development of a high-capacity (autonomy and payload) UAV equipped with a High-Purity Germanium (HPGe) detector.

Depending on the goal for which the UAV is to be used, it is necessary to find a balance between the capacity of the UAV, the type of radiation detector and the desired sensitivity and accuracy of the measurement. It is not possible to develop a generic UAV for all types of missions. One of the objectives of this work is to develop a rotary-wing UAV focused on the identification and quantification of both point and extended sources. With regard to extended sources, the purpose of the UAV developed in this work is to characterise areas of radiological anomalies in order to produce radiological maps of the environmental equivalent dose rate and to quantify the activity of the radionuclides present in specific places. All of this is framed within the framework of the actions of a radiological emergency.

2 Material and methods

2.1 Description of the rotatory-wing UAV

Using rotatory-wing UAVs (hereinafter drone) to accurately locate, identify and characterise radioactive sources in near-real time is a twofold challenge. To further optimise drone-based radiation sensing systems for another application, it is necessary to combine the appropriate drone and sensor components by understanding their nature, physics and advantages and disadvantages in the context of a mission's goals.

The drone selected for the study is an octocopter FPV8. Its main characteristics are: an average flight time of 20–30 min, automatic take-off and landing, automatic position maintenance, return home on signal loss, automatic route programming *via* GPS, an integrated camera with near real-time image recording and transmission, and a load capacity of 5 kg.

Depending on the type of measurement to be conducted, the detectors should be chosen carefully. In general, scintillation detectors with low resolution, such as CsI(Tl), are most suitable for detecting orphan sources, as detailed in Baeza *et al.* (2018). However, when accurate quantification of the activity of a radioactive source, whether it is an extended source or a point source, is required, LaBr₃(Ce) or NaI(Tl) detectors are more suitable. For this study, a LaBr₃(Ce) detector with a volume of 43.3 cm³ has been selected.

Each radiological measurement is associated with a GPS position provided by a GPS receiver. The management of the different devices installed on the drone and the data they provide are carried out by home-made software applications developed in different programming languages (Python, C++ and Wiring).

To ensure effective operation of the designed system with *in situ* and real-time detection, communication between the drone, its instruments, the operator, and decision-making centres is crucial. Two communication channels have been implemented, selected based on the radio-electrical environment during flight: a) Internet communication *via* 4G USB modem. b) Communication *via* LoRaWANTM technology, utilising 868 or 900 MHz frequency bands. This enables efficient communication while keeping the payload low.

2.2 Efficiency calibration

In order to calculate the activity of a radioactive source, it is essential to know the detection efficiency of the gamma detector used. The efficiency calibration of two source geometries has been implemented: a point source and an extensive homogeneous plane source.

In the case of a point source, the detection efficiency, ϵ , was determined experimentally by measuring different radioactive point sources (¹⁵²Eu, ¹³⁷Cs and ²⁴¹Am) of known activity placed at a distance of m from the detector, coinciding with its axis. The value of the efficiency is obtained by fitting the experimental measurements to the expression:

$$\epsilon = \frac{N}{A_{\text{source}} \times p(E)}, \quad (1)$$

where N is the area gross counts of the photopeak of interest per unit time recorded at the detector (cps) for each source, A_{source} is the decay corrected source activity, and $p(E)$ is the emission probability for the measured photopeak.

