3D cosmic-ray muon tomography using portable muography detector

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ABSTRACT: A feasibility demonstration of three-dimensional (3D) muon tomography was performed for infrastructure equivalent targets using the proposed portable muography detector. For the target, we used two sets of lead blocks placed at different heights. The detector consists of two muon position-sensitive detectors, made of plastic scintillating fibers (PSFs) and multi-pixel photon counters (MPPCs) with an angular resolution of 8 msr. In this work, the maximum likelihood-expectation maximization (ML-EM) method was used for the 3D imaging reconstruction of the muography. For both simulation and experiment, the reconstructed positions of the blocks produce consistent results with prior knowledge of the blocks’ arrangement. This result demonstrates the potential of the 3D tomographic imaging of infrastructure by using seven detection positions for portable muography detectors to image infrastructure scale targets.

KEYWORDS: Particle tracking detectors; Scintillators, scintillation and light emission processes (solid, gas and liquid scintillators); Particle detectors

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1 Introduction

Cosmic-ray muon radiography, also known as muography, is one of the effective techniques for nondestructive radiography. The technique has been used to survey the structure of huge objects with the basic principle similar to conventional X-ray imaging. The muography has been used in various fields, for example, the finding of a void in the Khufu’s pyramid [1], prediction of volcano eruption [2], and investigation of the melted core of the Fukushima Dai-Ichi Nuclear Power Plant [3]. However, only a few applications have published the three-dimensional (3D) muography based on the absorption method. Besides, all of these results are focused on geological objects, such as Asama Volcano [4, 5], Showa-Shinzan Lava Dome [6], ore exploration [7], and geological mapping [8, 9].

The application has expanded to smaller-scaled objects such as degradation surveys of social infrastructures, including concrete-based bridges, furnaces, dams, and valuable architecture. Portable muography detectors [10, 11] for smaller-scaled targets have been developed for their operation and maintenance. The muography has the potential to estimate the density variation caused by degradation in the object and can be mapped to the two-dimensional (2D) projection. The projection generally shows only the density integrated along the transmission path of muons but the spatial distribution along the muon’s path cannot be estimated directly. Thus, the tomography technique, such as filter back projection, ordered subsets expectation maximization (OSEM), and maximum likelihood-expectation maximization (ML-EM) method used in the medical field, is necessary to yield the spatial distribution inside the objects. However, direct measurement of the overall 3D image is impractical due to the low flux of terrestrial cosmic-ray muons, which is approximately 1 muon/cm²/min at sea level.
Moreover, the flux is drastically decreased in proportion to the cosine square of zenith angle of the incident cosmic-ray muons. Moreover, multiple detection positions are required for 3-dimensional (tomographic) measurement. A novel tomographic reconstruction algorithm is strongly required to decrease the number for minimizing the measurement time.

In the present work, we propose an approach based on the ML-EM algorithm [12] for cosmic-ray muon tomography. A simulation was developed to test the feasibility of the algorithm [13] and designed the experiment’s configuration using our developed portable muography detector [10]. Then, the 3D muography image from the experiment setup was also performed to confirm the feasibility.

**Figure 1.** Photo of two muon position-sensitive detectors fabricated in the portable muography detector. The detected positions of a muon trajectory are recorded as MPPC ID numbers \((i, j)\) and \((k, l)\) for upper and lower mu-PSDs.

### 2 Materials and methods

#### 2.1 Portable muography detector

A multi-purpose portable muography detector was developed for real-time monitoring of the degradation of infrastructures [10]. Figure 1 depicts a schematic view of the detector which is the combination of two muon position-sensitive detectors (mu-PSDs). Each mu-PSD is a combination of two layers of plastic scintillating fibers (PSFs; Kuraray, SCSF-78, 2.0 mm\(^2\), BJ). The PSF is a rectangular fiber with the \(2 \text{ mm} \times 2 \text{ mm}\) cross-section dimension and covered by a single clad layer. The two layers, each with \(12.8 \text{ cm} \times 12.8 \text{ cm}\) active area, are placed perpendicularly to each other to detect the hitting position of muons. The scintillation light generated by the incident cosmic-ray muons is propagated along the PSFs and detected by sixteen MPPCs (Hamamatsu, S12572-100C) which are connected on one side of each layer. Once a muon passes through the PSF, around 2,000 photons are generated on average. As a result of trapping efficiency and MPPC quantum efficiency curve, \(39.4 \pm 5.3\) p.e. are detected by a single muon hit. From the setup of the upper mu-PSD,
with 8.75 mm × 8.75 mm of one-pixel detection area, positioned 100 mm away from the lower one, the resolution of 8 msr was achieved. Signal charges from preamplifier connected to the MPPC is AD converted and record with the MPPC ID, \((i, j)\) and \((k, l)\) for the upper and lower mu-PSDs, respectively.

