

Development of a Portable Muography Detector for Infrastructure Degradation Investigation and its Feasibility Study

クラバ, チャイウォンコット

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Development of a Portable Muography Detector for Infrastructure Degradation Investigation and its Feasibility Study

Kullapha Chaiwongkhot

Department of Advanced Energy Engineering Science
Interdisciplinary Graduate School of Engineering Sciences
Kyushu University

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Chapter 1

Introduction

1.1 Background

Muons are the dominant charged particles among terrestrial cosmic-rays on the ground [1]. The energy spectrum of the terrestrial muons is widely distributed from low energy of several MeV to high energy of PeV. Because of the energy loss along the path, the momentum of the energetic muons is changed and the low energy muons are fully-stopped inside an object. If the muons rate is detected, the density and thickness of the object can be evaluated, in a similar way to basic principles of conventional radiography imaging with X-rays. This method is so-called cosmic-ray muon radiography or “muography”.

The muography is an effective technique for nondestructive radiography. The technique has been applied to large objects due to the high energy characteristic of the cosmic-ray muons. Since George estimated overburden thickness of a tunnel by attenuation rate of cosmic-ray muons in 1955 [2]. The muography has so far been applied to various fields and can be categorized into two major methods.

The first method is to measure the scattering angle of the cosmic-ray muon by the object to identify atomic numbers and this is called “scattering method”. There are many examples of application with this method: monitoring of legacy nuclear waste container [3], revealing of the nuclear reactor core image [4], investigation of the melted core of the Fukushima Dai-Ichi Nuclear Power Plant [5] and interrogation of homeland security [6]. The scattering method is difficult to be adapted to large object exploration because two muon trackers placed on both sides of the object to obtain the scattering angle are required.

The second method is attractive due to the ability in the exploration of the huge object, such as search of hidden chambers in the Khufu’s pyramid in Giza [7], prediction of volcano eruption [8] and investigation of the volcano inner structure [9]. These muography applications are based on “attenuation method”. This method utilizes the absorption ratio of the cosmic-ray muon according to the density and thickness of the penetrated object. The attenuation rate of the cosmic-ray muons after passing through a target object as a function of its direction is used to image the target object. The cosmic-ray muon tracker, at least one detector, is required for this method.

This study mainly aimed to observe the large object by using the attenuation method. As the applications have been spread wider, the development of muography detector system dedicated to each specific application is significantly required.

1.2 Motivations and Objectives

If some sort of degradation occurs in an infrastructure, the density of the degradation volume changes from its original value in many cases. Thus, the density distribution measurement is useful to investigate the degradation for operation and maintenance. As reviewed above, various applications of the density muography technique to geological imaging was reported, but only several applications to the modern artificial structure were limited. For observation of structure with a few tens centimeters (e.g., a concrete beam of a building), several tens msr of the detection angular resolution is required. To investigate such the infrastructure, the detector should be placed a few meters away from the target object. The expected resolution is determined by this condition. Moreover, the portability is required for use of muography detectors in the field. The stability of long-term operation is also required because of the low flux of cosmic-ray muons on the ground.

Many survey techniques are applicable for inspection and monitoring to assess infrastructure degradation. However, the famous techniques like seismic and vertical electrical sounding, for example, those are sensitive to noises arising in the city region. The conventional techniques such as ground penetrating radar [10], x-ray radiography and can survey only a short distance depth, mostly less than one meter. The capabilities of the detection depth inside concrete of some non-destructive investigation techniques were summarized in Ref [11]. Theses radiography workers must also undergo special training and certification to control the radiation hazard. The images obtained from the technique is also difficult to evaluate and the interpretations tend to be subjective. Furthermore, the spatial resolution of the other techniques [12] has not been fulfilled by the considering scope of the aforementioned large infrastructure. The neutron imaging technique using compact neutron source [13] was achieved to detect the position of water and voids in the concrete. The technique, however, used the neutron energy from 10 meV to 5 MeV generated by the accelerator in facilities [14] which differ from our intention on the outdoor measurement.

Muography fulfills these requirements. Muon detectors can be designed flexibly to attain the needed resolution and can be optimized to improve compactness and stability. Moreover, muography is not affected by noise arising from human activity. Muography measurement does not perturb the activity of the target, while almost all existing structural assessment methods necessitate the suspension of activity. For example, bridges must be closed for radar investigation, and incinerators must be stopped during visual or endoscopic inspections. Since the cosmic-ray is the natural source, it is the uniqueness of muography which do not need the active source generators. In addition, muography is a nondestructive method that safe for operators. The wide range of energy of cosmic-rays muon is also an advantage of the muography to measure various density and large size of the target object if the muography detector

can be specified the muon energy detection range.

The main objective of the present work is to develop a muography detector which can be used to investigate the degradation of infrastructures such as concrete based bridges, furnaces, dams, and valuable architecture. A multi-purpose portable muography detector with adjustable resolution and compact design were fabricated to meet the aforementioned resolution requirement as well as the feasibility demonstration of the infrastructure scale muography. The muon attenuation rate from approximately 1% to 100% is expected capability for the image of a concrete building. Because the detector is dedicated to the infrastructure survey, cosmic-ray muons ranging from 50 MeV to 10 GeV should be measured from 0 to 50 degrees of zenith angle. The portability of the muography detector is objected to carried by at least two operators and transportable by a car.

In order to enhance the potential of muography, 3D muography imaging is an innovative way to overcome some limitations of the attenuation method, especially for observation of the infrastructure-scale object. The exploration of water distribution inside a dam, for example, should be measured by 3D muography technique. However, there are several difficulties in the 3D muography measurement. If an object can be measured from all directions like medical X-ray CT, we could obtain the density distribution easily and simply. Unfortunately, it is impractical for the muography, because the cosmic-ray muons come from the only upside with low flux. To solve this ill-posed problem, the development of image reconstruction algorithms for the muography is strongly required.

1.3 Overview of Thesis

Chapter 1 of this thesis introduces the background and motivation of this work. A brief review of the muography and the feasibility demonstration in the past works are explained.

The overview of the cosmic-ray muons at ground level and the muography principle based on an attenuation technique is described in chapter 2. Moreover, the requirements to construct a muography detector for investigation of infrastructure are extracted and summarized in the chapter. The detector should have two muon position sensitive detectors to determine the track and flux of muons. They should be compact, and also have long-term stability. Because the detector is dedicated to the infrastructure survey, cosmic-ray muons ranging from 50 MeV to 10 GeV should be measured at zenith angles from 0 to 50 degrees.

Chapter 3 is devoted to the development of the portable muography detector. The mechanical design of both muon position sensitive detectors (mu-PSDs) and its supporting structure are explained. The electrical connection and the data acquisition system are briefly reviewed. The data analysis procedure includes event identification scheme, direction evaluation, and the computation of 2D imaging are presented. The equations related to acceptance evaluation, particle direction digitization, attenuation rate calculation, and definitions of important parameters are also given in this chapter.

The angular resolution of the detector, the detection uniformity of the two mu-PSDs, and the detection efficiency are discussed for evaluation of the detector performance in Chapter 4. The detection efficiency was determined experimentally under the constraints of an external trigger detector. According to the aforementioned requirement of angular resolution, the distance between the two mu-PSDs was set to 10 cm. Under this condition, the muon penetrating peaks to each PSF were clearly seen in the measured muon spectrum, and after the careful bias adjustment, the peak positions were stable for all MPPCs. Furthermore, the identified muon counts for each MPPC were divided by the acceptance calculated in Chapter 3, and then the detection uniformity was confirmed for the two mu-PSDs.

In Chapter 5, the results of the feasibility study of infrastructure muography are described for three demonstration experiments. Firstly, the open-sky measurements were conducted to validate the long-term stability of the detector. A weak daily deviation of muon flux was observed in both the outdoor and indoor measurements. However, the effect was less than 1.7 % and was negligible for muography. The open-sky measurement was also used to derive the intensity distribution of cosmic-ray muons as a function of zenith angle. The resultant zenith-angular spectrum was slightly different from well-known cosine square distribution but was consistent with the calculation result of the PARMA model which is based on more precise empirical model. Secondly, the capability of detecting the target object with the infrastructure scale was tested by an experiment with a lead block. The image of the lead blocks was clearly obtained at the expected position and the length of average muon trajectory in the lead block was nearly equal to the real length. Finally, the capability of the portable muon detector to observe the civil infrastructure was demonstrated by the muography of a seven-story building and the inner structure of the building was revealed by the muography.

In Chapter 6, an approach with the Maximum Likelihood- Expectation Maximization (ML-EM) algorithm is proposed for the 3D muography with the developed detector. The ML-EM method is applied to imaging reconstruction of both the muography simulation and measurement. The simulation results were used to optimize the measurement duration and to confirm the accuracy of the ML-EM algorithm. A feasibility demonstration of infrastructure-scale 3D muography was performed using a simple configuration with two lead blocks. It was found that the reconstructed positions of the blocks are reasonably reproduced with the prior knowledge of the block arrangement. The 3D muography is known as a strong ill-posed problem, but it was found that sufficient reconstruction can be achieved by the ML-EM method by optimization of parameters such as a number of positions and iteration numbers in the data analysis.

Finally, Chapter 7 gives a summary and conclusions, and the perspectives of the future work are also described.

Chapter 2

Muography

The overview of cosmic-ray muons at ground level is described in this Chapter. The zenith angle dependence of the cosmic-ray muons and their stopping power in matter, which play an important role in the muography based on the attenuation method, are emphasized. The attenuation method is also described in detail.

2.1 Cosmic-rays Muon at Ground Level

The muon was discovered by Anderson and Neddermeyer in 1936. It is an unstable elementary particle of two charge types, positive; μ^+ and negative; μ^- . It has a mass of $105.7 \text{ MeV}/c^2$ which is about 207 times larger than the electron mass. For both charge types of the muons, it interacts via Coulomb interaction in matter [15]. In this study, cosmic-ray muons are the radiation source for this imaging system.

Due to their greater mass, cosmic-ray muons are not as sharply decelerated when they encounter electromagnetic fields and do not emit as much bremsstrahlung as the electron. Most muons are produced high in the atmosphere (typically 15 km) and lose about 2 GeV to ionization before reaching the ground [16]. This allows the number of muons to deeply penetrate the atmosphere and reach the ground with the wide energy spectrum distributed from low energy of several MeV to high energy of PeV. The mean energy of muons on the ground is $\approx 4 \text{ GeV}$ [16]. Cosmic-ray muons are also the only source of the muons with energy higher than 100 GeV at ground level [15].

The primary cosmic-rays originating from outer space mostly consist of high energy protons (95%), alpha particles (5%) and a smaller fraction of heavier nuclei. Except for protons and electrons near the top of the atmosphere, secondary cosmic-ray particles are produced in the interaction of primary cosmic-rays with the air nuclides, like N, O, and others. It results in showers of secondary particles which typically include neutrons and charged mesons. Muons and neutrinos are products of the decay chain of charged mesons, while electrons and photons originate in decays of neutral mesons [16]. The mesons are composed of a large number of pions and kaons. The neutral pion mainly decays via electromagnetic interaction and produces two gamma rays, 2γ , that generate electromagnetic showers, e^+ , e^- and γ , which

do not deeply penetrate. Fig. 2.1 is a schematic of some important channels for the cosmic-ray muon generation in the atmosphere.

Muons are produced by a hadronic shower of mostly charged pion decay and charged kaon decay through important channels of:

$$\begin{aligned}\pi^+ &\rightarrow \mu^+ + \nu_\mu, \\ \pi^- &\rightarrow \mu^- + \bar{\nu}_\mu, \\ K^+ &\rightarrow \mu^+ + \nu_\mu, \\ K^- &\rightarrow \mu^- + \bar{\nu}_\mu.\end{aligned}$$

Therefore, muons are the dominant charged particles among terrestrial secondary cosmic-rays at sea level [1], approximately 70% muons and 30% electrons.

The weak interaction is the phenomenon underlying both the decay of μ^+ and μ^- and the nuclear capture of μ^- in muonic atom. The dominant decay mode of the muon generates an electron or positron and two neutrinos;

$$\begin{aligned}\mu^+ &\rightarrow e^+ + \nu_e + \bar{\nu}_\mu, \\ \mu^- &\rightarrow e^- + \bar{\nu}_e + \nu_\mu,\end{aligned}$$

with the average life time of 2.2 μs .

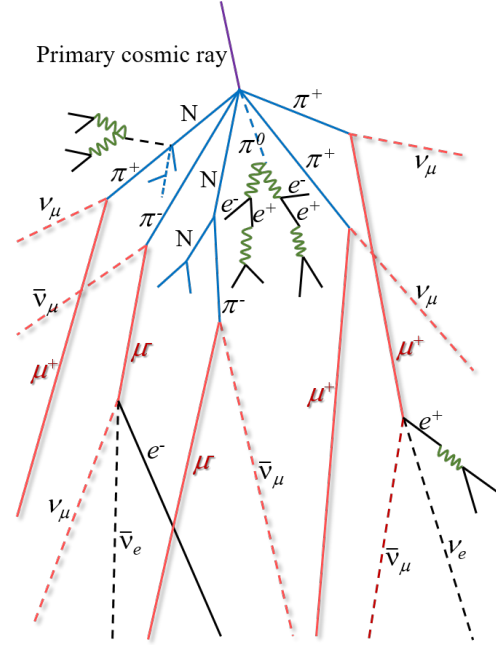


Figure 2.1: Schematic of some important channels for cosmic-ray muons generation in the atmosphere.

2.1.1 Zenith Angular Dependence of Cosmic-ray Muons

The energy spectrum of cosmic-ray muons on the ground varies with zenith angles. Fig. 2.2 presents the energy spectra of cosmic-ray muons as a function of zenith angle θ from EXPACS [17]. The peak of each energy spectrum is higher for the larger zenith angle, corresponding to the larger atmospheric thickness crossed by the muons, when the zenith angle increases. The muon intensity is peaked below 10 GeV at $\theta = 0^\circ$, while it is above 200 GeV at $\theta = 90^\circ$ [15]. To estimate the duration of muon detection, this dependency also needs to be taken into account. The muography, especially based on the attenuation method, is determined not only by the muon intensity but also the energy spectrum.

At sea-level, the universally accepted value of vertical absolute integral intensity of muons; $I_0(0^\circ)$; above 0.33 GeV/c of the muon momentum is around $8.3 \times 10^{-3} \text{ s}^{-1} \text{ sr}^{-1} \text{ cm}^{-2}$ [18]. The vertical absolute intensity is rather difference for each experiment conditions as reviewed in Ref. [1, 19]. The integral intensity around 1 muon/cm²/min for horizontal detectors is more familiar for experimentalists [16]. Due to the low intensity, the cosmic-ray muon measurement requires long detection time for each particular application. The overall angular distribution of muon intensity as a function of zenith angle θ in units of muon/cm²/sec/sr at $\theta \leq 75^\circ$ can be described by the expression

$$I(\theta) = I_0(0^\circ) \cos^n(\theta), \quad (2.1)$$

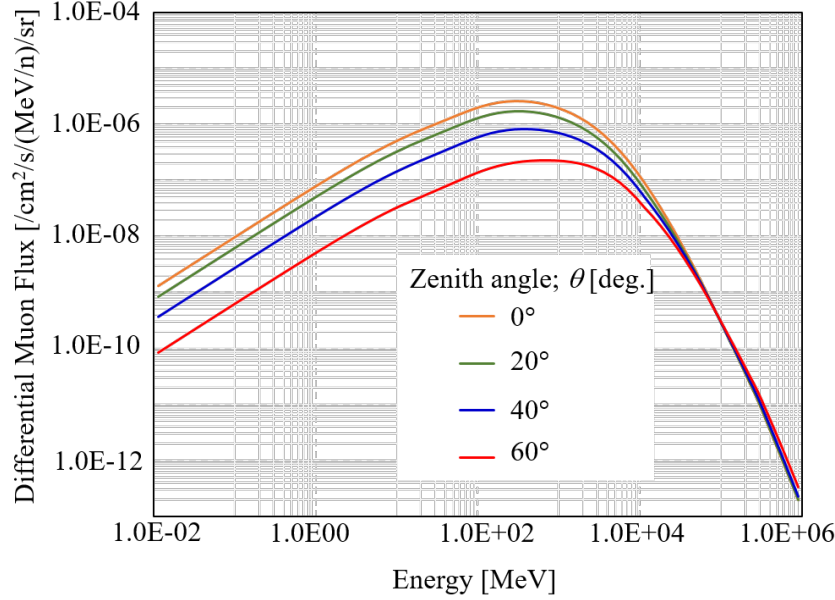


Figure 2.2: Energy spectra of cosmic-ray muons reaching the ground with various zenith angles, where the curves are the results of EXPACS [17].

where n is a function of the muon momentum [1]. For example, the exponent value for muon momentum above 0.35 GeV/ c and $\theta \leq 75^\circ$ is $n = 2.16 \pm 0.01$ [19].

2.1.2 Stopping Power of Muon

In matter, the penetrating muon loses its energy by ionization [20], radiative processes, e.g. Bremsstrahlung, photonuclear interactions and direct e^+e^- pair production [21]. Fig. 2.3 shows the stopping power dE/dx for positive muons in lead (blue triangle) and concrete (red circle) as a function of muon kinetic energy [22]. Both of materials is the major component of the target object in this muography study. At energy higher than a few keV until around term of hundred GeV of velocity $v = \beta c$, the main mechanism of energy loss is ionization. Cosmic-ray muon intensity is contributed in this region. The mean energy loss per traveled distance, or alternatively the stopping power of the matter, is described by the Bethe formula excluding the density-effect correction [15];

$$-\frac{dE}{dx} = 4\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A} \frac{1}{\beta^2} \left\{ \ln \left(\frac{2m_e \gamma^2 v^2}{I} - \beta^2 \right) \right\} \quad (2.2)$$

where r_e is the classical electron radius, m_e is the electron mass, N_a is the Avogadro number, and I is the mean excitation energy. Here, γ denotes the Lorentz factor; $\gamma = 1/\sqrt{1 - \beta^2}$. The stopping power depends on the penetrating material property through the atomic number; Z , atomic mass; A , and the density; ρ . The stopping power at high energy for all practical purposes in high-energy physics, dE/dx

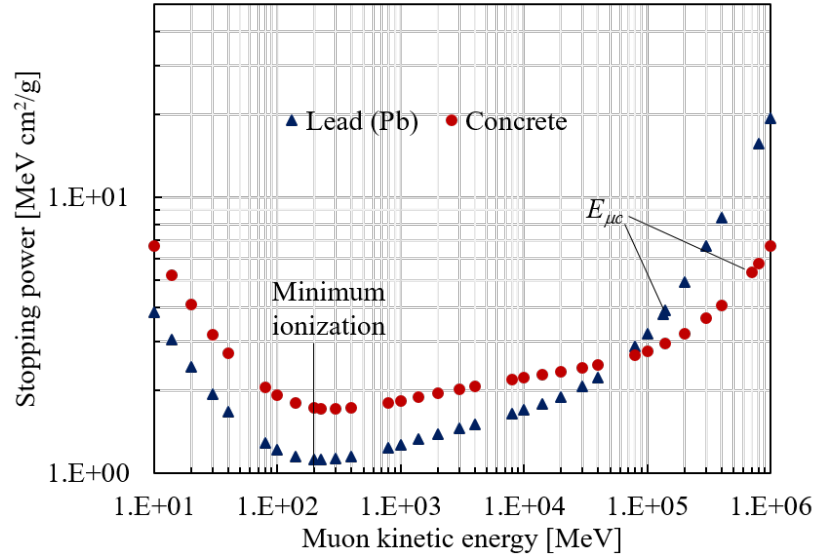


Figure 2.3: Stopping power dE/dx for positive muons in lead (blue triangle) and concrete (red circle) as a function of muon kinetic energy [22].

in a considered material is given by a function of β alone. Using of this formula enables us to obtain quantitative information regarding to the range of the muon in the matter. The stopping power decreases with increasing velocity in the ionization process. On the other hand, it increases due to the increase in radiative loss effect at higher energies above the critical energy $E_{\mu c}$ in Fig. 2.3 [22]. Thus, the minimum ionization exists at around 200 MeV [15]. The dominance of the muon velocity β is implicit in Eq. 2.2. Therefore, most relativistic particles like cosmic-ray muons have mean energy loss rates close to the minimum [23] corresponding to the logarithm term in the equation.

