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MONTE CARLO SIMULATIONS FOR AERIAL GAMMA SPECTROMETRY

Anna Selivanova, Marcel Ohera, Irena Cespirova, Lubomir Gryc

National Radiation Protection Institute (SURO), Prague, Czech Republic

E-mail: anna.selivanova@suro.cz

Article presents results of calculation modeling of IRIS integral system using Monte-Carlo method. For successful system operation the radionuclides spectra library was established for separate space conditions. Results of model developing demonstrated good agreement with results of full-scale measurements.

1. Introduction

A new software for aerial radiation monitoring is being developed in the National Radiation Protection Institute (SURO, Prague). This task belongs among working assignments of the Project of the Ministry of the Interior of the Czech Republic VH172020015 – Recovery Management Strategy for Affected Areas after Radiation Emergency. The National Radiation Protection Institute provides aerial gamma spectrometry measurements using a detection system IRIS (Integrated Radiation Information System) by Pico Envirotec [1].

2. Materials and methods

IRIS contains four NaI(Tl) detectors with a total detection volume of 16 liters mounted in two aluminum boxes (two detectors in each box). The detection system weighting approximately 107 kg also includes a laptop and a GPS unit. For the new software operating the IRIS detection system, a spectra library of selected radionuclides at chosen heights above the ground was created using a transport code MCNP6.1 [2, 3]. The MCNP model of IRIS was based on detector and photomultiplier tube sketches, box spatial parameters and comparison of measurements with simulations in selected point source geometries. The response of IRIS was scored using the F8 tally (pulse-height distribution) modified by the Gaussian energy broadening function.

3. Results and discussion

3.1. MCNP model

The mathematical model consists of four NaI(Tl) crystals and two boxes. Owing to the IRIS complexity, boxes variabilities were not included in the MCNP model, therefore cell copies of one box (Fig. 1) were used instead of two detailed boxes. Selected spatial parameters with corresponding labels are described in Table 1. For crystals, sodium iodine specifications were adopted from the PNNL Compendium [4] (material # 290). Several detector and box materials, their chemical compositions and densities were not exactly known. The box wall material was approximated by aluminum (material # 6). The amortization filling surrounding crystals was set as polyurethane foam (material # 253).

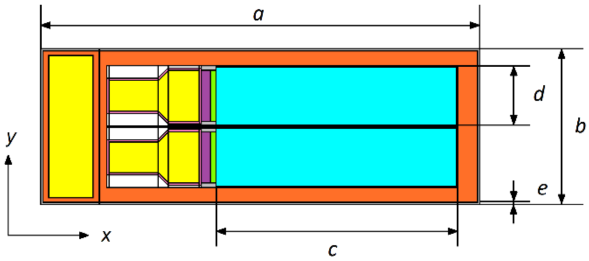


Fig. 1. MCNP model of IRIS

Table 1. Basis parameters of IRIS

Label	Parameter	Value [cm]
a	Box length	74,30
b	Box width	27,00
–	Box height	20,50
c	Crystal length	40,64
d	Crystal width	10,16
–	Crystal height	10,16
e	Wall thickness	0,30

3.2. Point source measurements and simulations

Two calibration sources of ^{137}Cs and ^{60}Co were located in four positions prior to the IRIS boxes at 50 cm and 1 m distances (Fig. 2). Using these geometries, eight separate measurements with sources (and one background measurement) were carried out. For comparison of acquired experimental spectra, simulations with the MCNP model of IRIS were performed. To accept the model, differences between measurements and simulations in full energy peaks not exceeding 10 % were required due to numerous spatial and material approximations. In order to compare with simulations, experimental spectra (after background subtraction) were normalized to source activities and measurement time. Reported results are summarized in Table 2. The relative values were arisen from the ratio of full energy peaks in spectra obtained from the simulations and measurements. Differences between full energy peak areas are in a range of 2–10 %, therefore the MCNP model was accepted for subsequent simulations. Selected experimental and simulated spectra of ^{60}Co (located centrally at 50 cm) are shown in Fig. 3.

