Study on Characteristics and Patterns of High-Altitude Intense Pulsed Gamma Environment

Authors: Zhang Dongya, Dong Jinzhuang, Liu Li, Niu Shengli, Shang Peng, Zuo Yinghong, Jinhui Zhu

Date: 2025-10-30T00:00:00+00:00

Abstract

High-altitude intense pulsed γ-rays propagating through the upper atmosphere generate intense radiation fields, which can cause performance degradation or functional failure of electronic systems in orbiting spacecraft. By employing the Monte Carlo method combined with variance reduction techniques, high-precision simulation of long-distance transport of intense pulsed γ-rays at high altitudes was achieved, and the spatial distributions of γ peak dose rate (silicon) and γ dose (silicon) under various source altitude conditions were calculated and presented. Based on the analysis of characteristics and patterns of intense pulsed γ radiation field distributions, the concept of mass thickness was introduced to describe the regularities of atmospheric absorption and scattering effects on γ-ray transmission, and a general calculation formula was developed for computing the spatial distributions of γ peak dose rate (silicon) and γ dose (silicon) under different source altitude conditions. The deviation of the formula’ s calculation results from numerical simulations is within 10%, providing a computational method for high-altitude intense pulsed γ-ray environments that balances calculation accuracy and efficiency for spacecraft radiation protection design.

Full Text

Preamble

Vol. XX, No. X, XXX 20XX
NUCLEAR TECHNIQUES Vol.XX, No.X XXX 20XX

Study on Characteristics and Patterns of High-Intensity Pulsed Gamma Radiation in High-Altitude Regions

Zhang Dongya[1], Dong Jinzhuang[1], Liu Li[1], Niu Shengli[1], Shang Peng[1], Zuo Yinghong[1]*, Zhu Jinhui[1]
[1](Northwest Institute of Nuclear Technology, Xi’ an 710024, China)

Abstract

Background: Intense pulsed gamma radiation generated by high-altitude gamma-ray transmission through the upper atmosphere creates strong radiation fields that can cause performance degradation or functional failure in onboard electronic systems of orbiting satellites. **Purpose:** To investigate the characteristics of intense radiation fields generated by the propagation of strong pulsed gamma rays in the upper atmosphere. **Methods:** This study employs Monte Carlo methods coupled with variance reduction techniques to achieve high-precision simulations of long-range pulsed gamma-ray transport. The methodology quantifies spatial distributions of peak gamma dose rates (Si) and gamma doses (Si) across varying source altitudes. Based on analysis of the dosimetric characteristics and patterns of pulsed gamma radiation fields, the concept of mass thickness is applied to describe the combined attenuation mechanisms (absorption and scattering) of the atmosphere on gamma ray propagation. **Results and Conclusions:** A universal computational formula is derived to calculate spatial distributions of gamma dose metrics under diverse source conditions. The formula exhibits less than 10% simulation discrepancy with numerical results, offering spacecraft radiation protection design a precision- and efficiency-optimized computational framework for high-altitude pulsed gamma radiation environments.

Keywords: Intense pulsed gamma radiation; Peak gamma dose rates (Si); Gamma doses (Si); Monte Carlo simulation

First Author: Zhang Dongya, male, born in 1994, received his doctoral degree from Fudan University in 2023, focusing on particle transport simulation and intense pulsed effects research.

Corresponding Author: Zuo Yinghong, E-mail: zuoyinghong@nint.ac.cn

Received: 20XX-00-00, **Revised:** 20XX-00-00

Introduction

As human space activities become increasingly frequent, the threat of space radiation environments to orbiting spacecraft has grown more severe [1-5]. Among these threats, high-altitude intense pulsed gamma radiation represents a high-energy transient radiation source that poses major challenges to the reliability and lifespan of spacecraft electronic systems. Such gamma rays are characterized by high instantaneous flux and broad energy ranges, and can directly damage semiconductor devices through ionization effects, leading to performance degradation or even functional failure of electronic systems [6-8]. Therefore, in-depth investigation of the transport characteristics and environmental distribution patterns of high-altitude intense pulsed gamma radiation is not only an important topic in space radiation effects research, but also a critical foundation for spacecraft radiation-hardening design.