The mu-PSDs are installed in a heat-insulating box where the temperature inside was controlled to 17 °C using a Peltier heating & cooling device (Ohm Electric Inc., BOXCOOL, OCE-F40F-D24) to keep the gain shift of the MPPCs at a low level. The detector properties such as stability, detection efficiency, and several measurement results are described in ref. [10].

The projection of an object is evaluated from the cosmic-ray muon’s absorption ratio distribution as a function of muon direction in muography based on absorption method. The direction is defined by the zenith angle and the azimuth angle; \((\theta, \varphi)\). This detector generally requires background and foreground measurements to derive the absorption ratio necessary for general muography detectors utilizing the absorption method. Given a background intensity \(I_0(\theta, \varphi)\), the absorption ratio \(R(\theta, \varphi)\) for measured intensity \(I_1(\theta, \varphi)\) can be expressed as follows:

\[
R(\theta, \varphi) = 1 - \frac{I_1(\theta, \varphi)}{I_0(\theta, \varphi)},
\]

(2.1)

The output data of the detector is discretized as \(R(\Delta x, \Delta y)\), where \(\Delta x = k - i\) and, \(\Delta y = l - j\) for a muon hitting positions \((i, j)\) and \((k, l)\), respectively. In the present paper, the authors refer to the absorption ratio distribution as a vector plot.

We successfully mapped the inner structure of a seven-story concrete building using this portable muography detector with an adjusted 8 msr angular resolution [10]. The portable muography detector was also used in this measurement.

2.2 Three-dimensional cosmic-ray muon tomography using ML-EM algorithm

Since the ideal detector for 3D tomography has a solid angle of \(4\pi\) sr from the target, as Radon’s theorem [13] proved, the target shape can be determined uniquely under this condition. However, as mentioned in the Introduction section, the effects of low cosmic-ray muon flux and its angular distribution on the measurement duration and the number of detection positions are significant constraints in muography. The constraint contributes to the demand for optimization between the shortest possible measurement duration, a reasonable statistical uncertainty of measurement, and the capability to reconstruct the 3D image. The numerical methods are required to solve this ill-posed problem. The Maximum Likelihood Estimation Maximization (ML-EM) method is a well-known iterative algorithm from its successfully proposed for “emission tomography” such as SPECT or PET scans to reduce measurement time which is the similar constrains to the muography. Thus, we adopted the method to improve the 3D cosmic-ray muon tomography. The ML-EM algorithm estimates the 3D density \(\lambda(b)\) of a voxel \(b\) that maximizes the likelihood of the projection \(n'(d)\) of pixel pair \(d = (i, j), (k, l)\). In this study, \(n'(d)\) was intended to be equivalent to the absorption ratio \(R(\Delta x, \Delta y)\) of the vector plot.

According to the flow chart in figure 2, the algorithm can be described in the following steps:

(i) The ML-EM method begins with an initial estimation of the \(\lambda^{(0)}(b)\) of a voxel \(b\) where \(b = 1, 2, \ldots, B\) and \(B\) is the number of voxels in the region of interest. The superscript represents the number of iteration loops which is zeroth at this initial step.
(ii) The projection $n'(d)$ is calculated from the initial estimation by

$$n'(d) = \sum_{b=1}^{B} \lambda^{(0)} p(b, d)$$

(2)

where $p(b, d)$ refers to the probability of detecting a muon event from the voxel $b$ by the pair-pixels $d$ where $d = 1, 2, \ldots, D$. Here $D$ denotes the total number of muon directions that can be detected by the detector pair-pixels. In this study, $p(b, d)$ is estimated by the distance-driven back projection method [14]. The method calculates the probability from the projected area ratio of the voxels to the detector pair-pixels onto a common plane.

(iii) Assuming that $\lambda^{(m)}(b)$ denotes the estimated density in a voxel $b$ at the $(m)$th iteration. The next approximation $\lambda^{(m+1)}(b)$ can be expressed by the ML-EM algorithm as proposed by Shepp and Vardi [12]:

$$\lambda^{(m+1)}(b) = \lambda^{(m)}(b) \left\{ \frac{1}{\sum_{d} p(b, d)} \sum_{d} \frac{n(d) p(b, d)}{n'(d)} \right\}.$$  

(2.2)

(iv) The updated projection $n'(d)$ of the $(m+1)$th iteration can simply be derived by the convolution process in equation (2).

(v) The updated $n'(d)$ was compared with the experimental absorption ratio $n(d)$, which is the absorption ratio $R(\Delta x, \Delta y)$ for this muography method. This step is the criteria to continue or stop the iteration.

In figure 2, the $(M)$th iteration indicates the last iteration that provides the finalized 3D density image $\lambda^{(M)}(b)$. However, the iteration stopping criterion is required for the acceptable quality. In this study, a simulation code was developed to estimate the number of iterations (see [13] for detail).

