Research on Accurate Virtual Trajectory Length Model for TGS Transmission Measurement

Authors: Rong-Rong Su, San-Gang Li, Chu-Xiang Zhao, LiYang, Ming-Zhe Liu, Shan Liao, ZhiZhou, Qing-Shan Tan, Zhi-Xing Gu, Xian-GuoTuo, YiCheng, San-Gang Li

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Abstract

To accurately reconstruct TGS transmission measurement images, this paper optimized the transmission reconstruction equation based on the actual conditions of TGS transmission measurement. An innovative virtual trajectory length model was developed using the transmission reconstruction equation and the Monte Carlo program Geant4. This model integrated the solution processes for trajectory length and detection efficiency within a unified framework. To mitigate the influence of the angular distribution of γ-rays emitted by the transmission source at the detector, transport processes of numerous particles traversing a virtual nuclear waste barrel with zero density were simulated, and relevant information at each step of particle transport was recorded. Simultaneously, the model addressed the non-uniform detection efficiency across the detector face by considering whether the energy deposited by particles in the detector equals their initial energy. Two models were established to validate the accuracy and reliability of the virtual trajectory length model: Model 1, representing a simplified nuclear waste barrel, and Model 2, which closely approximated the actual structure of a nuclear waste barrel. The results demonstrated that the proposed virtual trajectory length model significantly improved the precision of trajectory length determination, substantially enhancing the quality of reconstructed images. For instance, when comparing the reconstructed images of Model 2 using the “point-to-point” model and the average trajectory model, the SNR increased by 375.0% and 112.7%, respectively. Consequently, the virtual trajectory length model proposed in this paper is of paramount importance for the precise reconstruction of transmission images and can provide support for accurate determination of radioactive activity in nuclear waste barrels.

Full Text

Preamble

Research on an Accurate Virtual Trajectory Length Model for TGS Transmission Measurement

Rong-Rong Su[1], San-Gang Li[1],[2],†, Chu-Xiang Zhao[1], Li Yang[3], Ming-Zhe Liu[1],[2], Shan Liao[1], Zhi Zhou[1], Qing-Shan Tan[1], Zhi-Xing Gu[1], Xian-Guo Tuo[4], and Yi Cheng[1]

[1]Chengdu University of Technology, College of Nuclear Technology and Automation Engineering, 1#, Dongsanlu, Erxianqiao, Chengdu 610059, Sichuan, P. R. China

[2]Applied Nuclear Technology in Geosciences Key Laboratory of Sichuan Province (Chengdu University of Technology), 1#, Dongsanlu, Erxianqiao, Chengdu 610059, Sichuan, P. R. China

[3]University of Science and Technology of China, 230026, China

[4]School of Physics and Electronic Engineering, Sichuan University of Science and Engineering, Zigong, 643000, China

To accurately reconstruct TGS transmission measurement images, this paper optimizes the transmission reconstruction equation according to the actual conditions of TGS transmission measurement. Based on the transmission reconstruction equation and the Monte Carlo program Geant4, an innovative virtual trajectory length model was devised. This model integrates the solution processes for trajectory length and detection efficiency within a unified framework. To mitigate the influence of the angular distribution of γ-rays emitted by the transmission source at the detector, we simulated the transport processes of numerous particles traversing a virtual nuclear waste barrel with zero density and captured relevant information at each step of particle transport. Simultaneously, the model addressed the non-uniform detection efficiency across the detector end face by considering whether the energy deposition of particles in the detector equals their initial energy. Two models were established to validate the accuracy and reliability of the virtual trajectory length model: Model 1, a simplified nuclear waste barrel, and Model 2, which closely resembles the actual structure of a nuclear waste barrel. Research results indicate that the proposed virtual trajectory length model significantly enhances the precision of trajectory length determination, substantially elevating the quality of reconstructed images. For example, when comparing the reconstructed images of Model 2 using the "point-to-point" model and the average trajectory model, the SNR increased by 375.0% and 112.7%, respectively. Consequently, the virtual trajectory length model proposed in this paper holds paramount significance for the precise reconstruction of transmission images and can provide support for accurate detection of radioactive activity in nuclear waste barrels.