2.2 Principle of Muography based on Attenuation Method

Radiography is a conventional imaging technique using the energetic particles penetration to reconstruct the spatial profile of the depth or density of a target object. The most popular radiography is X-ray photography of a human body according to the penetration characteristic in term of a few tens of cm to around 1 meters. Due to very higher energy and wider energy distribution of cosmic-ray muons, it is suitable for measuring the spatial profile of a large-scale object, even larger than 0.1 km, target object [15]. It also can be performed without the use of artificial radiation. The idea of this muon radiography, or “muography”, was recognized in the past and was indicated an experimental test by Alvarez in 1970 [24], who applied the muography to find a hidden chamber in an Egyptian pyramid.

As aforementioned in Chapter 1, there are two muography methods, namely, scattering tomography and attenuation imaging. The muon scattering tomography was developed by Borozdin and the teammate at Los Alamos National Laboratory in 2003 [25]. The method exploits the multiple Coulomb scattering

of cosmic-ray muons. Therefore, at least two muon trackers are required for reconstruction of both incoming and outgoing trajectories for each particle. This method has been shown to be useful for material identification and fast (minute order) detection of compact high- Z objects such as uranium [6]. Thus, this method mainly applied to the security applications as reviewed in the introduction.

Although the scattering method is rather novel and attractive in the security field, the classical attenuation method is still outstanding in another field like an observation of internal imaging of the large-scale structure, (see Chapter 1). In Alvarez's experiment, even-through, they found there is no void whose size is same or larger as known chambers [24] at the time. A later effort, Morishima et al., discovered [7] a previously unknown void in the Great Pyramid in 2017. This discovery attracted the attention to the applications of the attenuation method. This study is also one of the challenges to demonstrate a new application to civic infrastructure degradation investigation. In this section, the muongraphy based on the muon attenuation imaging is described.

2.2.1 Muon Attenuation Method

The attenuation method of muography is based on the fully-stopping of low energy muons inside a target object, according to the energy lost along with its path. Therefore, the thickness of a target object can be evaluated from the muon attenuation rate, $D(\theta, \phi)$, of the cosmic-ray muon defined in term of the zenith angle θ and the azimuth angle ϕ . This angular measurement is intended to represent the spatial information of the object. The distribution of muon attenuation rate as a function of the direction of the incident muon is used to indicate the internal structure of a considered object. The muon attenuation rate can be obtained from the measurement by the following equation:

$$D(\theta, \phi) = 1 - \frac{I_k(\theta, \phi)}{I_0(\theta, \phi)}, \quad (2.3)$$

where $I_k(\theta, \phi)$ refers to the measured muon intensity with the target object and $I_0(\theta, \phi)$ denotes the muon intensity without the object. Index k denotes experimental conditions, such as open-sky, indoor or underground. The muon attenuation rate distribution; $D(\theta, \phi)$ varies with the thickness and density. Thus, if the density is known or can be estimated by examining the object's exterior, the structure profile inside the object can be obtained from the muon attenuation.

Generally, the reference attenuation distribution, $I_0(\theta, \phi)$, can be derived using several methods. The first method involves the simulation of numerous air showers caused by the primary cosmic-rays [17]. However, this simulation requires abundant computational resources and has not been compared sufficiently with the actual measurements, so the accuracy has not been verified. Another method involves extrapolating from a measurement of sea-level angular muon flux, such as the well-known Gaisser's formula [21] or its modified formula [26]. In this case, complications arise because the muon flux depends on atmospheric conditions and solar activity.

In this study, $I_0(\theta, \phi)$ was directly measured with the proposed detector in the open-sky environment near the target object. This approach avoids the aforementioned complications and simultaneously accounts for detector limitations such as angular acceptance and electronic conditions.

To evaluate the spatial profile, the thickness; $L(\theta, \phi)$ of the object is estimated from the attenuation rate. By considering the energy of the muons; $E_{th}(L(\theta, \phi))$, that have the range $L(\theta, \phi)$ in a target object of known density, the attenuation rate, $D(\theta, \phi)$, can be written as

$$D(E_{th}, \theta, \phi) = \frac{\int_{E_{th}(L(\theta, \phi))}^{\infty} \Phi(E, \theta, \phi) dE}{\int_0^{\infty} \Phi(E, \theta, \phi) dE}, \quad (2.4)$$

where, $\Phi(E, \theta, \phi)$ represents the muon flux in a unit of $\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}(\text{MeV/n})^{-1}$. $\Phi(E, \theta, \phi)$ is related to $I_k(\theta, \phi)$ by the equation

$$I_k(\theta, \phi) = \int_{E_{th}(L(\theta, \phi))}^{\infty} \Phi(E, \theta, \phi) dE. \quad (2.5)$$

Thus, the attenuation rate $D(E_{th}, \theta, \phi)$ is comparable with the measured attenuation rate $D(\theta, \phi)$ in Eq. (2.3). Therefore, the attenuation rate is related to the mean thickness of the penetrated object $L(\theta, \phi)$, in other words, the range of muon in target object's matter, through the function of energy $E_{th}(L(\theta, \phi))$.

Attenuation rate of cosmic-ray muons $D(E_{th}, \theta, \phi)$ with a given energy E_{th} , in Eq. (2.4), corresponds to the fraction of the integral flux of the cosmic-ray muons below E_{th} divided by the total integral flux. The cosmic-ray muon flux spectra $\Phi(E, \theta, \phi)$ from the EXPACS [17] was used to calculate $D(E_{th}, \theta, \phi)$ roughly. Fig. 2.4 shows an estimated attenuation rate of cosmic-ray muons $D(E_{th}, \theta, \phi)$ as a function of a given muon energy E_{th} . Attenuation rate $D(E_{th}, \theta, \phi)$ in the figure is estimated from the EXPACS [17] using the overall zenith angle integral flux.

For the developed muography detector, the attenuation rate from 1% to 100% was aimed to measure according to the cosmic-ray muons ranging from 50 MeV to 10 GeV should be measured from 0 to 50 degrees of zenith angle. Fig. 2.2. The attenuation rate region corresponds with from 10MeV of E_{th} which is indicated by the blue line in Fig. 2.4.

Then, the range $L(\theta, \phi)$ as a function of energy E_{th} can be calculated independently by using Eq. 2.2, and also, can be calculated by Monte Carlo simulation, for example, PHITS [27] and GEANT4 simulation toolkit [28]. Fig. 2.5 is an example of the simulated Muon range in lead as a function of a given muon energy E_{th} simulated from PHITS and GEANT4.

Finally, the function to roughly converse the measured attenuation rate $D(\theta, \phi)$ to the mean thickness of the penetrated object $L(\theta, \phi)$ for each incident muon direction (θ, ϕ) can be evaluated by substitution of E_{th} in Fig. 2.5 by the related attenuation rate $D(E_{th}, \theta, \phi)$ calculated from the fitting function of the plot in Fig. 2.4.

2.2.2 Requirements for a Muography Detection System

The objective of this study is to fabricate a multi-purpose portable muography detector based on the attenuation method for monitoring the degradation of civil infrastructures and detecting underground cavities is aimed to constructed. From Eq. (2.3), the derivation of the attenuation rate requires the detector of cosmic-ray muons for tracking the incident direction (θ, ϕ) .

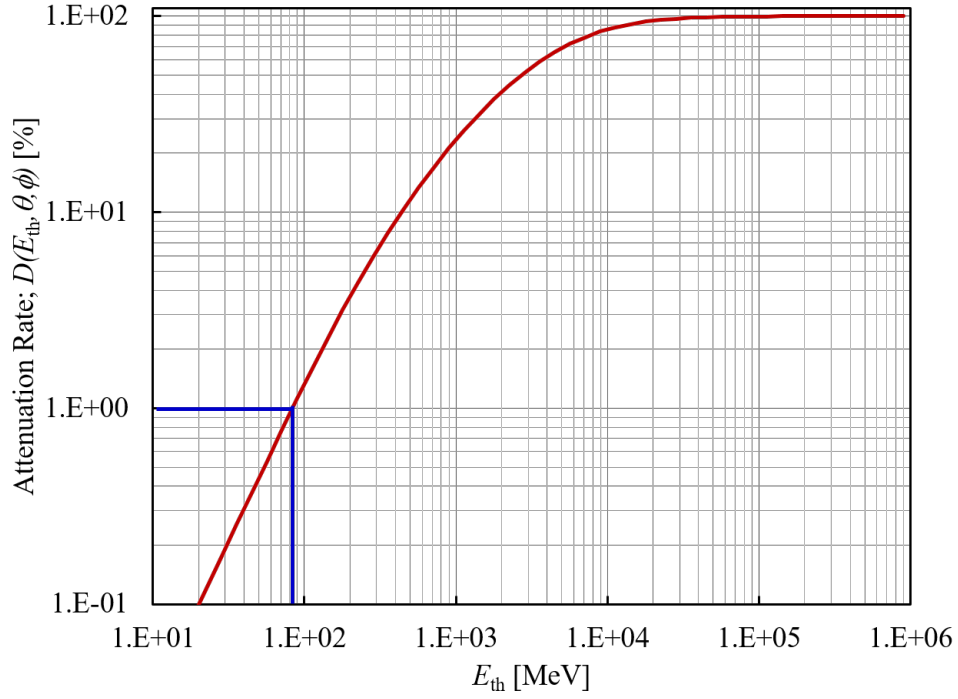


Figure 2.4: Attenuation rate of cosmic-ray muons $D(E_{th}, \theta, \phi)$ estimated from EXPACS [17] as a function of muon energy E_{th} .

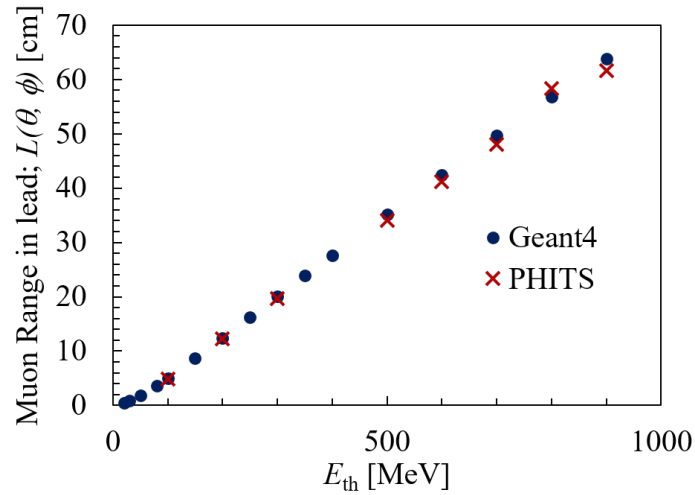


Figure 2.5: Muon range in lead as a function of a given muon energy E_{th} simulated from PHITS [27] and GEANT4 [28].

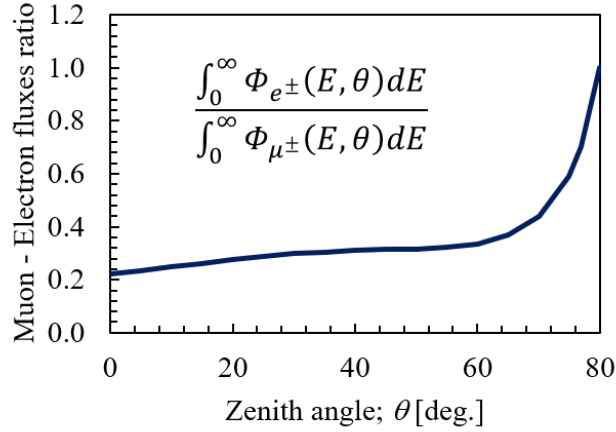


Figure 2.6: Muon and electron fluxes ratios estimated using EXPACS [17] as a function of zenith angle θ .

To observe internal structure in the order of a few tens of centimeters such as the concrete beams of a building, an angular resolution of several tens of msr is required. The resolution is estimated for the detector location of a few meters away from the target object. This resolution also needs to be optimized for the practical detection time which should be considered for each direction due to the aforementioned angular dependence (see Section 2.1).

In addition, the muon detector design must be optimized for the compactness and long-term stability. As aforementioned, the muography detector is objected to carried by at least two operators and transportable by a car. For this study, the measurement time for each target objects is expected to not longer than one month. The material selection for the muography detector has to account for the durability for long-term usage and convenience of transportation. Low electric power consumption is also required for the field-work. Online-monitoring system is beneficial to recognize the cosmic-ray muons variation such as temporal variations caused by the solar flare [29] and periodic variation caused by the interplanetary magnetic field [30]. It is also useful for the detection of the object with an uncertain volume, such as water level inside the dams.

Muons reaching the ground with θ slightly less than 90° have lower intensity on average but have higher intensity at energies higher than a few hundreds of GeV as shown in Fig. 2.2. This horizontal muon is reasonable to probe the huge object locating on the ground such as mountains. Due to the higher intensity, but lower mean energies of a few GeV, of vertical muons, they are also prominent to probe in a scale of the internal structure of the civic structure. However, it is essential to eliminate backgrounds due to other cosmic-ray components which have their angle-dependent intensities as well. The cosmic-rays electrons and positrons intensities, for example, are about one-quarter of the muon intensity at $\theta \approx 0^\circ$, but they are more than the muon intensity at the $\theta \geq 80^\circ$ as shown in Fig. 2.6.

The muography image, two-dimension (2D) projection, shows the thickness or density integrated along the transmission path of muons similar to other radiography techniques. Thus, it should be possible to reconstruct the 3D image by muography as well. However, according to the limitation in the number of detection positions and detection angle as aforementioned in Chapter 1, the development of a realistic technique of the muography with image reconstruction algorithms is strongly required. The muon detector should also be designed for compatible detection time and the number of detection positions should be minimized.

Chapter 3

Portable Muography Detector

A multi-purpose muography detector for use under a wide range of conditions was developed. It was designed with the performance goals of portability, compactness, electric power demand, online data acquisition, and low production cost. This chapter describes the mechanical design, structure, data acquisition system and data analysis procedure of the detector.

3.1 Muon Position Sensitive Detector

For attenuation method, the requirement on muon tracker was discussed in Chapter 2. A compact design muography detector was developed to meet those requirements. The developed portable muography detector consists of two muon position sensitive detectors (mu-PSDs). Fig. 3.1 illustrates a 3D sketch of the mu-PSDs structure. For multi-purpose applications which require various angular resolution, the distance d between the upper mu-PSD (mu-PSD1) and the lower mu-PSD (mu-PSD2) was designed to be adjustable. Each mu-PSD is a combination of two layers of plastic scintillating fiber; PSF (Kuraray, SCSF-78, 2.0 mm², BJ) arrays for two-dimensional detection, with pixels defined in the (x, y) plane as shown in Fig. 3.1.

The PSFs were chosen for their stability during long-term measurements. Each PSF has a 2 mm $\times$ 2 mm square cross-section with a length of 200 mm. The PSF core is made of polystyrene(PS) which has refractive index 1.59. As shown in Fig. 3.2 (left), the PSF is surrounded by the 0.08-mm thick cladding layer made of polymethyl-methacrylate (PMMA) with the refraction index of 1.49. The cladding has trapping efficiency 4.2% [31]. If an incoming energetic muon in direction $v(\theta, \phi)$ passed through the mu-PSDs, scintillation light is generated from the muon's energy lost inside the PSF as shown in Fig. 3.1. The scintillation light of the PSF has an emission peak 450 nm and decay time of 2.8 ns [31]. The PSF emission spectrum of various length S is shown in Fig. 3.2 (right), see. Ref [31].

Each layer consists of two horizontal planes of sixteen groups of PSFs, oriented perpendicular to each other. A group contains a bundle of four PSFs. Each group of PSFs is covered with aluminum foil to reflect the scintillation light internally and to avoid cross-talk. Since each layer consists of 16 groups, each mu-PSD offers 256 pixels for detection.

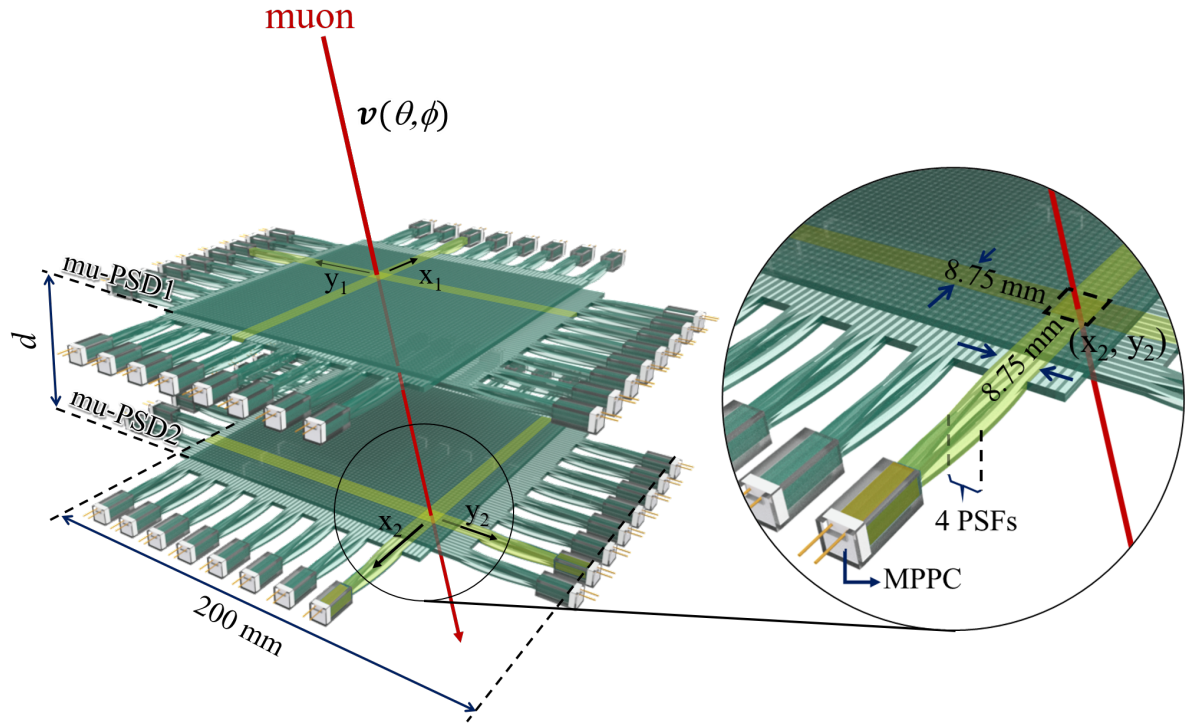


Figure 3.1: Sketch of the mu-PSDs structure.

The scintillation light propagates along the PSFs and is detected by a Multi-Pixel Photon Counter (MPPC); (Hamamatsu, S12572-100C) [32]) which is connected to one side of the PSF group, as shown in Fig. 3.1. Fig. 3.3 (left) presents a photograph of the MPPC which has effective photosensitive area $3 \text{ mm} \times 3 \text{ mm}$ in a ceramic package. According to the emission peak of the scintillated wavelength in Fig. 3.2 (right) [31], these MPPCs were chosen due to their peak sensitivity wavelength 450 nm as well as the time resolution in single photon level (FWHM) 400 ps [32]. Plastic sockets were particularly designed and precisely printed by a 3D printer to bundle the PSFs groups and connect to the MPPCs. The MPPCs were labeled by the identified number, called MPPC ID number, from 0 to 31 for mu-PSD1 and 32 to 63 for mu-PSD2. The MPPC ID number 0 to 15 and 16 to 31 are given for the position x_1 and y_1 , respectively. The MPPC ID number 32 to 47 for x_2 and the number 48 to 63 for y_2 are also assigned.

To meet the requirement of ten msr solid angle resolution, mu-PSD1 with approximately $8.4 \text{ mm} \times 8.4 \text{ mm}$ of one-pixel detection area was positioned at $d = 100 \text{ mm}$ away from the mu-PSD1. Resolution of 7 msr and the detection capability in the zenith angular region up to 50° were obtained with this configuration.