Current research on high-altitude intense pulsed gamma radiation primarily focuses on ground-based experimental simulations of space environments and numerical simulation methods [9-12]. In 1991, E.W. Enlow et al. conducted linear bipolar transistor gamma irradiation experiments and discovered the low gamma peak dose rate (Si) enhancement effect [13]. Since then, numerous domestic and international scholars have conducted extensive studies on various semiconductor devices using gamma-ray facilities [14-16]. However, because ground experiments cannot fully reproduce the complex physical conditions of real space environments, experimental results exhibit certain discrepancies from actual situations. On the other hand, traditional numerical simulation methods, particularly those based on Monte Carlo algorithms, while demonstrating excellent accuracy, suffer from excessive computational costs and long processing times when handling complex scenarios, making them unsuitable for rapid assessment and decision-making [17]. Additionally, theoretical formulas for vacuum conditions are often used to estimate gamma peak dose rates and gamma doses. However, in the high-altitude region between 30-80 km, atmospheric density varies dramatically, and interactions between gamma photons and atmospheric molecules exhibit significant path dependence: low-energy photons are easily absorbed by the atmosphere, while high-energy photons change propagation direction through Compton scattering, forming complex radiation field distributions. Vacuum theoretical formulas may overestimate direct gamma peak dose rates and underestimate the cumulative effects of scattered components in practical applications, thereby misleading spacecraft radiation protection design [9]. Therefore, there is an urgent need to establish a high-altitude gamma-ray transport simulation method that balances computational precision and efficiency to reveal radiation field evolution patterns under atmospheric effects.

This paper employs Monte Carlo methods combined with variance reduction techniques to calculate spatial distribution characteristics of gamma peak dose rates (Si) and gamma doses (Si) under different source altitude conditions. By studying the effects of atmospheric interactions on gamma-ray transport, we propose a set of computational formulas for high-altitude intense pulsed gamma environments that account for atmospheric absorption and scattering, capable of calculating gamma peak dose rates (Si) and gamma doses (Si) for source altitudes above 30 km.

1.1 Calculation Model

[Figure 1: see original paper] illustrates the geometric model for simulating long-distance gamma-ray transport in high-altitude atmosphere. The high-altitude atmosphere is a typical non-uniform continuous medium with density varying dramatically with altitude. The entire model is a cylinder with a height of 1000 km and radius of 1000 km. The cylinder is horizontally stratified, with a ground medium at the bottom and atmospheric medium above. Based on atmospheric density characteristics and computational precision requirements, the atmosphere from 0-500 km altitude is divided into 500 layers, each 1 km thick; the atmosphere from 500-1000 km is divided into 25 layers, each 20 km thick.

Each layer is filled with uniform-density air, with density taken as the average within the layer. Air density is provided by the MSIS00 atmospheric model [18]. A soil layer 2 km below the ground surface has a density of 1.52 g/cm^3. Variations in air composition with altitude are ignored. The radiation source is assumed to be an approximately isotropic point source in the simulation.

DXTRAN Variance Reduction Method: Gamma-ray transport in the thin high-altitude atmosphere environment is closely related to the gamma energy spectrum. The gamma energy spectrum and dose rate conversion coefficients used in this calculation are taken from the literature [19]. To address issues such as insufficient effective particle numbers and long computation times encountered when Monte Carlo methods simulate gamma-ray transport over large distances in high-altitude atmosphere, this paper adopts the DXTRAN sphere variance reduction method. Its core principle is that when a photon collides during simulation, in addition to the conventional secondary particles produced, a "virtual particle" is artificially generated at a specific "DXTRAN" surface. This virtual particle is directed straight to a predetermined DXTRAN region, thereby significantly increasing the effective count of particle flux reaching the region of interest [17]. The gamma source is set as an isotropic point source at 30 km altitude, with typical gamma photon weights. The recording point is at the same height as the gamma source, 400 km from the source. The DXTRAN sphere center coordinates match the recording point coordinates, with a DXTRAN radius of 5 km. Figure 2 shows variations in gamma dose, gamma peak dose rate, and computation time under different source particle numbers (NPS) before and after applying the DXTRAN sphere variance reduction (VR) method. The results demonstrate that while direct simulation and DXTRAN VR methods show similar trends in gamma dose and peak dose rate fluctuations with increasing particle numbers, the direct simulation requires significantly more time, indicating that DXTRAN can effectively reduce computation duration.

