Characterization and Calibration of High-Energy Electron Instruments Onboard the Arase Satellite

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Abstract  This study investigates the characterization and calibration of the high-energy electron experiments (HEP) instrument onboard the exploration of energization and radiation in geospace (ERG). Two detector modules, HEP-L and HEP-H, which employ stacks of multichannel silicon strip detectors, detect electrons in the energy ranges of 70 keV–1 MeV and 700 keV–2 MeV, respectively. The detector response to electron irradiation needs to be assessed to obtain accurate electron fluxes from these detectors. In this study, we perform Monte Carlo simulations using the Geant4 particle simulation tool to reconstruct incident electron fluxes from detected count rates. Based on the simulation results, we investigate the response characteristics of the detectors when electrons with a certain range of energy are irradiated onto them. A response function is constructed by combining the simulation results for different incident energies. A response matrix is calculated by binning the response function according to the energy channels of the detector, and an inverse matrix derived from the response matrix is used to calibrate the observational data. Compared with the data obtained from another electron instrument onboard the Arase satellite (MEP-e), whose energy range overlaps with that of the HEP, the differential flux data for the overlapping energy range (85–95 keV) are consistent with each other. The basic characteristics of the HEP detectors are thus confirmed to provide well-calibrated data.

1. Introduction

The electron radiation belts are the most energetic charged particle populations in the geospace, and their variations are determined by the delicate balance between the acceleration and loss of electron (Reeves et al., 2003). Several acceleration mechanisms have been proposed. Among the cross-energy coupling processes occurring via wave particle interactions (Miyoshi et al., 2013, Miyoshi, Shinohara, et al., 2018), chorus wave particle interactions are one of the most important mechanisms that cause a large flux enhancement of the outer belt (Miyoshi et al., 2003, Reeves et al., 2013, Thorne et al., 2013). In this process, sub-relativistic electrons serve as seed populations for subsequent accelerations to the megaelectron volt (MeV) range (e.g., Miyoshi et al., 2013, Jaynes et al., 2015). Moreover, radial diffusion is also an acceleration process to cause the flux enhancement of relativistic energy electrons (Baker et al., 1998, Kanekal et al., 2005). It is important to investigate the dynamics of tens to several hundreds of kiloelectron volt (keV) electrons to understand the acceleration processes of MeV electrons primarily forming the radiation belts. It is suggested that lower-energy seed electrons are also energized into the MeV range through drift-resonant interactions with ultra-low-frequency waves (Li & Hudson, 2019).

The exploration of energization and radiation in geospace (ERG), a Japanese geospace satellite is also known as Arase, was launched in December 2016 to observe the inner magnetosphere with the main objective of understanding the acceleration and loss processes of relativistic electrons in geospace (Miyoshi, Shinohara, et al., 2018). Eight scientific instruments to measure plasma/particles, fields, and waves were installed on the satellite. Arase has an elliptical orbit with a perigee of ~400 km, an apogee of ~32,000 km altitude, an inclination of ~31°, and an orbital period of ~9.5 h. The high-energy electron experiments (HEP) instru-
The HEP measures the electron energy deposit using a stack of silicon semiconductor devices. When electrons enter the HEP instrument, they penetrate the aluminum window that prevents contamination by protons (see Section 2.1 and Figure 1 for full description). However, owing to this window, the original information of the incident electrons, such as particle energy and incident directions, change. Since the electron energy loss and scattering in the detector need to be modeled for reconstructing such original information, we need to establish a calibration technique for the HEP instrument by considering the actual space environment to use the data for scientific purposes.

The particle instruments onboard the spacecraft can be calibrated in two ways. One method is an electron or proton beam test using the actual flight model for instrument calibration using the ground facility (Cattaneo et al., 2011; Hayashi et al., 2013). Although the beam test is possible for the selected energy band, the setup of the calibrations is complicated, and it takes time to realize the experiment. Another method is a computer simulation to reconstruct the interaction between a particle and a detector, which enables calibration with various energy sources and particles in the simulation (Baker et al., 2013; Mizuno et al., 2010).