Assuming that the geometry of the source can be assimilated to a flat and homogeneous infinite surface, the detection efficiency is determined semi-empirically. The components involved in this calculation are the gross count for a given energy, the photon flux reaching the detector and the activity of the source, as proposed by Beck *et al.* (1972) and detailed in ICRU report n° 53 (ICRU, 1994) *i.e.*:

$$\frac{N}{A_x} = \left(\frac{N}{N_0} \right) \left(\frac{N_0}{\phi} \right) \left(\frac{\phi}{A_x} \right), \quad (2)$$

Where $\frac{N}{A_x}$ are the gross counts registered under the photopeak for each energy E_i , depending on the concentration existing in the source, *i.e.*, the detection efficiency. $\frac{N}{N_0}$ is the detector's angular correction factor for the energy E_i . $\frac{N_0}{\phi}$ is the count per unit of total uncollimated flux of a parallel beam of photons of energy E_i incident normally on the surface of the detector. Finally, $\frac{\phi}{A_x}$ is the primary flux of gamma photons of energy E_i emitted depending on the activity present in the radioactive source, expressed in ($\gamma \text{ cm}^{-2} \text{ s}^{-1} \text{ Bq}^{-1} \text{ g}$). The value of this term is tabulated in the ICRU report 53 and depends on the depth distribution of the radionuclides.

Concerning the calculation of the minimum detection activity (MDA), is computed as Nir-El and Haquin 2001 indicate for *in situ* gamma spectrometry. *In situ* measurements using germanium or scintillation detectors have been extensively tested and are widely cited in the literature.

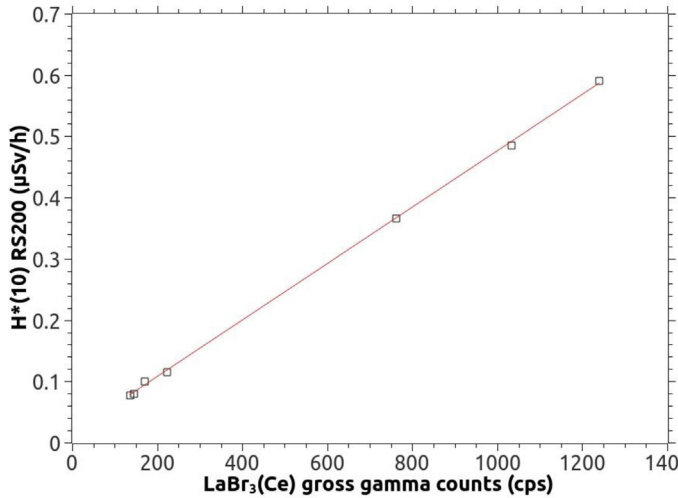


Fig 1. Cross-correlation between $H^*(10)$ measurements from the Reuter-Stokes ionisation chamber and gross gamma counts from the drone mounted $\text{LaBr}_3(\text{Ce})$ scintillation detector. Measurement conditions: 1 m above the ground on a flat surface without obstacles or vegetation within a radius of over 30 m. Homogeneous distribution of natural radionuclides at depth.

(Baeza and Corbacho, 2005; Tyler, 2004, 2008; Arnold *et al.*, 2012; Ji *et al.*, 2019).

2.3 Correlation between $H^*(10)$ dose rate and gross gamma counts

There is a direct relation between the ambient dose equivalent rate $H^*(10)$ and the corresponding measured pulse height spectrum $\vec{n}$ defining the response vector $\vec{v}$

$$H^*(10) = \vec{v}^T \vec{n}. \quad (3)$$

There are several methods to derive area doses from pulse height spectra, which are described in the bibliography (Toivonen *et al.*, 2008; Reginatto, 2010; Casanovas *et al.*, 2016; Drombrowski, 2014).

In this study, we have utilised an experimental method based on comparing the equivalent dose rate measured by a Reuter Stokes RS200 ionisation chamber and the gross gamma counts registered by the gamma detector mounted on the drone at various locations where the ambient equivalent dose rate is in the range of 0.050–0.6 $\mu\text{Sv/h}$. The measurements were conducted on a flat surface with no obstacles and at a height of 1 m above the ground. The relationship between data can be fitted to a linear function (Fig. 1). The RS200 ionisation chamber is considered a reference device for the measurement of ambient dose equivalent rate (Duch *et al.*, 2008). The linear fitting parameters are as follows: slope: $(4.61 \pm 0.04) \times 10^{-4}$; y-intercept: 0.016 ± 0.003 ; $R^2 = 0.9998$. Therefore, this experimental calibration has yielded a dose rate conversion factor function:

$$H^*_{(10)\text{drone}}(\mu\text{Sv/h}) = 4.61 \times 10^{-4} \cdot \text{Total Gamma counts(cps)} + 0.016 \quad (4)$$

