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Calibration of a system for air-borne gamma spectrometry survey and mapping implementation

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Depending on the area of the territory that has to be surveyed and the desired resolution of the gamma- spectrometry map, the operation method has to be chosen. It includes the type of air-craft, detector system, flight plan – speed, height, direction and distance between profiles. In the current article gamma-spectrometry mapping over 4.4 km^2, using helicopter and in compliance with IAEA's recommendations, is described. The factors, that affect the measurement were reviewed and taken into account in choosing the calibration method. Its validity is proven by two comparisons. The first one is between the results from high altitude measurements and the expected attenuation of the cosmic radiation in the atmosphere. The second one is between values from the mapping after the calibration and results from sampling ground measurements. The calculation done upon the task completion is explained. Representative part of the results from the particular mapping is given as color images extracted from the genuine gamma maps.

Keywords: Airborne, Radioactive pollution, Gamma-mapping, Spectrometry, NaI(Tl), Calibration method

INTRODUCTION

Airborne-gamma mapping could be implemented in many different ways (IAEA, 1991) [3], (A. Elkhadragy *et al*., 2017) [5], (Horsfall, 1997) [6], (Grasty and Minty, 1995) [7]. Using the modern technology, it is possible to cover all the segments in scaling (Kaiser *et al*., 2016) [12], (Gabrlik and Lazna, 2018) [11]. According to the required space resolution and minimum detectable activity (MDA), we choose the proper parameters of the detector system, the aircraft and the flight plan. For accurate results the most important thing stays the adequate calibration.

In the current article the calibration methods used during an implementation of middle scaled air-borne gamma spectrometry mapping is described. It is performed over two fields of 3.2 km^2 and 1.2 km^2 flat land territory on the Danube river coast near Oryahovo, Bulgaria, using a helicopter and a 16 liter NaI(Tl) scintillating detector system. The site conditions do not allow trivial calibration. The main task is choosing the best fitting methods, adapting them to the specific conditions and verifying the results after adaptation of the particularly chosen method.

Our team works on such projects for more than 25 years. We have already implemented many terrestrial radiation surveys using from handheld to large sodium detectors. Our latest measurements include pixelated cadmium zinc telluride (CZT) detector for stationary gamma-mapping, *in-situ* HP Ge detector and UAVs carrying different detectors (Iliev and Dankov, 2018)[9]. We completed an air-borne gamma spectrometry mapping in 2013, using a helicopter. Later, in 2018, we had the opportunity to work again on gamma-spectrometry mapping using the same detectors, but with another helicopter and new software, which required new setting of the system and new calibration. Its basic principles are summarized in this article.

As the results from the survey have to be representative in the face of the regulatory units, we followed all the precepts of the International Atomic Energy Agency (IAEA). Most of them are in the two TECDOCs 1092 and 1363 [1, 2], Technical Report Series – No. 323 [3] and ICRU report No. 53 [4]. The report No. 323 [3] recommends five energy windows to be taken into account for geophysical surveying:

Table 1. Radionuclides suggested by IAEA for monitoring during airborne gamma-spectrometry mapping and their energy regions of interest (ROIs).

Window	Lower [MeV]	Upper [MeV]	Peak [MeV]	Radio-nuclide
Total counts	0.41	2.81		
Potassium	1.37	1.57	1.46	K-40
Uranium	1.66	1.86	1.765	Bi-214
Thorium	2.41	2.81	2.614	Tl-208
Cosmic	3.0	and higher		

EXPERIMENTAL

Equipment

In the current survey we used a complete gamma spectrometry system, which has 4 NaI(Tl)

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scintillating detectors. Each detector is with a volume of 4 liters and has its own photomultiplier tube (PMT) and 1024 channel analyzer (MCA). The energy resolution is better than 8% for ^{137}Cs and the sensitivity is 144 cps/(nSv/h) for ^{137}Cs and 96 cps/(nSv/h) for ^{60}Co.