![Figure 2](image_url)  

Figure 2. A flow chart of the ML-EM algorithm.
3 Experiment

3.1 Measured objects

For this feasibility study, we used lead blocks to reproduce the absorption ratio of the infrastructure buildings because the whole system scale can be reduced 4.4 times based on the density difference. Particularly, 20 cm of lead thickness corresponds to a five- or six-story building with a 15 cm thick floor of concrete. Therefore, we placed two different sized rectangular lead blocks ($20 \times 20 \times 20$ cm$^3$ and $20 \times 20 \times 30$ cm$^3$) at the different height from the detector level (58.5 cm for smaller and 112.6 cm for larger lead blocks), as a configuration of the measurement setup shown in figure 3.

![Figure 3](image.png)

Figure 3. The sketch of the set of the lead blocks configuration for the experiment.

3.2 Simulations to determine experimental conditions

The detection positions, measurement times, and the ML-EM convergence conditions was determined by the simulation (See ref. [13] for the detail). Figure 4 depicts the considered coordination of detector positions in unit of centimetre. In this paper, the detector position is expressed by the IDs shown in figure 4. The detector position, located along the $x$-axis for seven different positions, and the others are varied along the $y$-axis. The coordinate $(x[\text{cm}], y[\text{cm}])$ represents the position of the center of the mu-PSD2 in each simulation. The origin, position ID 3 in the figure, was set at the center of the mu-PSDs located under the center of the lower lead block, vertically. The absorption...
ratio maps were calculated for all eleven positions using a Monte Carlo method [13]. The number of simulated events was $10^7$ muons for each detector position, with a statistical uncertainty of less than 1% for all of the pixel of absorption ratio maps.

We performed the ML-EM analysis using the simulated data with four difference number of detection points (ID = 3, 5, 7 and 11 positions) and four difference the number of iterations (5, 10, 15 and 20 iterations) in the reconstruction procedure to find optimal condition. Then, the minimized number of detection positions for the practical measurement was designed from the quality of the reconstructed 3D image.

**Figure 4.** Detection positions for 3D cosmic-ray muon tomography in a unit of cm. The coordination represents the center of mu-PSDs given the origin at the 3rd measurement position.

Figure 5 shows the 3D images, $\lambda^{(m)}(b)$ for all $b$, projected to the $xz$ plane in different conditions. The number of the detection position of 3, 5, 7, and 11 in the figure is the result from the combination of the detector position ID of 2–4, 1–5, 0–6, and 0–10, mentioned in figure 4, respectively. Without the projection from the various detection positions along the $y$-axis, the position of the upper block is not clear. However, for the seven detection positions, the result is reasonable for finding the center position of two lead blocks. Thus, the seven detection positions, which are position ID 0–6 in figure 4, were chosen, with 20 iterations for the 3D image reconstruction of the measurement result.

In this study, only the size and location of the lead blocks were included in the simulation [13], i.e., the muon interaction in the matter was out of the simulation scope. Furthermore, as the absorption ratio is proportional to the object’s thickness for the ideal homogeneous material target, the absorption ratio maps ($n(d)$) from the simulation was determined by the average thickness that the incident particle passed through, instead of the particle absorption ratio according to the density of the matter [13]. The average thickness was calculated by a Monte Carlo method. A random line was generated inside the acceptance of a specific pixel pair and the length inside the lead block was measured along to the line. This process was iteratively done while the average of their thickness is not converged. The converged average is used as “the average thickness.” In contrast to the present feasibility study, an object to be measured, e.g. an infrastructure building, may have unknown degradation inside. However, because the size of the degradation is considered
Figure 5. 3D image, $\lambda^{(m)}(b)$ for all $b$, projected on the $xz$ plane calculated from the simulations for optimizing the number of detection points and iteration number in the ML-EM method. The contour plot was calculated on the 2 cm binning for both $x$ axis and $z$ axis. Dashed and solid lines show the lead blocks region.

a very small region, we can ignore them to calculate the average thickness. Even the degradation region is rather large, we can measure the average thickness by putting a reference object near the object during the measurement for thickness calibration.

4 Data analysis

Figure 6 (a) is an example of the average thickness resulted from the simulation [13]. The simulation provided the two lead blocks thickness map ($n(d)$) without the artefact noise, which is the high statistical uncertainty of detected muons count. The simulation could identify the projection pixels that contain the information of two lead blocks. Thus, the simulated results suit for minimizing the number of detection points, measurement time and iteration number as explained in the previous section. Figure 6 (b) depicts the absorption ratio mapping derived from the same setup measurement. In contrast, the measured result contained the noise in some pixels, which corresponds to the relative statistical uncertainty distribution of the low muon count pixels in figure 6 (c).