3 Results and discussion

3.1 Commissioning of the drone. Quantification of a radioactive debris container

The localisation of point sources (orphan sources) is based on the systematic sampling of an area with measurements using short integration times, typically in the order of 1–2 s. However, the MDA increases significantly as the integration time decreases and distance from source increases. Consequently, once the source is located, it is important to increase the measurement time to improve the accuracy in the quantification of the activity of the source. Once the radioactive source has been identified, it is possible that it cannot be considered a point source due to its size. Consequently, quantifying its activity may not be feasible as the appropriate detector efficiency calibration is unavailable. Therefore, it may be useful to take the measurement far away from the radioactive source to consider it, for practical purposes, as a point source. For a point source, an efficiency calibration is available, and corrective factors are applied to account for attenuation due to distance and the layer of air between the source and the detector. In this sense, the inverse square law will apply where the distance, d , from the source is at least 10 times ' x ', where ' x ' is the longest dimension of the source (Bevelacqua, 2004; Knoll, 2010). It should be noted that if other radioactive sources are present, their influence on the obtained activity results cannot be disregarded as the detector moves away from the source for which the activity is to be determined.

To test the ability, of the drone developed in this work, to quantify a non-point radioactive source, an outdoor test was conducted using a radioactive source of known activity. For this, several flights were carried out over a container with low-medium activity material, specifically scrap metal from the decommissioning of the José Cabrera nuclear power plant (Spain). The characteristics of this container were as follows: $90 \times 90 \times 180$ cm (width $\times$ height $\times$ length); mass 550 kg; volume 1237 L. It had previously been characterized by the radioactivity laboratory located in the nuclear power plant itself. The mean activities of the radioactive material it contained were ^{137}Cs : $(1.40 \pm 0.12) \cdot 10^5 \text{Bq/kg}$ and ^{60}Co : $(1.67 \pm 0.21) \cdot 10^5 \text{Bq/kg}$. The reference activity decay corrected values used for the identification and quantification of the radioactive source using the drone were ^{137}Cs : $(75 \pm 7) \text{MBq}$ and ^{60}Co : $(81 \pm 7) \text{MBq}$.

This radioactive source can be classified as category 3 according to IAEA security guide No. RS-G-1.9. (IAEA, 2005)

A series of flights were conducted over the container at various heights (1–10 m) and for different acquisition times (60–300 s). To adjust the activity values for measurements taken when the detector is more than 1 m from the container, a correction factor has been applied which takes into account both the attenuation of the gamma photons in the air and the geometry. The expression used to calculate the efficiency, ϵ_d , of the detector for point sources placed along the detector axis at distances, d , greater than 1 m, is as follows:

Table 1. Experimental activities measured with the LaBr₃(Ce) detector mounted on the drone at various heights and for different measurement times.

Distance source — detector (m)	Acquisition time (s)	Photopeak (energy keV)	Gross area ± uncertainty	Efficiency (x10 ⁻⁵)	Activity ± uncertainty (MBq)	Detection Limit (MBq)	Relative difference (measure/reference) (%)
1	60	¹³⁷ Cs (661.7)	2830 ± 130	4.96	1.1 ± 0.1	0.12	-99
		⁶⁰ Co (1173)	3200 ± 100	3.31			
		⁶⁰ Co (1332)	3110 ± 70	3.02	1.6 ± 0.2	0.08	-98
2	60	¹³⁷ Cs (661.7)	920 ± 70	0.0967	19 ± 3	3.6	-75
		⁶⁰ Co (1173)	1170 ± 60	0.0648			
		⁶⁰ Co (1332)	1210 ± 50	0.0593	32 ± 4	2.5	-60
4	300	¹³⁷ Cs (661.7)	2420 ± 120	0.0239	40 ± 5	4.7	-47
		⁶⁰ Co (1173)	3100 ± 100	0.0161			
		⁶⁰ Co (1332)	3160 ± 70	0.0147	68 ± 8	3.6	-15
10	300	¹³⁷ Cs (661.7)	580 ± 60	0.0036	64 ± 10	17	-15
		⁶⁰ Co (1173)	690 ± 40	0.0025			
		⁶⁰ Co (1332)	590 ± 40	0.0023	91 ± 12	16	13