The vertical alignment of the two mu-PSDs requires enough good precision. First of all, a simulation is made to check the effect of the vertical misalignment if the detector was shifted from each other along both x -axis and y -axis. The uniform source was placed under the displaced detector. Then, the detected count distribution was fitted by Gaussian function. Ideally, if the detector is good alignment

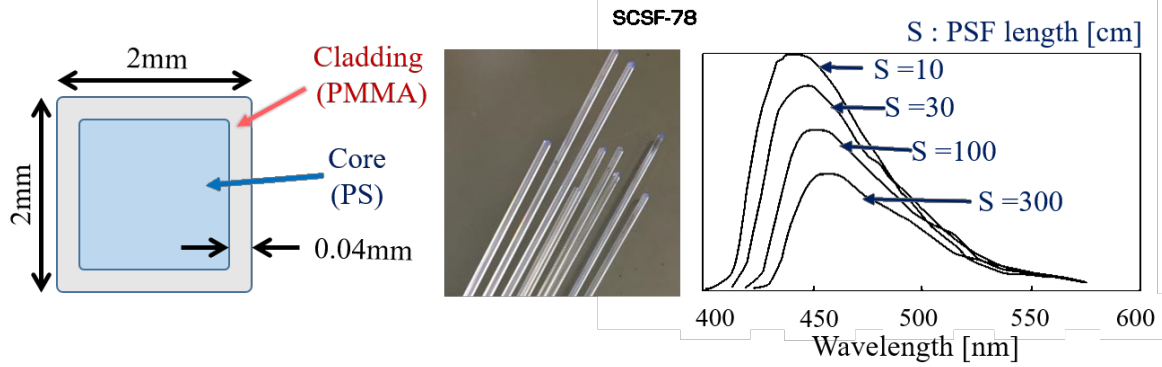


Figure 3.2: Overview of the PSF spec; its square cross-section geometry (left), a photograph of the PSFs (center) and emission spectra (right) [31].

the peak of the fitting function should be at pixel 0 of the detected image. Figure 3.4 shows a plot of displacement along x -axis and y -axis as a function of the detected count peak position shifting in a unit of detected image pixel. From the simulation, misalignment of 20 mm displacement can cause the shifting image result for one pixel. This result can be experimentally confirmed by the muography image of the measurement without the target object or using of a standard source. A ^{90}Sr β -ray source was used to check the alignment. The source was placed at each corner of the upper mu-PSD, and the count distribution was measured from the lower mu-PSD. Misalignment can be estimated from distortion of the count distribution.

However, more accurate alignment, less than 20 mm displacement, can be done. For finer adjustment, the uniformity of the azimuth differential flux distribution was considered [33]. Misalignment between the mu-PSDs was less than 0.5 mm, which was concluded by careful measurement with laser marking device.

3.2 Support Parts

The detector was designed based on the portable requirement for multi-purpose operation. Figure 3.5 presents the photograph of the muography detector with the plastic scintillator. The detector is placed inside a $450 \text{ mm} \times 450 \text{ mm} \times 450 \text{ mm}$ light shielded and thermal insulator box. A Peltier cooling and heating unit (OCE-F40F-D24 by Ohm Co., Ltd.) is installed to suppress the temperature variation which causes the gain and dark-count events fluctuation of the MPPCs. The temperature can be automatically controlled within $17.0 \pm 0.3^\circ\text{C}$ inside the box in the temperature range of 0 to 35°C of the outside. This temperature is optimized for stable performance and to avoid dark-count events in the MPPCs. Besides, a plastic scintillator plate with $200 \text{ mm} \times 200 \text{ mm} \times 20 \text{ mm}$ is also used as a muon coincidence detector to suppress the dark-count event contribution. The detail of this detection system is described in Section 3.3.

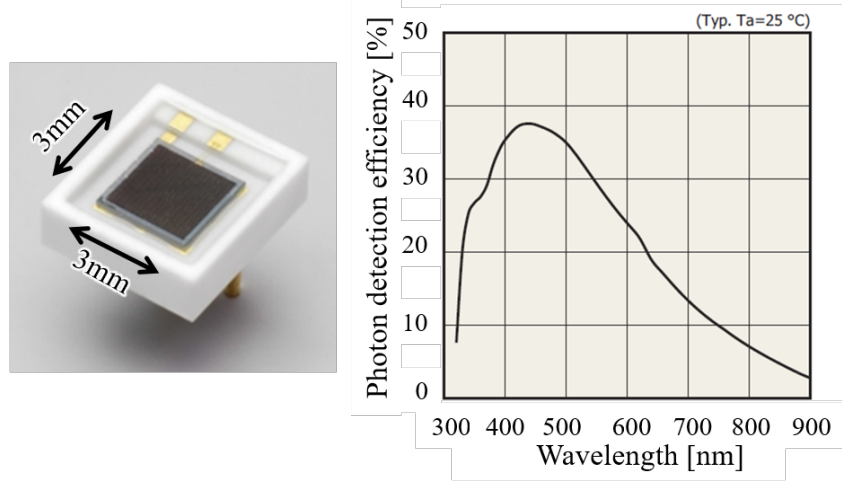


Figure 3.3: A photograph of a MPPC (left) and detection efficiency as a function of the detected wavelength (right) [32].

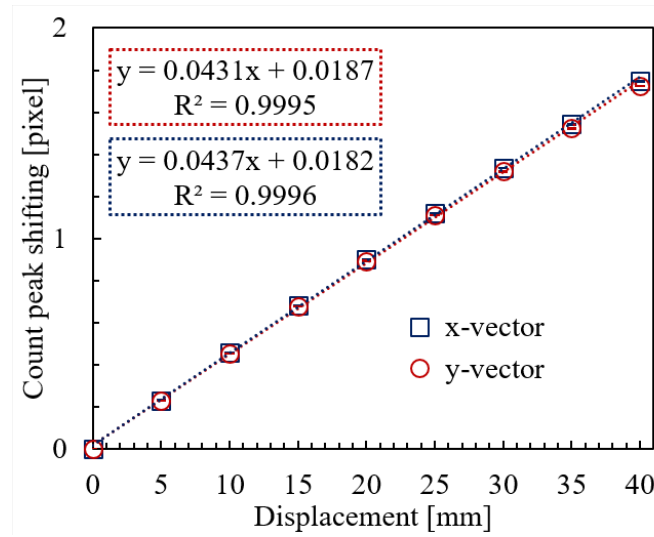


Figure 3.4: Simulation of the vertical misalignment effect in the case of $d = 10$. The displacement along x -axis and y -axis is plotted against the detected count peak position shifting.

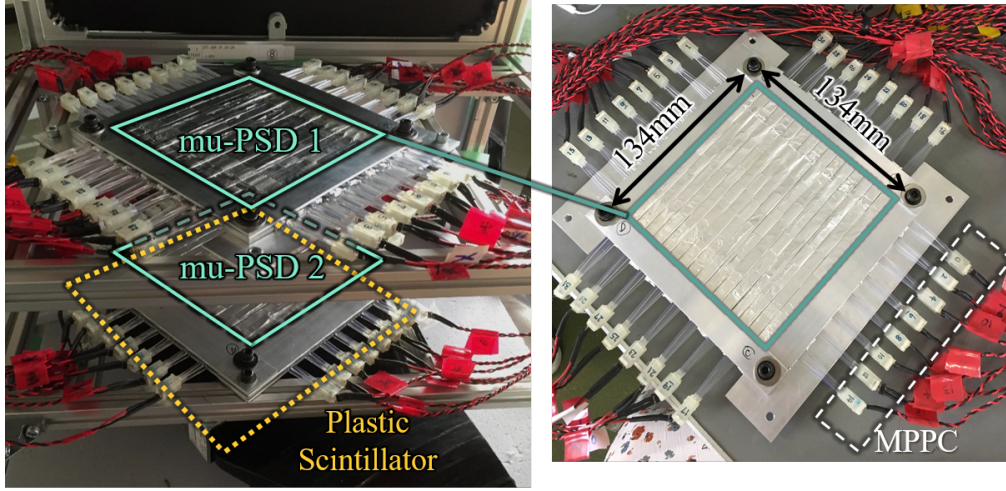


Figure 3.5: The detector consists of two planes of mu-PSDs and the plastic scintillator inside the light shield box. Covered by aluminum foil on each PSFs group, the detector area is 134 mm $\times$ 134 mm.

3.3 Data Acquisition System

The data acquisition system is triggered by the coincidence of the mu-PSDs with an external plastic scintillator. The 64 MPPCs were driven and read-out by the 64-channel NIM EASIROC module [34,35]. The module can handle 64 MPPCs and has the onboard bias power supply and ADC for pulse height digitization and the 64-channel logic output of self-trigger. The bias power supply is adjustable from a front-end computer. The output bias voltage gain is also adjustable for each MPPC on the front-end computer. Controls and data transfer are through SiTCP technology [36] implemented in FPGA. An EASIROC module contained two chips of FPGAs. Each one can receive 32-channel signals. The MPPC ID 0 to 31, of mu-PSD1, and ID 32 to 63, of mu-PSD2, were connected separately to the port of each chip. The EASIROC module can provide self-coincident 64-channel signals if the internal discriminator threshold is well-adjusted. The threshold is adjustable in the hardware. This internal threshold indicates a characteristic performance of each chip. For this reason, the output signal pulse height must be calibrated in an offline analysis.

In this study, the external-trigger signal was applied from an external-coincident module. The external-trigger signal was made from the coincidence between the MPPC signals and the plastic scintillator plate signal. The triggered signals from the MPPCs, later called “triggered events”, are shaped in the module. When a triggered signal arrived, all 64-channel pulse heights of the signal are digitized before being recorded in the front-end computer. Thus, the number of only baseline voltage level signals, so-called pedestal signal, are large. The amount of the pedestal signal of each MPPC is ideally equivalent to the total number of muon events, which are detected by other MPPCs. These offset signals are considered and the muon events are identified in the offline analysis.

For this muography detector, the bias voltage applied to each MPPC is less than 70 V. The bias voltage for each MPPC was carefully adjusted to avoid the overlap of the signal pulse heights of muon events and the dark-count events from the MPPCs [33]. Total electrical power consumption for the whole system including the front-end computer was less than 155 W. The low electrical power consumption is not only an achievement of this DAQ system, but the whole system is also compact. All modules can be fitted in one portable 6-slots NIM power-supply bin.

3.4 Data Analysis Procedure

In this section, an overview of the offline data analysis procedure including of muon identification process from the pedestal and the suppressed dark-count events are presented. Finally, the imaging process of the density muography for the interior structure profile survey is described in this section.

3.4.1 Event Identification Scheme

Figure 3.6 shows an example of pulse height distributions in ADC channel from a single MPPC. The pulse-height distribution of triggered events is plotted with a solid blue line. This distribution includes the pedestal and dark-count events, which appear around channel 800. The muon event signals appear after channel 1000. To extract muon events from the triggered signals, the pulse heights are first amplified to make the dark-count events distinct through fine adjustment of the MPPC bias voltage. Then, the pedestal and dark-count events are filtered out by eliminating all events for which the pulse height is less than a threshold level.

The pulse height distributions in Fig. 3.6 is also zoomed in x -axis and showed in a yellow square(right). A number of single photo-electron peaks (p.e.) can be seen. The distance between the peaks is a characteristic of each MPPC according to the adjusted ADC gain on the EASIROC module and optical connection quality between the PSF and MPPC. By fitting with Gaussian function, the distance between the peaks in the unit of the number of ADC channel is evaluated. The various distance of each MPPC is plotted in Fig. 3.7.

The peak of pedestal signals is the lowest peak position. It is corresponding to the DAC discriminator threshold value which was adjusted on the EASIROC module. As aforementioned, it is a characteristic of each chip. The Gaussian function was also used to fit the lowest peak position.

The threshold level for each MPPC was adjusted individually. The threshold level of each MPPC channel in Fig. 3.6 is calculated from the expression;

$$\text{Threshold} = \text{Pedestral} + N_{\text{p.e.}}, \quad (3.1)$$

where $N_{\text{p.e.}}$ is the number of the photo-electron peak which was estimated to be the threshold level. In this study, $N_{\text{p.e.}}$ is chosen to be 7. The value 7 is roughly approximated from a crossing of the dark-count distribution and the overall muon distribution, in the average of every channel.

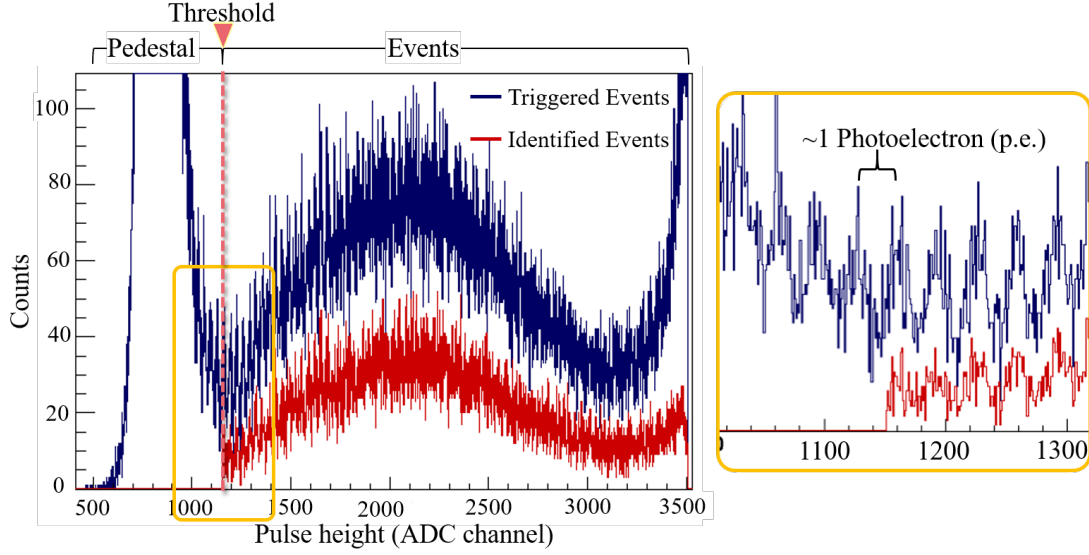


Figure 3.6: An example of the pulse-height distributions from one MPPC. The distribution of triggered events (upper) and the distribution of identified events (lower) are included. A number of single photoelectron peaks can be seen in zoomed x -axis scale (yellow square).

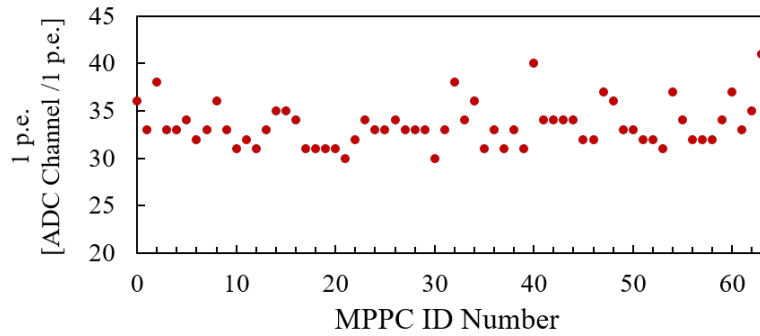


Figure 3.7: Various distance between the single photon peaks of each MPPC.

In addition, only the triggered events that passed through the aforementioned filter process and were detected coincidentally by all four layers of the mu-PSDs were determined as “identified event”. Here, the identified events are designated as muon events. The spectrum of the identified events is represented by the red line in Fig. 3.6.

3.4.2 Detection Acceptance

First of all, the direction of the detected muon has to be evaluated. As shown in Fig. 3.1, let us consider if a given incoming cosmic-ray muon is detected by a pair of pixels at (x_1, y_1) and (x_2, y_2) in the upper and lower mu-PSDs, respectively. The muon trajectory in direction (θ, ϕ) is represented by a red arrow in Fig 3.1. The coordinates (x_1, y_1) and (x_2, y_2) are discretized and represent the center position of the pixel. The discrete direction of the muon is defined with the vector “ $v_{i,j}$ ” where;

$$x^{[i]} \equiv x_1 - x_2 \quad \text{and} \quad y^{[j]} \equiv y_1 - y_2. \quad (3.2)$$

The indices i and j are defined as the discrete x -vector and y -vector where

$$i = N_{x1} - N_{x2} \text{ and } j = N_{y1} - N_{y2}.$$

N_{x1} and N_{x2} are defined as pixel number of x_1 and x_2 as well as N_{y1} and N_{y2} are defined as pixel number of y_1 and y_2 , respectively. In the case of the developed muography detector, all of N_{x1} , N_{x2} , N_{y1} and N_{y2} labeled from 0 to 15 corresponding to the MPPC ID. Therefore, the x -vector is represented by $i \in [-15, -14, \dots, 14, 15]$ and y -vector is represented by $j \in [-15, -14, \dots, 14, 15]$.

Then, the direction (θ, ϕ) of a muon event is determined from the two positions detected by the mu-PSDs. All identified event paths are represented by discrete vectors $(v_{i,j})$. Thus, the mu-PSDs can show the result in $(2N_x - 1) \times (2N_y - 1) = 961$ vectors, in other words the number of image pixels, where the number of the PSF groups in each layer is $N_x = N_y = 16$.

The detector acceptance is calculated in order to eliminated the inequality of detection direction due to the geometry of the detector. The acceptance can be expressed by;

$$A(v_{i,j}) = d\Omega(v_{i,j}) \times P(v_{i,j}), \quad (3.3)$$

where $d\Omega(v_{i,j})$ and $P(v_{i,j})$ are the solid angle of a pair of pixels that detects the direction $v_{i,j}$ and the probability that the incident muon $v(\theta, \phi)$ will be detected as a vector $v_{i,j}$.

The solid angle of each pair of pixels $d\Omega(v_{i,j})$ is practically contained all muon trajectories which capably detected by the pair (x_1, y_1) and (x_2, y_2) , if the detector is treated as a point. This cause the complication in the direct calculation, since the mu-PSDs are two plates of a parallel rectangular detector. The $d\Omega(v_{i,j})$ is varied according to the relative position of the pair of pixels, nevertheless, it is an exception if the absolute value of vectors $v_{|i|, |j|}$ are same. In that case, the vectors typically have the same solid angle. The $d\Omega(v_{0,0})$, the normal direction to the detector plane, has the largest solid angle. Thus, I defined that the $d\Omega(v_{0,0})$ represents “angular resolution” of the detector.

The probability $P(v_{i,j})$ is calculated from the number of the pair of pixels, which has an equivalent detectable angle, divided by the total number of the pixels that can be paired up. For example, the developed detector has totally 256 possible pair of pixels. The factor $P(v_{0,0})$ is normalized to 1 due to all 256 possible pairs could accept the direction $v_{0,0}$. In contrast, $P(v_{15,15})$ is equal to 1.56×10^{-2} due to only 1 possible pair could accept the direction $v_{15,15}$. The detail of the estimation of the developed detector acceptance is available in reference [33].

The probability $P(v_{i,j})$ is simple to calculate, but there are several complications for direct calculation of the acceptance by Eq. (3.3) due to the $d\Omega(v_{i,j})$ calculation. The aforementioned point-like detector treating in the $d\Omega(v_{i,j})$ calculation is not the only one complication. The actual detector effective area is unequal to the measured $134 \text{ mm} \times 134 \text{ mm}$ area in Fig. 3.5 due to the thickness of the PSFs' cladding and the wrapped Al-foil. This causes some undetectable events, defined as "lost events", which expected to be detected if the detection effective area is equal to the measured detection area. Another error is caused by the detected position of x -vector and y -vector in each mu-PSD. The coordinates x and y are not exactly in the same plane, due to the thickness of the PSF.

For this study, I derived a Monte-Carlo simulation algorithm to simplify the calculation. The number of 10^7 events were randomly generated from $134 \text{ mm} \times 134 \text{ mm}$ plane source with uniform direction; ($\theta \leq 90^\circ$). The source was placed under the mu-PSD2. The precise effective volume of the PSFs was taken into account. The acceptance was evaluated from the number of simulated muon event that passed through all four layer of both mu-PSDs in the effective volume. In the case of $d = 10 \text{ cm}$, the solid angle distribution $d\Omega(v_{i,j})$ from the simulation is shown in Fig. 3.8 (a). An average percentage of the undetected ratio by the aforementioned non-sensitive area is also present in Fig. 3.8 (b). The angular distribution of the acceptance $A(v_{i,j})$ is shown in Fig. 3.8 (c). Although, the total percentage of the whole detector lost event is less than 1%. I found that around 22% of the vertical muon ($v_{0,0}$) was lost. The asymmetric distribution of x -vector and y -vector caused by the aforementioned PSF thickness also can be seen in the large zenith angle events. This simulation was also adapted to compute the angular resolution of the muography detector. The results are described in the next Chapter. This precise calculation of the muography detector acceptance is essential for the calculation of the vertical absolute integral intensity of muons.

