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Removing the dose background from radioactive sources from active dose rate measurements in the Lunar Lander Neutron & Dosimetry (LND) experiment on Chang'E 4

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Abstract: The Lunar Lander Neutron & Dosimetry (LND) experiment is part of the scientific payload of the Chinese Chang'E 4 spacecraft which landed on the Moon on January 3, 2019. The LND measures the radiation environment on the surface of the moon in preparation of future manned missions to the Moon. There are, however, also four radioactive sources on the lander, a radioisotope thermoelectric generator (RTG) and three radioisotope heater units (RHUs) which provide heat and power for the instruments on the Chang'E 4 lander. The radiation emitted by these radioactive sources leads to a non-negligible background which interferes with the measurements of LND.

The aim of this paper is to describe the method that how to remove the background from these radioactive sources on the Chang'E 4 lander. We measured the effect of the RTG and RHUs on LND in a laboratory on Earth which is a very different environment from that on the Moon. We discuss how to take these major differences into account using a combination of scaling laws and Monte-Carlo simulations.

Keywords: Models and simulations; Radiation calculations; Particle detectors; Space instrumentation

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Contents

1 Introduction

The Lunar Lander Neutron & Dosimetry (LND) experiment (as shown in figure 1) [1] on China's Chang'E 4 spacecraft which landed on the Moon on January 3, 2019. LND was designed and selected to measure both the charged and neutral particle radiation environment on the lunar surface in preparation of human exploration. In order to survive the very cold and long lunar nights, the Chang'E 4 lander spacecraft relies on a combination of one radioisotope thermoelectric generator (RTG) and three radioisotope heater units (RHU1-3). These contribute a significant background to the LND measurements of absorbed dose rate which needs to be accounted for in order to provide an accurate assessment of the lunar radiation environment. LND was calibrated in a heavily shielded nuclear facility in Tianjin, China, and is now measuring the radiation environment on the far side of the Moon. Thus, the calibration environment was characterized by a full containment of the experiment, while half of its current measurement environment on the Moon points towards open space. This may be an extreme example for the differences between calibration of a nuclear detector and its final use, but nevertheless, it serves as an instructive example on how to account for such differences.

The active component of the four radioactive sources (one RTG, three RHUs) is plutonium oxide ($^{238}PuO_2$), which provides heat and power through the α decay of ^{238}Pu. The radioactive sources continuously produce neutrons and gamma-rays [2]. These particles are highly penetrating and can pass through the various shielding and spacecraft structures and cause a substantial background which is also measured by LND. The backgrounds to LND's measurements contributed by each radioactive source were measured with LND as well as with a Bonner sphere and a gamma dosimeter in the summer of 2018, i.e., shortly before launch (December 7, 2018). These measurements provide an accurate calibration of the RHU/RTG induced background, including spectra of the energy depositions in individual detectors, as well as LND's scientific data [1]. The RTG and RHU1 have the same power (120W) and RHU2 and RHU3 are both identical, smaller heater units of 5W each.

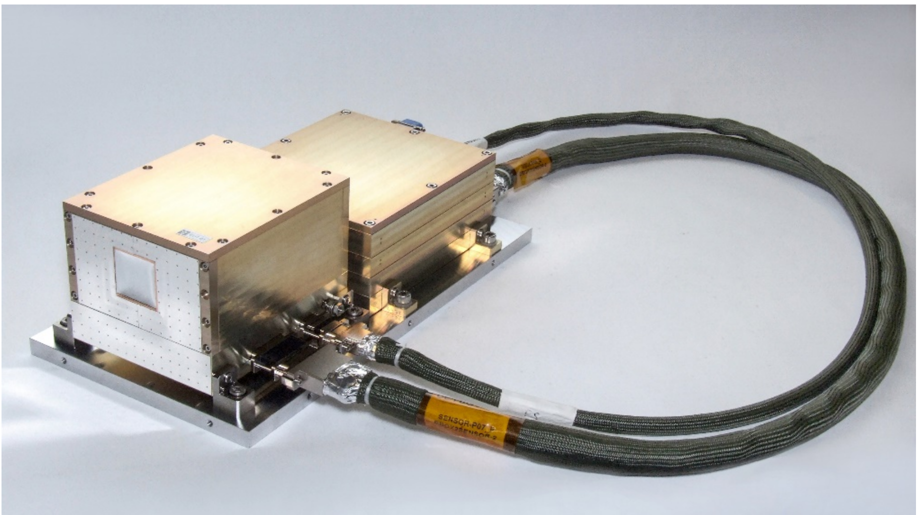

Figure 1. The Lunar Lander Neutrons & Dosimetry (LND).