2 Results and Analysis

Peak Gamma Dose Rate (Si) Spatial Distribution

[Figure 3: see original paper] presents the relationship between simulation results of peak gamma dose rates and distance for different source altitudes under typical scenarios. [Figure 4: see original paper] shows the proportion of direct radiation components in peak gamma dose rates for different source altitudes obtained via Monte Carlo methods. In the simulation, each gamma photon' s transport path was tracked throughout its entire trajectory. The direct dose rate is defined as the dose rate contributed by photons reaching the detection region without experiencing any scattering processes, obtained directly through statistical counting to ensure physical accuracy. Meanwhile, the spatial distribution of peak gamma dose rates under vacuum conditions is calculated using the following formula:

$$D_\gamma = \frac{K}{R^2}$$

where D_γ is the gamma peak dose rate, R is the distance in km, and K is a constant.

Without considering atmospheric effects, the gamma peak dose rate at a transmission distance of 400 km is 1.94×10^6 Gy(Si)/s under typical scenarios. As shown in [FIGURE:3(a)], when the source altitude is low and the observation point altitude is not lower than the source altitude, the simulated gamma peak dose rates are all smaller than those calculated by the vacuum formula. [FIGURE:4(a)] shows that the direct radiation proportion in gamma peak dose rates exceeds 98%, indicating that gamma peak dose rates are primarily affected by atmospheric absorption. Furthermore, for a fixed source altitude and same transmission distance, smaller emission angles (θ) result in more pronounced atmospheric absorption effects on gamma peak dose rates.

As shown in [FIGURE:3(b)], when the source altitude is not lower than 80 km and the observation point altitude is not lower than the source altitude, the simulated gamma peak dose rates approximately equal those calculated by the vacuum formula within 400 km, and atmospheric effects on gamma peak dose rates become negligible. As illustrated in [FIGURE:3(c)] and [FIGURE:4(b)], when the source altitude is low and the observation point altitude is not higher than the source altitude, gamma peak dose rates are mainly affected by atmospheric absorption. Under fixed actual gamma-ray propagation path lengths, smaller emission angles cause more path segments to lie in the middle and upper atmospheric regions favorable for absorption and scattering, leading to greater dose rate reduction.

As shown in [FIGURE:3(d)], when the source altitude exceeds 80 km and the observation point altitude is above 80 km, atmospheric effects are negligible. When the observation point altitude is below 80 km, gamma peak dose rates are primarily affected by atmospheric absorption. Notably, if comparing dose responses per unit ground projection distance, the data could be normalized by $\sin\theta$. However, this study focuses on the absolute dose rate received by detectors in real three-dimensional space, thus retaining original dimensions to serve actual detection scenario modeling and prediction.

Gamma Dose (Si) Distribution

[Figure 5: see original paper] shows the relationship between simulation results of gamma doses and distance for different source altitudes under typical scenarios. Under vacuum conditions, the spatial distribution of gamma doses is calculated using the following formula:

$$D_\gamma = \frac{K'}{R^2}$$

where D_γ is the gamma dose and R is the distance in km.