The transmitted muon rate as a function of the incoming muon direction $I_k(\theta, \phi)$, for instance, requires the acceptance for its calculation. By considering the characteristic angular acceptance of each pair of pixels $A(v_{i,j})$, the discrete transmitted muon rate can be calculated as

$$I_k(v_{i,j}) = \frac{N_k(v_{i,j})}{A(v_{i,j}) \times t_k}, \quad (3.4)$$

where $N_k(v_{i,j})$ is the number of identified event in a duration t_k . To compute the background transmitted muon rate without object as a function of the incoming muon direction $I_0(v_{i,j})$, Eq. (3.4) is used. The $I_0(v_{i,j})$ distribution was expected to shown the zenith angle, θ , dependence of cosmic-ray muon.

It is explicit that since $I_0(v_{i,j})$ is directly measured in this study, the acceptance function $A(v_{i,j})$ is self-subtracted in the attenuation rate calculation according to Eq. (2.3). Thus, for the practical using, the attenuation rate $D(v_{i,j})$ is calculated from

$$D(v_{i,j}) = 1 - \left(\frac{N_k(v_{i,j})}{t_k} \cdot \frac{t_0}{N_0(v_{i,j})} \right). \quad (3.5)$$

This is the prominent point of this method. The term of the geometrical condition was not needed to take into account in this muography detection system.

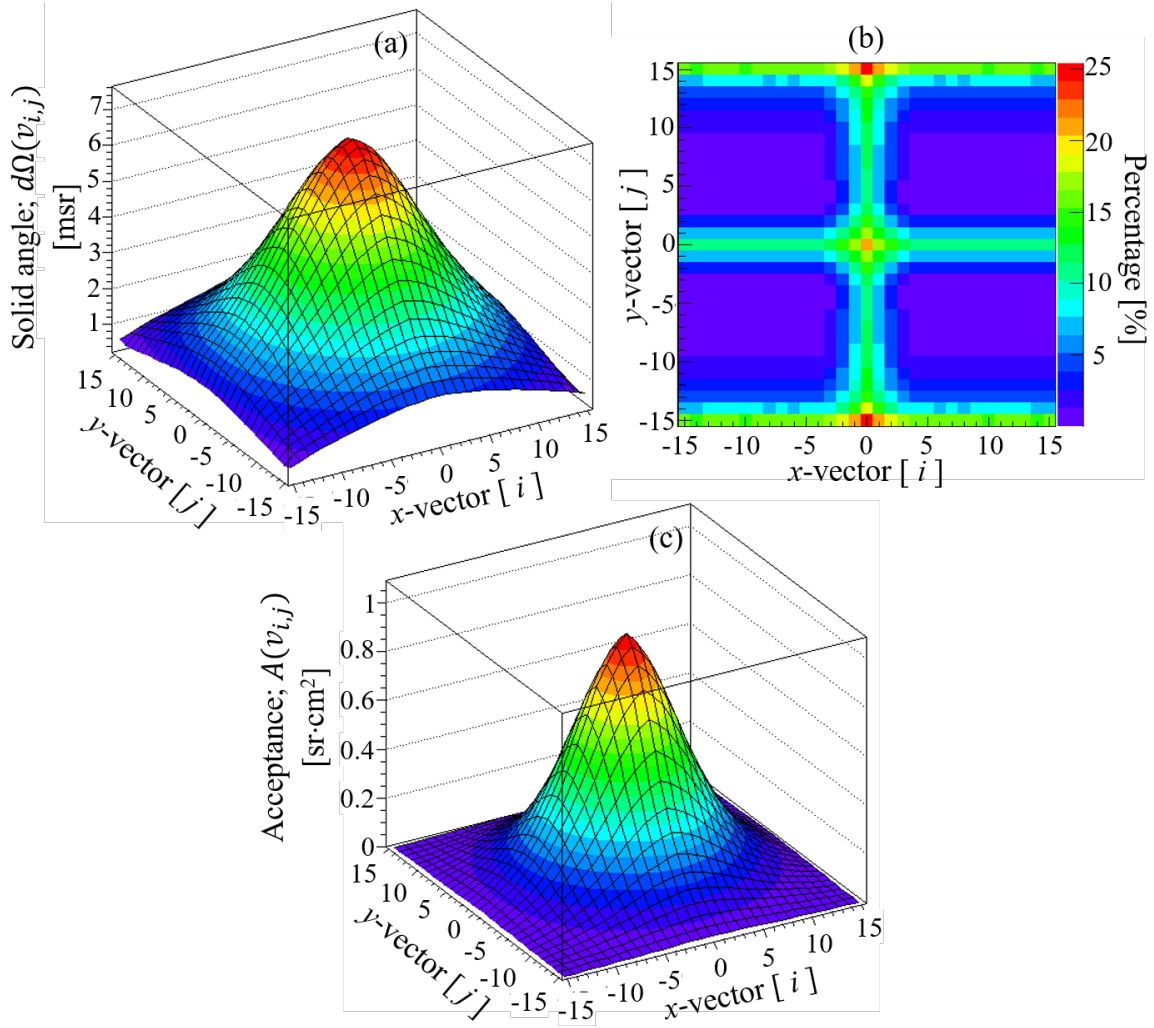


Figure 3.8: A Monte-Carlo simulation result for (a) solid angle distribution $d\Omega(v_{i,j})$, (b) average percentage of lost event from the expected detection area and (c) the angular acceptance $A(v_{i,j})$ in the case of $d = 10$.

Chapter 4

Detector Performance

The flexibility of the muography detector's angular resolution was evaluated using a Monte Carlo simulation program. For the muon direction tracking, the uniformity performance of the whole mu-PSDs is strongly required. The detection efficiency of each layer is also presented. The detection system was tested indoors and under open-sky condition. In this Chapter, the performance of the detector is described from these operation tests.

4.1 Angular Resolution

Solid angle $\Omega(v_{i,j})$ is known as a critical factor in making a uniform detection, especially for the detector system that involves the overlapping of the detection acceptance. The mu-PSD of the developed detector is one of the examples. The maximum detectable zenith angle of the nearby pairs of pixels are obviously overlapped. The solid angle is a measure of describing how a target object is observed at a given point. The solid angle of each pair of pixels $d\Omega(v_{i,j})$ represent the angular resolution of each detectable vector $v_{i,j}$. For the case of the rectangular pair of pixels of the mu-PSD1 and mu-PSD2, the calculation is extremely difficult to solve analytically. A Monte Carlo simulation is rather required.

A simulation program was written in C++ with the ROOT toolkit [37]. The precise 3D geometry of the mu-PSDs is input to the simulation program. The 3D geometry includes non-sensitive cladding layer, wrapped aluminum reflector and the effective volume of the PSF core. Then, muon events are generated uniformly in every direction (θ, ϕ) and randomly for the position $(x, y, 0)$ in a plane source. The origin of z -axis was defined to be the center of the mu-PSD2, under its lowest outermost layer of the wrapped aluminum reflector. Here, the particle source with the same size as the detector area, $134 \text{ mm} \times 134 \text{ mm}$, was placed under the mu-PSD2. For the detection of cosmic-rays, none of the particles essentially deduced to come from the earth. Hence, the source was generated at the zenith angles $\theta \leq 90^\circ$. The solid angle 2π of the hemisphere is the maximum solid angle that can be detected by a point-detector. The program counted the number of the generated muon $N(v_{i,j})$ which coincidentally passed through all four layers of the mu-PSDs from the total number of the generated events N_{total} . Then, the solid angle $d\Omega(v_{i,j})$ was computed from:

$$d\Omega(v_{i,j}) = 2\pi \frac{N(v_{i,j})}{N_{total}}. \quad (4.1)$$

The angular resolution of the detector was represented by the largest solid angle at $d\Omega(v_{0,0})$.

The distance d between the two mu-PSDs was designed to be adjustable for the flexibility in the angular resolution. In consequence of the low rate of cosmic-ray muons at ground level, the muography detector has to optimize the compactness of the detector, detection resolution and the practical time consumption for each target object. The Monte Carlo simulation was used to estimate the detector vertical resolution $d\Omega(v_{0,0})$ as a function of the distance d . Fig. 4.1 shows the simulation result from 10^8 generated events.

From Fig. 4.1 the distances 10 cm and 15 cm of d meet aforementioned required resolution of the infrastructure measurement with 7 msr and 3 msr, respectively. Fig. 4.2 shows the simulated solid angle of each pair of pixels $d\Omega(v_{i,j})$ as a function of the zenith angle θ from setup of d at 10 cm (red solid circle) and 15 cm (blue hallow square). The θ was calculated from the center position of the pixels. The 15 cm, even though, provided the better angular resolution, the 10 cm exploited the better measurement time consumption. From indoor measurements on the top floor of a concrete building, 1.1 and 0.6 of muon count rate in units of count per second were detected by the setup of $d = 10$ cm and 15 cm, respectively. The detection time of the 10 cm distance is almost two times shorter than the 15 cm distance.

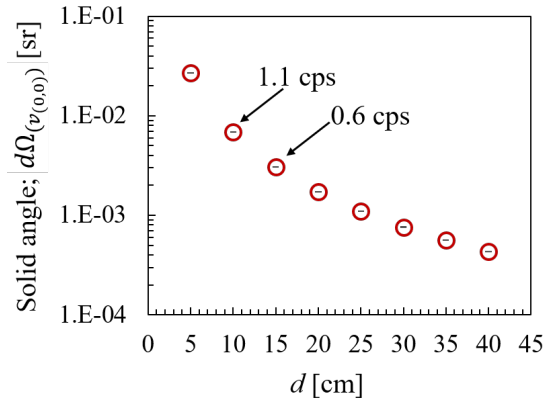


Figure 4.1: Solid angle resolution as a function of distance between the mu-PSDs.

Then, the number of generated events as a function of zenith angle; $N(v(d\theta))$, integrated over all azimuth angle; $\phi \in [0, 2\pi]$ in the simulation was considered. The number $N(v(d\theta))$ was normalized at $\theta = 90^\circ$. The normalized number of only coincident events; $n(v(d\theta))$, from various setup of distance between both mu-PSDs is plotted as a function of d in Fig 4.3. The maximum θ that can be detected by each set up can be estimated from the plot. Measurement within $\theta \leq 40^\circ$ was expected for this feasibility test according to the environment condition in the open-sky measurement, which will be described in the next chapter. The number $n(v(d\theta))$ is higher for the closer distance d corresponding to the larger total angular acceptance. Thus, for this detector feasibility study, $d = 10$ cm was chosen to save the time for various commissioning.

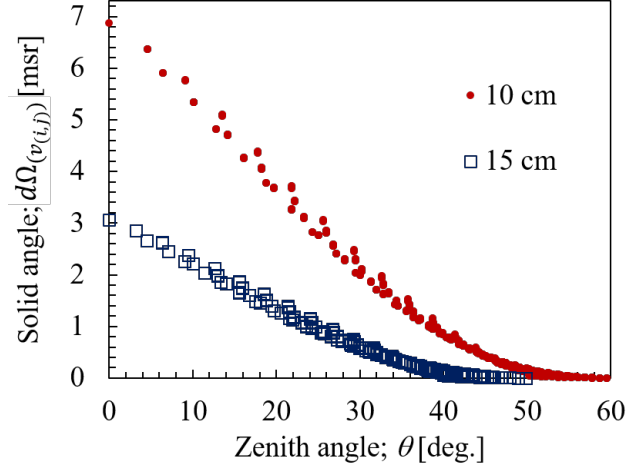


Figure 4.2: Simulated solid angle of each pair of pixels $d\Omega(v_{i,j})$ as a function of the zenith angle θ from setup of d at 10 cm (red solid circle) and 15 cm (blue hollow square). The θ was calculated from the center position of the pixels.

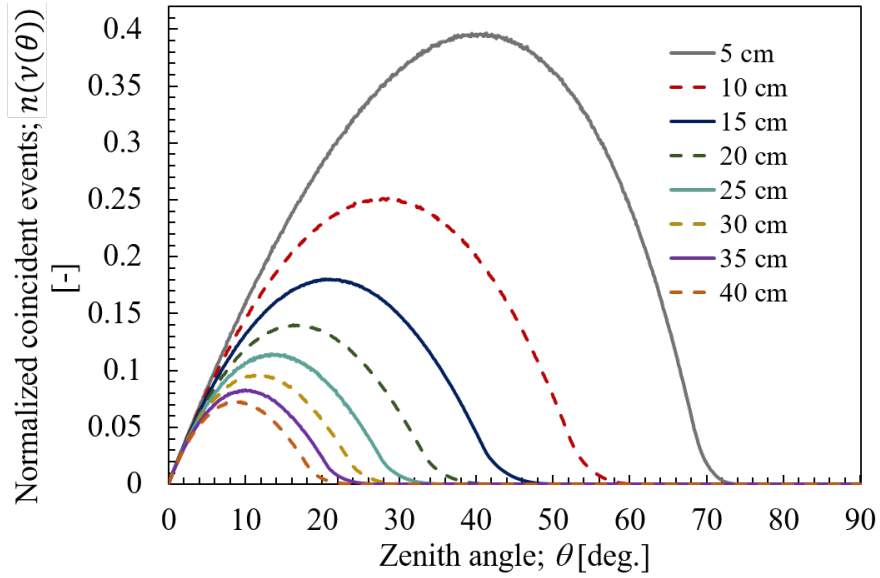


Figure 4.3: Normalized coincident events ratio ($n(v(d\theta))$) over all azimuth angle; $\phi \in [0, 2\pi]$, as a function of θ from various setup of distance between both mu-PSDs; d [cm].

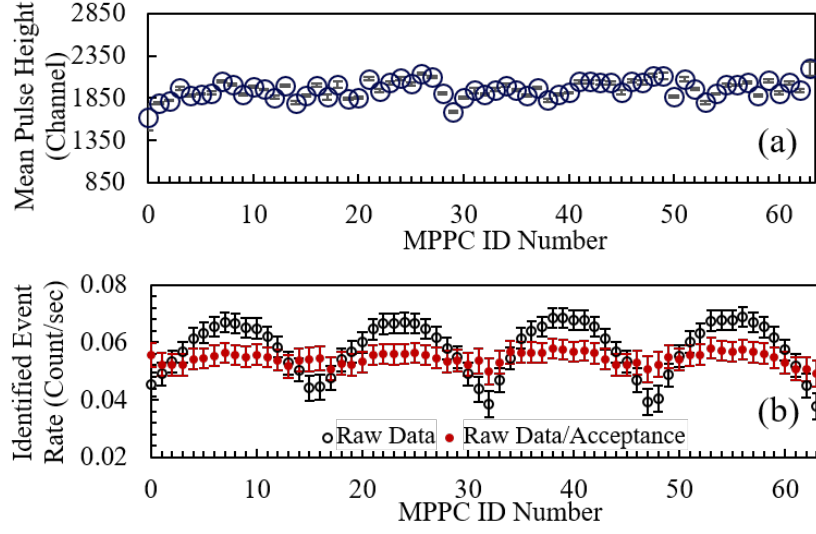


Figure 4.4: Mean pulse height calculated from the peaks of Gaussian fitting of the identified events distribution (a) and the identified event rate (b) for each MPPCs, black markers are raw identified events, and red closed circles are corrected data.

4.2 Uniformity of Detection System

To achieve the uniform performance of all MPPCs, the bias voltage of each MPPC was adjusted. The pulse height distribution of identified muon events was plotted as a function of ADC channel. The distribution of each MPPC was fitted with a Gaussian function. The bias voltage applied to the MPPCs was iterative re-adjusted until the peak positions became a steady trend, not overlapping with the dark count event and minimized overflowing out of the ADC channel range. The finalized mean pulse heights of identified events of each MPPCs are plotted in Fig. 4.4 (a). The deviation is around 3.0% of the peak positions.

The identified event rates are shown in Fig. 4.4 (b) for each MPPC. The black hollow markers show the identified event rates. According to the smaller acceptance of the PSF group near the edge than the groups near the center, the lower detected event rate of the former is indicated. The highest event rate occurred at the center of each layer. Thus, four symmetric curves appear. To check the uniformity of the detection system corrected for the effects of geometry, the detector acceptance $A(v_{i,j})$ defined by Eq. 3.3 is applied to yield the corrected event rate. The corrected rate in Fig. 4.4 (b) (closed red circles) is acquired from the raw count rate divided by the detector acceptance. The deviations of less than 2×10^{-3} count/sec in the corrected rate confirm the uniformity of the detection system once the MPPC bias voltages have been adjusted and the geometry effect is corrected.

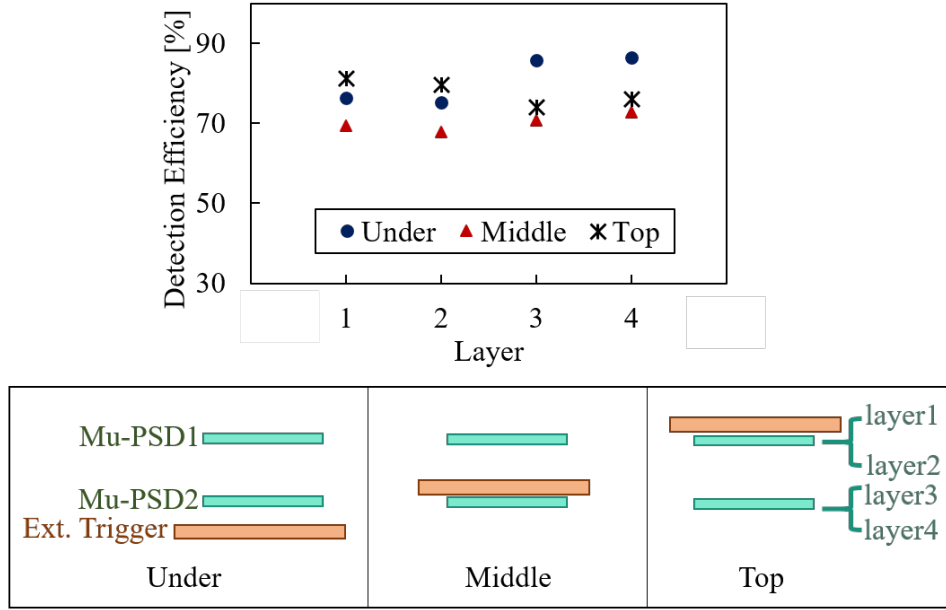


Figure 4.5: Detection efficiency of mu-PSD layers from the uppermost layer (1) to the lowest (4) with different position of the plastic scintillator plate, used as an external trigger generator.

4.3 Detection Efficiency

Since only events detected by all four layers of the mu-PSDs are identified as muon events, the performance of each mu-PSD layer was calculated to find the overall detection efficiency. The detection efficiency of the mu-PSD layer was calculated from the number of identified events detected by that layer divided by the number of events detected coincidentally by the other three layers. The denominator represents the actual number of muon events that pass through the detector. Percentages for 76.2 ± 0.1 , 74.9 ± 0.4 , 85.9 ± 0.3 and 86.4 ± 0.2 of detection efficiency was calculated for each layer of the mu-PSDs, which are listed from the uppermost layer to the lowermost layer.

The plastic scintillator plate used as an external trigger generator was also placed next to the lower mu-PSD as shown in Fig. 3.5. The higher efficiency of the lower layer results from the higher possibility of an event to be passed through the lower detector and hit the external trigger. In Fig. 4.5, the effect of the plastic scintillator plate positions on the detection efficiency of each layer was indicated. The better efficiency was obtained from the layer placed closer to the external trigger plate. Note that these percentages were calculated by considering only practically detected events. These results exclude the consequences of events lost in the gap between the effective volume of PSFs due to the thickness of the aluminum reflector and cladding layers of each PSF.

Although, the position of the plastic scintillator plate effects the detection efficiency. Due to the direct detection of the background muon, this geometrical limitation is eliminated according to the attenuation rate in Eq. 3.5.

Chapter 5

Feasibility Study of Infrastructure Muography

To assess the feasibility of this prototype and demonstrate the applicability of the developed detector, the following experiments were conducted. First, the long-term detection stability was tested in two experimental conditions. The detector was placed in a thin-walled prefabricated hut to measure under open-sky condition. Then, the same period of measurement was performed under underground condition. Second, angular muon count rates were evaluated from an experiment on the top floor of a concrete building. The uniformity performance over the whole detectable vectors $v_{i,j}$ was experimentally confirmed in this feasibility study. Third, to test the basic muography characteristics, a muography measurement of a simple high-density object was conducted. A lead block was set up as a target object. The block size was approximated to have muon count rate as similar as a scale of the internal structure of a concrete building. From these feasibility study results, it turned out that the developed detector was ready for practical applications. Finally, a muography of a concrete building with known structure was carried out to demonstrate an infrastructure survey and image its spatial profile.