The half-life of ^{238}Pu for radioactive α-decay is 87.7 years [3]. Within the decay chain, neutrons are produced by (α, n) reactions. The (α, n) reactions with low Z isotopes (especially ^{17}O/^{18}O, as this reaction is energetically not allowed for ^{16}O.) in RTG/RHUs is the primary source of the neutron background. Another neutron source of the RTG/RHUs is the spontaneous fission of ^{238}Pu with a half time of 5×10^{10} years [4]. Because this is much longer than the α-decay half -life, we have neglected it in the further considerations. The reactions producing the gamma-ray background from the RTG/RHUs are similar to the those for the neutron background mentioned above and include (1) spontaneous fission of ^{238}Pu; (2) induced fission; (3) (α, nγ) reactions with light elements present in the RTG/RHUs, especially ^{17}O/^{18}O. In addition to these reactions, radioactive decay always produces gamma rays to allow the nucleus to de-excite [5]. The exact amount of the RTG and RHU's plutonium, as well as detailed information about its interior position and the shielding provided by the RTG and RHUs are, however, not known to us. Therefore, we did not model the (unknown) internal structure of the RTG/RHUs, but used published measurements of the gamma-ray spectra of the RTG [10] used by the ESA/NASA Ulysses space mission [11]. We scaled it to the measurements acquired with LND at the Tianjin facility. For the neutrons, we used the spectrum published by Taherzadeh [4], who measured it for plutonium dioxide fuel, and scaled it to the LND data. Because the half-life of ^{238}Pu is much longer than the mission lifetime of Chang'E 4, we may consider the background radiation caused by the RTG/RHUs to be comparatively stable and we can estimate the background radiation of LND on the lunar surface using ground test results from Earth after the corrections discussed in the following sections.

2 Radioactive source background test: measurements

LND's sensor head consists of ten silicon solid-state detectors (A-J) [1], each 500 microns thick. The second detector, B, is used for measuring the total absorbed dose rate on the lunar surface. The detectors B, C, and D are packed as close together as possible as shown in figure 2. We define the inner segment of C as C_1 and the outer one as C_2. The neutral particles are determined by measuring the energy deposition in C_1 in anti-coincidence with detectors B and D as well as C_2. So the absorbed dose rate of neutral particles selected by $C_1\,\overline{BDC2}$ can be called neutral absorbed dose rate.

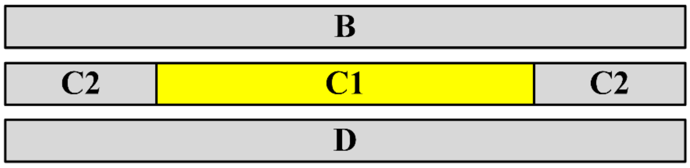

Figure 2. LND measures neutral particles with the inner segment of detector C, C1, in anti-coincidence with all surrounding detector segments (B, D, and C2).

During the calibration measurements, all unnecessary equipment was removed from the test room to simplify the setup as much as possible. LND was placed in the correct positions and orientations with respect to the RTG/RHUs and, when appropriate, aluminum shielding was added to simulate the shielding between RTG/RHUs and LND in the Chang'E 4 lander. The omni-present background from cosmic rays and natural activity was accounted for by subtracting data from background runs without the RTG/RHUs. For these background runs LND was kept in the same position and orientation as for the runs with the respective RTG/RHUs. Figure 3 shows the spectra acquired with the B detector (magenta solid line) and the C1 detector segment (blue solid line) with the RTG present. The corresponding background measurements are shown as dashed lines. The signal is clearly substantially larger than the natural background present in the calibration facility, which illustrates the importance of accounting for the influence of the RTG and RHUs in the measurements on the Moon. A photograph of the experimental setup for this case is shown in figure 4. This procedure was repeated for the three RHUs.