Keywords: Tomographic Gamma Scanning, transmission measurement reconstruction, Geant4, trajectory length model, non-uniform detection efficiency

INTRODUCTION

Tomographic Gamma Scanning (TGS) has undergone substantial improvement and development from Segmented Gamma Scanning (SGS) technology. SGS divides the measured waste barrel into multiple segments, assuming a uniform distribution of the medium in each segment. However, this approach falls short of meeting the demands of actual nuclear waste barrels and proves effective only for detecting low-density or relatively uniformly distributed nuclear waste barrels with known medium-to-high density characteristics [1–3]. In response to these limitations, TGS has evolved from two-dimensional scanning to three-dimensional scanning based on SGS. While conducting axial segmented scanning on nuclear waste barrels, TGS introduces translational and rotational scanning for each segment, providing information on the “depth” of nuclear waste barrels that SGS technology cannot offer [4, 5]. TGS excels in detecting the distribution of media in nuclear waste barrels and extends the detection range of non-destructive analysis technology to non-uniformly distributed medium and high-density nuclear waste barrels [6].

TGS technology involves both transmission measurements and emission measurements [7, 8]. During transmission measurement, the nuclear waste barrel is divided into several voxels. The transmission data measured by the detector are then utilized to reconstruct the linear attenuation coefficient of each voxel using a reconstruction algorithm [9]. The emission measurement process aims to acquire a radioactive intensity distribution map within a nuclear waste barrel [10]. To ensure the accuracy of the obtained radioactive intensity distribution, it becomes imperative to apply the attenuation coefficient derived from the transmission measurement process [11]. This coefficient enables meticulous point-by-point correction for self-absorption. Thus, the accuracy of the linear attenuation coefficient reconstructed from transmission measurement is pivotal, directly influencing the accuracy of the radioactive intensity distribution map obtained from emission measurement [12–14].

To reconstruct the linear attenuation coefficient, Estep et al. from Los Alamos National Laboratory in the United States simplified the physical model of TGS transmission measurement [15]. The transmission source and detector were treated as dimensionless point sources and point detectors, respectively. Simultaneously, the ray beam emitted by the point source was regarded as parallel beams. This simplified model was called a “point-to-point” model [16]. The model significantly simplifies the calculation of the linear attenuation coefficient and currently serves as the mainstream model for calculating trajectory length. However, in actual TGS systems, γ-rays are emitted by the transmission source at a certain cone angle and pass through the nuclear waste barrel, resulting in a corresponding angle for the large-sized detector. With the translation and rotation of the transmission source and detector (or nuclear waste barrel) during the transmission measurement process, the distributions of the trajectory length of the ray passing through voxels change accordingly [17]. The disparity between the “point-to-point” model and the actual device resulted in a significant error between the computed trajectory length and the trajectory length of the actual rays passing through the voxel, directly leading to poor image quality in transmission measurement reconstruction.

Additionally, some researchers, recognizing the angular distribution of emitted γ-rays on the detector in TGS systems, have proposed various models to solve trajectory length. Li Lei from Chengdu University of Technology introduced a Monte Carlo simulation calculation model based on surface flux, Zhang Quanhu from the Institute of Atomic Energy proposed an average trajectory model, and Han Miaomiao from Harbin Engineering University proposed a "point-detector (PD)" model for solving the average trajectory. However, these models failed to consider the practical scenario of the detector detecting emitted rays: the detection efficiency of γ-rays varies at different positions on the detector end face (an uneven response) [18].

To reduce the impact of an uneven response, Zhang Quanhu from the Atomic Energy Institute proposed a Monte Carlo trajectory length model based on the Cyrus-Beck algorithm. Test results demonstrated the superiority of their model over the average trajectory model and the "point-to-point" model [19]. Nevertheless, the trajectory length solved by this model was related to the barreled medium and cannot be determined in advance; repeated MC simulations were required to obtain the trajectory length, making the calculation process complex. For samples with medium to high density media, there is a significant error [20]. In addition, due to the fact that the model does not consider the structural parameters of the actual nuclear waste barrel and the beam limiting effect of the collimator used in High Purity Germanium (HPGe) detectors, it is currently unable to be applied in practice and further research is needed [21]. Although this model has various shortcomings, its research results indicate that reducing the impact of detection uneven response of detector end face is an effective method to improve the accuracy of trajectory length.