$$\varepsilon_d = \left\{ \begin{array}{ll} \varepsilon_{1m} \times \frac{e^{(-\mu_a \rho_a d)}}{4\pi d^2} & ; d > 1 \\ \varepsilon_{1m} & ; d = 1 \end{array} \right\}, \quad (5)$$

where ε_{1m} is the experimental efficiency at a distance of 1 m, μ_a is the mass-attenuation coefficient in air (0.661 keV: 0.07538 cm²/g; 1173 keV: 0.05840 cm²/g; 1332.5 keV: 0.05518 cm²/g), ρ_a is the air density: 0.012923 g/cm³, and d is the separation in the air between the source and the detector.

It is important to note that expression (5) is a simplification, as it does not consider other parameters that also influence detector efficiency, such as the angle of incidence of photons at distances beyond 1 m (Ritter, 2021).

Detection limits have been determined using the L. Currie criteria (Currie, 1968).

Table 1 shows the activity values, detection limits, and its comparison to the reference values obtained from the different measurements.

The measurements carried out at distances close to the container (1–2 m) give lower activity values than reference values. These results were to be expected because the efficiency calibration used was for a point source and the size of the radioactive source is too large to be considered a point source. However, for the measurement carried out at a distance of 10 m between the container and the drone, the measured activity values are of the same order of magnitude as reference values, despite the relative difference between measured activity and the reference activity still being significant (~15%). However, this is considered to be a very satisfactory result for the objectives of using this type of device for *in situ* measurements with short acquisition time and applying a simplification to determine the efficiency of the detector at distances greater than 1 m.

3.2 Radiological characterisation of phosphate sludge landfill

The study area chosen to carry out a radiological characterisation using the measurements provided by the

drone system developed in this work was a former phosphate production plant located in the southeast of Spain (37.61 N; -0.965). Today, process wastes are still present, consisting mainly of phosphate sludge. Between 2005 and 2006, a detailed radiological study of these areas was carried out (CSN, 2009). The study area consists of two parts. One, where the buildings were located (now demolished), with a total surface of 180 000 m². The second area, where there are three phosphate sludge ponds and various phosphate waste drifts has a total surface of 150 000 m². Both areas are at an elevation between 9 and 21 metres above mean sea level.

Measurements were taken in a grid of approximately 10 × 10 m over the phosphate sludge ponds. The flight altitude was 1 m. These are optimal conditions for a suitable *in situ* gamma spectrometry measurement, since most of the photon flux reaching the detector, which is located 1 m above the ground, comes from an area equivalent to a circle with a radius of 10 m (ICRU, 1994). At each point, a 30 s measurement was taken. The efficiency calibration for an infinite plane source with a homogeneous distribution in depth was used to determine the activity levels for natural radionuclides: ⁴⁰K, ²²⁶Ra (from its daughter: ²¹⁴Pb and ²¹⁴Bi assuming they were in equilibrium with their parent radionuclide) and ²³²Th (²²⁸Ac). In the event of an emergency, the most appropriate distribution would be an infinite plane where the radionuclides have been deposited in the surface layer.