Absorbed dose is the energy deposited in a medium by ionizing radiation per unit mass. Thus, the absorbed dose [6] to Silicon (unit: μGy) is given by the equation

$$\text{Absorbed Dose} = 1.602 * 10^{-7}\,(\mu\text{Gy}) * \Delta\,(\text{MeV})\,/\Delta\text{M}\,(\text{g}) \tag{2.1}$$

where ΔE is the total deposited energy in keV, and ΔM is the mass of detector in grams.

Table 1 lists the total absorbed dose rates measured by the LND's B detector with the RTG/RHUs present, the corresponding background absorbed dose rate, as well as the differences, i.e., the absorbed dose rates due to the neutrons and gamma rays emitted by the RTG/RHUs. Similarly, the results of neutral radiation dose rates detected by C1 are shown in table 2.

Due to the different activities of the four sources and the relative position of the LND, their contribution to the background of LND is also different. The background caused by the RHU2 and RTG is the main factor. The experimental results in table 1 show that the total absorbed dose rate of the RTG/RHUs on LND is 6.18 ± 0.15 μGy/h, and the neutral absorbed dose rate from the RTG and RHUs at the Tianjin facility is 2.13 ± 0.12 μGy/h. In the following we will derive an estimate for this background on the Moon.

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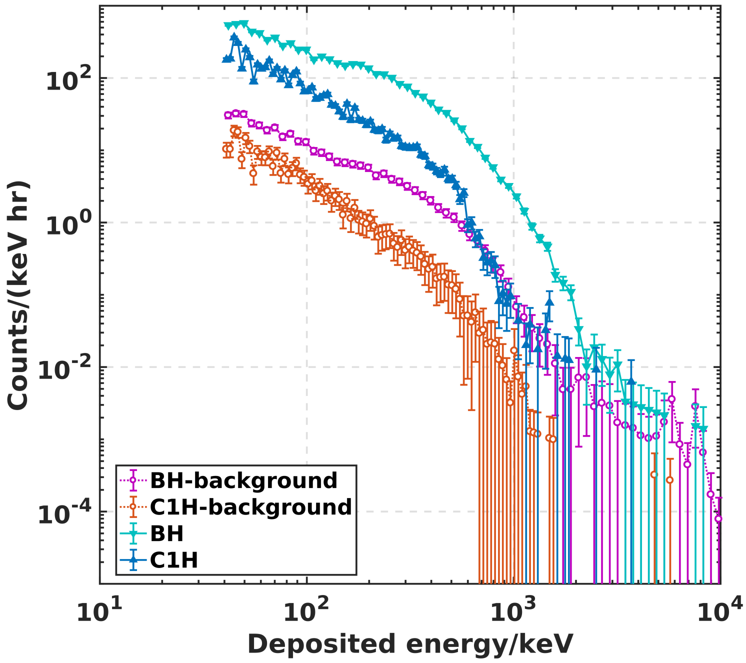

Figure 3. The deposited energy spectrum in detector B and C1 with the Chang'E 4 RTG present (solid lines, filled symbols) and the corresponding background measurements (dashed lines, empty symbols). The Green solid line shows the spectrum of energy deposited in the B detector, while the blue solid line shows the spectrum of energy deposited by neutral particles in detector C1, i.e., using the anti-coincidence discussed in the text. The dashed curves show the corresponding background measurements.

Figure 4. Test setup for the RTG in the Tianjin facility. LND is on the right of the yellow vehicle, while the RTG is set on the black laboratory table. The Al plate also on the right corner of the yellow vehicle, is mounted between the RTG and LND to mimic the shielding by the Chang'E 4 lander vehicle.

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Table 1. Total absorbed dose rate for RTG/RHUs measured in B. Dr = absorbed dose rate.