Each pair of detectors is in a rugged plastic box (Fig.1).

Fig. 1. Opened detector protection box, keeping a pair of NaI(Tl) detectors used in the survey.

The information is transferred to a PC through an interface box using standard TCP/IP which makes it flexible. We used a rugged laptop Getac V200 with two GPS modules (integrated and external). The software allows us to monitor the whole data stream at real time. It displays the current spectrum from each detector, dose rate alarm if a threshold is passed, the recognized radionuclide, GPS coordinates and all the other monitored parameters as altitude, flight height, detector temperature, PMT high voltage, gain, etc. The data can be exported to many different popular file formats for post-processing with other software tools. All the equipment is installed on a helicopter Schweizer 333 (269D) (Fig. 2) and can operate autonomously, but we had one operator on board for immediate support to prevent any simple failures.

The territory to be investigated was relatively small (3.2 km^2 and 1.2 km^2) and there was no near suitable runway for a fixed-wing airplane, that is why we chose a rotorcraft.

The most important benefit of the helicopter is its lower speed, which, with an optimum at about 60-80 km/h, allows better space resolution of the gamma map. This is a starting point for most of the other parameters of the flight plan.

Another starting point is the requirement for the achieved MDA. It is fundamental for all the other calculations and requirements to the detector system and to the survey methods. The requested MDA was 1 kBq/m^2 for ^{137}Cs.

Calibrations on the ground

The detector system needs a series of calibrations of different parameters (IAEA-1363, 2003) [2], (Grasty and Minty, 1995) [7]. The high voltage and gain calibrations are part of the energy calibration and are both performed automatically on the basis of the ^{40}K energy peak in the spectrum. It is performed on every start of the system and corrects the drift of the peak through neighbor channels. To reduce its duration there is additional amount of ^{40}K in the detector box, which is removed during the flight to reduce the intrinsic background. As long as the measured radioactivity during flight is relatively low, compared to the system counting speed, correction for the dead time will practically not change the results and it is not done.

Fig. 2. The spectrometry system installed on Schweizer 333 (269D).

The efficiency calibration was performed on the ground using ^{137}Cs and ^{60}Co with known activity and at a certain distance. The response of the system in the particular ROI *versus* source activity gives the system efficiency. As another part of the efficient calibration can be considered the determination of the MDA for the technogenic radionuclides. It is done in the same way, on the ground using ^{137}Cs and ^{60}Co. But this time by finding the distance from which the system unambiguously recognizes the presence of the source. As we know, for a point source far enough from the detectors, the response is inversely proportional to the square of the distance, so we can calculate the attenuation of the gamma-field intensity by the particular distance. For calculating the MDA, we used the net signal (excluding the background spectrum). Even if the natural background is higher, the ^{137}Cs or ^{60}Co MDA will not be affected because the recognition algorithm works for every single ROI.

Flight plan

We chose the height of the flight to be the maximum height that allows the required MDA to be achieved on the basis of the calculated MDA during the calibrations on the ground. The resultant height for MDA = 1 kBq/m^2 (^{137}Cs) was about 70 m. To ensure reserve in the achieved MDA we did not use the maximum height, but reduced it to 60 m. The spot "seen" by the detector was the spot from which 60-70% of the signal was coming. It was a circle on the ground with a radius equal to the flight height. According to this rule, the distance between flight profiles should be 120 m at maximum, and we chose 100 m to ensure 20% overlay in case of deviation from the straight line during the flight. The integration time of the detector system is 1 sec but a moving average was calculated over the last 5 sec. It means that, if we want symmetric pixels on the map, the speed of the aircraft has to be not more than 120 m/s and the best choice would be anything below 24 m/s. We used the lowest possible speed in which the particular elicopter and pilot could ensure stable flight. It was about 17 m/s which gave us integration time of about 7 s – better than the integration time of 5 s.