The MDA values for a 30 s acquisition time and 1 m flight altitude are of the order of: ⁴⁰K: 300 Bq/kg; ²¹⁴Pb: 30 Bq/kg; ²¹⁴Bi: 30 Bq/kg; ²²⁸Ac: 40 Bq/kg.

The conversion factor from gross gamma counts to H*(10) detailed in Section 2.3 was also used to measure the ambient dose equivalent rate H*(10) throughout the area.

Furthermore, the H*(10) values was also calculated from the activity measurements of the ⁴⁰K, ²²⁶Ra and ²³²Th natural radionuclides measured by the drone-based system. For this purpose, the terrestrial component of the H*(10) was calculated using the following expression (Lemercier *et al.*, 2018).

Table 2. Activity levels of ^{40}K , ^{214}Pb , ^{214}Bi and ^{228}Ac measured by the drone. Ambient equivalent dose rate measured: (1) from the ^{226}Ra activity levels. (2) from gross gamma counts (cps) conversion factor. $\text{H}^*(10)$ values recorded by RS200 ionisation chamber.

	Soil activity levels				Ambient equivalent dose rate $\text{H}^*(10)$		
	^{40}K (Bq/kg)	^{214}Bi (Bq/kg)	^{214}Pb (Bq/kg)	^{228}Ac (Bq/kg)	$\text{H}^*(10)^1$ ($\mu\text{Sv/h}$)	$\text{H}^*(10)^2$ ($\mu\text{Sv/h}$)	RS200 ± 0.001 ($\mu\text{Sv/h}$)
Control	480 $\pm$ 90	20 $\pm$ 5	21 $\pm$ 6	33 $\pm$ 9	0.05 $\pm$ 0.03	0.078 $\pm$ 0.006	0.077
1	< MDA	960 $\pm$ 180	720 $\pm$ 140	< MDA	0.51 $\pm$ 0.14	0.59 $\pm$ 0.02	0.591
2	< MDA	790 $\pm$ 150	740 $\pm$ 140	< MDA	0.47 $\pm$ 0.13	0.52 $\pm$ 0.02	0.475
3	< MDA	410 $\pm$ 80	490 $\pm$ 100	< MDA	0.29 $\pm$ 0.08	0.48 $\pm$ 0.02	0.476
4	< MDA	370 $\pm$ 70	450 $\pm$ 90	< MDA	0.27 $\pm$ 0.08	0.49 $\pm$ 0.02	0.476
5	< MDA	730 $\pm$ 140	670 $\pm$ 130	< MDA	0.44 $\pm$ 0.11	0.53 $\pm$ 0.02	0.522
6	< MDA	540 $\pm$ 100	640 $\pm$ 120	< MDA	0.37 $\pm$ 0.10	0.49 $\pm$ 0.02	0.485
7	< MDA	480 $\pm$ 90	410 $\pm$ 80	< MDA	0.29 $\pm$ 0.08	0.37 $\pm$ 0.02	0.366
8	< MDA	630 $\pm$ 120	700 $\pm$ 130	< MDA	0.42 $\pm$ 0.11	0.47 $\pm$ 0.02	0.382
9	< MDA	580 $\pm$ 110	570 $\pm$ 110	< MDA	0.37 $\pm$ 0.10	0.47 $\pm$ 0.02	0.433
10	< MDA	130 $\pm$ 30	90 $\pm$ 20	< MDA	0.10 $\pm$ 0.03	0.21 $\pm$ 0.01	0.253