Radioactive source	Dr_B/(μGy/h)	Dr_{bkgnd}(μGy/h)	$Dr_B - Dr_{bkgnd}$
RTG	2.21 ± 0.08	0.11 ± 0.03	2.10 ± 0.09
RHU1	0.74 ± 0.05	0.11 ± 0.03	0.63 ± 0.06
RHU2	2.22 ± 0.08	0.11 ± 0.02	2.11 ± 0.08
RHU3	1.45 ± 0.06	0.11 ± 0.02	1.34 ± 0.06
total	6.62 ± 0.11	0.44 ± 0.05	6.18 ± 0.15

Table 2. Total (neutral) absorbed dose rate for RTG/RHUs measured in C1.

Radioactive source	Dr_n (μGy/h)	$Dr_{n,bkgnd}$ (μGy/h)	$Dr_n - Dr_{nbkgnd}$
RTG	0.72 ± 0.07	0.03 ± 0.02	0.69 ± 0.07
RHU1	0.24 ± 0.04	0.03 ± 0.02	0.21 ± 0.04
RHU2	0.76 ± 0.07	0.03 ± 0.01	0.73 ± 0.07
RHU3	0.53 ± 0.06	0.03 ± 0.01	0.50 ± 0.06
total	2.25 ± 0.12	0.13 ± 0.03	2.13 ± 0.12

3 Simulation of the laboratory setup

In the Tianjin calibration, radiation was emitted in all directions, not necessarily isotropically, because of the internal structures and self-shielding of the RTG and RHUs. Neutrons and gamma rays which have scattered of the walls, ceiling, and floor contribute to the measurements made by LND. On the lunar surface, however, there is no scattering off the walls and ceiling, but only off the lunar surface on which Chang'E 4 landed. Therefore, we need to determine the fraction of the particles detected by LND which were not scattered (i.e., came directly from the source) or were only reflected off the floor, as opposed to all particles which could reach LND. The simulation of this Tianjin calibration test is described below, some sample particle trajectories are indicated in figure 5.

The simulation model was set up as shown in figure 6. We used a custom GEANT4 setup with QGSP_BERT_HP, which at lower energies uses the High Precision neutron models and cross section data based on the ENDF/B-VII [8, 9]. We tracked every particle so as to know the path by which it reached LND, i.e., whether they hit LND directly or were scattered of the floor, walls, or ceiling. This was done for all four sources.

We recorded all particles which hit LND and were detected in detector C1 only (i.e., a neutral particle) or in detector B. For particles detected in B, we added the energy deposition to the energy already accumulated in B (to derive the total absorbed dose in B). For particles detected in C1 only, we accumulated the "neutral dose" as well. Subsequently, we filtered for those particles which hit B (C1) directly (i.e., without scattering off the walls, ceiling, or floor) and those which reached B (C1) via walls, ceiling, and floor, keeping track of which was their first scattering "surface". If their first scattering was on the ceiling or walls, their contribution was accepted for the simulation of the laboratory situation, but not for the simulation of the Moon. If their first and only scattering

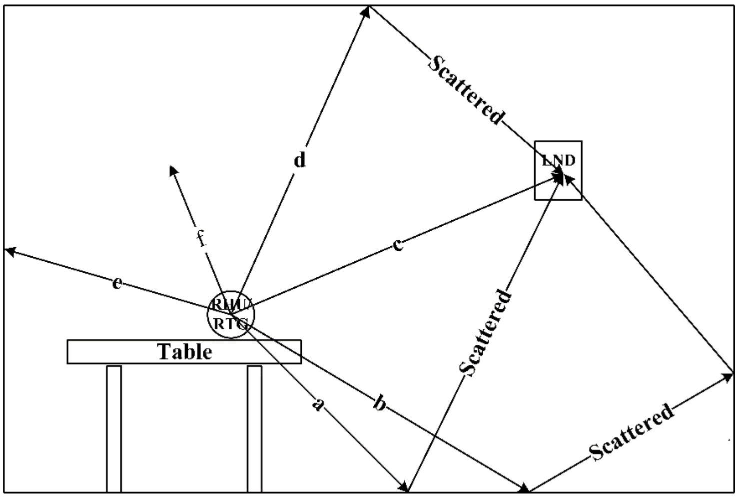

Figure 5. Illustration of the scattering by floor, walls, and ceiling of the test facility. This scattering results in an enhanced background compared to the situation on the Moon. Trajectories ‘a’ stands for the particles that only scattered by floor before entering LND; trajectories ‘c’ stands for the particles enter LND directly without scattering; trajectories ‘b’, ‘d’ stand for the particles that scattered by walls or ceiling before entering LND; trajectories ‘e’ stands for particles ‘absorbed’ by floor, walls or ceiling; ‘f’ stands for the particles that scattered by atmosphere.

