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Monte Carlo simulations of the High Energy X-ray spectrometer (HEX) on Chandrayaan-I

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Abstract. This paper addresses the requirements for designing a space-based, low energy (30-270 keV) γ-ray experiment, using laboratory calibration data and Monte Carlo simulation tools.

Keywords : Chandrayaan-I, HEX, Monte Carlo simulation

1. Introduction

Chandrayaan-I (Goswami et al. 2009) was India's first mission to the Moon and HEX (High Energy X-ray Spectrometer) (Sreekumar et al. 2009) was one of the eleven instruments flown on it. HEX was designed to measure the intensity of lunar X-rays and γ-rays in the energy range 30-270 keV. The compound semiconductor, CZT (Cadmium-Zinc-Telluride) was used for spectroscopy purposes. For such an instrument immersed in the dynamic space-radiation environment, one of the steps of payload design was to determine the detector background and use the knowledge to optimize experimental design. The HEX background consists of radiation interacting directly with the detector and with materials surrounding it, producing secondary radiation, which then enters the detector. In order to suppress this background, the CZT detector was provided with an anti-coincidence detector (ACD) system, which consisted of CsI(Tl) scintillators coupled with photomultiplier tubes. Due to spacecraft constraints, it was required to optimize the design of HEX with regard to the ACD system, the heaviest subsystem of the payload. The optimization was carried out using the Monte Carlo simulation toolkit Geant4 (Agostinelli et al. 2003), keeping in mind the effects of design change on the science goals. As a part of determination of CZT background and background rejection efficiency (BRE) of the ACD, the response of the two detectors were modeled using laboratory calibration data and the

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Table 1. Tabulations of the simulation results for ACD geometry optimization.

N[a]	CSE%	CSE %/kg
5	21	8.03
4	5	–
1	16	7.21

Notes: (a) this column labeled by 'N' indicates the number of components that make up the configuration.

Geant4 toolkit. The following sections will discuss the above, and will include the results from the HEX background modeling and the contribution of this work to the HEX experiment as well as to space science missions.

2. Detector design optimization

Three different geometries of the CZT-ACD combination were modeled using Geant4; an ideal 5-component geometry, where CsI(Tl) crystals surround the CZT detector, a 4-component geometry, where the crystals cover 4 lateral sides of the CZT and a 1-component geometry where a single CsI(Tl) crystal covers the bottom of the CZT detector. The design optimization was constrained using the Compton scattered continuum; one can define the **Compton suppression efficiency** (CSE)

$$\mathrm{CSE}\% = \frac{C_{\mathrm{noACD}_{\Delta E}} - C_{\mathrm{ACD}_{\Delta E}}}{C_{\mathrm{noACD}_{\Delta E}}} \times 100\% \qquad (1)$$

where $C_{\mathrm{noACD}_{\Delta E}}$ are the counts in CZT energy spectrum without ACD, $C_{\mathrm{ACD}_{\Delta E}}$ are the counts in CZT energy spectrum with ACD, ΔE is energy range of interest. A cut-off CSE of 10% was defined as a bench-mark for selection. In order to take into account possible different thickness of the selected ACD geometry, the computed CSE was normalized with mass to get CSE in %/kg.

For each case, the CSE was computed and tabulated in Table 1; it can be seen that the CSE %/kg for the 1-component geometry is not very different from the ideal one, while the CSE due to the 4-component geometry contribute below CSE cut-off. Therefore, by eliminating the 4 side mounted ACDs, one can achieve a 41.7% reduction in weight of the system. Once the number of components in the ACD unit was frozen, the same technique was used to optimize the thickness of the detector. Balancing between the cut-off CSE criterion and maximum CSE %/kg, it was found that an ACD thickness of 1 cm was optimum. The weight reduction then achieved was 60.2%. Thus, the optimum design of a 1-component ACD consisting of a 1 cm thick CsI(Tl) crystal was chosen for the final flight design.