In this paper, we report on the calibration of the HEP instrument using the simulation toolkit Geant4 (Agostinelli et al., 2003), which is a physics-based tool kit that reproduces particle interaction with matter. Although Geant4 was developed for high-energy particle physics, it can be utilized to particle detectors onboard spacecraft; the Geant4 simulation shows excellent agreement with pre-flight calibration experiments in a ground facility, as evident from for example, Figures 20, 21 in the Baker et al. (2013). Using the toolkit, we study the response of the HEP instrument to electrons of various incident energies and numerically evaluate the geometric factor and detection efficiency. Using the results from the Geant4 simulation, we further calibrate the actual HEP data and prepare calibrated electron fluxes, which are already open to the public as HEP Level-2 products (3-D flux, v01_01, Mitani, Takashima, et al., 2018) from the ERG-Science Center. In this study, we use the raw count data included in the version v01_01 data (not the latest version) for the present calibration study, because we show the validity of our calibration method to derive the v01_01 flux values from the raw counts. This work provides information that can be applied to the latest version of the data files. Furthermore, we compare the calibrated HEP fluxes with Level-2 data of MEP-e (omniflux, v01_02, Kasahara, Yokota, Mitani, et al., 2018), whose energy range overlaps with that of the HEP, to validate our calibration method.
2. Specifications of HEP and Reconstruction Using Geant4

2.1. Basic Characteristics of Detectors

The HEP instrument consists of two detectors, HEP-L and HEP-H, to cover different energy ranges. The HEP-L and HEP-H were designed to detect electrons with the energy ranges of 70 keV–1 MeV and 700 keV–2 MeV, respectively. Both detectors have three detector heads, as shown in Figure 1. A detector head covers a 60 × 10° field of view (FOV). With the spin motion of the satellite, the instrument can scan the entire velocity space of 4π steradians, providing a 3-D distribution function of electron flux at every spin period of ∼8 s.

The HEP-L and HEP-H detectors use silicon strip detectors (SSDs) to measure the energy and incident direction of incoming particles. Before the particles reach the SSDs, they pass through a collimator and aluminum window. The collimator located on the front sides of the detectors limits the incoming direction of the particles. The aluminum window located between the collimator and the detectors prevents protons and low-energy electrons from reaching the SSDs. The first layer of the SSD functions as a trigger for the following layers and, in combination with the slit at the outlet of the collimator, defines the direction of the particles. After the electrons pass through the first layer, the subsequent layers measure the energy deposition at each point.

Figure 2 shows the configuration of the collimator and SSD of the HEP instrument. The HEP-L has four layers of SSDs. The front layer has a thickness of 50 μm, and the other layers have a thickness of 600 μm each. A 12.5-μm-thick aluminum window is located in front of the SSDs. The HEP-H has a 300-μm-thick aluminum window, 50-μm-thick front SSD, and seven layers of 600-μm-thick SSDs. The differences between these two detectors are their collimators, window parts, and the number of stacked SSDs. A bigger collimator was used for the HEP-H because the electron flux generally decreases in the higher energy range. A thicker aluminum window is adopted for the HEP-H to exclude low-energy electrons.

The housing shields of the HEP-L and HEP-H are made of aluminum with average thicknesses of 8 and 7 mm, respectively. These thicknesses are based on a preceding study and design data for the HEP instrument. Even if a particle penetrates the housing shield without passing through the collimator and interacts with the SSDs, such an event is not recorded unless the particle deposits energy on the first layer.

2.2. Simulation Setup Using Geant4

The geometry of the HEP instrument was designed using the Geant4 toolkit (Agostinelli et al., 2003). Geant4 is a simulation toolkit developed by CERN that simulates the interaction between high-energy particles and matter using the Monte-Carlo method. It has been widely used for the development of high-energy particle detectors in particle accelerators and for medical and space applications. In this study, the FTFP-BERT physics list from Geant4 version 10.04 was used. Note that this includes particle interaction which contains all the standard models of electromagnetic (EM) process physics. This physics list simulates all interactions of hadrons and leptons with the detector and passive material. For details, we refer the interested reader to Allison et al. 2016 and Wright & Kelsey 2015. We implemented a low-pressure hydrogen gas model to simulate the vacuum state (1.008 g/mol, 1e–25 g/cm³, 2.73 K, 3e–18 Pa).
For the simulation, we reproduced the geometry of one of the three heads of each of the HEP-L/H detectors, as shown in Figure 3. The shape and position information of the collimators, aluminum windows, and SSDs of each detector was adopted exactly as in the actual detectors to reproduce their observational FOVs. The outer walls of each detector were shielded with aluminum. For SSDs, the multiple strip structure was implemented in the simulation to identify the interaction of particles with each strip channel. We examined the Geometric factor (G-factor), detection efficiency, and detector response characteristics using these reconstructed models.