With the chosen parameters the first measurement flight gave basic information about the distribution of the contamination interpreted using infinite model. If some artificial contamination is found, according to its distribution, we have to plan a second flight. The plan, most often, uses a point model for point source, where the helicopter needs to hang above the source for more precise determination of its activity and line model for objects as rivers, channels or pipes, where the new flight profile should follow the object line.

As seen on Fig. 3, proper distribution modeling can be critical in defining the contamination shape, size and position.

Calibration of the system in the air

The background during flight consists of four components: intrinsic, cosmic, radon and fallout. They affect the system simultaneously, and we have to separate them in order to take into account their exact effect over the spectrum. As there were no representative data for the fallout background and after several measurements on the ground surface near the monitored terrain, showing insignificant presence of fallout, we did not make any fallout corrections.

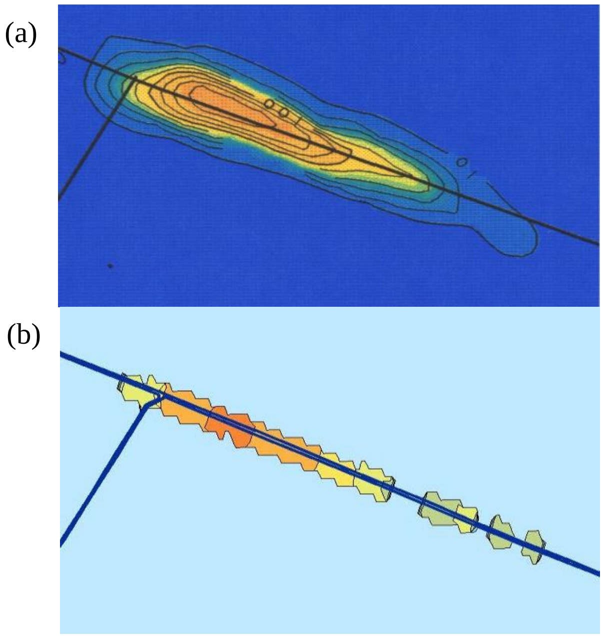

Fig. 3. Comparison between infinite model (a) used in previous surveys and line model (b) over the same water channel.

The presence of radon can be tracked by observing the counts in ^{214}Bi ROI (561 to 657 keV), as ^{214}Bi is a stable radon daughter with gamma emission at 609 keV. Its photo peak is masked by the Compton continuum of the other monitored isotopes (K, U and Th) and its quantitative evaluation requires additional spectral integrations and more complex calculations (IAEA-1363, 2003) [2] or special calibration. The radon concentration in the area was monitored with measurements on the ground and considered as insignificant for our purposes. Over the water, the average of the corrected NORM ROIs should be very close to 0, but not 0. If a high level of U is seen, this may indicate the presence of radon. However, during the flights the ^{214}Bi ROI was also monitored in case of considerable deviations. Two different measurements at the same position and same height should provide similar Bi/U ratio. A higher ratio could indicate a higher radon level during the corresponding measurement period.

The intrinsic and cosmic background corrections start with acquisition of a 15 min spectrum at each altitude – 1800 m, 2300 m and 2800 m. The height of the flight should be more than 1000 m and the weather has to be clear. The 15 min are divided into three 5 min intervals. On fig. 5 each blue dot gives the result for 5 min integration. The cosmic background depends on the altitude and can be calculated for a certain geographic region (EAURADOS, 2004) [8], but the most accurate way to evaluate it is to be empirically reached with real measurement of the particular system. According to some initial information about the detector system response to high energy cosmic radiation given by the manufacturer like the limit of the energy range and anisotropy, the theoretical model that we considered as best for our purpose could be represented as follows:

$$D = A.\exp(0.00038.h) + B \qquad (1)$$

where:

D = cosmic dose rate;

A = cosmic dose rate at sea level;

h = altitude;

B = aircraft background dose rate.

In Eqn. 1 we have to consider that the cosmic dose rate (D) and the cosmic dose rate at sea level (A) are values measured by the particular detector system, and are not the real cosmic dose rates, because of the detector system specifics.