The measurement time for each position was evaluated using the simulated projection and relative statistical uncertainty. In order to minimize the measurement time, each position measurement was designed to stop when the whole block projection had less than 7% of relative statistical uncertainty. Figure 6 (c), for example, shows the relative uncertainty of each pixel-pair when the measurement at the position ID 2 was finished. Table 1 presents the duration of measurement for each position. Recall from the simulations to determine the experimental conditions section, only seven detection positions, position ID 0–6, were performed. Moreover, the cosmic-ray muon background measurement was carried out for 208 h without the lead blocks to know absorption ratio.
Figure 6. (a) Lead thickness along to directions of the vectors from pixel in bottom mu-PSD to that in top mu-PSD. Absorption ratio of measured data (b) is consistent with (a). Experimental statistical uncertainty is shown in (c) and is kept lower than 10% where the lead block region.

Due to the lower number of detected muons from the experiment than the simulation, the relative statistical uncertainty was used as a threshold to filter out some pixels in the resultant vector map. If the relative statistical uncertainty of the pixels is greater than 7%, the pixels were ignored by the imaging algorithm. The uncertainty is also used to weight the probability parameter, $p(b, d)$ to decrease the affection of the higher uncertainty pixel.

| Position ID | Position $(x, y, z)$ [cm] | Duration [hours] |
|-------------|-----------------------------|-----------------|
| 0           | ($-50, 0, 0$)               | 407             |
| 1           | ($-34, 0, 0$)               | 308             |
| 2           | ($-18, 0, 0$)               | 166             |
| 3           | ($0, 0, 0$)                 | 89              |
| 4           | ($18, 0, 0$)                | 164             |
| 5           | ($34, 0, 0$)                | 344             |
| 6           | ($50, 0, 0$)                | 334             |
| 7           | ($0, -50, 0$)               | -               |
| 8           | ($0, -25, 0$)               | -               |
| 9           | ($0, 25, 0$)                | -               |
| 10          | ($0, 50, 0$)                | -               |

5 Results and discussion

Figures 7 (a) and 7 (b) present the reconstructed positions of the lead blocks in 3D from the simulation and experiment, respectively. The data of seven detection positions were included in the 20 iterative calculations, and the voxel size was set to $2 \text{ cm} \times 2 \text{ cm} \times 2 \text{ cm}$. The experimental 3D muography also indicated the visible high statistical uncertainty of detected muons count pixel around the blocks’
Figure 7. 3D muography; (a) from simulation and (b) from experiment.

position. However, for both simulation and experiment, the image reproduces reasonably well the position of the upper and lower lead blocks, as shown in the red line and black line, respectively. The center of mass calculated from the image vector $\lambda^{(m)}(b)$ based on simulation is located at $(0, 0, 65)$ for the upper block and at $(-26, 0, 122)$ for the upper block. The center of mass obtained from experimental data is located at $(2, 0, 68)$ for the upper block and at $(-22, 0, 122)$ for the upper block. The 3D image reconstructed from simulation certified the accuracy of the developed ML-EM algorithm. The overestimated size of the upper blocks along the $z$-axis is reasonable for detection positions where they are located only on the $xy$ plane. The clearer reconstructed image of the lower block than the upper one is mainly caused by contribution in the detector field of view due to the different height from the detector. Tomography generally requires at least 180 degrees of measured angles for well-posed conditions, and reconstructed images become worse with decreasing measured angles. In addition, the blurred region of the reconstructed upper block is corresponding to the lacking information of the block due to the experiment setup. The upper block tends not to be measured in various direction for all detection positions. The space between the blocks, for example, can be observed only at the position ID 0, 1 and 2. The reason why the centers of mass of both 3D images are displaced from the actual setup at $(0, 0, 68)$ for the upper block and at $(-25, 0, 123)$ for the upper block is due to $xy$ plane constraint. Remarkably, there is no initial bias input in this reconstruction. These reconstructed 3D images are calculated from the uniform initial estimation of the image vector $\lambda^{(0)}(b)$ value of 1 for each voxel.

6 Conclusion

In this study, the ML-EM method was used for the 3D image reconstruction of cosmic-ray muon tomography based on the transmission method. The feasibility study was performed under limited detection angles and the acceptance of a portable muography detector. A portable muography detector was used to detect two sets of lead blocks placed at different heights to the detector. Monte
Carlo simulation was used to optimize the measurement duration and confirm the accuracy of the ML-EM algorithm. Finally, the 3D muography image was reconstructed using the ML-EM method from the simulation and the to know absorption ratio projection obtained by the peer set up measurement. It was found that the image reproduces the position of the two blocks reasonably well. The experimental 3D image confirmed the feasibility of the 3D muography used in our portable muography detector on the infrastructure scale target. The iteration stopping criteria of the image reconstruction will be determined in the near future.

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