5.1 Stability Test of Long-term Measurement

The detector was completely constructed as the portable design. As a next step, the long-term stability was tested. The long-term measurement was set up under two conditions. First, a test experiment under an open-sky condition was set up in a prefabricated hut with a sufficiently thin roof and walls. Second, detection under an underground condition was set up on the basement of a seven-story concrete building nearby the prefabricated hut. Both of measurements were performed at Chikushi campus, Kyushu University (33°31'N, 130°28'E, 35 m above sea level). Each measurement was kept over 264 hours.

The stability of the developed detector is obviously seen from the steady trends over the whole period of measurement in Fig. 5.1. The red line presents the frequency of the triggered events from the open-sky measurement. The blue line shows the result of the measurement on the underground of the building. The stability can be indicated by the ratio of the standard deviation and the average value of both histograms. The triggered event rate was 5.42 ± 0.09 Hz on average for the open-sky measurement. For the underground measurement, the triggered event rate was 2.74 ± 0.04 Hz. The ratio of both measurements was only 0.03.

The diurnal variation can be seen, especially in the open-sky measurement. There are several possible causes of the variation. The well-known effect by the Earth's relative motion in the interplanetary magnetic field [38] was considered as one possibility. The effect produces the variations at 1 and 2 cycles per day [39].

The cosmic-ray muon rate corrected with the atmospheric temperature and pressure from the multi-directional muon telescope of Nagoya University [40] was used to compare with the result in Fig. 5.2. The measurement practically separated into three measurement periods due to stopping periods to take the data and check the detection system. The stopping time took no longer than 1 hour. The three measurement periods were separated by the black dash line according to the short stopping of the experiment. The diurnal variation can be seen in the Nagoya detector's intensity. However, the experiment trend in Fig. 5.2 do not match totally the referenced rate. Thus, it was concluded that the periodic variation was not mainly affected by the aforementioned daily circles' variation.

The atmospheric pressure and the temperature change from day and night time are expected to be a major cause of the variation of interest. Because the prefabricated hut has a very thin wall without air-conditioning. The mu-PSDs themselves, although, have the temperature control system with the heat insulator shielding. But the environmental pressure and temperature effect on the electronic devices which some parts also directly connect to the MPPCs inside the shielding. This trigger rates, however, are calculated from the intrinsic triggered events before the particle identification process and without subtraction of the season effect. The experiment to observe the periodic variations of the muon events over the effect of temperature and pressure have been investigated by this developed detector by our group. The pressure change was found to be the major cause of this variation. An experiment to confirm the pressure effect will be done in the future work.

In this open-sky measurement, the cosmic-ray muon count rates were recorded over the whole azimuth angle range and at zenith angles below 40° , because muons coming from zenith angles larger than 40° would be perturbed by a five-story concrete building located near the prefabricated hut. The information from this open-sky experiment is used as $I_0(\nu_{i,j})$ in the following feasibility demonstration in Section 5.4, muography of a building.

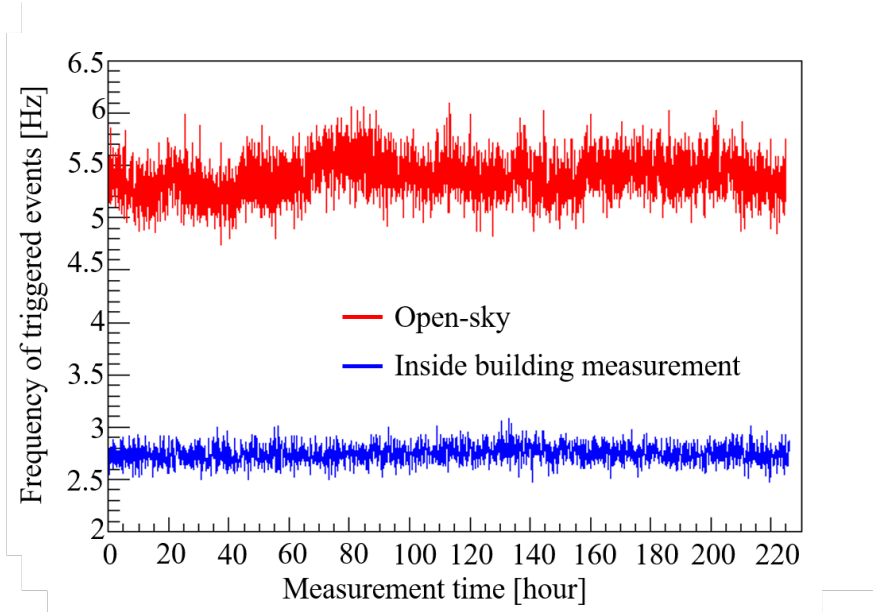


Figure 5.1: Frequency of trigger events during the open sky measurement (red) and the feasibility demonstration experiment on the basement of a building (blue).

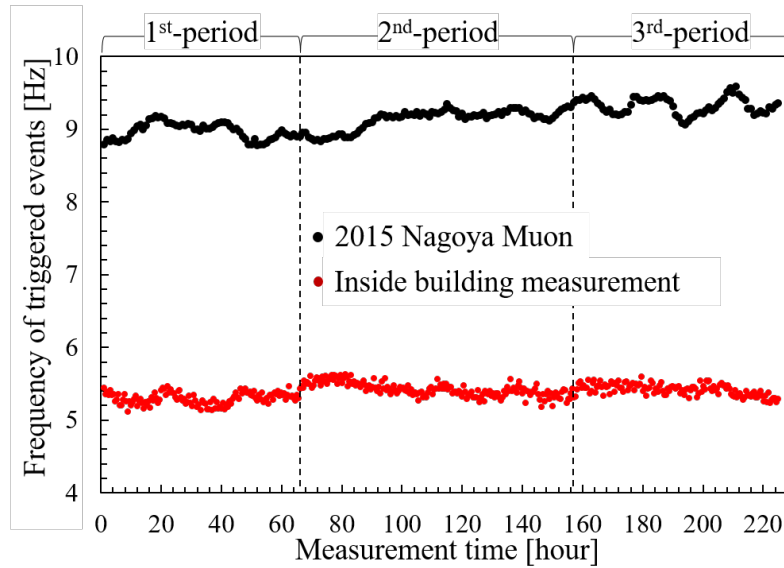


Figure 5.2: Cosmic-ray muon rate from multi-directional muon telescope of Nagoya University [40](black) and the frequency of trigger events during the open sky measurement (red).

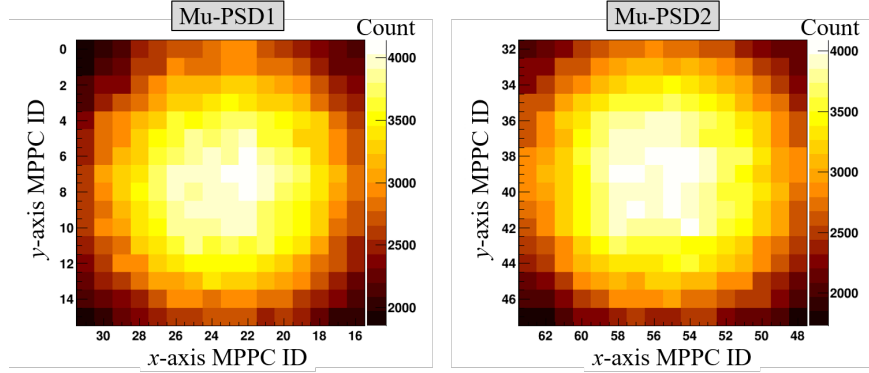


Figure 5.3: The measured muon counts in each detector pixel of mu-PSD1 (left) and mu-PSD2 (right).

5.2 Angular Dependence of Muon Count Rates

For muography, the information on muon rate without any obstacles $I_0(\theta, \phi)$ at the measurement location is essential. In this study, the muography image evaluated from the actual measurement of the zenith-angle dependent muon count rate, $N_0(v_{i,j})$. Thus, the uniformity of $N_0(v_{i,j})$ as a function of the muon direction $v_{i,j}$ has to be confirmed. For this test, the muography detector was placed inside an experiment room on the top floor of a concrete building. The room was chosen to avoid the effects of the environmental temperature. Moreover, since the experiment room has a 15cm thick roof made of concrete, the effect of the cosmic-ray electron can be decreased. The experiment room is covered by the concrete walls and rood about 15 cm in thickness. According to results of PHITS simulation [27], about 70% of the cosmic-ray electron was predicted to be blocked by the 15-cm concrete. The room temperature was controlled around to around 25°C.

The experimental data was taken over 203 hours. Figure 5.3 shows the distributions of the muon event counts detected by each detector pixel of mu-PSD1 (left) and mu-PSD2 (right). Both of distributions is symmetric with respect to the origin (0, 0). The highest counts are observed around the center of the detection area. These distributions confirm that both of mu-PSDs has the good alignment.

The recorded muon vectors $v_{i,j}$ was plotted in Fig. 5.4. The uniformity of azimuth distribution can be seen in the $N_0(v_{i,j})$ distribution. The statistical error (S.E.) of 2% and 8% are also indicated by the solid white line. Circle shape of the S.E. lines is one way to guarantee the vertical alignment of the developed detector. This distribution is an example of the background muon distribution that was used to evaluate the spatial profile according to Eq. (3.5).

To find the corrected angular distribution of unobstructed muon intensity $I_0(v_{i,j})$ as shown in Eq. (3.4), the number of the muon events; $N_0(v_{i,j})$ was divided by the detector acceptance $A(v_{i,j})$, from Fig. 3.8(c), and detection time t_k . The percentage of the lost event in Fig. 3.8(b) was also taken into account. Figure 5.5 is a plot of the absolute intensity of muons; $I_0(v_{i,j})$, in a unit of $\text{s}^{-1}\text{sr}^{-1}\text{cm}^{-2}$, against the zenith angle θ . In the figure, the red and blue markers represent the measured muon intensity from a measurement in the prefabricated hut and on the top floor of a building, respectively. Here, $I_0(v_{i,j})$ is an

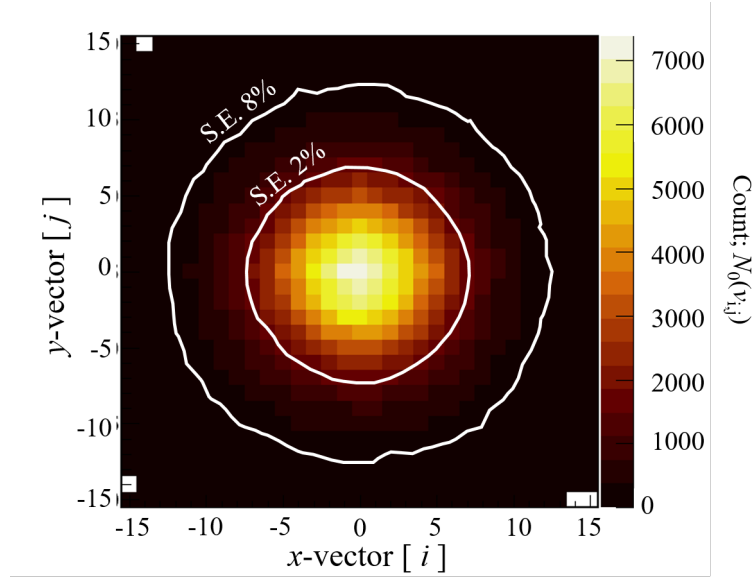


Figure 5.4: The measured muon counts as a function of muon direction $v_{i,j}$. The statistical error (S.E.) of 2% and 8% are also shown.

average of the measured count rates overall detected azimuth angle ϕ which share the same value of θ .

The black dash line represents the $\cos^2(\theta)$ function normalized to the rate at 0° from the empirical formula in Eq. (2.1). The measured $I_0(v_{i,j})$ in Fig. 5.5 is in rather a disagreement with the cosine-powered formula. One obvious difference is the absolute intensity which the measured $I_0(v_{i,j})$ is higher than the accepted formula [18]. This difference was expected to be caused by the $I_0(v_{0,0})$ applied to the cosine formula which includes only the muon events, but the measured intensity was included the aforementioned cosmic-ray electron and positron component. In addition, the difference in the shape of the distribution was expected to cause by the rough calculation of the exponent $n = 2$ of the empirical formula itself. The measurement results included the muon counts from the overall detectable region while the formula estimated at muon energies of only a few GeV.

Although the formula $\cos^2(\theta)$, was not fit with the measured $I_0(v_{i,j})$, the reference solid green line is in good agreement with the measured one. Here, the solid green line represents an absolute intensity of cosmic-ray muon and electron combination as a function of zenith angle normalized to 0° . This reference rate was calculated from the cosmic-ray muon spectra obtained by EXPACS [17] which is more precise because the overall energy of the muon is also taken into account. These results confirm the influence of cosmic-ray electron and positron component on the data obtained from the developed muography detector.

These angular distributions confirmed the correction of the alignment and exhibit the uniformity of angular detection in both azimuth and zenith distributions. As a next step, the feasibility of the detector as an infrastructure scale probe was tested. A lead block was chosen to be the target object. The result will be described in the next Chapter.

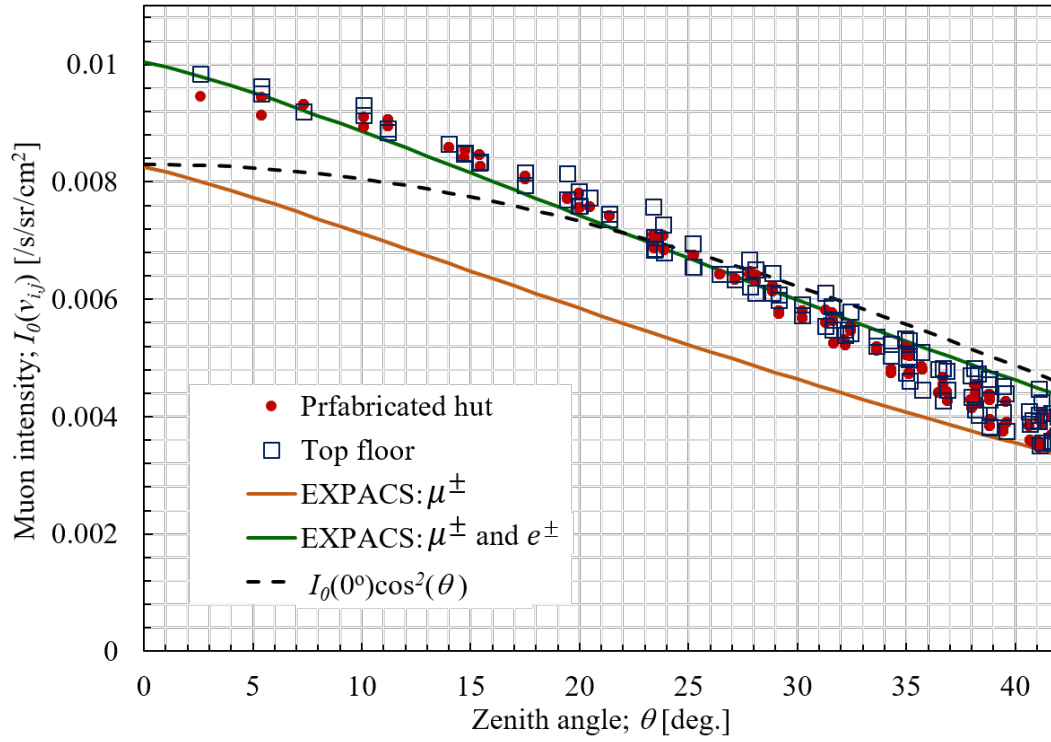


Figure 5.5: The absolute intensity of muons; $I_0(v_{i,j})$, in a unit of $\text{s}^{-1}\text{sr}^{-1}\text{cm}^{-2}$, as a function of zenith angle compares with the accepted formula of $\cos^2(\theta)$ [18] distribution and the calculated distribution from EXPACS [17]. The red and blue markers represent the measured muon intensity from a measurement in the prefabricated hut and on the top floor of a building, respectively. The black dash line represents the cosine formula distribution according to the empirical formula of the cosmic-ray muon intensity at sea level in Eq. (2.1). The solid green line and orange line represents an absolute intensity of muons together with electrons and only muons, respectively, calculated from the cosmic-ray muon spectra of EXPACS.

5.3 Lead Block Detection Test

In this experiment, the feasibility of the developed muography detector was confirmed to provide a muography image of an object on the scale of civic infrastructure. A lead block with dimensions $200\text{mm} \times 300\text{mm} \times 350\text{mm}$ and density 11.34 g/cm^3 was placed as shown in Fig. 5.6. The measurement took 168 hours. The block was placed 127 cm away from the detector at the zenith angle of 30° . This azimuth angle was defined relative to the detector geometry. The zero value of the azimuth angle is defined as 45° counter-clockwise from the south, for this experiment. The lead block obstructed incoming muons in the zenith angle region from 20° to 40° , and the azimuth angle region from 33° to 57° . The center of the lead block, the point “C”, is located at the zenith angle of 30° . Detected cosmic-ray muons, which pass through the point C, have penetrated in the mean distance of approximately 50 cm in the lead block.

The lead block was chosen as a relatively small measurement target, because of its larger stopping power compared with materials using for infrastructure (e.g. concrete). The size of the lead block was chosen with the concrete thickness of typical civic infrastructure in mind. According to the simulation by PHITS [27], the range of 50 cm in lead corresponds to the range of around 180 cm in the concrete for the same muon energy. 180 cm is the estimated thickness of thin concrete regions of the seven-story building that was measured and will be described in the next section.

Moreover, the experiment was repeated with the same setup and duration, but without the lead block. The repeated measurement aimed to collect the unobstructed background muon rate $I_0(v_{i,j})$ under the effects of components such as wall and columns of the experimental room. The detected muon rate with the lead block $I_{Pb}(v_{i,j})$ was divided by the detection intensity obtained by the background measurement $I_0(v_{i,j})$ according to Eq. (2.3). Then, the muon attenuation distribution as a function of incident muon direction, $D(v_{i,j})$, was calculated.

The muon attenuation distribution $D(v_{i,j})$ is shown in Fig. 5.7. The identified particles that travel through zenith angles of $\theta = 20^\circ$ to 37° and azimuth angles from $\phi = 37^\circ$ to 60° . The yellow dashed line indicates the approximate area of image pixels which was predicted to consist of the lead blocks information. The pixel of the attenuation rate of $26\% \pm 4\%$ is estimated to be in the direction coincides with the direction in which the muons were obstructed by the lead block. This result shows that position identification of an infrastructural scale target is possible. Relative statistical errors (R.E.) of 3% and 5%, are shown with the solid contour line. The R.E. was calculated from S.E. of both the measurements with the lead block and the background measurement without the block.

In addition, the measured muon attenuation rate of about 26% at the point C (i.e., at 30° zenith angle and 40° azimuth angle) was supported by the following simulation. Muons with kinetic energy below 720 MeV are entirely eliminated inside the lead block within 50 cm as estimated from the PHITS simulation [27]. The attenuation of the cosmic-ray muons was calculated from the ratio of the integral flux of cosmic-ray muons with energy lower than 720 MeV to the total integrated flux of the typical cosmic-ray muons flux spectrum, taken from EXPACS [17].