3. Simulation and Results

3.1. Geometric Factor

The G-factor is used to convert the count rates of particles measured by a detector to a differential flux in physical units. The G-factor is a function of the size of the detection area and the solid angle defined by the collimator, given in units of cm\(^2\) sr. It is used as the fundamental parameter of a particle telescope (Sullivan, 1971)

In the design phase of HEP, the G-factor for a module was determined based on the maximum count rates for the HEP electronics. The G-factor was calculated for a simple geometric structure based on the square dimensions of the entrance and exit holes of the collimator. Here, we calculate a more accurate G-factor using the detailed structure of the collimator.

We evaluated the G-factor in this study as follows. First, we eliminated the aluminum window from the detector geometry because the G-factor is assumed to depend only on the trajectories between the detector and the collimator. Note that electrons are likely to be scattered by the window, which may affect the estimation of the detection efficiency. When we analyze electron counts registered by the instrument with the realistic configuration, we should consider not only the G-factor but also the detection efficiency. We investigated this in the next section. Then low-energy (1 keV) electrons were irradiated isotropically outward from the first layer of the SSD surface in the omni-direction of the half-sphere on the collimator side. If electrons reached the outer boundary of the simulation area without any interaction, they were counted as escaped particles. The solid angle of the FOV of the detector for inbound particles was estimated by calculating the ratio of the number of escaped electrons to the total number of radiated electrons. Then the G-factor can be derived by multiplying the solid angle and the detection area, as follows:

\[
G \text{ - factor} \approx 2\pi \times \text{Sensor Area} \times \frac{\text{Number of escaped particles}}{\text{Number of irradiated particles}}
\]

The simulation was performed for each strip on the first layer SSD of each module, HEP-L/H. The starting point was selected randomly on the surface area, and the total number of irradiated particles in each strip was set to \(10^8\) counts.
Figure 4 shows the G-factors for each strip of the silicon detector evaluated using the Geant4 simulation. The largest G-factor is observed at the center of the SSD owing to the characteristics of the collimator, and it decreases toward the edges of the detector. The G-factors for the strips at the edges are zero because the step-shaped collimator interferes with the paths of the electrons moving toward those strips around the edges.

3.2. Characteristics of the Energy Spectrum

When electrons enter the detector, their energies are reduced slightly due to scattering in the aluminum window. The Geant4 simulation reproduced such an energy loss. We irradiated an electron beam in the direction normal to the detector surface to investigate the relationship between the energy spectrum of the incident electrons and that of the measured electrons. In the simulation, we irradiated $10^5$ electrons with energies ranging from 1 to 2,500 keV at intervals of 1 keV onto both HEP-L and HEP-H.

In Figure 5a, the red line indicates the detected energy spectrum obtained by irradiation of 1 MeV electrons onto HEP-H. The highest spectral peak is around 900 keV because electrons lose about 100 keV of energy in the 300-μm-thick aluminum window. Further, another spectral peak below 0.1 MeV and a bump around 0.3 MeV are observed in the red spectrum in Figure 5a. To understand the characteristics of the spectrum, we perform a simulation using an “ideal detector” in which the area of the SSDs is enlarged into a rectangle shape (22.5 × 63.0 mm), which is sufficiently large to detect most electrons, with all the other conditions remaining the same as those in the HEP-H simulation. The simulated spectrum is shown as a black line in Figure 5a. A comparison between the two spectra reveals that the peak below 0.1 MeV and the bump around 0.3 MeV in the red spectrum appears to be caused by electrons that escape without hitting the SSDs of the lower layers. Figures 5b and 5c show the expected spectra according to the number of hits for the ideal detector and HEP-H, respectively. In the figures, the red, blue, magenta, and green lines indicate spectra in the cases where only the first layer SSD (SSD1), only SSD1 and 2, only SSD1, 2, and 3, and SSD1, 2, 3, and 4 detect energy, respectively. The red line in Figure 5c forms a peak below 0.1 MeV, and the blue line forms a bump around 0.3 MeV. Thus, the peak below 0.1 MeV on the red line in Figure 5a is caused by electrons that deposit energy only on the first SSD layer and escape without hitting any other SSDs. On the other hand, the bump near 0.3 MeV is caused by those that deposit energy only on the first and second layers.