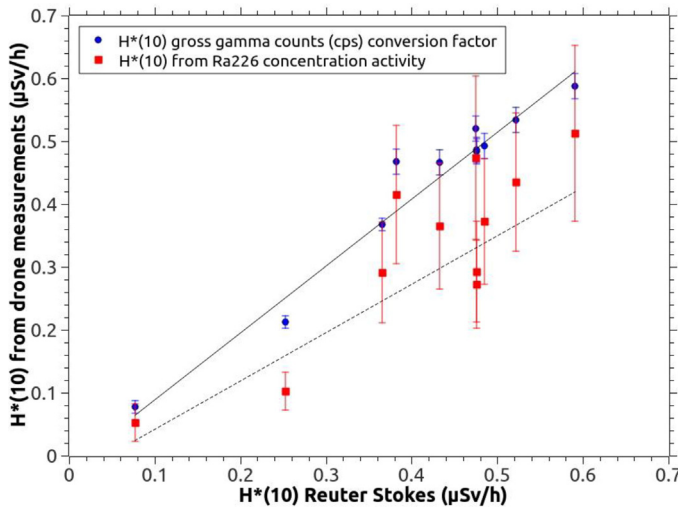


Fig 2. Correlation between $\text{H}^*(10)$ values measured with the RS200 ionisation chamber and $\text{H}^*(10)$ values measured with a $\text{LaBr}_3(\text{Ce})$ scintillation detector mounted on a drone. Blue dots: $\text{H}^*(10)$ values obtained from gross gamma counts (cps) to $\text{H}^*(10)$ conversion factor. Red dots: $\text{H}^*(10)$ values obtained from ^{226}Ra concentration activity measured *in situ*.

$$\begin{aligned} \text{H}^*(10)(\eta\text{Sv/h}) = & (0.0512 \times A_{\text{K}-40}) \\ & + (0.749 \times A_{\text{Th-series}}) \\ & + (0.564 \times A_{\text{U-series}}) \end{aligned} \quad (6)$$

The cosmic component of the $\text{H}^*(10)$ was calculated from the altitude measurements, h in metres above mean sea level, using the model proposed by Rybach *et al.*, 1997.

$$\text{H}^*(10)(\eta\text{Sv/h}) = 37.0 \times e^{(3.8 \times 10^{-4} \times h)}. \quad (7)$$

To measure the background radiation outside the study area, a control zone was selected (37.6144N; -0.96998). At this point, three measurements were taken by the drone 1m

above the soil (acquisition time: 300 s). The measured dose rate and error was: 0.078 ± 0.006 mSv/h

The $\text{H}^*(10)$ measured values have been checked with those measured by RS200 ionisation chamber in the same place.

Table 2 shows the activity levels of ^{40}K , ^{226}Ra (^{214}Pb and ^{214}Bi) and ^{232}Th (^{228}Ac) measured by the drone. In addition, the $\text{H}^*(10)$ values calculated both from the gross gamma counts (expression (4)) and from the activity levels (expressions (6) and (7)) is shown. The ambient dose rate measured by the RS 200 ionisation chamber is also shown. Furthermore, Figure 2 illustrates the correlation between $\text{H}^*(10)$ values measured by RS200 ionisation chamber and $\text{H}^*(10)$ derived from drone measurements.

Firstly, it should be noted that no net activity higher than MDA could be detected for ^{40}K and ^{228}Ac at all the points where gamma spectrometric measurements were carried out over the phosphate sludge ponds (points 1 to 10). This is not the case for the control zone, which was located in an undisturbed place far from the phosphate sludge ponds and was considered as environmental background.

Secondly, a high concentration of ^{226}Ra progeny is observed. The average value and standard deviation of ^{226}Ra activity measured in sample points 1 to 10 corresponding to the phosphate sludge ponds is of the order of 500 ± 200 Bq/kg in accordance with activity values measured in a previous study (CSN, 20 09): ^{226}Ra : 860 ± 340 Bq/kg; ^{40}K : 160 ± 100 Bq/kg; ^{232}Th (^{228}Ac): 50 ± 20 Bq/kg.