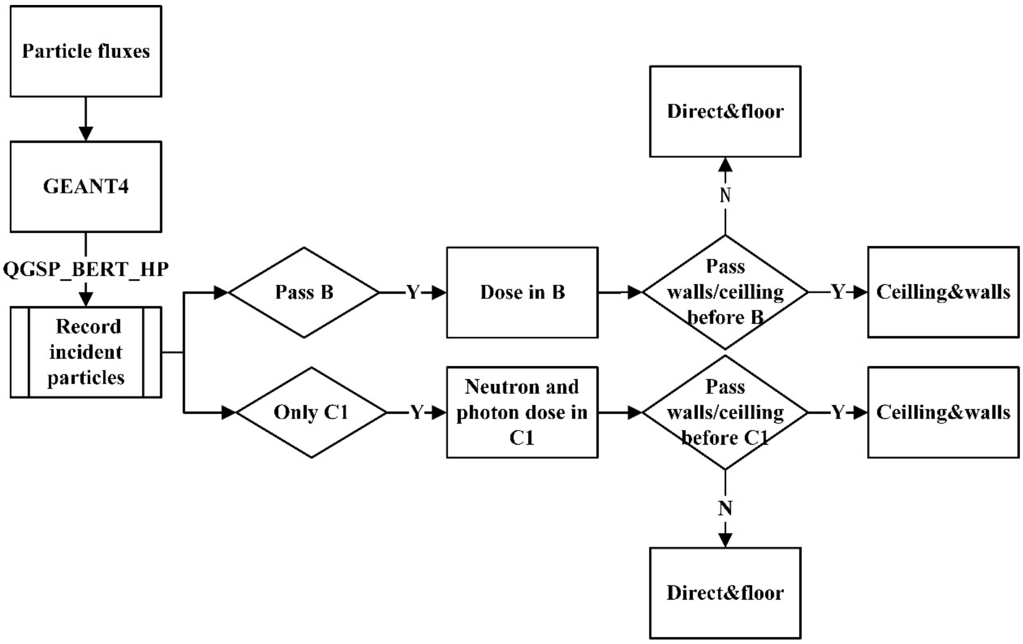

Figure 6. Logic schematic diagram of simulation.

“surface” was the floor, or they reached LND without scattering, they were accepted for both cases. All other cases were only accepted for the simulation of the laboratory situation. This allows us to discriminate between the situation for the Moon and the laboratory using the same (time consuming) simulation. In other words, we only had to simulate the (more complicated) laboratory setup, but

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not the Moon, which saved considerable computation time. In fact, the composition of the lunar soil and concrete is not exactly the same (especially for water content), so the scattering effect on the neutrons and gamma rays is also different. The Monte Carlo program was used to simulate the lunar soil [12] and concrete [7, 8], using the very much simplified geometry as shown in figure 7. We use the neutron (gamma) spectrum of PuO_2 for concrete and lunar soil simulation. We define the dose ratio=dose(lunar)/dose(concrete), so the dose ratio in detector B is DR_B, while the neutral dose ratio in detector C is DR_C. The results are shown in the table 3.