We investigated the scattering angle at the aluminum window and SSD1 to confirm this hypothesis. A schematic view of the detector placement and the definition of azimuthal ($\phi$) and scatter ($\theta$) angles are shown in Figure 6a. The Z-axis is defined as the direction perpendicular to the SSD plane, $\phi$ is the azimuthal angle, and $\theta$ is the zenith angle to the z-axis. The Y-axis ($\phi = 90^\circ, 270^\circ$) is along the long side of the SSD. Figures 6b and 6c show the $\theta$–$\phi$ distribution of the electron direction scattered at the aluminum window and at SSD1, respectively. For a beam perpendicular to the window and SSD1 (Z-axis direction), electrons are scattered isotropically in the azimuth direction at the aluminum window. The scattered angle distribution has a peak.
at $\theta_1 \approx 20^\circ$. As the short side of SSD1 is 5.53 mm and the distance between the aluminum window and SSD1 is 2.48 mm, electrons with large scattering angles fall to the loss detection area located next to SSD1. The outer shape of SSD1 observed from the center of the aluminum window is projected onto the $\theta$–$\phi$ plane as a red curve in Figure 6b. As evident from the figure, electrons with $\theta$–$\phi$ values on the right side of the curve do not reach SSD1. When electrons scattered by the aluminum window reach SSD1, they deposit energy onto the detector and scatter again at SSD1. Unlike the $\theta$–$\phi$ distribution at the aluminum window, the distribution at SSD1 is anisotropic because the electrons scattered by the aluminum window do not fully reach SSD1. The scattering angle distribution of the electrons on the detector surface in SSD1 shows more scattering in the Y-axis direction ($\phi_2 = 90^\circ, 270^\circ$) of the SSD. The analysis shows that there exist electrons that deposit energy only on SSD1 and escape from the HEP-H because SSD1 does not have sufficient width in the X-axis direction.

3.3. Efficiency of the Detector

The shape of the spectrum also affects the peak efficiency, which represents the detection efficiency for a specific energy particle. The peak efficiency is defined as the ratio of the number of electrons that fully deposit their energy onto the detector to the total number of irradiated electrons. In actual beam test conditions, the peak efficiency is difficult to evaluate accurately owing to the uncertainty of electrons that are scattered or absorbed by the aluminum shield. However, in a detector simulation, we can determine the exact value of peak efficiency because the simulation can track all the particle trajectories and their deposited energies from each material. In the present simulation, the number of peak counts can be evaluated as the number of events in which the entire incident energy is deposited onto the silicon detectors and/or
The peak efficiency is expressed as follows:

$$\text{Peak efficiency} = \frac{\text{Counts}(\text{eDep}_\text{Si} + \text{eDep}_\text{Al} = \text{incident energy}) - \text{Counts}(\text{eDep}_\text{Al} = \text{incident energy})}{\text{Counts}(\text{All Event})}$$

Here, “eDep_Si” and “eDep_Al” represent the energy deposits at the silicon detectors and aluminum window, respectively. “Counts(”) indicates the electron counts for which the conditions in parentheses are satisfied.

Figure 7 shows the peak efficiencies of the HEP-L and H. The maximum efficiencies were observed at approximately 600 and 1,000 keV for HEP-L and H, respectively. Below this energy, more electrons stop at the aluminum window; thus, the peak efficiency is reduced. Above this energy, the peak efficiency is also reduced because more electrons pass through all the detectors and do not deposit their entire energy onto the detector. We can obtain an energy-dependent efficiency by combining it with the Geometric factor described in the previous section.

4. Calibration of HEP Data

4.1. Inverse Matrix Method by Using Simulation Result

Unlike the data from the beam test on the ground, observational data in the geospace are always affected by the scattering of high-energy particles (Nwankwo et al., 2020). As observed from the spectrum with a monoenergetic beam in Figure 5, the low-energy channels include the scattering...
components of higher-energy incident particles, which prevent accurate measurement of the incident electron fluxes. We adopted the simulation result and created a response matrix to calibrate the observed spectrum of each HEP-L/H detector to obtain the exact incident energy spectrum.

We develop a calibration method to obtain input particle fluxes, in which we apply the response function based on the Geant4 simulations to the observed counts. We term this an “inverse matrix calibration”. The calibration method using the response function has been studied and used in the fields of spectroscopy and imaging for data calibration (Brown et al., 1982; Pratt & Mancill, 1976). The inverse matrix calibration method adopts the simulation result and applies it to actual spacecraft data in radiation spectroscopy.