Table 2. Peak area ratio of MCNP/experiment for selected source positions

Nuclide and source position	1 m, center	50 cm, center	50 cm, down	50 cm, on top
^{137}Cs, 662 keV	0,98	1,05	0,99	1,03
^{60}Co, 1173 keV	1,03	1,10	1,07	1,08
^{60}Co, 1332 keV	1,01	1,08	1,05	1,07

Fig. 2. Point source positions (to the left, not to scale), measurement with a source located centrally at 50 cm (to the right)

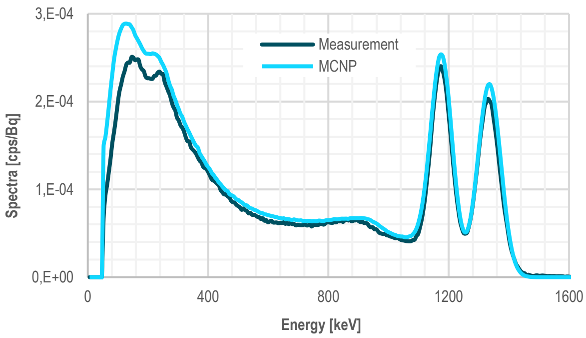


Fig. 3. Experimental and simulated spectra of ^{60}Co source located centrally at 50 cm

3.3. Set up of large semi-infinite sources

To assess semi-infinite source parameters (thickness and radius), two preliminary simulation tests with ^{40}K were carried out. In both tests, IRIS surrounded by air was in 1 m above the ground. For air and soil, materials # 4 and # 105 [4] were used. The ^{40}K source was homogeneously distributed in soil cylinders with altering thickness and radius. Depending on source parameters, IRIS changes in spectra were studied (after renormalization to source volume) relatively to responses to sources with maximum parameter values. In the first test, source thickness was varied from 1 cm to 2 m with fixed 1 m radius. Results of the first test are presented in Fig. 4. The IRIS response increases depending on soil thickness and reaches saturation at approximately 50 cm of source thickness with a spectra contribution loss of 3 %. At 1 m source thickness, the contribution loss does not exceed 1 %, therefore this thickness was chosen for subsequent large-scale sources simulations. In the second test, source radius was increased from 10 m to 50 m with constant 1 m thickness. The second test results are shown in Fig. 5. The response saturation was not reached and the response growth is expected for source radii larger than 50 m. However, differences between two responses decrease with radius increasing and the response difference between radii of 40 m and 50 m is less than 1 % (Table 3). From the results, the source radius of 40 m was chosen for following semi-infinite sources simulations for IRIS at 1 m above the ground.

Table 3. Spectra differences depending on ^{40}K source radius

Radius [m]	Spectrum ratio [-]	Spectrum difference [%]
10	0,92	–
20	0,96	4,12
30	0,98	2,00
40	0,99	1,23
50	1,00	0,70

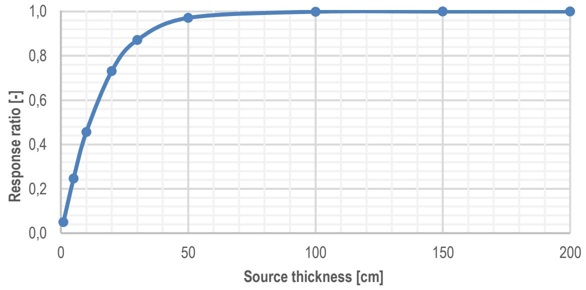


Fig. 4. Spectra changes depending on ^{40}K source thickness

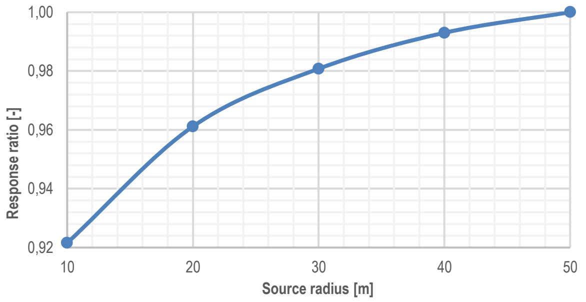
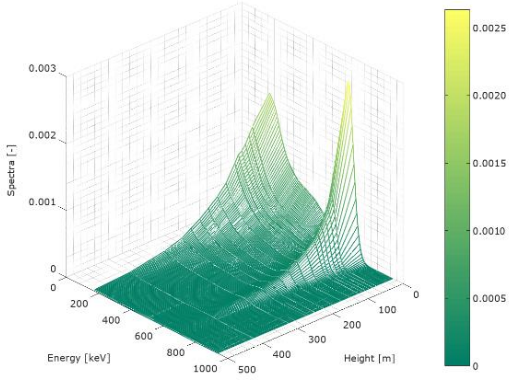