According to this formula, the gamma dose at 400 km distance is 0.06 Gy. As shown in [FIGURE:5(a)], when the source altitude is low and the observation point altitude is not lower than the source altitude, the simulated gamma doses are all smaller than those calculated by the vacuum theoretical formula, indicating that atmospheric absorption affects gamma doses more significantly than scattering. As shown in [FIGURE:5(b)], when the source altitude is not lower than 80 km and the observation point altitude is not lower than the source altitude, the simulated gamma doses approximately equal those calculated by the vacuum theoretical formula within 400 km, and atmospheric effects on gamma doses become negligible.

However, as shown in [FIGURE:6(a)], unlike peak gamma dose rates, the direct radiation proportion in gamma doses for 30 km source altitude first decreases, then increases, and finally stabilizes with increasing distance, reaching a minimum of 65%. Moreover, smaller emission angles (θ) yield larger stable values for the direct radiation proportion. This is related to high-energy photons becoming low-energy photons through Compton scattering effects, which are then absorbed through the photoelectric effect. Gamma peak dose rates are mainly contributed by high-energy photons and are less affected by atmospheric scattering, whereas gamma doses are contributed by both high-energy and low-energy photons and are more significantly affected by atmospheric scattering. Lower emission angles correspond to higher atmospheric density, making scattered photons more easily absorbed.

As shown in [FIGURE:5(c)] and [Figure 6: see original paper], when the source altitude is below 60 km and the observation point altitude is not higher than the source altitude, gamma doses are primarily affected by the combined effects of atmospheric absorption and scattering. Combined with [FIGURE:5(d)], when the source altitude is between 60-80 km and the observation point altitude is not higher than the source altitude, gamma doses are mainly affected by atmospheric absorption; when the source altitude exceeds 80 km, atmospheric effects become negligible.

2.3 Study of High-Altitude Intense Pulsed Gamma Environment Patterns

2.3.1 Peak Gamma Dose Rate (Si)

As discussed in Section 2.1, for source altitudes above 80 km, the spatial distribution of gamma peak dose rates approximates that under vacuum conditions, and gamma peak dose rates can be calculated using formula (1). For source altitudes below 80 km, gamma peak dose rates are primarily affected by atmospheric absorption and can be calculated using the following formula:

$$D_\gamma = \frac{K}{R^2} \cdot D_f^1$$

where D_f^1 is the absorption factor characterizing atmospheric absorption effects on gamma peak dose rates (Si).

Mass thickness is used to describe atmospheric absorption and scattering effects on gamma rays within 500 km altitude. The atmosphere is horizontally stratified into layers, with the i-th layer having mass thickness S_D^i. The relationship between S_D^i and altitude is as follows: $S_D^i = \int \rho_i(h)dh$, where ρ_i is the atmospheric density of layer i.

As shown in [Figure 1: see original paper], assuming gamma rays travel in a straight line from source point A to observation point H, the propagation path crosses the atmospheric stratification model, passing through N layers total. Here, N represents the number of discrete atmospheric layers traversed by the ray path, θ is the observation direction angle relative to the horizontal (positive in the counterclockwise direction), H_h is the observation point altitude, and A_h is the source altitude. The distance between adjacent points along the path is X_n, and the mass thickness M traversed by gamma rays along the path is:

$$M = \sum_{i=1}^{N} \rho_i \cdot X_n^i$$

where ρ_i is the atmospheric density of the i-th layer along the path.

Calculations were performed for various source altitudes, emission angles, and detection distances. The relationship between absorption factor and mass thickness is shown in [Figure 7: see original paper]. Results indicate that the absorption factor exhibits exponential attenuation with increasing mass thickness, attenuating more rapidly in low mass thickness regions (< 1000 g/cm^2) before gradually leveling off, consistent with classical gamma-ray attenuation behavior in matter. When gamma rays do not scatter with the atmosphere, photon intensity attenuation at specific energies follows the Lambert-Beer law [19]. In this study, although the gamma-ray source has a continuous energy spectrum and specific temporal structure, the low density and long mean free path in the upper atmosphere result in small scattering contributions, making the attenuation trend of gamma peak dose rates approximately follow this exponential law. This phenomenon is similar to the characteristics found by Ye Erlei et al. [21] in soil sample gamma self-absorption correction factor studies, where "absorption is significant at low mass thickness and saturates at high thickness," and also consistent with trends observed by Xie Dongcai et al. [22] in gamma-ray transmittance through various shielding materials, which can be expressed by formula (8):