In relation to the values of ambient equivalent dose, $\text{H}^*(10)$, a high agreement may be observed between the values measured by the drone from the gross gamma counts, applied with the conversion factor to $\text{H}^*(10)$, and those recorded by the RS200. The Pearson's coefficient obtained is 0.978. This is not the case with the dose rate calculated solely from the values of ^{226}Ra activity measured, which in some cases are lower by 40% than the previous values (points 3 to 6). The Pearson's coefficient is: 0.869. The contribution of ^{40}K and ^{232}Th to ambient dose rate over the phosphate sludge ponds is practically negligible. Consequently, the ^{226}Ra activity measured by the drone in points 3 to 6 has probably been underestimated compared to what actually exists. However,

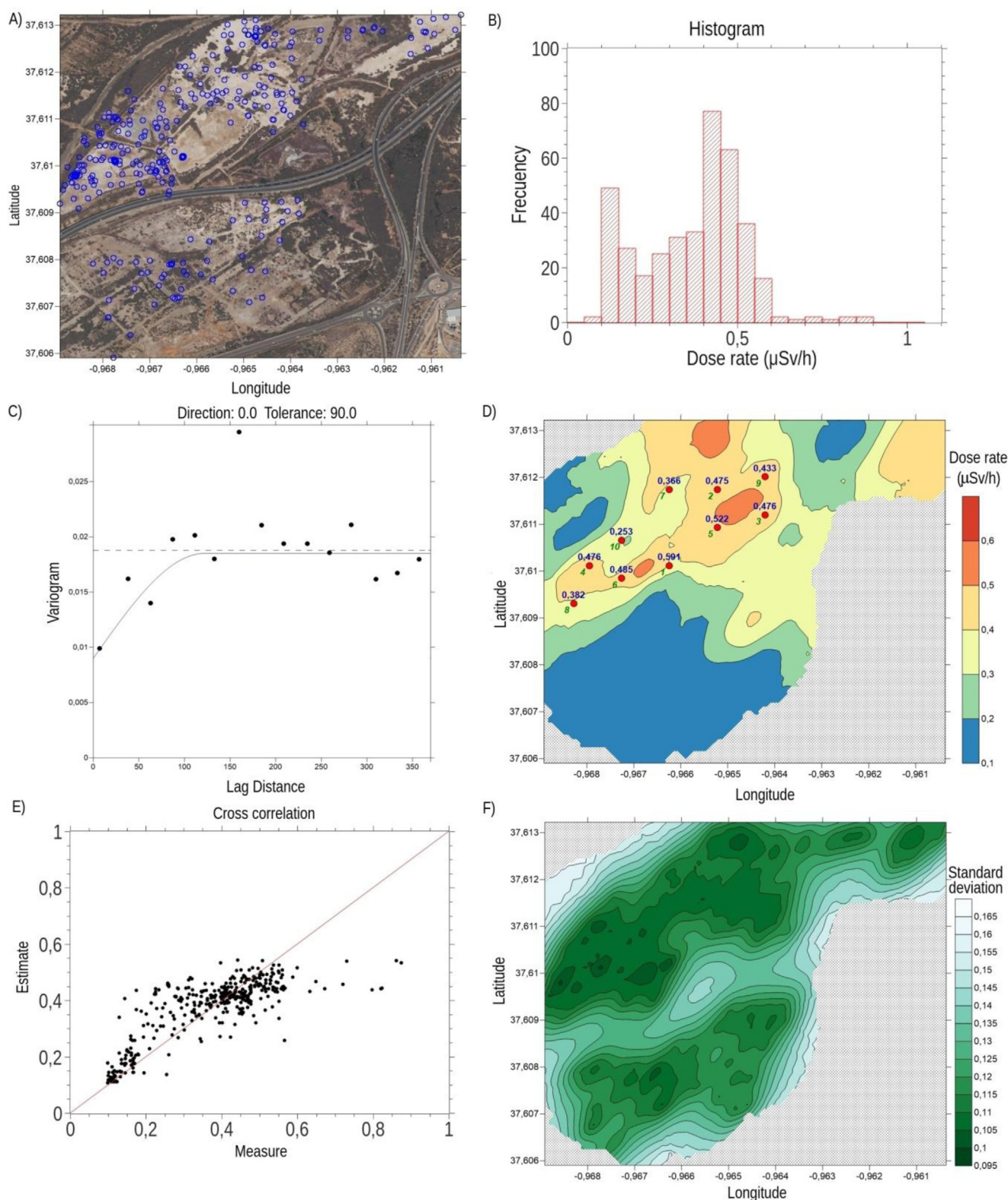


Fig. 3. A) Ortho-image of the study area showing drone measurements points. B) Histogram of dose rate data recorded by drone. C) Variogram. D) Ambient Equivalent Dose Rate $H^*(10)$ contours map. Red dots: $H^*(10)$ measurements recorded by RS200 ionisation chamber. Blue number: $H^*(10)$ values measured by RS200. Green number: Identification point at Table 1. E) Cross correlation between dose rate data measured and estimated by kriging spherical interpolation. F) Standard deviation map obtained from kriging spherical interpolation.

considering that these measurements take only 30 s, the result can be considered highly satisfactory.

Mapping is the final step in obtaining a comprehensive view of ambient dose equivalent rate levels in an area. Ordinary Kriging interpolation provides an optimal estimate based on observations and spatial relationships (Mabit and Bernard, 2007), yielding more realistic results than inverse distance weighting interpolation. However, to obtain an adequate contour map using ordinary kriging, it is necessary to follow several steps that ensure it. First, it has been verified that the data distribution approximately follows a normal distribution. The histogram is shown in Figure 3B. Next, a variogram was performed to obtain the parameters of the spherical function that will be used to determine the ordinary kriging interpolation. The obtained variogram is shown in Figure 3C. The optimal interpolation parameters indicate a radius and anisotropy angle of 2 and 48°, respectively. Furthermore, the optimal range has been 200 m. The ambient dose rate $H^*(10)$ contour map was generated and is presented in Figure 3D.