During the flight planning there was a potential problem that we had to solve. First calibration flight had to be over water to eliminate the gamma-rays coming from the ground. Near the current terrain there was a water basin that we could use – Danube river, but it was not allowed to perform our flights at higher altitudes above it, because it is a restricted border area. So we had to use flights at high altitudes and heights only over the ground (soil and rocks). This made the calibration method more specific and had to be validated. We suggested this to be done in two approaches. The first one was to create a graph of the cosmic radiation background, in the cosmic ROI, against altitude. Similarity between the fit on the graph and Eqn. 1 could prove the validity of the calibration method.

The second approach to the calibration validation is a comparison to direct sampling measurement done on the ground with an *in-situ* HP Ge spectrometer. It is calibrated to show specific activity for the particular geometry and for the same radionuclides (^{40}K, $\mathrm{Th}_{\mathrm{equivalent}}$, $\mathrm{U}_{\mathrm{equivalent}}$). The sampling points coordinates are chosen after the map is created. The criteria are – one sample measurement in the area with the lowest activity and one with the highest activity, in order to cover the full range of the mapped values.

The other background components could also be extracted from the results of the height flights measurements. With higher altitudes the cosmic background increases, the Earth gamma-rays are reduced by the flight height and the aircraft background stays constant. With building a graph of the counts for every region of interest (ROI) against the altitude, we can evaluate each background component. The cosmic radiation affects all the ROIs, but the ROI that is above 3MeV is affected only by the cosmic rays. Using this effect, and knowing the detector efficiency for every ROI, we can calculate the net counts coming from the cosmic rays. The procedure for separation of the background components we used for this calculation is fully described by Grasty and Minty, 1995 [7] and TECDOC-1363 [2].

A linear regression (fig. 4) of the cosmic window counts on another ROI counts yields the cosmic sensitivity represented by the slope of the regression line and its zero intercept is the aircraft background for that ROI:

$$N_{ROI} = a_{ROI} + b_{ROI}.N_{COS} \qquad (2)$$

where:

N_{ROI} = aircraft + cosmic background count rate in the particular ROI;

N_{COS} = cosmic ROI counts;

a_{ROI} = aircraft background in the particular ROI;

b_{ROI} = cosmic background in the particular ROI normalized to unit counts in the cosmic ROI.

The self-background calibration should be performed every time the helicopter or part of it changes, because this component of the background includes the effect of the fuel, the pilot and even the presence of an operator onboard and includes not only the possible internal activity, but also gamma-rays attenuation or even secondary radiation from the interactions between cosmic high-energy radiation and any part of the aircraft.

RESULTS AND DISCUSSION

Fig. 5 shows the measured total counts in the cosmic ROI against altitude. It has and exponential fit, very similar to the expected one in Eqn. 1. This is enough to conclude that the results from the first approach are acceptable.

Creating the maps

The representations of Normally Occurring Radioactive Materials (NORM) and technogenic radioactive contamination distributions have principal differences. NORM always exist and we can only evaluate their values in units of mass concentration. At the same time for technogenic radionuclides Search and Investigation Algorithm (SIA) is used. The algorithm is based on monitoring the variance in each region of interest (ROI) of the energy spectrum. When the variance is noticeable, or in other words – meets some criteria, then the net value in the ROI is being calculated and given as a result in activity. And finally the activity is represented as a point or infinitely distributed, depending on the distribution model. Even if we do not know the SIA mathematics we can use it to find the MDA empirically, by finding the minimum activity that shows on the data records. The ratio between the K, U and Th ROI should also be consistent. It's not possible to have a high content of Th and no U or K, because of the Compton counts due to Th in these ROIs.

Activity calculations are based on the function describing the sensitivity of the detector *versus* height. The activity was calculated for every single ROI. The result is given in Bq/m^2 for the infinite contamination model and in Bq for the point source model for each radionuclide corresponding to the particular ROI.