This paper optimizes the transmission reconstruction equation according to the actual TGS transmission measurement situation, which took into account the angular distribution of γ-rays emitted from the transmission source on the detector and the varying detection efficiency when they reached different points on the detector end face. To obtain the equivalent trajectory length matrix elements and detection efficiency of the optimized transmission image reconstruction equation, we proposed a virtual trajectory length model based on Geant4. Leveraging the capability of Monte Carlo program Geant4 which can simulate the transport process of numerous particles and capture some information at each step, we simulated the transport of particles emitted by a transmission source passing through a virtual waste barrel with a density of 0. Taking into account the varying detection efficiency at different points on the detector end face, we determined whether particles are detected by the detector based on whether the energy deposition of each particle in the detector equals its initial energy. This virtual model had reduced the impact of the uneven response function of the detector end-face detection efficiency, providing a simple and accurate solution for trajectory length.

II. METHOD

A. Optimization of transmission reconstruction equation

In traditional TGS transmission measurement, the transmission reconstruction equation is represented by Eq. (1) [22]:

(cid:88) µjTij = pi

Where, pi represents the negative logarithm of the γ-rays transmittance at the i-th transmission measurement position, also known as projection; Tij represents the trajectory length of the j-th voxel that the γ-rays pass through at the i-th position; µj represents the linear attenuation coefficient of the j-th voxel; n represents the total number of voxels.

In actual TGS transmission measurements, γ-rays emitted by the transmission source exhibit an angular distribution, and the detection efficiency of all points on the detector end face is not the same. The TGS transmission formula is as follows [23]:

(cid:80)N k=1 k (cid:88)   k exp (cid:88) (−xikjµj)

Where, pi represents the transmissivity at the i-th position; k represents the detection efficiency of the k-th point on the detector end face for a certain energy γ-rays; xijk represents the length of the trajectory where the ray, passing through the k-th point of the detector end face, intersects the j-th voxel at the i-th measurement position; N is the total number of γ-rays emitted by the transmission source within the solid angle of the detector.

(cid:88) (−xikjµj) qk = exp

Where, qk represents the attenuation rate that the k-th ray passes through the material without considering the detector efficiency.

Thus, Eq. (4) can be obtained:

Eq. (9) can be transformed as follows:

(cid:88) (cid:88)

Next, we can obtain the following Eq. (5) by taking the negative logarithm for both sides of Eq. (3):

− ln qk = (cid:88) xikjµj

Then:

. . . xi1n xi11 xi12 xi13 . . . xi2n xi21 xi22 xi23 xiN 1 xiN 2 xiN 3 . . . xiN n ln q1 ln q2 ln qN

According to Taylor's formula, Eq. (7) can be obtained:

ln qk = (qk − 1) − (qk − 1)2 + . . .

Then:

. . . xi1n xi11 xi12 xi13 . . . xi2n xi21 xi22 xi23 xiN 1 xiN 2 xiN 3 . . . xiN n q1 − 1 q2 − 1 qN − 1 ln q1 ln q2 ln qN

(cid:88) kxik1 + µ2 (cid:88) kxik2 + ··· + µn = −k[(1q1 − 1) + (2q2 − 2) + . . . + (N qN − N)]

(cid:88) kxikn

By substituting Eq. (4) into equation Eq. (10), we can obtain:

(cid:88) kxik1 + µ2 (cid:88) = k(1 − pi) (cid:88) kxik2 + ··· + µn (cid:88) kxikn

The equivalent trajectory length can be expressed as:

Tij = (cid:80)N k=1 kxikj (cid:80)N k=1 k

The equations in the system of equations can be expressed as Eq. (13):

(cid:88) µjTij = ln(pi/ i) pi/ i − 1 (1 − pi)

The formulate for the equivalent trajectory length, which takes into account the endpoint detection efficiency, is shown in Eq. (12). By substituting the obtained equivalent trajectory lengths Tij, as well as the detection efficiency i, and the transmissivity pi into Eq. (13), the equation system for transmission image reconstruction can be obtained.

Where, k = ln(pi/ i) pi/ i−1 is an error correction value; i represents the detection efficiency of a detector for a certain energy γ-rays at the i-th measurement position.