Figure 8 shows the simulation results where electrons are irradiated with energies ranging from 1 to 2,500 keV with intervals of 1 keV. The horizontal axis is the observed energy by the instrument that is, reconstructed in the simulation, and the vertical axis is the incident energy of electrons. A color scale shows the number of particles that fall in each incident energy–observed energy bin. The number of electrons used for each irradiation energy was $10^5$, which can be considered sufficient for determining the peak spectrum. The smallest height of the spectrum beam peak is approximately 100 counts in the HEP-L 2500 keV beam simulation. The red grid lines indicate energy bin boundaries for creating a matrix defined by the HEP energy channel. The response matrix $R$ was created by summing the counts inside the bins separated by red lines and normalizing by the total number of incident electrons. Thus, the relation between the observed electron counts and the number of incident electrons is expressed using the response matrix as follows:

$$C_{\text{obs}}(E_o) = R \cdot C_{\text{true}}(E_i)$$

Here, $C_{\text{true}}(E_i)$ is the energy spectrum of the incident electron counts and $C_{\text{obs}}(E_o)$ is the energy spectrum of the observed electron counts.

The input electron fluxes are derived using the inverse of the response matrix as follows:

$$C_{\text{true}}(E_i) = R^{-1} \cdot C_{\text{obs}}(E_o)$$

Using the established inverse matrix, we can reconstruct the real energy spectrum of the incident electrons from an observed electron energy spectrum. The examples of the response matrix $R$ and inverted matrix $R^{-1}$ for HEP-H are shown in Table 1.
4.2. Calibration Result Using the Inverse Matrix Method

We apply the inverse matrix method to the raw count data of the HEP and derive the incoming electron fluxes. The results are shown in Figure 9. As the MEP-e instrument (Kasahara et al., 2018a) measures electrons with energies in the range of 10–90 keV, which overlaps with the energy range of the HEP-L, we show the energy spectrum from the MEP-e instrument and compare it with that of the HEP-L. In the figure, the spectra of the overlapping part are compared before and after the calibration. The MEP-e is expected to provide relatively correct electron flux values because it uses both an electrostatic analyzer and an energy detector employing avalanche photodiodes to measure the exact energy of the incident electrons and to prevent contamination by penetrating high-energy particles. As shown in Figure 9, the flux differences in the overlapped energy range between the MEP-e and HEP-L decreased after the calibration of the HEP-L.

Figure 10 shows a comparison of the differential fluxes of electrons with the energies of approximately 87.5 keV obtained by the MEP-e and 95 keV obtained by the HEP-L from July 2017 to June 2018. Note that the red and blue dots are obtained from the data before and after the calibration of the HEP-L, respectively. Each dot is plotted using spin-averaged differential fluxes for a satellite spin (∼8 s). The calibrated data (blue dots) show better agreement between the MEP-e and HEP-L. The data points before the calibration (the red dots) were improved closer to the 1:1 ratio line by the calibration. Considering that the MEP-e has been well calibrated, it is evident that the correction through the inverse matrix works well and improves the HEP electron fluxes. To confirm this result further quantitatively, we define a “comparison ratio”, which assesses how distant a data point is from the \( y = x \) line. Here, \( x \) is the flux value from the MEP-e and \( y \) is that from the HEP-L. The comparison ratio is calculated using the following formula:

\[
\text{Comparison ratio} = \frac{d}{r} = \frac{x - y}{x + y}
\]
Figure 9. Energy–time diagram of magnetospheric electrons observed by HEP-L/-H on March 31, 2017 (left). Energy spectrum obtained by MEP-e and HEP at 02:35:42 UTC (marked red vertical dashed line on the left figure) on the same day (right).

Figure 10. Comparison of differential flux from MEP and HEP at 95 keV channel (upper) and distribution of each observation ratio (lower). The red color indicates uncalibrated data, and the blue color indicates calibrated data.
Here, $d$ is the distance from the $y = x$ line, and $r$ is the distance from the origin to the closest point along the $y = x$ line for individual data points. The difference between the two fluxes can be evaluated regardless of the magnitude of the flux by using the comparison ratio rather than the simple ratio of the two values ($x/y$). The histogram of the comparison ratios for all the data points in the upper panel is shown in the bottom panel of Figure 10. A comparison ratio of zero indicates that the observations of the HEP-L and MEP-e are consistent with each other. As observed from the figure, the average distribution for the uncalibrated data is approximately 0.3, but it improves to approximately 0 for the calibrated data. In addition, 93% of the calibrated fluxes have absolute values of a comparison ratio of 0.5 or lower. Thus, it is confirmed that the calibrated fluxes show better consistency with the MEP-e fluxes than the uncalibrated fluxes.