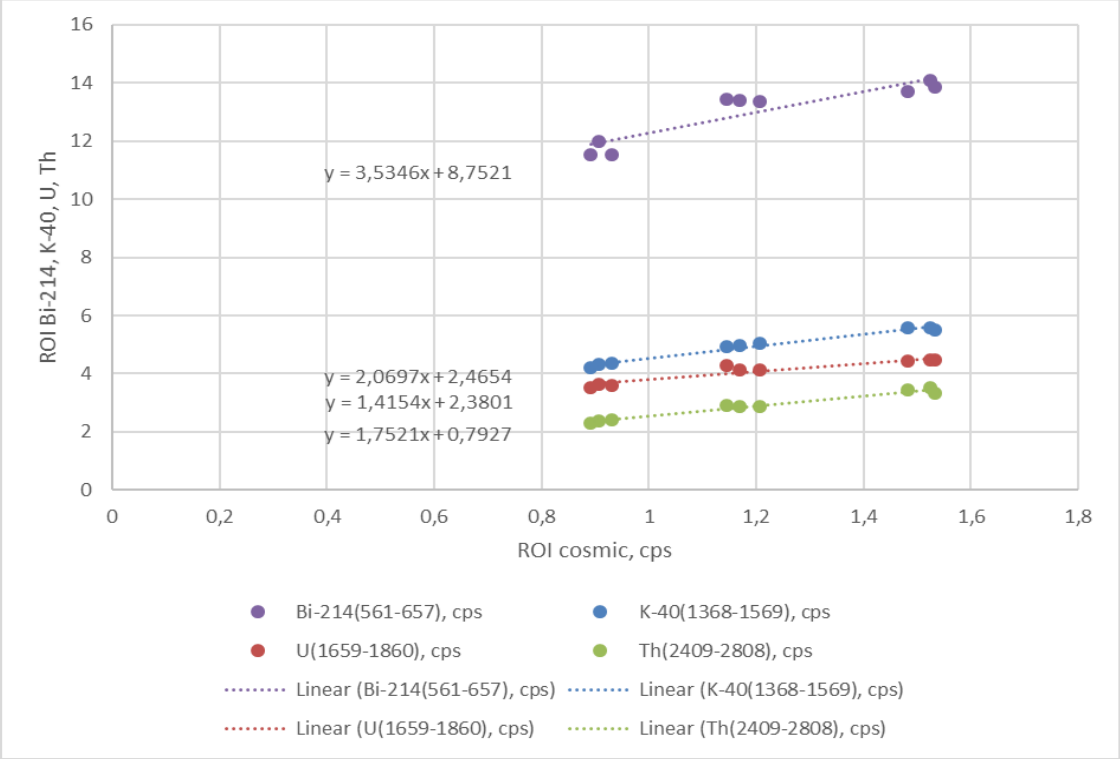

Fig. 4. Results from the height flights: each color represents different ROI; each graph can be fitted to linear regression of the ROI to the cosmic ROI; each point represents a measurement with 5 min integration time. The slope of the regression represents the cosmic sensitivity and the zero intercept is the intrinsic background.

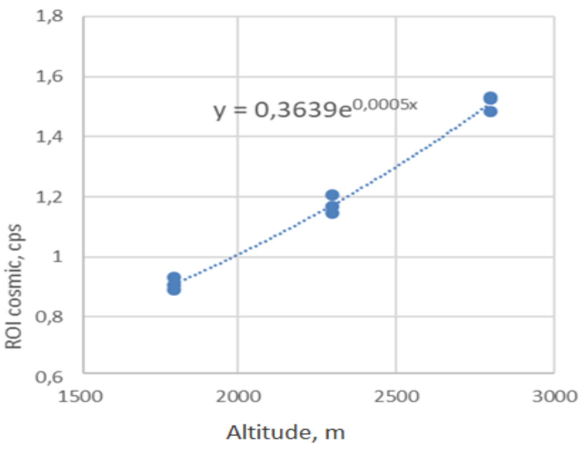

Fig. 5. Exponential fit of the measured cosmic background. Each blue point represents integration for 5 min