$$D_f = a \cdot e^{-bM} + c$$

To verify the accuracy of the absorption factor description, the modified formula (3) and vacuum theoretical formula (1) were used to calculate gamma peak dose rates for source altitudes of 30-80 km with observation direction horizontal ($\theta = 0$). The relative deviation (σ) from Monte Carlo simulation results as a function of distance is shown in [Figure 8: see original paper]. The vacuum theoretical formula only considers geometric attenuation without accounting for atmospheric absorption, resulting in calculated gamma peak dose rates generally lower than Monte Carlo simulation results, with this relative deviation increasing with transmission distance up to nearly 100%. The modified formula introduces atmospheric absorption factors based on Monte Carlo simulations. When mass thickness is less than 1000 g/cm^2, the maximum relative deviation between calculated gamma peak dose rates and Monte Carlo results is less than 2%; when mass thickness exceeds 1000 g/cm^2, the maximum relative deviation approaches 10%. This difference mainly arises because atmospheric density changes dramatically and nonlinearly within the 30-80 km range, mass thickness calculation heavily depends on density, and gamma-ray absorption attenuation follows an exponential form that is extremely sensitive to mass thickness variations. At lower altitudes with larger mass thickness, small changes in mass thickness can lead to significant deviations.

Gamma Dose (Si)

As discussed in Section 2.2, for source altitudes above 80 km, the spatial distribution of gamma doses approximates that under vacuum conditions, and gamma doses can be calculated using formula (2). For source altitudes below 80 km, atmospheric effects cannot be neglected, and gamma doses can be calculated using the following formula:

$$D_\gamma = \frac{K'}{R^2} \cdot D_f^2 \cdot B_f^2$$

where D_f^2 is the absorption factor characterizing atmospheric absorption effects on gamma doses (Si), and B_f^2 is the scattering factor characterizing atmospheric scattering effects on gamma doses (Si).

[Figure 9: see original paper] shows the relationship between absorption factors for gamma doses and gamma peak dose rates versus mass thickness for different source altitudes and emission angles. The absorption factor for gamma doses exhibits similar distribution to that for gamma peak dose rates versus mass thickness, and can also be described by formula (8).

[FIGURE:10(a)] shows the relationship between scattering factors for gamma doses and mass thickness for 30 km source altitude and different emission angles. When mass thickness is less than 100 kg/m^2, scattering factors for different emission angles follow similar patterns. When mass thickness exceeds 100 kg/m^2, scattering factors for different scenarios first increase then decrease with increasing mass thickness, with larger emission angles showing smaller variation ranges of scattering factors with mass thickness.

[FIGURE:10(b)] shows the distribution of scattering factors within 5 km distance for different source altitudes versus mass thickness. Scattering factors within 5 km for different source altitudes also follow specific patterns that can be expressed by formula (10):

$$B_f = d \cdot M^e \cdot e^{-fM}$$

When source altitude is below 60 km and gamma rays propagate upward ($30° \leq \theta \leq 90°$), atmospheric scattering effects have a limited influence range. Beyond 5 km transmission distance, the scattering factor can be represented by the mass thickness at 5 km transmission, $M_{A1}(h, \theta, 5)$, i.e., $B_f^2 \approx B_f^2(M_{A1})$. However, when gamma-ray emission angles are small, atmospheric scattering effects become more complex and difficult to describe with appropriate formulas.