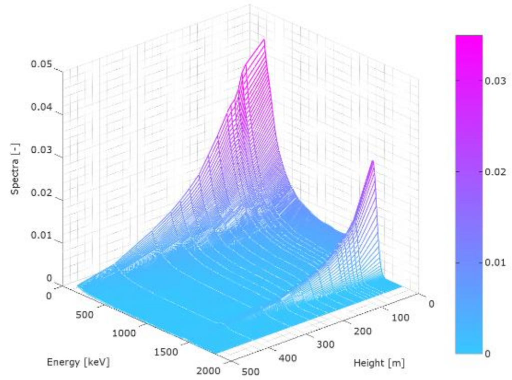
Fig. 5. Spectra changes depending on ^{40}K radius

3.4. Background simulations

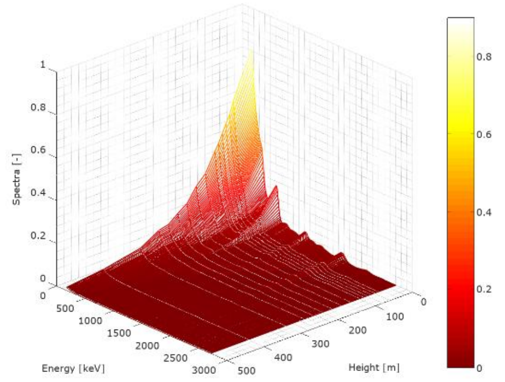
After semi-infinite source parameters determination simulations of spectra of ^{40}K, ^{226}Ra, ^{232}Th and ^{137}Cs were performed. For ^{226}Ra and ^{232}Th a secular equilibrium with daughter products was considered. In case of ^{40}K, ^{226}Ra and ^{232}Th, sources were homogeneously distributed in soil cylinders with 1 m thickness. For ^{137}Cs, exponential decline with soil depth (relaxation depth 3 cm) was used. In spectra simulations, thresholds were considered: an energy threshold of 30 keV and a yield threshold of 1 %, therefore in case of ^{226}Ra or ^{232}Th roughly 30 energies were simulated. Simulations were performed for IRIS heights 1–500 m above the ground (with source radii depending on detector height). Although variance reduction techniques, mainly dxtran spheres with weights, were used, estimated tally relative errors in the vast majority of simulations were above 1 %, therefore obtained spectra were additionally filtered. Spectra of selected radionuclides for heights 1–500 m are shown in Fig. 6. For better distinguishing, spectra are presented in different color schemes.



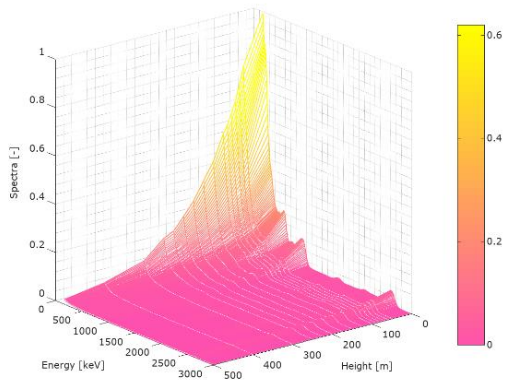
^{137}Cs – relaxation depth



^{40}K – homogeneous distribution



^{226}Ra – homogeneous distribution



^{232}Th – homogeneous distribution

Fig.6. Library spectra of ^{137}Cs, ^{40}K, ^{226}Ra, ^{232}Th for IRIS heights 1–500 m above the ground

3.5. Airborne measurements

During airborne measurements with point sources ^{137}Cs and ^{60}Co, IRIS was inside a Mil Mi-17 helicopter at chosen heights above the ground. Specific/surface activities of ^{40}K, ^{226}Ra, ^{232}Th and ^{137}Cs were provided from ground *in situ* measurements. For comparison with simulations, experimental spectra at approximately 100 m above the ground were used. Spectra of point sources of ^{137}Co and ^{60}Co were subsequently simulated at 100 m above the ground considering source materials and geometries and helicopter fuselage approximation (aluminum ellipsoid). To compare with measurements, simulated spectra of ^{40}K, ^{226}Ra, ^{137}Cs (Fig. 6) and spectra of point sources of ^{137}Cs or ^{60}Co were multiplied by known activities and summed together. Experimental and final simulated spectra of point sources of ^{137}Cs and ^{60}Co with natural background are presented in Fig. 7 and Fig. 8. For ^{137}Cs, the difference in the full energy peak is 7 %. In case of ^{60}Co peaks, differences are approximately 8 % and 6 %. The ^{40}K full energy peak is clearly observed in measured and simulated spectra of ^{137}Cs and ^{60}Co (Fig. 7 and Fig. 8). Peak differences in case of ^{40}K are 5 % and 6 % for ^{137}Cs and ^{60}Co spectra. Comparing spectra in a range of 40 keV – 3 MeV, both simulations lie below measurements in a region of lower energies. For ^{137}Cs, simulated spectrum is underestimated with a difference of 10 %; in case of ^{60}Co, undervaluation in the entire spectrum is around 20 %. Contribution losses in simulations are possibly implicated by yield thresholds and missing cosmic/radon contributions. However, differences in full energy peaks did not exceed 10 % and the required correspondence was achieved.