Concentration calculations are equivalent to the activity calculation, but a relaxation coefficient β is taken into account (ICRU Report-53, 1994)[4]. It represents the vertical distribution of the nuclides in the soil (defined by the relaxation mass per unit area). Value of β mainly depends on contamination's age. At the same time, most of the gamma rays are attenuated in the upper 30 cm of the soil, and almost none of the gamma radiation is coming from more than 50 cm under the ground surface (IAEA-1363, 2003) [2]. In this manner, mass or volume concentrations can be evaluated only for the upper layer of the soil.

Ground dose rate calculations were done in three steps. First is the measured dose rate at the point of the detector, from which the intrinsic background, the cosmic background and local radon background should be subtracted. The second step is to correct for the height, using the equivalent height at standard conditions and the height-to-sensitivity function. Other function parameters are air pressure and air temperature as well. The third step is to add the cosmic background calculated at ground level.

The result consists of a variety of maps representing concentrations of the monitored radio-isotopes and calculated dose rates. In Fig. 6, a simple preview of the maps is shown in the form of color images extracted from the genuine maps, just for illustrative purposes. The “x” marks show the sampling coordinates for the measurements on the ground.

The results from the second approach also confirmed the applicability of the calibration method in the particular conditions.

Uncertainty

The first thing we have to know about uncertainty is that it is quite high. But we have to consider that this survey method is mainly indicative and for rough evaluations. The method has first been created for geological purposes. It is macroscopic and its idea is to be used over a wide open territory in order to find some regions of interest. If we use the detector system on the ground or in short-distance geometry the uncertainty will be lower and can be defined, but on 60 m above cross-country terrain there are many valuable factors affecting the result. The most important is the accurate measurement of the distance to the object on the ground.