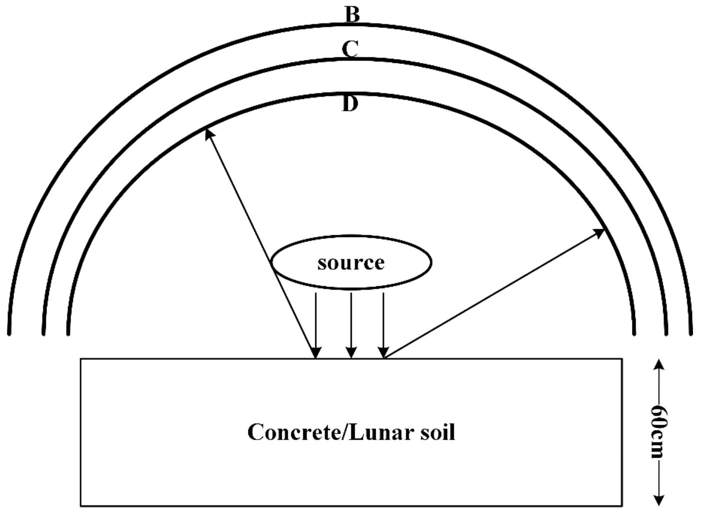

Figure 7. The simplified geometry for the simulation of concrete and lunar soil. B,C,D are three Si detectors with the thickness of 0.5 mm. If the particles pass the detector B/C/D, the particles are considered to be scattered by concrete/Moon.

Table 3. The simulation results for neutron and gamma scattered by lunar soil or concrete. Dose ratio (DR) = Dose(lunar)/Dose (concrete).

Particle type	DR_B	DR_C
Neutron	59% ± 7.6%	100% ± 16%
gamma	88% ± 11%	92% ± 10%

4 Results

In this section we compare the simulation and the measurements results of Tianjin calibration test. For the rest of this paper we introduce the following notation $A_{b,e}(s)$, where the 'A' stands for the dose rate (measurements (M) or simulations (S)); the 'b' stands for the type of particles (neutrons or gamma rays); the 'e' stands for the environment (lab, floor, ceiling, etc.); and 's' is the type of source (RTG, RHU1-3). For example, some specific definitions of RHU2 and RHU3 are shown in table 4.

We simulated neutron and gamma radiation emitted by the RTG and three RHUs. Consider, for example, the gamma-ray spectrum of RHU2. From our simulations we can determine the energy

Table 4. Some specific definitions of RHU2 and RHU3. In the definition, 'M' stands for measurements, 'S' stands for simulation; 'n' stands for neutron, 'g' stands for gamma; 'ng' stands for neutron *and* gamma, 'df' stands for the particles that entered detector directly (d) or only passing through the floor (f) before entering detector, 'cw' stands for the particles that pass through ceiling or walls before entering detector, 't' stands for 'total', i.e., all particles that entered detector.

Source	Measure	Simulate(direct/floor)	Simulate(ceiling/walls)	Simulate(total)
RHU2	$M_{ng,lab}(RHU2)$	$S_{g,df}(RHU2)$	$S_{g,cw}(RHU2)$	$S_{g,t}(RHU2)$
		$S_{n,df}(RHU2)$	$S_{n,cw}(RHU2)$	$S_{n,t}(RHU2)$
RHU3	$M_{ng,lab}(RHU3)$	$S_{g,df}(RHU3)$	$S_{g,cw}(RHU3)$	$S_{g,t}(RHU3)$
		$S_{n,df}(RHU3)$	$S_{n,cw}(RHU3)$	$S_{n,t}(RHU3)$

deposited in detector B, and convert it to the (simulated) dose (rate) measured by B by dividing by its mass (and exposure duration). This can be done for all particles (i.e., the laboratory condition) or only those particles which hit B directly or only via the floor of the laboratory (as on the Moon). Because we simulate the radiation dose measured with the LND B detector, we can easily filter out all gamma rays which were scattered by the walls and ceiling of the test room. The radiation dose produced by the particles which entered detector B directly or only passing through the floor before entering detector B is $S_{g,df}(RHU2)$. Similarly, we can simulate the radiation dose which produced by same number(N) of neutrons, and their direct contribution to the radiation dose, $S_{nd(RHU2)}$, or the one via the floor, $S_{nf(RHU2)}$.

For each of the four sources (RTG, RHU1, RHU2, RHU3) we have the measured dose rates in B and C1. In the following, we will attempt to derive a weighting factor x (y) for gamma rays (neutrons) which is equivalent to the probability of measuring a gamma ray (neutron) from the RTG/RHU, as shown in eq. (4.1) and eq. (4.2). It turns out that we only need to determine the ratio m = x/y, as we shall see shortly in eq. (4.3) and eq. (4.4).

$$x = N_{gamma}/N_t \tag{4.1}$$

$$y = N_{neutron}/N_t \tag{4.2}$$

where N_{gamma} is the number of gamma from RTG/RHU in one hour, and $N_{neutron}$ is the number of neutron from RTG/RHU in one hour, and $N_t = N_{neutron} + N_{gamma}$. So '$S_{g,t}(RHU2) \times (x \times N_t)/N$' is the dose rate due to gamma rays emitted by RHU2 in the simulation.