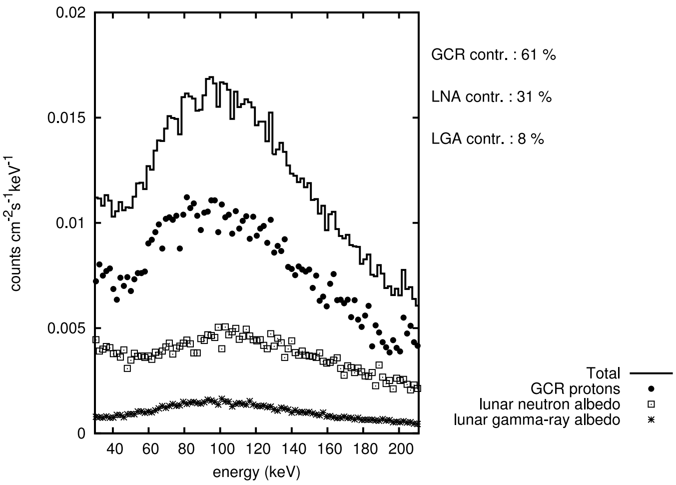

Figure 1. The total CZT background is represented by the solid line, the closed circles represent the contribution due to GCR protons, the open squares represent the contribution due to LNA, and the asterisks represent the contribution due to the LGRA.

3. Modeling the detector response

The CsI(Tl) scintillator was calibrated as a function of incident photon energy and position on the crystal surface with respect to the photomultiplier tubes. The response of the CZT detectors were studied as a function of energy and temperature. The response of the two detectors were parameterized and included in Geant4 applications specific to each detector. The physical model of the detector geometries were modeled in the corresponding application. Photons of specific energies were made incident on each detector and the energy deposition spectra were determined. Comparison of the modeled spectra with experimentally measured spectra revealed good matches, and thus helped build confidence in the modeling methodology and was important to predict the CZT detector background and ACD BRE.

4. Background modeling

Using Geant4, the physical geometry of the Chandrayaan-I spacecraft and the HEX payload were modeled. Some of the approximations were, (i) apart from the HEX payload, none of the other instruments or other subsystems of the spacecraft were included in the model and (ii) the space-radiation sources used for the background modeling were the galactic cosmic ray (GCR) spectrum for average solar activity (Reedy 1987), lunar γ-ray albedo (LGRA) (Banerjee & Gasnault 2008) and lunar neutron albedo (LNA) (Adams et al. 2007). The CZT and ACD system responses were included in the application. Figure 1 shows the result of the background simulation and as can be seen, the contribution to the total background due to the GCR component dominates at 61% while that due to LGRA contributes only 8% to the total background. The output of the ACD is read out into 4 channels ranging from 30 keV to >250 keV, each having a width of 100 keV. The background modeling showed that the ACD channel ranging from 170-250 keV showed the highest intensity of events coincident with CZT events. The simulation therefore would help in selecting the ACD channel which has the highest BRE.

5. Conclusions

Modeling the HEX background is a composite work that started with the validation of different aspects that would be used as input to the simulation. All these steps culminated with an estimation of the revised background calculation and prediction of the BRE of the ACD. This would help in computing line sensitivities of the various lunar γ-rays of interest in the 30-270 keV range. The HEX CZT background measured in space was found to be ~3 times larger than that estimated in the present work; the reasons for this may lie in the approximations made in the spacecraft physical model and the source geometry with respect to the spacecraft, as well as the fact that that no detailed measurements of the in-situ particle background were available.

Monte Carlo methods combine tracking of particles through complex geometries and a variety of physical processes and models pertinent to any incident particle can be defined. Monte Carlo simulations were used extensively in this work with regards to the HEX experiment and have proved an excellent tool for space science studies. Payload design can be optimized according to mission specifics with regards to maintaining or enhancing performance. Detector response can be modeled by including instrument calibration parameters. Instrumental background can be estimated for the detector due to different sources of space radiation, taking into account their variation with time; background modeled in this way can be used in data analysis. Monte Carlo simulations are thus very useful in total system design.

The work presented is an important step where a Monte Carlo simulation tool was used by ISRO in the area of payload design. This is a useful beginning as far as future experiments are concerned, as a working system has been developed for payload design optimization, response modeling and background estimation, which can be refined further.

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