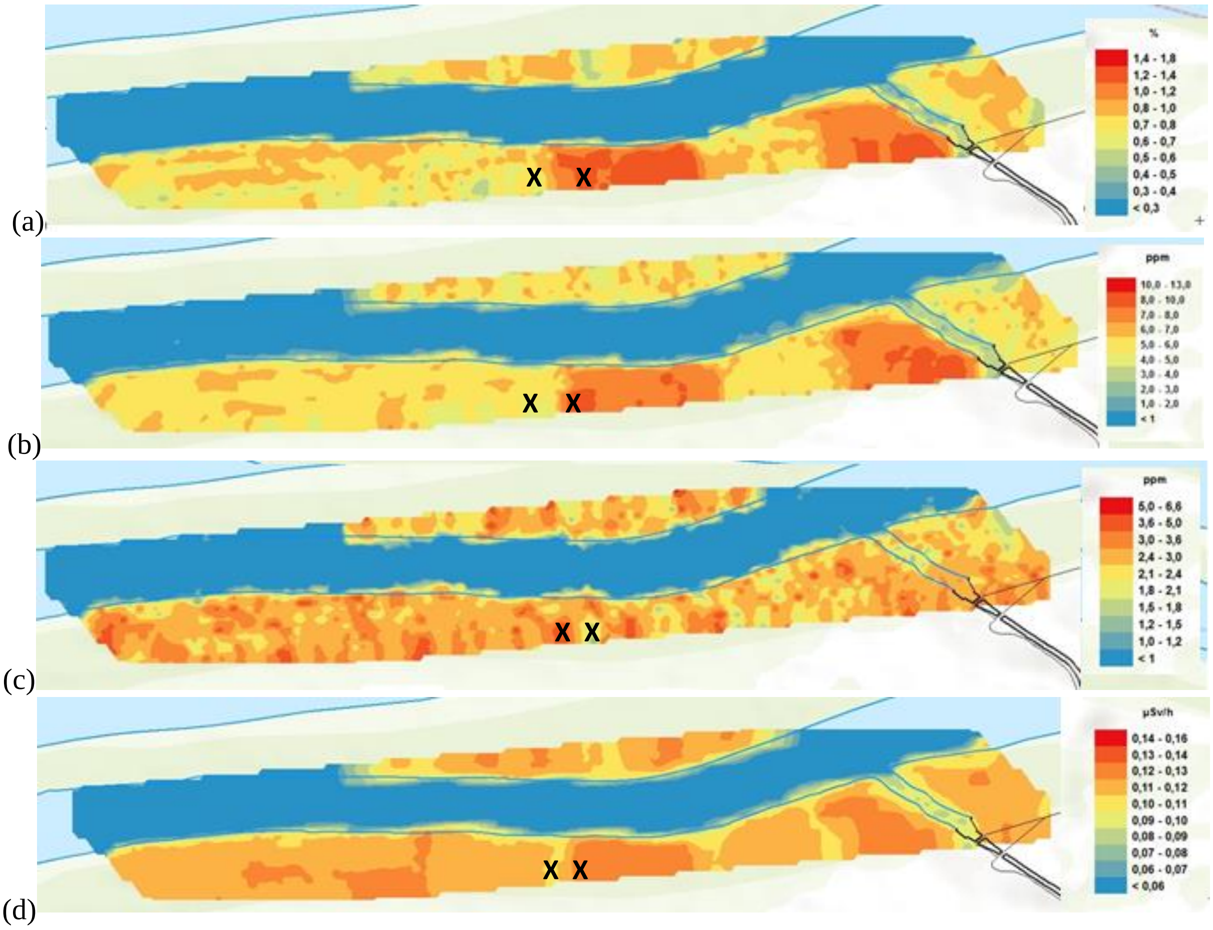

Fig. 6. Images from the resulting gamma maps of NORM: (a) ^{40}K in %; (b) $\mathrm{Th}_{\mathrm{equivalent}}$ in ppm; (c) $\mathrm{U}_{\mathrm{equivalent}}$ in ppm; (d) ground dose rate calculated according to TECDOC-1363 [2] in µSv/h. The “x” marks show the ground measurements positions.

The barometric altimeter gives us altitude, but not exactly the distance and the GPS altitude, even when corrected with the geoidal shape of the Earth, does not provide definable precision. The atmospheric pressure, temperature and humidity also significantly affect the attenuation in air, but usually in open space they can vary and change quickly. With the current system it is not possible to monitor all these parameters. The amount of the gamma-photons reaching the detector also depends on the substrate under the contamination. Its density and Z_{eff} affect its backscattering. Very significant error could appear when the model we choose does not correspond to the real contamination shape. As we usually start with an infinite model, the system result will be divided to the “visible” area of the detector and the result for the surface activity will always be underestimated. For point source estimation, in the activity calculation we assume that the source is right under the helicopter, but in practice there could be a difference. For an accurate quantitative evaluation of the activity of the contamination we have to know all the affecting factors which will lead the investigation to another direction. Because of all mentioned above, in our survey we consider the uncertainty evaluation as not reasonably achievable.

CONCLUSION

The airborne gamma-spectrometry mapping is a macroscopic method for quick investigation of large territories and its nature does not assume high accuracy. In any case, improving the calibration can enhance the reliability of the results.

Because of the increasing contribution of cosmic radiation with height, it should be considered during the interpretation of the results. It is not possible to exclude the cosmic radiation on the base of its energy, because it covers all the spectrum and even causes secondary radiation after interaction with the flying vehicle. Building a graph of the counts in the cosmic ROI to altitude we can quantitatively verify our system response to this kind of radiation. And plotting graphs for each relation between cosmic ROI and every other ROI shows linear regressions. Their slope and zero intercept are the sensitivity to cosmic radiation and the intrinsic background, respectively. Comparison of the resultant altitude function of the cosmic radiation contribution and a typical one shows satisfactory incidence, as the comparison between the results for activity and those from a stationary spectrometer for *in-situ* measurements.

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