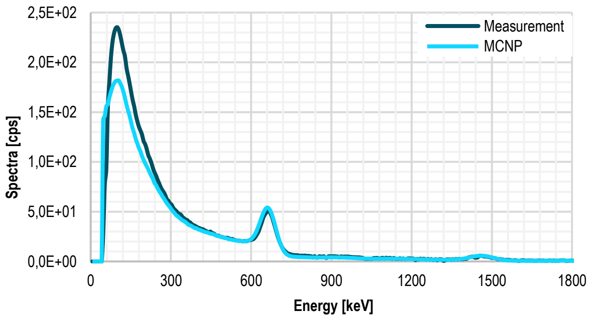


Fig. 7. Experimental and simulated spectra of a ^{137}Cs point source with natural background at 100 m above the ground

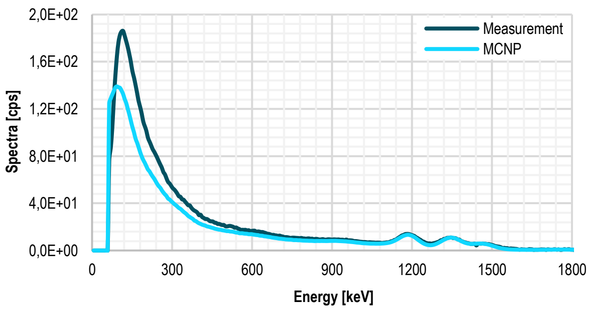


Fig. 8. Experimental and simulated spectra of a ^{60}Co point source with natural background at 100 m above the ground

4. CONCLUSION

The MCNP model of the IRIS detection system was created and tested with point sources and airborne measurements. Using the MCNP transport code, the library spectra of natural radionuclides and ^{137}Cs with relaxation depth 3 cm for aerial gamma spectrometry were obtained. Despite of numerous model approximations, the model demonstrates good agreement between measurements and simulations. Full energy peak differences between measurements and simulations do not exceed 10 % in case of ^{137}Cs, ^{60}Co and ^{40}K. Among following research efforts belong simulations of selected artificial radionuclides typical for radioactive releases and nuclear accidents (surface plane sources).

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АУА ГАММА-СПЕКТРОМЕТРИЯСЫНА АРНАЛҒАН МОНТЕ-КАРЛО ӘДІСІ БОЙЫНША МОДЕЛДЕУ

А. Селиванова, М. Охера, И. Чеспирова, Л. Грыц

Ұлттық радиациялық қорғау институты, (SURO), Прага, Чехия

Мақалада Монте-Карло әдісін қолдана отырып IRIS интегралдық жүйесін есептік моделдеу нәтижелері ұсынылған. Жүйенің ойдағыдай жұмыс істеуі үшін кеңістіктегі белгілі бір жағдайларға арналған радионуклидтер спектрінің кітапханасы құрылды. Моделді пысықтау нәтижелері заттай алынған өлшемдер нәтижелерімен жақсы үйлесетінін көрсетті.

МОДЕЛИРОВАНИЕ ПО МЕТОДУ МОНТЕ-КАРЛО ДЛЯ ВОЗДУШНОЙ ГАММА-СПЕКТРОМЕТРИИ

Селиванова А., Охера М., Чеспирова И., Грыц Л.

Национальный институт радиационной защиты (SURO), Прага, Чехия

В статье представлены результаты расчетного моделирования интегральной системы IRIS с использованием метода Монте-Карло. Для успешного функционирования системы была создана библиотека спектров радионуклидов для определенных пространственных условий. Результаты отработки модели продемонстрировали хорошее согласие с результатами натурных измерений.