The muon attenuation simulation yields the attenuation rate of approximately 21%, about 5% lower than the experimental result. The other components of cosmic-rays such as electron and positron

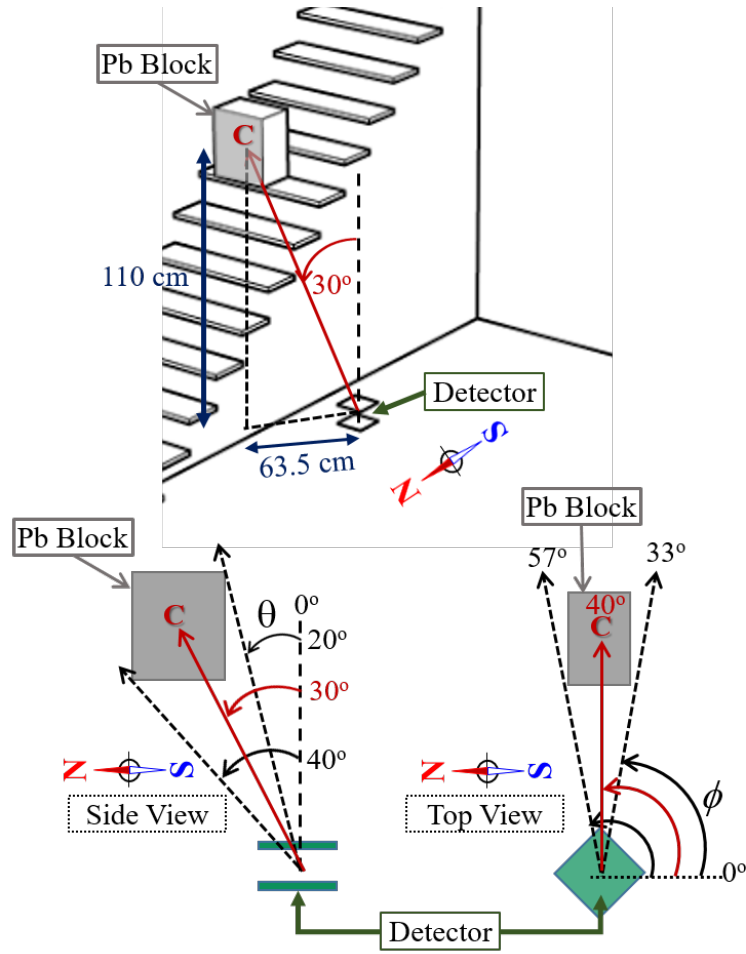


Figure 5.6: Sketch of the lead block measurement in three dimensions drawing (top), side-view configuration (lower left) and top-view configuration (lower right). Point “C” marks the center of the Pb block volume.

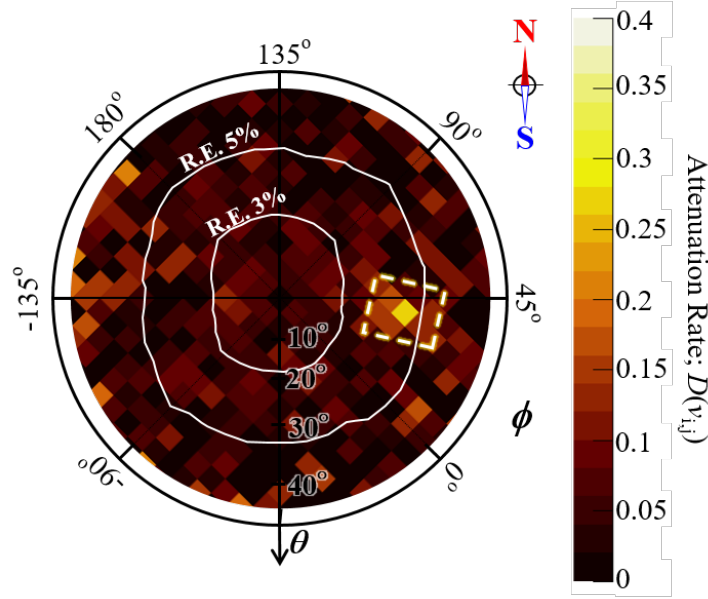


Figure 5.7: Muon attenuation rate distribution of measurements with and without a lead block as a function of muon incident direction, (θ, ϕ) . The measured shadow of the 238 kg lead block is marked with the yellow dashed line. Relative statistical error (R.E.) of 3% and 5% are showed by the solid contour.

showers, which also pass through the roof of the experiment room, were not included in the simulation. Therefore, the rate obtained from the simulation shows an underestimation. According to EXPACS [17] prediction, the cosmic-ray electron components ($e^\pm$) are approximately 25% of the total flux of $\mu^\pm$ and $e^\pm$ as shown in Fig. 2.6. The PHITS simulation [27] indicated that 70% of the $e^\pm$ components fully stop inside 15cm concrete roof of the experiment room. That means only 7.5% of the $e^\pm$ components can reach the detector. This is reasonable if the relative statistical error was also taken into account.

5.4 Muography of a Building

A muography of a building with known structure was performed to demonstrate an infrastructure survey and image its spatial profile by using the developed detector. The detector was placed in the basement of a seven-story concrete building located at Chikushi campus of Kyushu University, as shown in Fig. 5.8.

5.4.1 Measurement Results

For the 390-hours measurement in the basement of the building, the muon event rate (counts per minute) as a function of the incident direction $I_t(v_{i,j})$ is plotted in Fig. 5.9 (a). The reduction of muon intensity due to the building structure is noticeable, as the distribution is deformed from the background

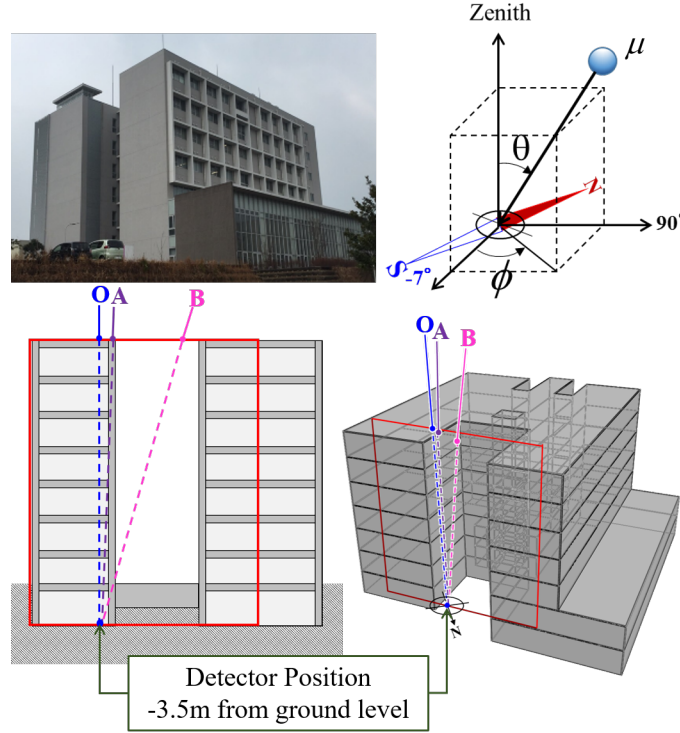


Figure 5.8: A drawing of the seven-story concrete building and the detector configuration.

count rate distribution $I_0(v_{i,j})$ in Fig.5.9 (b). The background muon count rate $I_0(v_{i,j})$ was obtained from the open-sky measurement in Section 5.1. The prefabricated hut, where the open-sky measurement was performed, was located nearby the seven-story building. The muon attenuation rate $D(v_{i,j})$ was deduced from Eq. (2.3) using these measured $I_k(v_{i,j})$ and $I_0(v_{i,j})$. Figure 5.10 presents the measured muon attenuation rate distribution as a function of discrete zenith and azimuth angles $D(v_{i,j})$. The distribution in Fig. 5.9 (c) indicates the relative statistical error from the $N_0(v_{i,j})$ and $N_t(v_{i,j})$ distributions of the both of measurements. The error corresponds to the pixel-by-pixel calculation of $D(v_{i,j})$. The relative statistical error in the region of interest is lower than 10%.

The distribution of muon attenuation rate shows an overview of the internal structure from the detector's point of view in Fig. 5.10. The point "O" at the center is the detector location as indicated above in Fig. 5.8. The region "A" and "B", are highlighted for the following discussion. The region A, for example, corresponds to $\theta = 0^\circ$ to 30° and $\phi = 207^\circ$ to 225° in which strong attenuation is observed. As shown in Fig. 5.8, the muons directions in the region A pass through a vertical concrete wall. Thus, the penetration length is expected to be the longest in this region. The observed attenuation can be explained by this trajectory. On the other hand, the penetrating length of the highlighted region B is shorter since the muons reach the detector through the concave part of the building, as shown in Fig. 5.8. The region B corresponds to $\theta = 10^\circ$ to 40° and $\phi = 153^\circ$ to 200° . Thus, rather weak attenuation is observed in this region.

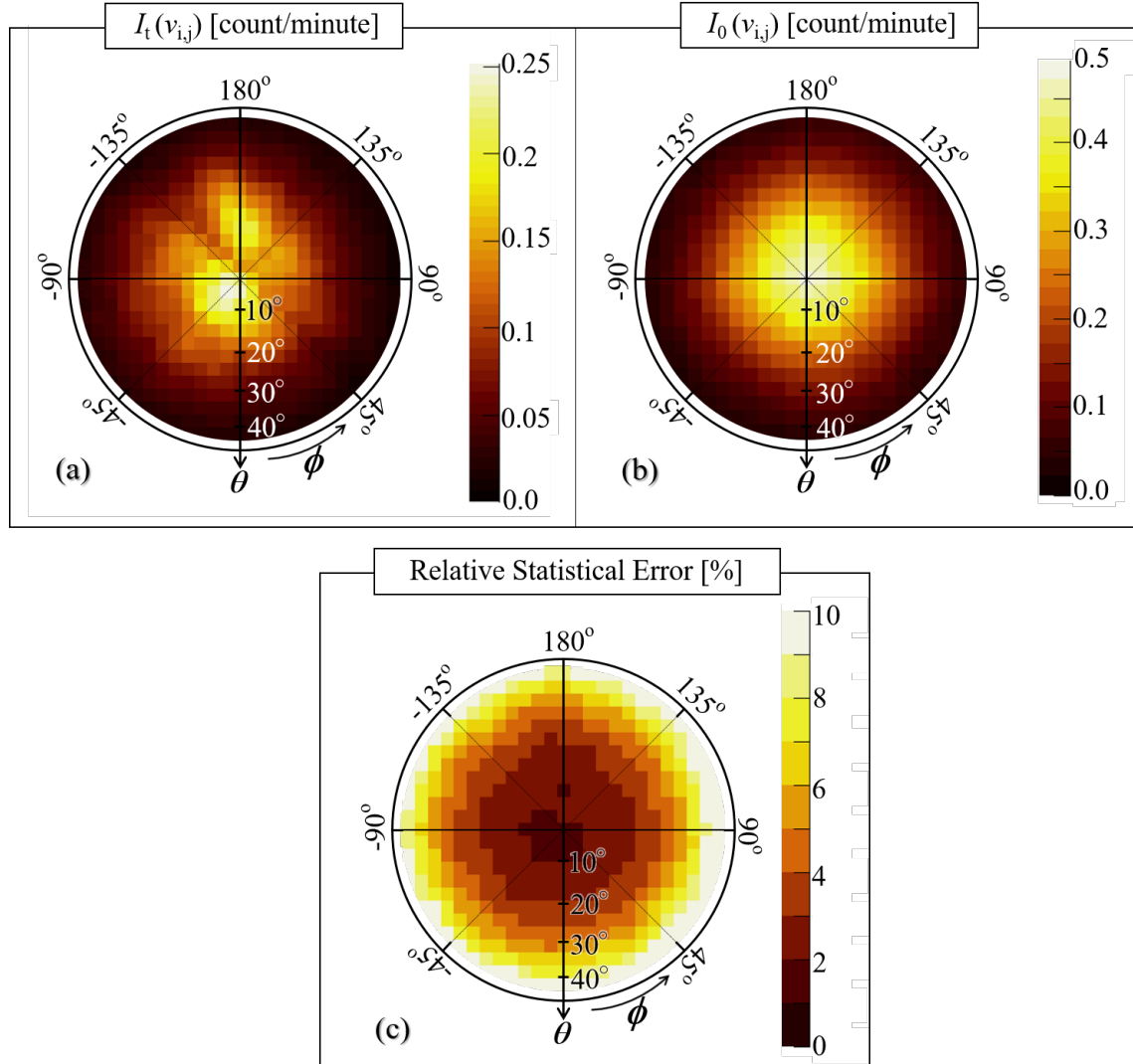


Figure 5.9: The muon event rate(counts per minute) as a function of the incident muon direction; (a) $I_t(v_{i,j})$ measured in the basement of a concrete building and (b) $I_0(v_{i,j})$ measured under the open-sky conditions in the nearby prefabricated hut. Statistical error of the attenuation rate distribution (c) as calculated pixel by pixel is included.

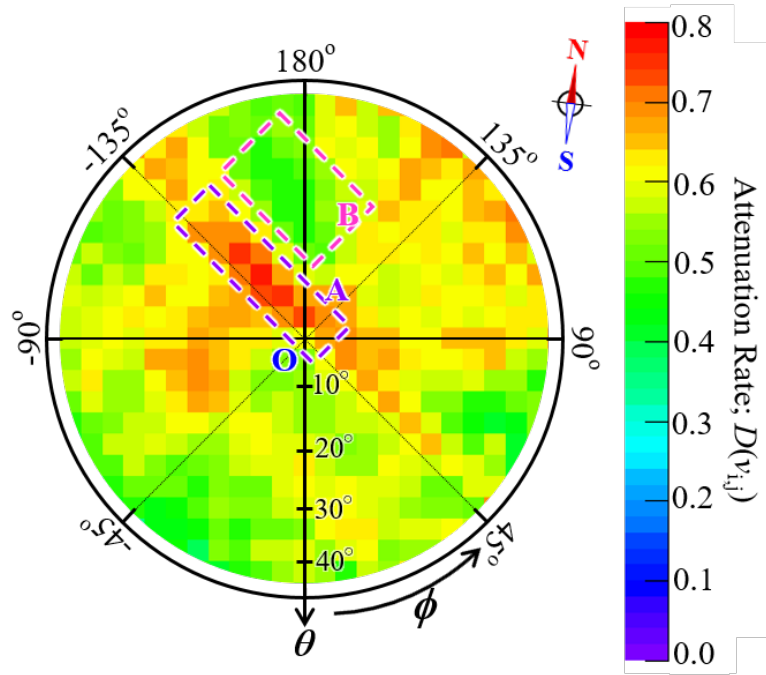


Figure 5.10: Muon attenuation rate measured as a function of the incident muon direction defined by zenith and azimuth angles $D(v_{i,j})$. The shadow shows the building core structure. The detector position at 0° zenith angle is labeled with “O” at the center of the plot. Areas “A” and “B” are examples of the largest and smallest thicknesses of the concrete structure, respectively.

5.4.2 Conversion to Interior Structure Profile

To demonstrate a quantitative result, a rough function to convert the attenuation rate $D(v_{i,j})$ to the object thickness was determined by a simulation. The material in the simulation used to find this function is assumed to be concrete, as it is the main component of the infrastructures which is the main target of the detector. Additional material used to construct the building and material under the ground were not considered. As described in the data analysis part of Section 3.4, the relation between the muon attenuation rate and the fully-stopped muon kinetic energy was determined from the muon spectrum given by EXPACS [17]. For this demonstration, the integral spectra were assumed to be applied for all zenith angles. Muon attenuation in several concrete blocks of various thicknesses was also estimated by simulation with PHITS [27]. The simulated concrete has the density of 2.3 g/cm^3 . The composition of the concrete used in this study is presented in Table 5.1. A linear relation between concrete block thicknesses 80 cm to 910 cm and the maximum kinetic energy of absorbed muon was observed.

Table 5.1: The defined concrete compound by weight ratio for the simulation.

Composition	Weight Ratio
H	0.08476
O	0.60409
Si	0.24186
Ca	0.02048
Mg	0.00299
Na	0.00947
Al	0.02483
K	0.00686
Fe	0.00426

The conversion function from the attenuation rate to the concrete thickness is determined by curve fitting of the simulated data by a third-order polynomial. The function is given by

$$L(v_{i,j}) = (2.03 \times 10^3)D(v_{i,j})^3 - (1.21 \times 10^3)D(v_{i,j})^2 + (9.73 \times 10^2)D(v_{i,j}) - 2.84, \quad (5.1)$$

where $L(v_{i,j})$ is the thickness of the concrete along the muon path in direction $v_{i,j}$, in units of cm. The estimated result quantitatively reproduce the muon attenuation measured in the directions along which the concrete thickness was known, which are marked as the regions A and B in Fig 5.11. Let us first consider the region A. The concrete thickness in the direction of $(30^\circ, 180^\circ)$, at pixel $(v_{2,3})$, presumed by muography was about 810 ± 70 cm. The error was calculated from the relative statistical error shown in Fig. 5.9 (right). For comparison, the total length of concrete in this direction was estimated from structural drawings of the building. These drawings indicate that a muon incident to the direction $(v_{2,3})$, reaches the detector after passing through concrete about 1,000 cm thick. Note that the accuracy of my interpretations of these drawings was in the order of tens of centimeters. The whole building was

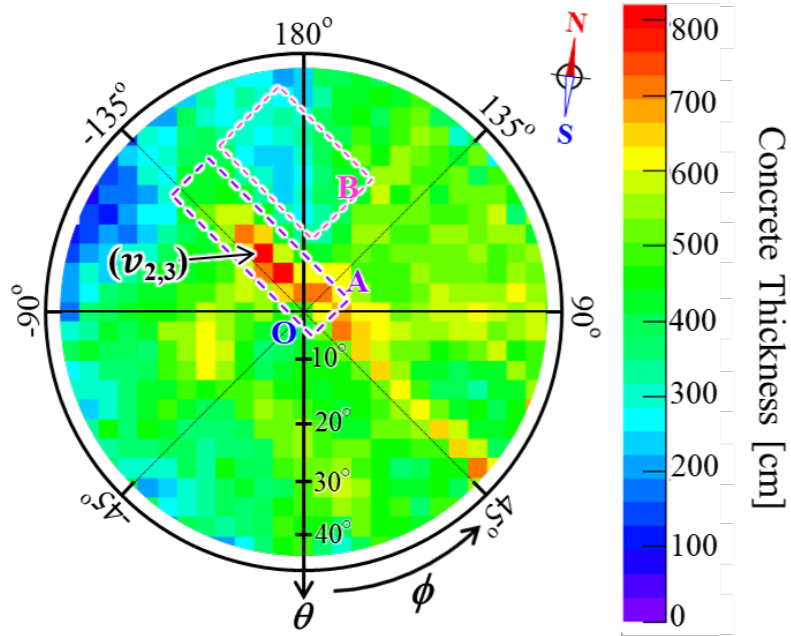


Figure 5.11: Calculated concrete thickness as a function of the muon incident direction defined by zenith and azimuth angles from the normalized muon attenuation distribution measured; (θ, ϕ) .

assumed to be made of homogeneous concrete. Obstructions due to many heavy instruments installed inside this building (e.g. iron reinforcing bar) were not included in the drawing.

Next, let us consider the incident direction marked as the region B in Fig 5.11. The concrete thickness as estimated by muography distributes among approximately 230 ± 40 cm to 340 ± 60 cm. From the drawing, it was found that muons passing through this region penetrate about 140 cm to 340 cm in the concrete. These muography results are reasonably consistent with the drawings. Several underestimations were caused by the materials buried in the ground in the region B which were not considered in this demonstration.

Finally, this feasibility test demonstrates the applicability of the developed detector for muography of large structural objects on the scale of a concrete building. The muon attenuation rate distribution clearly reconstructs the relative distribution of the structural profile. From the two highlighted regions, the thickness distributions show the relative difference in thickness between thin obstacles and thicker ones. The preliminary conversion function to estimate the thickness from the attenuation rate yields underestimated results for the region having thick structure, while good results are obtained for the thinner region. This underestimation is explained by the assumption that the structure is composed of homogenous concrete. High energy cosmic-ray electrons and positrons also cause the error in the region of low thickness due to their potential to reach the detector. Because the electron components and muons were not identified by this developed detector, it is possible that the electrons were counted as muon events. The Monte Carlo simulation used for the muon range is also one of the possible causes of inaccuracy. The simulation by the GEANT4 simulation toolkit [28] also obtained good agreement with the PHITS simulation [27] as was shown in Fig. 2.5. On the other hand, only one empirical model for the muon flux spectrum, EXPACS [17], was applied to estimate the integrated flux. The zenith angle dependence of the muon rate should be discussed in a forthcoming study. Various models should be compared in the future to improve the accuracy of the conversion function.

Chapter 6

Study of ML-EM based 3D Muography

The developed muography detector was used to project the internal structure of the seven-stories concrete building. In Chapter 5, the projected image shown in Fig. 5.10 reveals the main features of the infrastructure of the building. It demonstrated the feasibility of the detector for an infrastructure scale probe. As a next step, the development in the precision of quantitative analysis is not an only effort to improve the ability of the detector. Here, the 3D image technique was also adapted to apply with the developed detector to push the new direction of the attenuation based muography.

The measured two-dimension (2D) muography projection basically shows the variance in integrated thickness of each muon directions, but the spatial distribution along the path itself cannot be directly estimated. The tomography technique like medical CT is necessary to yield the spatial distribution inside target objects. However, the direct measurement of the overall 3D image is impractical because of the aforementioned low incident rate of cosmic-ray muons, approximately $1 \text{ muon/cm}^2/\text{min}$, at sea level. In addition, the distribution of the muon intensity as a function of zenith angle (see. Fig. 5.5), cause the angular limitation of the detection. To resolve these problems, the development of a novel technique of the muography with image reconstruction algorithms is strongly required.