However, Eq. (8) does not take into account the endpoint detection efficiency k. If both sides are left multiplied by the detection efficiencies, then [28]:

(cid:2) 1 2 . . . N (cid:3) = −k (cid:2) 1 2 . . . N (cid:3) . . . xi1n xi11 xi12 xi13 . . . xi2n xi21 xi22 xi23 xiN 1 xiN 2 xiN 3 . . . xiN n q1 − 1 q2 − 1 qN − 1

B. Model of virtual trajectory length based on geant4

To solve the optimized transmission image reconstruction equation, obtaining the equivalent trajectory lengths, detection efficiency, and transmissivity in advance is necessary. Transmissivity can be obtained through detector counting conversion; for detection efficiency, a passive efficiency calibration method based on Monte Carlo is utilized. This method requires calculating the detection efficiency of the detector relative to the radiation source for a certain energy gamma ray at each measurement position in advance based on Monte Carlo. As of now, there has been little research regarding the solution to the equivalent trajectory length formula Eq. (12). The trajectory length obtained using Eq. (12) can be interpreted as the average length of all γ-rays detected by the detector that pass through the j-th voxel. If the trajectory lengths of all γ-rays passing through the j-th voxel can be calculated, and whether each ray has been detected by the detector can be determined [24]. By averaging the trajectory lengths of the detected rays, the equivalent trajectory length can be obtained. The Monte Carlo program Geant4 can track the trajectory lengths of each interaction step between primary or secondary particles and matter, and obtain the geometric information of each step, which provides the possibility for simulation to obtain equivalent trajectory lengths [25, 26].

In order to solve for the equivalent trajectory length and detection efficiency, this paper introduces a novel approach by constructing a virtual waste barrel and integrating the solution processes into a unified model. This model, based on Geant4, simplifies the solving process and introduces a pioneering method for determining equivalent trajectory lengths.

The virtual trajectory length model was structured as follows:

Firstly, based on the TGS experimental setup, a TGS simulation model without nuclear waste barrel was constructed. The space containing the virtual waste barrel was divided into multiple segments, and one segment was selected for simulation to calculate the equivalent trajectory length [27]. The virtual waste barrel segment was further divided into N × N voxels, and the medium within the segment was filled with a vacuum. The voxel segmentation of a single-layer nuclear waste barrel and the emission status of rays are shown in Fig. 1 [Figure 1: see original paper].

Considering the uneven response of the detector's end face detection efficiency, the simulation included the process that particles passing through the virtual waste barrel were detected by the HPGe detector. If the energy deposited in the detector differs from the particle's initial energy, it was assumed that the particles have not been detected, and the trajectory lengths passing through all voxels were considered as zero. The cumulative trajectory lengths of all particles with the same emission energy passing through the same voxel were then calculated. Dividing the total trajectory length by the number of particles with non-zero trajectory length yields the equivalent trajectory length corresponding to the voxel. Further, dividing the number of particles with non-zero trajectory length at a specific energy by the total number of emitted particles at that energy yields the detection efficiency of γ-rays at a particular location, denoted as i.

The next step involved simulating the transportation process of numerous particles passing through the virtual waste barrel segment at a specific location. Leveraging Geant4 functions such as "G4Step", "Getname()", "GetTouchableHandle()", and "GetPostStepPoint()", the name of voxels traversed by the particles and the length of trajectory within these voxels were obtained. Notably, due to the absence of any substance in the virtual waste barrel, particle rays follow a straight-line transport path without undergoing any physical processes

[29].

Image reconstruction algorithm

The current image reconstruction algorithms can be roughly divided into two categories: analytical methods and iterative reconstruction algorithms [30]. This paper focuses on accurately obtaining the transmission measurement trajectory length, and refrains from delving deeply into the intricacies of the reconstruction algorithm. The optimization of the algorithm will be discussed in subsequent research. Consequently, for image reconstruction, the Maximum Likelihood Expectation Maximization (MLEM) algorithm is employed [31], and its iterative formula is as follows [32, 33]:

µ(k+1) (cid:80) i Tij (cid:88) j Tijµ(k) (cid:80)

Where, k is the number of iterations of the algorithm, µ(k) is the estimated value of the linear attenuation coefficients on all voxels during the k-th iteration, pi is the projection value obtained during the i-th transmission measurement of the substance to be measured, Tij is the trajectory length value on the j-th voxel during the i-th measurement.