RHU2 and RHU3 are identical for our purposes (and have the same heating power of 5W), and so we can use the following formulas (4.3) and (4.4) to calculate the ratio of weighting factors for neutrons and gamma rays, m = x/y,

$$S_{g,t}\,(RHU2) * (x * N_t)/N + S_{n,t}\,(RHU2) * (y * N_t)/N = M_{ng,lab}\,(RHU2) \tag{4.3}$$

$$S_{g,t}\,(RHU3) *(x*N_t)/N + S_{n,t}\,(RHU3) *(y*N_t)/N = M_{ng,lab}\,(RHU3) \tag{4.4}$$

From our simulations we can derive the ratio of doses from gamma rays (neutrons) which hit an LND detector directly or via a single scattering with the dose rate from all gamma rays (neutrons) which interact with that detector. This probability, P_{RHU2} is given by eq. (4.5) below.

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From table 1, we can take the background-corrected value for $M_{ng,lab}$ (RHU2) (2.11 ± 0.08 μGy) and multiply it by P_{RHU2} (97%) to obtain the expected value for the radiation background due to RHU2 on the Moon. These corrected values are given in table 4, the total background due to the combination of RTG and RHUs is 5.20 ± 0.56 μGy/h.

$$P_{RHU2} = (m * S_{g,df}(RHU2) + S_{n,df}(RHU2))/(m * S_{g,t}(RHU2) + S_{n,t}(RHU2)) \tag{4.5}$$

$$D_{Moon2} = M_{ng,lab}\,(RHU2) * P_{RHU2} \tag{4.6}$$

Table 5. Result for radiation dose rates in B for direct/floor from RTG/RHU.

Radioactive source	P_{RX}	Lunar background (μGy/h)
RTG	74%	1.56 ± 0.29
RHU1	51%	0.32 ± 0.11
RHU2	97%	2.05 ± 0.35
RHU3	95%	1.27 ± 0.3
total	/	5.20 ± 0.56

As discussed for the example of RHU2, the probabilities for direct or single-bounce contributions to the dose rate in B, P_{RX}, are shown in the second column of the table 6. The third column is the thus corrected contribution of the RTG or RHUs to the measured dose rate on the Moon. Obviously, although the radioactive sources RTG and RHU1 have the largest heating power (120 W), the probability to detect their radiation in LND is quite different, which is due to the different distances and shielding between them and the LND. Moreover, because LND is much farther away from RHU1 than from the RTG, the contribution of radiation scattered by the walls and ceiling is higher than for the RTG and our simple model may not be very accurate for this large difference in distances. Because the contribution from RHU1 is also small compared to the others, we include this uncertainty in our error estimate. But for RHU2 and RHU3, the radiation dose rate measured in Tianjin is dominated by the particles which reach LND without scattering off the walls or ceiling, because of the closer distance between the two radioactive sources and LND.

The radiation dose rates from the RTG/RHUs measured in C1 show similar results as the radiation dose rates for B analyzed above. We use the same method to calculate the neutral channel (C1) efficiency of background radiation dose rates from the RTG/RHUs. The results are shown in table 6. The total neutral radiation dose rate is 1.69 ± 0.46 μGy/h.

Table 6. Result of neutral radiation dose rates direct/floor from RTG/RHUs.