I propose an approach with the Maximum Likelihood- Expectation Maximization (ML-EM) algorithm for the muography with the developed muography detector. A feasibility demonstration of infrastructure scale muon tomographic 3D imaging of lead blocks was performed by a simple experimental setup. The portable muography detector was used to detect two sets of lead blocks, placed at a different height with respect to the detector. The feasibility is demonstrated by simulation. Then, the 3D muography image from an experiment with the same setup was performed to confirm the feasibility. A preliminary Monte-Carlo simulation of the mean thickness projection of the blocks, which was expected to be experimentally detected, was also conducted to optimize the measurement duration and confirm the accuracy of the ML-EM algorithm.

In this Chapter, the ML-EM algorithm is described. The feasibility is demonstrated by the simulation for an experimental configuration. Then, an experiment with peer-setup was conducted to demonstrate the feasibility of the 3D muography.

6.1 ML-EM Algorithm

As aforementioned, the measurement duration and angle of detection are the major constraints in muography. To reconstruct the 3D image from the 2D projection of the muography, numerical methods are required. Among various conventional image reconstruction methods used recently, the iterative algorithms derived from the Maximum Likelihood Estimation Maximization (ML-EM) [41] has some advantages over the analytic algorithms such as the filtered back projection [42].

By using the ML-EM method, the incomplete set of projection data can be utilizable and the statistical noise artifact can be reduced. These advantages are suitable for the muography imaging which gains the effect of the statistical errors because of the low rate of the cosmic-ray muon and the limitation of detection positions and angles.

The density profile is represented by the distribution of the magnitude of image vector $\lambda^{(k)}(b)$ in three dimension region of interest. The ML-EM algorithm estimates the image vector $\lambda^{(0)}(b)$ of a voxel b that maximizes the likelihood of the measured data at the projection pixel d . The algorithm can be described in several steps:

1. Starts with an initial estimate of the image vector $\lambda^{(0)}(b)$ of a voxel b ; where $b = 1, 2, \dots, B$ and B is the number of the 3D image voxels in the region of interest.
2. Calculates the 2D re-projection of the 3D image to the detector plane by

$$n'(d) = \sum_{b=1}^B \lambda^{(k)}(b) p(b, d) \quad (6.1)$$

where $p(b, d)$ is the probability of detecting an muon event from the voxel b to be detected by a pair of pixels d where $d = 1, 2, \dots, D$. The probability $p(b, d)$ is a characteristic for each detection configuration, so, $p(b, d)$ is called “system parameter”. Here, D is the total number of the muon directions which are allowed to be detected by the muography detector pair of pixels. Thus, d can be defined from the detected x -vector $[i]$ and y -vector $[j]$ as;

$$d \equiv (i + N_x - 1) \times (j + N_y - 1). \quad (6.2)$$

The values minus one appears since $N_x = N_y = 16$, (see Section 3.4.2), but the values of i and j include zero.

3. If $\lambda^{(k)}(b)$ denotes the estimated image vector at the k^{th} iteration, the new $\lambda^{(k+1)}(b)$ by the ML-EM algorithm as proposed by Shepp and Vardi; [41];

$$\lambda^{(k+1)}(b) = \lambda^{(k)}(b) \left\{ \frac{1}{\sum_{d=1}^D p(b, d)} \sum_{d=1}^D \frac{n(d) p(b, d)}{n'(d)} \right\}. \quad (6.3)$$

For muography, the vector $n(d)$ denotes the muon attenuation rate detected by the detector pair-pixels d . The $n'(d)$ represents the calculated projection from the reconstructed image.

4. Then, the image vector $\lambda^{(k+1)}(b)$ is used to re-calculate the new $\lambda^{(k+2)}(b)$ from Eq. (6.4) to Eq. (6.3) and so on. The image vector density is iteratively calculated until the projection $n'(d)$ becomes close to the maximum-likelihood of the measured projection $n(d)$.

In this study, $p(b, d)$ is estimated, firstly, in the conventional Monte-Carlo simulation. Then, the distance-driven back-projection method [43] is applied to decrease the calculation time. The detail of both methods is described in Section 6.4.

However, the stopping criterion for the iteration scheme is required for an acceptable quality of the image among the set of the reconstructed image from the iterative calculations. In this study, a Monte Carlo simulation was made to estimate the muography projections. The simulation was applied to the experiment duration optimization and the number of the 3D image reconstruction iteration.

6.2 Thickness Projection Simulation

The main purpose of this developed portable muography detector is the investigation of the infrastructure degradation. The degradation often run-down inside the target object and becomes invisible from the outside. The muography has a potential to do this nondestructive survey if the non-degradation conditions can be estimated in advance. The mechanical drawing of a building is an example of the prior knowledge. The precise external structure can be recognized as well as the density can be evaluated from the used material. Then, a simulation to predict the muography result of the prior-knowledge is required.

In this beginning step, the Monte Carlo simulation system was derived to reproduce an actual muography detection with the estimation of the objects projected image from the 3D drawing. Thus, the simulation has to contain the same geometry and the precise acceptance of the actual detector. The average thickness of the objects detectable by each pair of pixels d is mapped, thus, the simulation is called “thickness projection simulation”. It is designed to preview the result as the detector field of view and is suitable for the field-work experiment setup.

6.2.1 Simulation Algorithm

The overview idea of the simulation is to generate randomly the muon events. By using the prior knowledge of the object drawing, the muography detector model is located in the object space. As shown in Fig. 6.1, two detected positions of the cosmic-ray muon on the precise effective volume of each mu-PSD model are randomly created. The created positions, named as (x_1, y_1, z_1) and (x_2, y_2, z_2) for mu-PSD1 and mu-PSD2, respectively, in Fig.6.1. A “muon trajectory” is originated by the linear function extrapolation of (x_1, y_1, z_1) and (x_2, y_2, z_2) . Then, “sampling points” are defined with the uniform step size; dr , along with the trajectory. The number of the sampling points; n_s , are counted if the sampling point position located inside the object region. The integrated thickness of the object $L(v_d)$ can be calculated simply from

$$L(v_d) = n_s \times dr. \quad (6.4)$$

The detected muon counts $N_k(d)$ by each pair of pixels d is also recorded. Since the precise geometry of the detector is applied, the data analysis is exactly the same procedure as that used in the actual measurement projection explained in Chapter 3. However, instead of the attenuation rate $D(v_{i,j})$ evaluation, the average thickness; $\bar{L}(v_d)$, overall simulated muon events detected by a pair of pixel d is computed. The measured projection $n(d)$ in Eq. 6.3 is substituted by the attenuation rate $D(v_{i,j})$ from the experiment or the average thickness $\bar{L}(v_d)$ from this simulation.

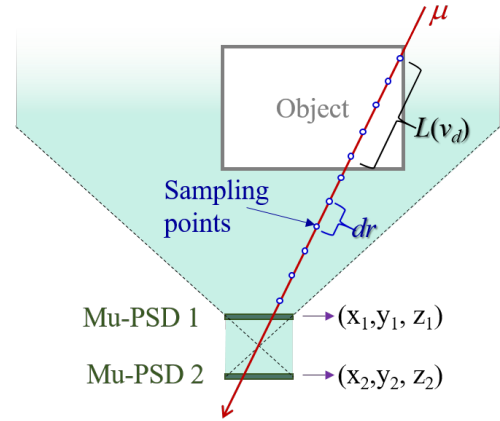


Figure 6.1: Diagram shows an overview of the thickness projection simulation procedure.

6.2.2 Example of the Simulation

The muography of the seven-story building was demonstrated to show the feasibility of the developed detector as aforementioned in Chapter 5. The thickness projection simulation was applied to predict the result as shown in Fig. 6.2(a). The figure is an example of the simulated thickness projection which estimated the muography result from the prior knowledge of the building drawing. Fig. 6.2(b) is the muon attenuation rate $D(v_{i,j})$ in Chapter 5. The average concrete thickness $\bar{L}(v_d)$ from the simulation in Fig. 6.2(b) shows the corresponding result to the experiment. The main feature square shape of large thickness concrete of the building indicated in the same pixel projection.

The simulation will be utilized for calculating the empirical conversion formula between the detected attenuation rate and the concrete thickness in near future. The conversion formula will be developed using the angular dependency characteristic of the cosmic-ray muon intensity.

For this 3D muography study, this simulation is used to predict the measurement result of the configuration target object. Since there are detection positions required for the 3D image reconstruction, the prior prediction result is strongly required. The experiment time prediction and the number of the 3D image iterative reconstruction estimation were utilized the simulated result as well. The detail will be described in the following sections.

6.3 Setup for Feasibility Study of 3D Muography

In this feasibility demonstration, a simple experimental setup of lead blocks was configured. Two sets of lead blocks with different size were arranged at a different height with respect to the muography detector as shown in Fig.6.3. The size and position of the blocks were deduced from the scale of the concrete infrastructure which is the major target of the muography detector.

Figure 6.3 shows three sketches of the lead blocks set configuration with the detection positions. The sketches consists of (a) 3D drawing, (b) cross-section at $y = 0$, and (c) top view. The center of the

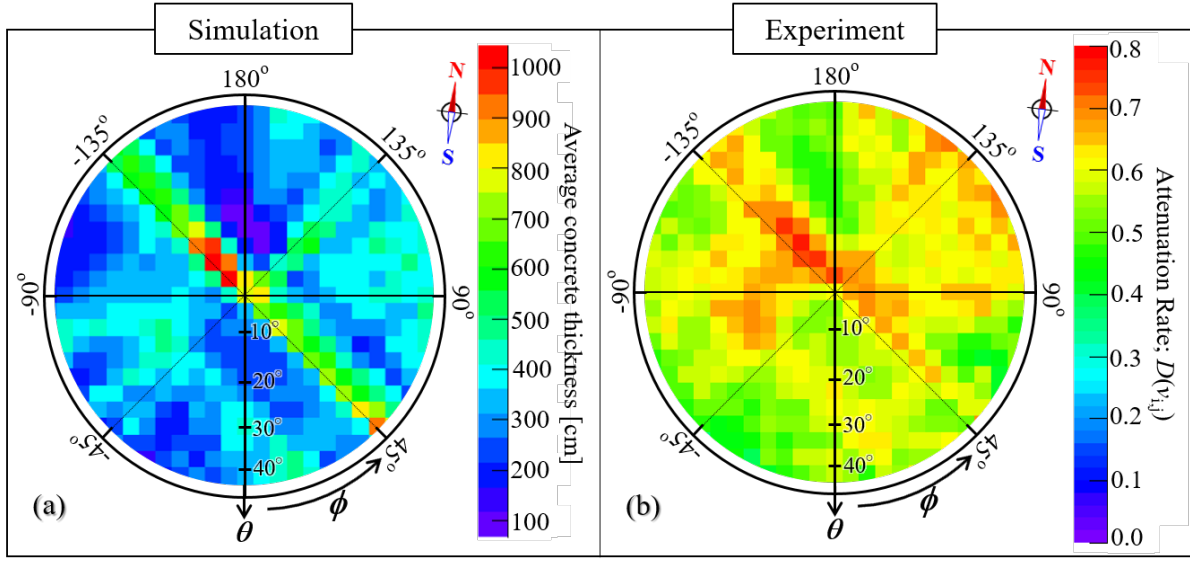


Figure 6.2: An example of the thickness simulation result. The muography of a seven-story building by (a) the thickness projection simulation and (b) the measurement result.

lower block was placed above the origin of the system coordinate. This center is defined to locate at the center of the mu-PSD2. The configuration in Figs.6.3(a) and 6.3(b) are labeled by the position “3” of the detector position.

The thickness projection simulation was performed for 11 positions of the detector as indicated in Table 6.1. Figure 6.3(c) also shows the detector positions which were located along the x -axis for 7 different positions and the others were varied along the y -axis. The coordinate (x [cm], y [cm], z [cm]) represents the position of the center of the mu-PSD2 in each simulation. The optimized number of detection positions for the practical measurement was designed from the quality of the reconstructed 3D image from these simulation result.

Table 6.1: The position of the detector for each simulation.

Position No.	(x [cm], y [cm], z [cm])	Position No.	(x [cm], y [cm], z [cm])
0	(-50, 0, 0)	6	(50, 0, 0)
1	(-34, 0, 0)	7	(0, -50, 0)
2	(-18, 0, 0)	8	(0, -25, 0)
3	(0, 0, 0)	9	(0, 25, 0)
4	(18, 0, 0)	10	(0, 50, 0)
5	(34, 0, 0)		

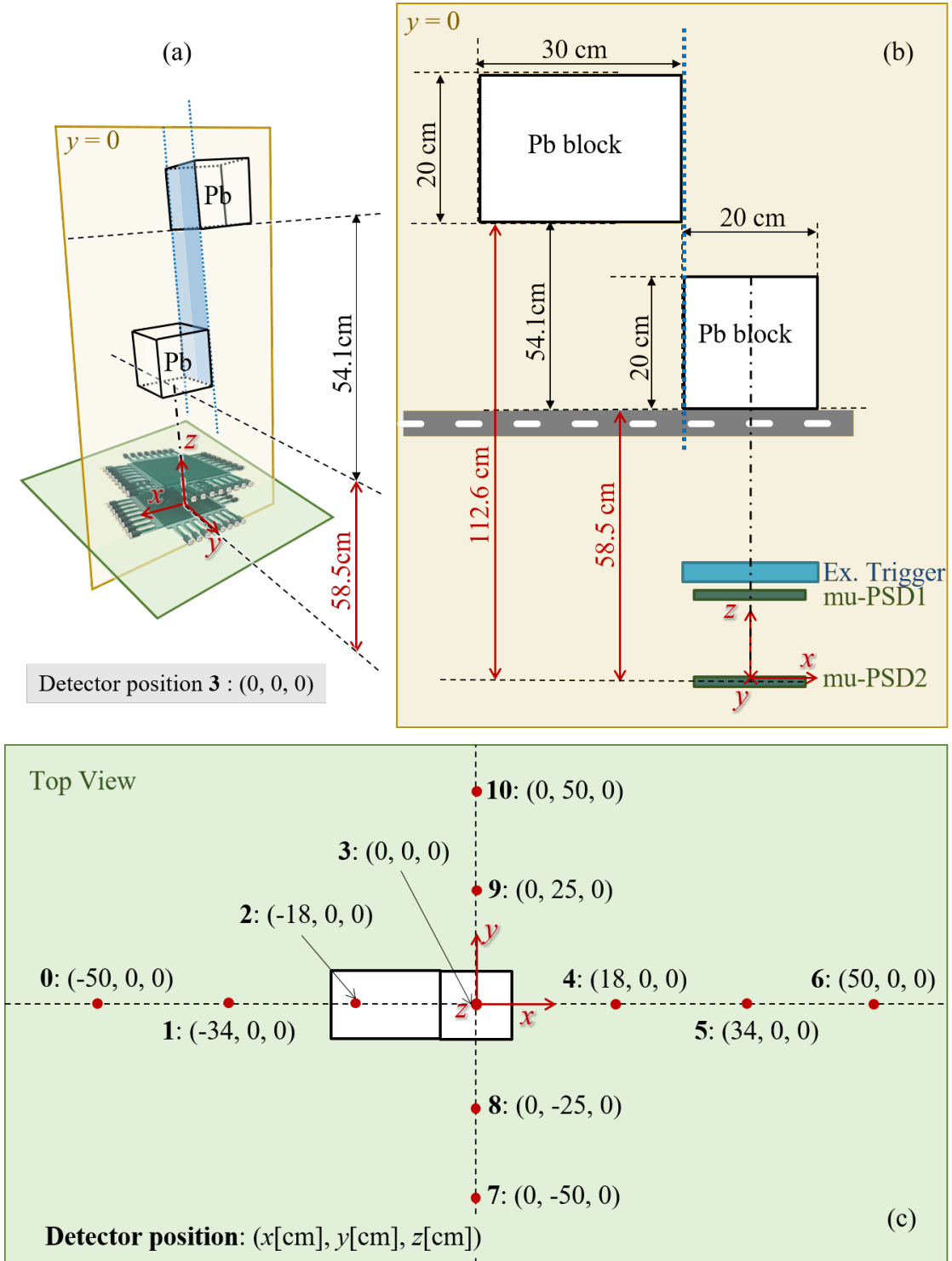


Figure 6.3: Sketch of the set of the lead blocks configuration with the detection positions: (a) 3D drawing, (b) cross-section at $y = 0$, and (c) top view.

6.4 3D Image Reconstruction of Simulated Data

Before demonstration of the 3D muography reconstruction, the calculation of system parameter is essential. To minimize the measurement time, the thickness projection was simulated for all of these 11 detection positions. Then, the optimized number of detection position for the practical measurement was designed from the quality of the reconstructed 3D image.

6.4.1 Calculation of System Parameter

First of all, to conserve the computational resources, the 3D bounded region for the image reconstruction was designed. The region of interest was defined as

$$x[\text{cm}] \in [-49, 21], \quad y[\text{cm}] \in [-17, 17], \quad z[\text{cm}] \in [34, 182]. \quad (6.5)$$

The boundary was chosen based on the experimental setup explained in Section 6.3.

As aforementioned in Section 6.1, the system parameter $p(b, d)$ is the probability of detecting a muon event from the voxel b to be detected by a pair of pixels d . Thus, the $p(b, d)$ depends on the geometrical acceptance of the muography detector and the target object configuration. The identity of each experimental configuration forced us to calculate the system parameter for each particular experiment.

For the beginning step, I have made a simulation to predict the $p(b, d)$ based on the experimental setup plan in Fig. 6.3. The simulated events were supposed to have a uniform probability to penetrate everywhere over the whole region of interest. All generated events are also assumed to have no interaction inside the region of interest. Thus, every events path can exactly be fit with the linear function. The simulation generated the events in random position (x, y, z) in each voxel b inside the region of interest and isotropic direction (θ, ϕ) . The developed muography detector with precise geometry also input in the simulation. The simulated muon, which coincidentally passed through a pair d of pixels of the mu-PSDs, was recorded by the same analysis procedure described in Section 3.4. The system parameter element $p(b, d)$ is computed by the following expression;

$$p(b, d) = \frac{N(b, d)}{N_{tot}(b)}, \quad (6.6)$$

where $N(b, d)$ is the number of events generated from the voxel b and detected by a pair of pixels d , and $N(b)_{tot}$ is the total number of muons generated inside the voxel b . The $p(b, d)$ has been calculated for all possible positions of detection.

Figure 6.4 (left) is an example of the simulated system parameter. The figure shows the projection of the calculated system parameter on xz -plane. In this simulation, each voxel has a volume of $2 \times 2 \times 2$ [cm³]. The number of detection positions was set to be 7 along the x -axis, the position number **0** to **6** in Table 6.1. The simulation is generated the events until the number of coincident events $N(b, d)$ is equal to 10^6 events.

Ideally, the system parameter should be computed once and stored for any image reconstruction that with same detector configuration. However, large memories are required. For the total B voxels

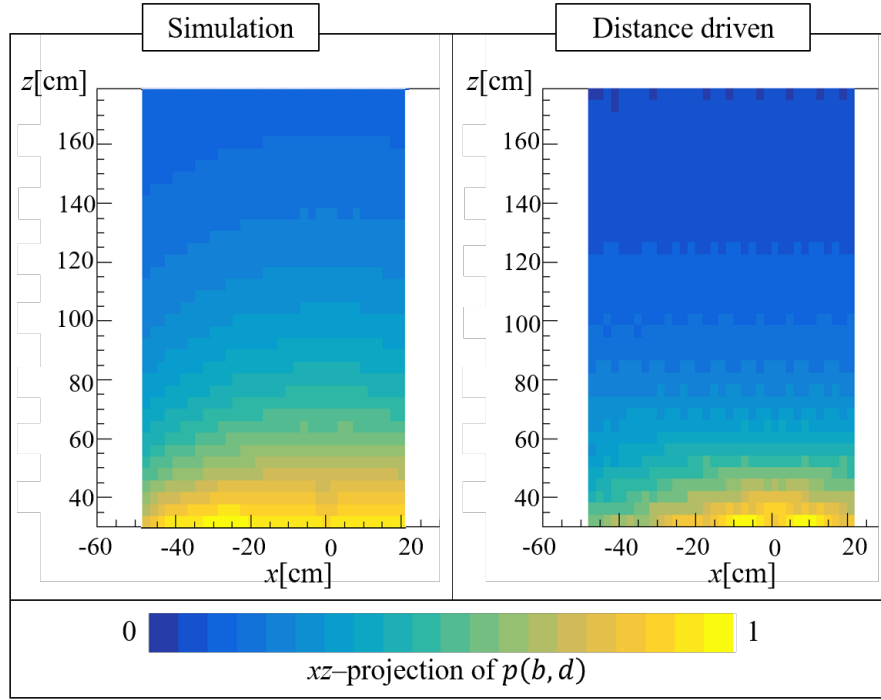


Figure 6.4: Projection of the system parameter $p(b, d)$ on xy -plane calculated from two approaches: (left) Monte-Carlo simulation and (right) distance-driven method.

of the region of interest for the reconstructed image and total D pair of pixels of the detector together with the total number of detection positions; N_{po} , the memory of $B \times D \times N_{po}$ value is needed. Each simulation takes a long time to obtain the precise result. This estimation method, although the method itself is not much complicated, practically difficult for the beginning step. Many trial and error process needed to be done to find the conditions of muography using the developed muography detector. Other estimation approaches which are faster and flexible in this developing step were considered.