We generated histograms of the comparison ratio using data taken every five days from July 2017 to June 2018 to validate the calibration result over a long time interval. Figure 11 shows the time variation of the histograms, in which the color contour indicates the count of the comparison ratio. The peak positions of the five-day histograms obtained from the calibrated data are indicated by blue bars and those from the uncalibrated data are indicated by green bars. The vertical bars indicate the standard deviation of the histograms for the calibrated data.

4.3. Discussion

In this study, the inverse matrix method was established to derive incident electron fluxes from the HEP observation data. This method can effectively correct the contamination of high-energy electrons into low-energy channels. In fact, we can observe consistency between the electron fluxes observed by HEP-L and those observed by MEP-e. However, the application of the method to actual observations has several limitations, which are discussed below.

When a large number of particles are detected, the comparison ratio for the calibrated differential fluxes between the HEP-L and MEP-e is close to 0. However, when the observed particle counts are low, the difference between the two instruments becomes significant. Figure 12 shows the dependence of the comparison ratio on the raw counts of the HEP-L.
Note that the data under $L^* < 2.5$ ($L^*$ is Roederer’s L-value based on the Tsyganenko 89 model) are not included because the noise of the signal was recorded when the high-voltage power of MEP-e was turned off while the satellite passed through the perigee of orbit. When the raw counts of the HEP-L observation are low, the comparison ratio deviates significantly from zero. Hence, a careful analysis of HEP-L data is required when the original HEP-L count is small.

Although the present inverse matrix method has successfully corrected the HEP flux values, several aspects still need to be improved in the calibration method. For example, this calibration method relies on a simulation with only a unidirectional pencil beam entering normal to the detector from the front side. However, each HEP module has a 60-degree FOV, and obliquely incident particles may affect the calibration parameter. If particles enter the detector at a certain angle from the normal direction, the effective thickness of the aluminum window becomes larger. A thicker aluminum window would affect the energy deposit and scatter direction, and change the response of the instrument.

Another aspect is that the present inverse matrix method does not consider the effect of high-energy electrons beyond the maximum energy channel of the detector. This is because the range of the matrix must be the same for the incident and observed particles when we create an inverse matrix. Hence, we cannot incorporate the effects of high-energy electrons, even with simulation results. Therefore, in this study, only the influence of the electrons in the observed energy range can be considered. The effects of other high-energy particles, such as protons, will be considered in future studies.

5. Summary and Conclusions

In this study, we conducted data calibration of the HEP instrument on board the Arase satellite. To calibrate the data, we performed Monte Carlo simulations to calculate the response function of the detector using the Geant4 simulation toolkit and reconstructed the geometry of the HEP detector. We created the response matrix for calibration based on the simulation of incident electrons with energies ranging from 1 to 2,500 keV. Then we calibrated the HEP observation data using the inverse matrix method.

The results and their implications are summarized below:

The calibration of the HEP instrument developed in this study was tested by a comparison with the MEP-e observations for the overlapped energy range. The result is consistent with each other. Further, we compared the long-term variations and confirmed that the present calibration shows good consistency between the MEP-e and HEP-L. This result indicates that the inverse matrix calibration method developed by using Geant4 in this study effectively improves the flux observed by a multi-energy channel particle detector.

We have figured out that the energy spectral bump structure at a few hundred keV when the detector is irradiated with a monoenergetic electron beam. This phenomenon is caused by the finite geometry of the SSDs, in which significantly scattered electrons can miss some of the SSDs, depositing only a fraction of their entire energy. This bump structure feature changes the response of the detector, especially in the lower energy range. Based on the peak efficiency calculation depending on the electron energy, we confirmed that the maximum efficiency of the HEP-L and HEP-H is obtained at 600 and 1000 keV, respectively.

Data Availability Statement

Science data of the ERG (Arase) satellite was obtained from the ERG Science Center (ERG-SC) operated by ISAS/JAXA and ISEE/Nagoya University (https://ergsc.isee.nagoya-u.ac.jp/index.shtml.en, Miyoshi, Hori, et al., 2018). The present study analyzed HEP Level-2 3-D flux v01_01 data (Mitani, Takashima, et al., 2018) and MEP-e Level-2 omniflux v01_02 data (Kasahara, Yokota, Mitani, et al., 2018), orbit information Level 3 t89 v02 data (Miyoshi, Shinohara, & Jun, 2018). The results of the simulation data set uploaded to the Zenodo server https://doi.org/10.5281/zenodo.5023571.
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