The cross-correlation between the measured dose values and those estimated with the spherical function has been verified. Figure 3E displays this cross-correlation, where an adequate correspondence is observed across a wide range of dose rate values, with the exception of the higher dose values measured in the study area. However, it can be demonstrated that there are significant differences between estimated and measured values. These differences are also illustrated in the kriging deviation error map shown in Figure 3F. As can be seen, the highest dose rate values are observed above the phosphate sludge ponds and in the phosphogypsum piles. Outside these areas, dose rate values range from 0.1 to 0.2 $\mu\text{Sv/h}$, indicating surface contamination probably caused by former industrial activity with significant ^{238}U series radionuclide content.

The measurements obtained by the Reuter Stokes ionisation chamber (red dots and blue values) align with the contour levels shown on the map.

4 Conclusions

A versatile radiation system was implemented on a rotary-wing UAV to identify and quantify radioactive anomalies above the background. Calibration was performed for both point sources and extended sources.

Quantification of ^{137}Cs and ^{60}Co in low to medium activity scrap container from the José Cabrera nuclear power plant (Spain) was conducted. Results for point source measurements differed by 15% from reference values, a satisfactory outcome.

Characterisation of the former industrial area “El Hondón” with elevated ambient dose equivalent rates was achieved using the drone. Four hundred 30 s measurements were taken. A comparison with a Reuter Stokes ionisation chamber showed differences of less than 16%. A contour map of the ambient dose equivalent rate highlighted concentrated high doses over the phosphate sludge ponds.

The results demonstrate that radiological characterisation of a site using a system such as the one presented in this work can be carried out with sufficient sensitivity to enable an immediate response by the competent authorities.

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Conflicts of Interest

The authors declare that they have no conflict of interest.

Authors contributions

JA Corbacho: Conceptualization, manuscript writing, figure drafting. JM Caballero: Experimental, Investigation. JA Baeza: data collection.

Ethics approval

Ethical approval was not required

Informed consent

This article does not contain any studies involving human subjects

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