Radioactive source	P_{RX}	Moon background (μGy/h)
RTG	64%	0.44 ± 0.37
RHU1	30%	0.06 ± 0.10
RHU2	97%	0.71 ± 0.19
RHU3	96%	0.48 ± 0.17
total	/	1.69 ± 0.46

5 Error estimation

While an exact quantification of the errors associated with the many steps of the procedure described in this paper is probably not possible, we attempt to estimate them as well as we can. There are a number of sources of errors, some physical, some statistical, and some from modeling, which we summarized in the following. The room in which the RTG/RHU calibrations was simplified for our simulations, we did not simulate every corner and door. We account for this uncertainty with an overall 3% error. Similarly, the spectrum of the RTG and RHUs is unknown to us but we use the one for ESA's Ulysses mission [11] and Taherzadeh measured [4]. We account for this uncertainty by an overall 5% error. Finally, GEANT4 itself is not free of uncertainties and we include another 5% error to account for this. Adding quadratically, we arrive at an error estimate of 7.7%. The uncertainties given in tables 1, 2, 5 and 6 were calculated using standard error propagation for equations (4.3), (4.4), and (4.5) to arrive at a final error of 0.56 μGy/h for detector B and 0.46 μGy/h for detector C1.

6 Summary and conclusions

In this paper we have used the LND instrument aboard Chang'E 4 to describe how the background from RTG and RHUs in measured dose rates can be corrected based on simulations and calibrations. The method involves measuring and modeling the background from each RTG/RHU in a calibration facility. The situation in free space (or in our case on the Moon) can not be calibrated without breaking strict regulations in radiation protection legislation, but it can be simulated. We have shown that carefully keeping track of the simulated radiation allows us to reuse the same simulation as performed for the calibration facility and simply ignore those particles that reached the detector via interactions with the walls or ceiling. This method allowed us to provide an estimate of the radiation background due to the RTG and RHUs,

Previous measurements by Chandrayaan-1 and LRO of the dose rate in lunar orbit values range from 9 to 13 μGy/h for the total dose rate from charged and neutral particles. We found a value of 5.2 ± 0.56 μGy/h for the total dose rate due to the RTG and RHUs, while their contribution to dose rate from neutral particles (neutrons and gamma rays) was 1.69 ± 0.46 μGy/h. This is a substantial contribution and the background corrections discussed in this paper are indeed important.

Acknowledgments

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References

[1] R.F. Wimmer-Schweingruber et al., *The Lunar Lander Neutron and Dosimetry(LND) Experiment on Chang'E 4*, manuscript to be submitted to *Space Sci. Rev.* (2019).

[2] V.P. Chechev et al., *The Evaluation of 238Pu, 240Pu, and 242Pu Decay Data*, in *AIP Conference Proceedings. Vol. 769: International Conference on Nuclear Data for Science & Technology*, American Institute of Physics, College Park U.S.A. (2005).

[3] NuDat2.5., http://www.nndcbnl.gov/nudat2/ (2011).

[4] M. Taherzadeh and P.J. Gingo, *Neutron Radiation Characteristics of Plutonium Dioxide Fuel*, *Nucl. Technol.* **15** (1972) 396.

[5] R.A. Neff, M.E. Anderson, A.R. Campbell and F.X. Haas, *Some Neutron and Gamma Radiation Characteristics of Plutonium Cermet Fuel for Isotopic Power Sources*, in *Proceedings of the National Symposium on Natural and Manmade Radiation in Space*, Washington U.S.A. (1972), pg. 853.

[6] C. Zeitlin et al., *Comparisons of high-linear energy transfer spectra on the ISS and in deep space*, *Space Weather* **17** (2019) 396.

[7] R. Khabaz, *Analysis of neutron scattering components inside a room with concrete walls*, *Appl. Radiat. Isot.* **95** (2015) 1.

[8] Geant4 collaboration, *Geant4's Guide for Application Developers*, Version Geant4.10.0 (2013).

[9] G.F. Cao et al., *Test of hadronic interaction models in GEANT4 at low energy using the BESIII data*, *Nucl. Instrum. Meth.* **A 606** (2009) 700.

[10] E.A. Hawley, *Radiation Measurements on the Qualification RTG*, Technical report (1984).

[11] K.-P. Wenzel, R.G. Marsden, D.E. Page and E.J. Smith, *The Ulysses Mission*, *Astron. Astrophys. Suppl.* **92** (1992) 207.

[12] R. Battiston, M.T. Brunetti, F. Cervelli, C. Fidani and M. Menichelli, *A Moon-borne electromagnetic calorimeter*, *Astrophys. Space Sci.* **323** (2009) 357.

2020 JINST 15 P01032