Image quality evaluation methods

To assess the quality of reconstructed images of nuclear waste barrels, various evaluation methods are essential, encompassing visual inspection and profiles for qualitative assessment, as well as mean square error (MSE) and signal-to-noise ratio (SNR) for quantitative analysis [34].

MSE is used to represent the difference between the reconstructed image and the reference image, and a smaller MSE value indicates better quality of the reconstructed image. In this paper, SNR is also employed to evaluate the noise level of the reconstructed image, where higher SNR values correspond to lower image noise.

The calculations of MSE and SNR are shown in Eq. (15) and Eq. (16), respectively:

(cid:35) MSE = (cid:88) (cid:88) (µRec(m, n) − µRef(m, n))2

(cid:34) (cid:80)M (cid:80)N (cid:80)N (cid:80)M SNR = 10 log10 n=1(µRef(m, n))2 n=1(µRec(m, n) − µRef(m, n))2

Where, µRec(m, n) represents the reconstruction values of the m-th row and n-th column of the reconstructed image; µRef(m, n) represents the reference values of the m-th row and n-th column of the reference image.

III. RESULT ANALYSIS AND DISCUSSION

A. Simulation model of nuclear waste barrel

In order to evaluate the virtual trajectory length model, Geant4 was employed to simulate the TGS system. Two different models were designed for this purpose. The first model, labeled as Model 1, was a nuclear waste barrel without concrete filling. It consisted of four distinct materials: fiber, concrete, water, and aluminum. The geometric representation of Model 1 can be seen in Fig. 2(a). Additionally, a second model, labeled as Model 2, was created to assess the practical applicability of the virtual trajectory length model. Model 2 was a nuclear waste barrel filled with concrete, as depicted in Fig. 2(b). Fibers were positioned at three specific locations within Model 2, while the remaining space outside those regions was filled with concrete. In order to evaluate the quality of the reconstructed transmission images, reference images of nuclear waste barrels are needed [35]. In this study, parallel beam γ-rays were used to vertically irradiate the nuclear waste barrel model. The intensities of the rays at different positions passing through the model were obtained, which allowed the acquisition of a reference image for the nuclear waste barrel [36]. In the reference image, different colors represent distinct densities of the medium [37], as shown in Fig. 2(c) and (d). It is important to note that in the projection calculations, the count of particles without attenuation is based on the number of particles passing through a barrel wall. The count after particle attenuation utilizes the particle count values that particles pass through either Model 1 or Model 2. As a result, the reconstructed image did not include the barrel wall, thus circumventing the potential influence of nuclear waste barrel walls on the results.

B. Comparison of different models for trajectory lengths

To validate the accuracy of the trajectory length method proposed in this paper, two different models were incorporated. The first model is the “point-to-point” model established by Estep, and the second model is the average trajectory model proposed by Zhang Quanhu. These models provide additional trajectory length data for reference when using a virtual model to extract trajectory lengths for image reconstruction. When reconstructing the images using trajectory lengths obtained from the “point-to-point” model and the average trajectory model, the projection data had not been corrected for detection efficiency. However, when utilizing the virtual model for trajectory length, the projection data underwent correction for detection efficiency. The reconstruction images of Model 1 are labeled as Fig. 3 Figure 3: see original paper, (c), and (e), and the reconstruction images of Model 2 are labeled as Fig. 3(b), (d), and (f).

C. Qualitative evaluation

In the reconstruction image (Fig. 3(a)) corresponding to the “point-to-point” model, the result appears unclear, failing to accurately capture the specific structure of the medium in Model 1. Conversely, the reconstruction image under the average trajectory length model, as depicted in Fig. 3(c), offers a more distinct representation of the medium structure. This suggests that the average trajectory length model exhibits superiority over the "point-to-point" model. In the reconstruction image (Fig. 3(e)) corresponding to the virtual trajectory length model, it becomes apparent through visual inspection that the reconstructed medium (both shape and position) within the barrel aligns more closely with the reference image of Model 1, signifying a substantial improvement in reconstructed image quality.