To verify the accuracy of absorption and scattering factor descriptions, the modified formula (9) and vacuum theoretical formula (2) were used to calculate gamma doses for source altitudes of 30-80 km with observation direction horizontal ($\theta = 0$). The relative deviation (σ) from Monte Carlo simulation results as a function of distance is shown in [Figure 11: see original paper]. Similarly, the vacuum theoretical formula only considers geometric attenuation without accounting for atmospheric absorption and scattering, resulting in large deviations from Monte Carlo simulation results that increase with transmission distance. The modified formula introduces atmospheric absorption and scattering factors. Within 5 km transmission distance, deviations between calculated results and Monte Carlo simulations are less than 5%. Beyond 5 km, most calculated results deviate less than 5% from Monte Carlo results, while a small portion shows deviations of 5%-40%, mainly because atmospheric scattering effects are complex and difficult to describe with appropriate formulas for low source altitudes and small emission angles. Here, the mass thickness at 5 km transmission was used for description, introducing larger errors.

Gamma peak dose rate refers to the maximum dose rate produced by gamma rays at a given moment, dependent on the source energy spectrum and time structure, and primarily affected by atmospheric absorption. This effect can be described using mass thickness—the greater the mass thickness, the more pronounced the absorption effect, which explains why Monte Carlo simulation results are often lower than vacuum theoretical formula calculations. Gamma dose refers to the cumulative energy deposited by gamma rays over a period of time, integrating the dose rate at each moment, and is primarily affected by the combined action of atmospheric scattering and absorption. Atmospheric absorption attenuation can also be described by mass thickness, while atmospheric scattering often accompanies changes in the gamma energy spectrum—greater atmospheric density leads to more pronounced scattering enhancement. These two competing mechanisms cause Monte Carlo simulation results to approach vacuum theoretical calculations in certain scenarios. When source altitude is low and gamma-ray emission angles are small, atmospheric scattering effects are particularly complex, and no suitable formula has yet been found to describe them.

Conclusions

High-altitude intense pulsed gamma radiation poses significant challenges to the reliability and lifespan of spacecraft electronic systems. This paper employs Monte Carlo methods combined with DXTRAN sphere variance reduction techniques to address issues of insufficient effective particle numbers and long computation times in simulating gamma-ray transport over large distances in high-altitude atmosphere, enabling calculation of spatial distribution characteristics of gamma peak dose rates (Si) and gamma doses (Si) under different source altitude conditions.

Through analysis of high-altitude atmospheric effects on gamma-ray transport, results show that above 80 km altitude, atmospheric effects on gamma-ray transport are negligible, and spatial distribution patterns of gamma peak dose rates (Si) and gamma doses (Si) can be described by vacuum formulas. Below 80 km altitude, gamma peak dose rates (Si) are primarily affected by atmospheric absorption, with absorption factors following an exponential relationship with mass thickness. Gamma doses (Si) are mainly affected by combined atmospheric scattering and absorption, with absorption factor distributions similar to those for gamma peak dose rates versus mass thickness, while scattering factors are difficult to describe with appropriate formulas due to dramatic changes in the gamma energy spectrum.

Based on the action patterns of atmospheric absorption and scattering on gamma-ray transport, this paper summarizes universal computational formulas for calculating spatial distributions of gamma peak dose rates (Si) and gamma doses (Si) under different source altitude conditions. Within 5 km range, formula calculations deviate less than 5% from numerical simulations; within 400 km range, most calculations deviate less than 5% from Monte Carlo results. This method improves computational efficiency and accuracy for high-altitude gamma-ray environments, providing reliable data support for spacecraft design and safe operation, and helping optimize spacecraft protection measures to reduce potential radiation hazards to equipment and personnel.

Author Contributions

Zhang Dongya: Monte Carlo simulation, data analysis, and manuscript writing. Dong Jinzhuang: Data analysis and manuscript writing. Liu Li: Proposed writing ideas, participated in data analysis and manuscript revision. Niu Shengli: Reviewed and revised the manuscript. Zuo Yinghong: Proposed research ideas, coordinated project planning and manuscript revision. Shang Peng: Participated in data analysis and manuscript revision. Zhu Jinhui: Provided manuscript guidance and revision.

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