In the reconstruction images of Model 2 (Fig. 3(b), (d), and (f)), it becomes more apparent that, in comparison to the "point-to-point" model and the average trajectory length model, the virtual trajectory length model exhibits superior reconstruction quality. This model not only successfully reconstructs the filling material within the barrel but also effectively restores the pertinent information of the measured medium.

The reconstruction and reference images' profiles of the two models are presented in Fig. 4 Figure 4: see original paper, (e), and (d), (f), respectively. The positions of the profiles are illustrated in Fig. 4(a) and (b). Upon comparing the images, it becomes apparent that the reconstructed images' profiles using the virtual trajectory length model exhibit a higher degree of consistency with the reference image's profile diagram. The overall trends of their profiles are closer and smoother, indicating that the proposed virtual trajectory length model significantly reduces the noise level in the reconstructed images. The reconstruction results of the virtual trajectory length model show a qualitative improvement, whether for the assumed Model 1 or Model 2, which is closer to the real waste barrel environment.

D. Quantitative evaluation

Under various trajectory length models, the MSE and SNR of the reconstructed images for both Model 1 and Model 2 were presented in Fig. 5:

In Fig. 5(a) and (b), the virtual trajectory length model shows significant advantages over the "point-to-point" model and the average trajectory length model for Model 1. Compared to the "point-to-point" model, the virtual trajectory length model reduced the MSE by 57.8% and increased the SNR by 192.3%. The average trajectory length model, addressing the overlooked solid angle problem inherent in the "point-to-point" model, yields trajectory lengths that are closer to the actual values. However, in comparison to the average model, the virtual trajectory length model proposed in this paper still achieves a 37.6% reduction in MSE and a 56.1% improvement in SNR. This discrepancy can be attributed to the following factors: (1) the number of detector end face grids. The process of a large number of particles reaching the detector end face and being detected was simulated in the virtual trajectory length model. It is worth noting that the number of end face grids is much greater than the average model, reaching millions or even billions of levels (determined by the number of emitted particles, more particles will lead to more grids). (2) non-uniform detection efficiency. The proposed model takes into account the non-uniform detection efficiency of the actual TGS detector end face. This consideration results in a smaller deviation between the obtained trajectory length and the actual trajectory length.

In the objective assessment of the reconstruction results for Model 2, the virtual trajectory length model consistently demonstrates superior reconstruction quality. Compared to the "point-to-point" model and the average trajectory model, the MSE decreased by 85.4% and 72.5%, respectively. In addition, compared to the "point-to-point" model and the average trajectory model, the SNR increased by 375.0% and 112.7%, respectively. These results confirm that the trajectory length model proposed in this paper can improve the quality of reconstructed images and effectively reduce noise.

Based on the comprehensive qualitative and quantitative analyses conducted above, it can be concluded that the virtual trajectory length model proposed in this paper, which accounts for the non-uniform detection efficiency of the detector end face and the angular distribution of γ-rays at the detector, can accurately reconstruct the distribution of the medium within the nuclear waste barrel. The reconstruction quality achieved by this model is significantly superior to that of both the "point-to-point" model and the average trajectory model.

IV. CONCLUSION

This paper optimizes the transmission reconstruction equation based on the actual situation of TGS transmission measurement, presenting a novel virtual trajectory length model. Unlike conventional methods such as the Cyrus-Beck algorithm for calculating equivalent trajectory length, this model leverages the inherent characteristics of Geant4. It ingeniously devises a model wherein a multitude of particles traverse a virtual waste barrel and are subsequently detected, yielding the equivalent track length.

In contrast to the average model, this virtual trajectory length model features more grids on the detector end face, effectively mitigating the impact of γ-rays on the angle distribution of the detector. Moreover, by accounting for the energy deposition process of each particle in the detector, it successfully circumvents the issue of non-uniform detection efficiency encountered in actual TGS detector end faces. The comparison results show that the virtual trajectory length model can accurately reconstruct the medium distribution within the nuclear waste barrel, surpassing the performance of both the "point-to-point" model and the average trajectory model. Furthermore, the virtual trajectory length model proposed in this paper will be extended to solve the emission track length and an emission track length model including detection efficiency will be constructed, so as to avoid complicated detector efficiency calibration during emission measurement.

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Note: Figure translations are in progress. See original paper for figures.

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