Several approaches to estimate the system parameter exists. Many methods derived for the analysis projection and back-projection such as the pixel-driven approaches [42,44,45] and ray-driven approaches [42,46,47]. However, simple pixel-driven projection and ray-driven back-projection are rarely used due to its generating of high-frequency artifact [43]. The distance-driven approach was introduced by De Man and Basu in 2002 [43]. The approach has low complexity and can avoid the artifact characteristics of the pixel-driven projection and ray-driven back-projection method. Thus, the distance-driven method idea was adapted in this study.

The distance-driven method works by mapping the boundaries of the image voxel b and the detector pixel d onto a common plane [43]. The idea was adapted to estimate the system parameter as shown in Fig. 6.5. The position of a voxel b was defined by the center point $(x(b), y(b), z(b))$ of the cubic voxel, with respect to the origin $(0,0,0)$, in Fig. 6.3. The $z(b)$ plane was used as the common plane for the projection. If the projection of the geometrical acceptance of a given detector pair of pixels d on $z(b)$

plane is the light blue area in the figure, the system parameter $p(b, d)$ can be estimated by;

$$p(b, d) \approx \frac{A}{dx \times dy}, \quad (6.7)$$

where $dx \times dy$ is the area of the projection and A is the overlap area between the projection area of the detector pair of pixels d and the cross-section area of the voxel b at $z(b)$.

Note that, here, the prediction of the $p(b, d)$ by the distance-driven method was under the assumption of the uniform probability over the whole area of the projection of d at the same height $z(b)$. The acceptance distribution actually has a decreasing trend nearby the edge or corners of the square detection pixel. In Fig. 6.4(right), the approximately obtained $p(b, d)$ using distance-driven method was projected on xz -plane. The overall trend of both distributions is similar. More uniformity in height was shown in the approximation based on the distance-driven method. For more convenience, however, the use of the approximated $p(b, d)$ was sufficient to obtain the following desirable results.

6.4.2 Measurement Duration Estimation

The 3D image of the lead blocks was derived from thickness projection simulation in advance. In this study, 10^7 muon events were generated for each detection position. It resulted in the relative statistical error less than 1% of all detected pair-pixels d . Figure 6.6 is an example of the thickness projection result at the detection position “7”. The average thickness $\bar{L}(v_d)$ was used to be the vector $n(d)$ in Eq. 6.3. The simulation provided the lead blocks thickness projection without the artifact noise. The projection pixels which contain the blocks information can be recognized from the simulation. In contrast, the measured projection contained the noise pixels, especially in the large zenith angle pixels. The noise corresponds to the relative statistical error distribution because of the low muon intensity and small acceptance for large zenith angles. The experiment results are shown later, (see Section 6.5). The high level of the noise can be seen as expected. Thus, the simulated projec-

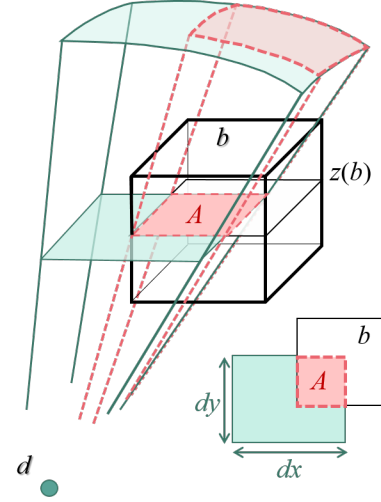


Figure 6.5: Diagram shows the idea of the distance-driven method to calculate $p(b, d)$.

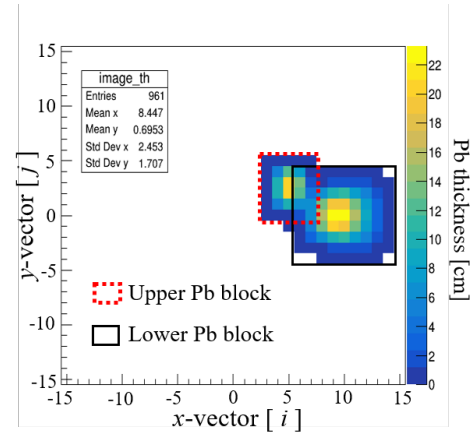


Figure 6.6: An example of the 2D projection at detection position “7” from the thickness projection simulation.

tion was used to distinguish the pixels which contained the measured data of the lead blocks from the pixels which contained the noises.

The duration measurement for each position was evaluated from the simulated projection and with the relative statistical error. The error estimated from the background measurement is shown in Fig. 5.4. Each position measurement was designed to stop after the whole blocks projection had less than 7% of relative statistical error.

6.4.3 3D Image from Simulated Thickness Projection

The ML-EM method was applied to the image reconstruction of the simulation data. Fig. 6.7(a) presents the reconstructed positions of the lead blocks in three dimensions. The projections on the xz and yz planes are also shown respectively. The image was calculated for 20 iterations. All data of simulated 11 positions of the detector was included in this calculation. One can see that the image reproduces reasonably well the position of the upper and lower lead blocks as shown in the red dash line and black solid line, respectively.

To optimize the experimental condition, various conditions of the number of the detection positions and the iteration “ k ” were investigated. Fig. 6.8 shows the images in different conditions. The number of position of 3, 5, 7 and 11 in the figure consists of the detection position **2-4**, **1-5**, **0-6** and **0-10**, respectively. The detection position number is shown by the bold number in Fig.6.3(c). The image of the two lead blocks becomes clear with an increase in the number of detection positions and iterations. Without the projection from the various detection positions along the y -axis, the position of the upper block is not clear. For the 7 detection positions, however, the result is reasonable for finding the center position of two lead blocks.

Fig. 6.9 show the χ^2 error between the measured projection and the reconstructed image projection as a function of the number of iterations. The differentiate of the error $\Delta\chi^2$ from time to time of iteration is smaller than 0.001 near the 20 times of iteration. The χ^2 error become a steady trend after the 20 iterations in Fig. 6.9. Thus, for this demonstration of the 3D muography, the 20 iterations was chosen to show the result. However, the χ^2 error seems independent of the number of the detection position as the same trends occur for the varying number of the position. Thus, the proper stopping criteria of the ML-EM iterative calculations will be required in the future work. Thus, the experiment was designed to measure the lead blocks for 7 positions, for this demonstration of 3D muography.

6.5 3D Muography Image Reconstruction

The experiment was setup in the top floor of a concrete building of Chikushi campus, Kyushu University. To calculate the muon attenuation rates $D(v_{i,j})$ by Eq. (3.5), the background muon rate $I_0(v_{i,j})$ have to be directly measured for every lead block detection positions. Thus, the set of lead blocks positions were moved with the relative positions same as simulation setup, respected to the detector, instead of the moving of the detector. Fig. 6.10 show a photograph of an experimental configuration.

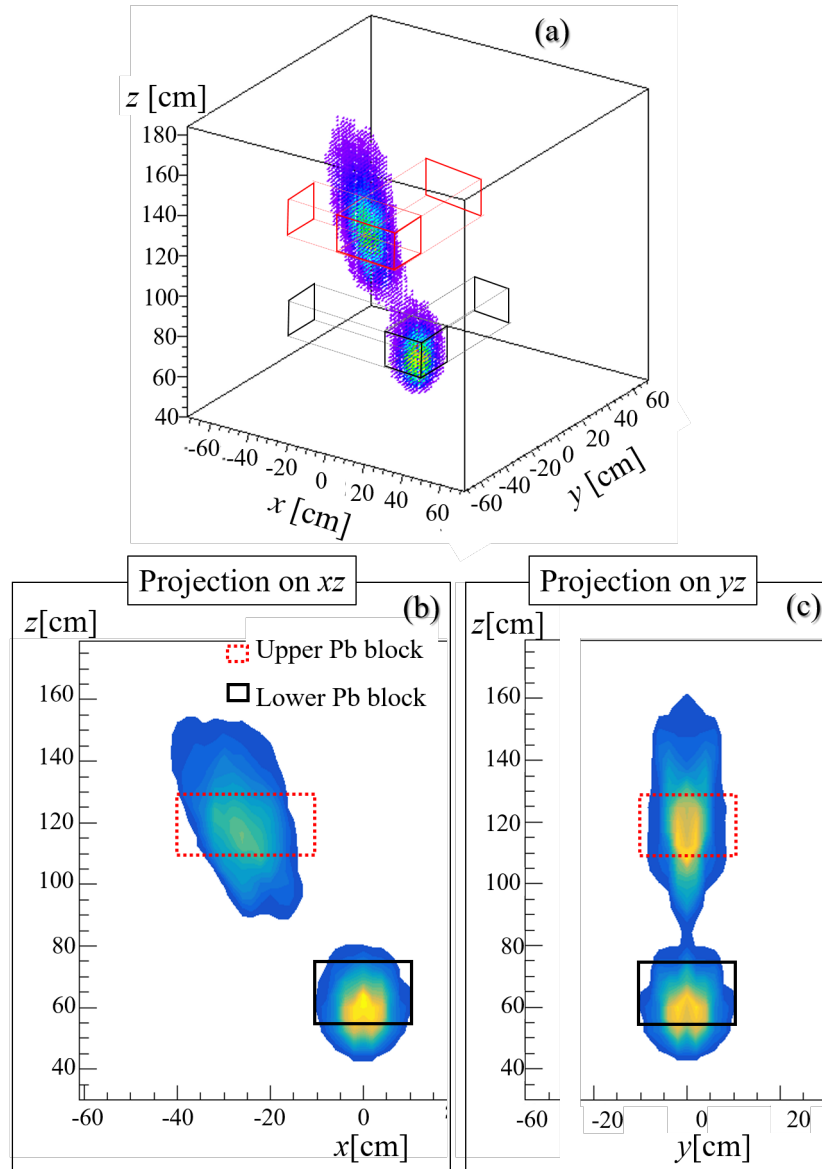


Figure 6.7: The 3D image (a) reconstructed after 20 iterations with the projection on (b) yz plane and (c) xz plane.

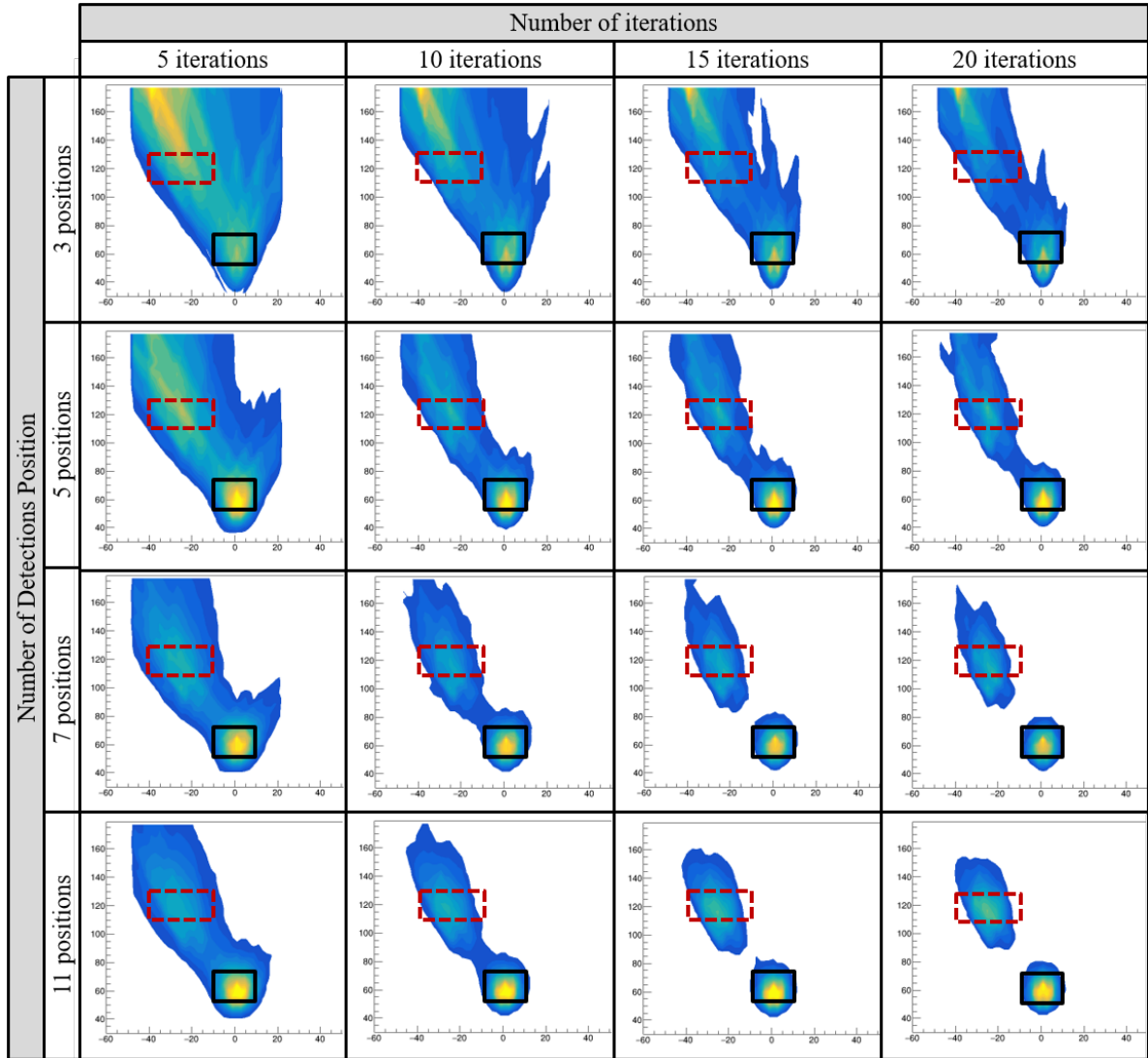


Figure 6.8: The 3D images reconstructed in different conditions of the iteration number and the number of detection positions.

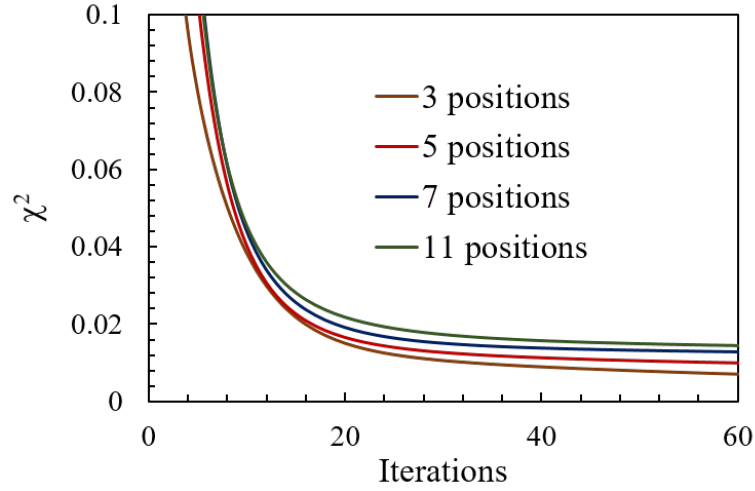


Figure 6.9: The χ^2 error between the measured projection and the reconstructed image projection as the function of the number of iterations.

Table 6.2 present the duration of measurement for each position. As shown in the table, only 7 detection positions were adapted. The determination of the number of practical detection position is described in the next section. Moreover, the cosmic-ray muon background measurement to evaluate $I_0(v_{i,j})$, without the lead blocks, was also made for 208 hours. The muon counts as a function of incoming muon direction $N_0(v_{i,j})$ is shown in Fig. 5.4.

Table 6.2: The measurement duration [hour] for each detection positions.

Position No.	(x[cm], y[cm], z[cm])	Duration [hour]
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)	-

Muography 2D projections at detection position from “0” (top) to “3” (below) and from “4” (top) to “6” (below) are shown in Fig. 6.11 and Fig. 6.12, respectively. The attenuation rate $D(v_{i,j})$ mapping from the measurement of the same setup is shown in the middle column of Fig. 6.11 and Fig. 6.12.

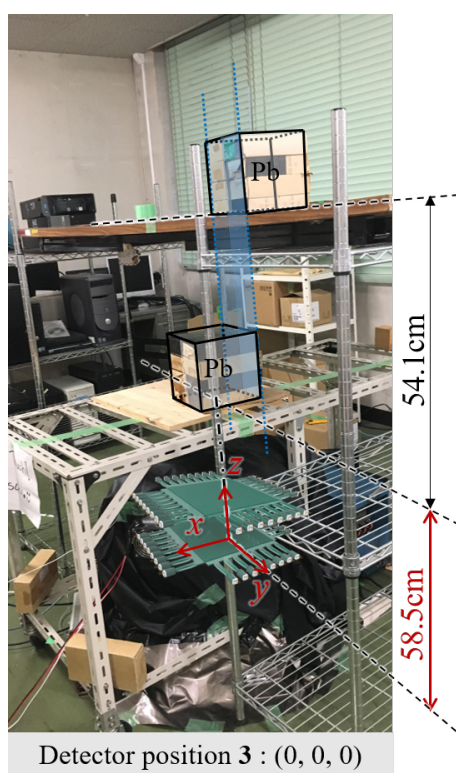


Figure 6.10: A photo of the experimental setup with 3D drawing.

The measured result contained the noise which corresponds to the relative statistical error distribution at large zenith angles as predicted. Each position measurement was designed to stop after most of the blocks projection had less than 7% of relative statistical error. From the arrangement defined in Fig.6.3, the lower block is closer to the detector than the upper block. Thus, the image of the lower block became sharper compared with the upper one corresponding to the number of the pair-pixels which can accept the blocks information.

Due to higher level noises from the experiment than the simulation, the ML-EM algorithm was adapted to 3D image reconstruction of the muography. The relative statistical error was applied, as a threshold, to filter out some pixels of 2D projection of muography. If the relative statistical error of the pixels is higher than 7%, the pixels were not taken into account in the imaging algorithm. The threshold level corresponds to the experimental condition of the measurement duration. In addition, the error was also applied to weight the system parameter; $p(b, d)$, for decrease the coefficient of the higher error pixel.

The reconstructed positions of the lead blocks in three dimensions from the simulation and experiment were presented in Fig. 6.13(a) and Fig. 6.13(b), respectively. The data of 7 detection positions were included in the 20 iterative calculations. The voxel sizes is $2 \text{ cm} \times 2 \text{ cm}$. The experimental 3D muography also indicated the visible noise around the blocks position. Figure 6.14 shows the projection of the 3D muography on xz -plane which calculated from the vector $n(d)$ from the simulation (Fig. 6.14(a)) and experiment (Fig. 6.14b).

One can see that, 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 3D image reconstructed from simulation certified the accuracy of developed ML-EM algorithm. The center of mass calculated from the image vector $\lambda^{(k)}(b)$ from the simulation is located at $(0, 0, 65)$ for the upper block and at $(-26, 0, 122)$ for the upper block. From experiment, the center of mass is located at $(2, 0, 68)$ for the upper block and at $(-22, 0, 122)$ for the upper block. The overestimated size of the upper blocks along the z -axis is reasonable for the detection positions where were located only on the xy plane. This expected to be one of the reasons why the center 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. It is remarkable that all of these reconstructed 3D images are calculated from the uniform initial estimation of the image vector $\lambda^{(0)}(b)$ value of 1 for every voxel.

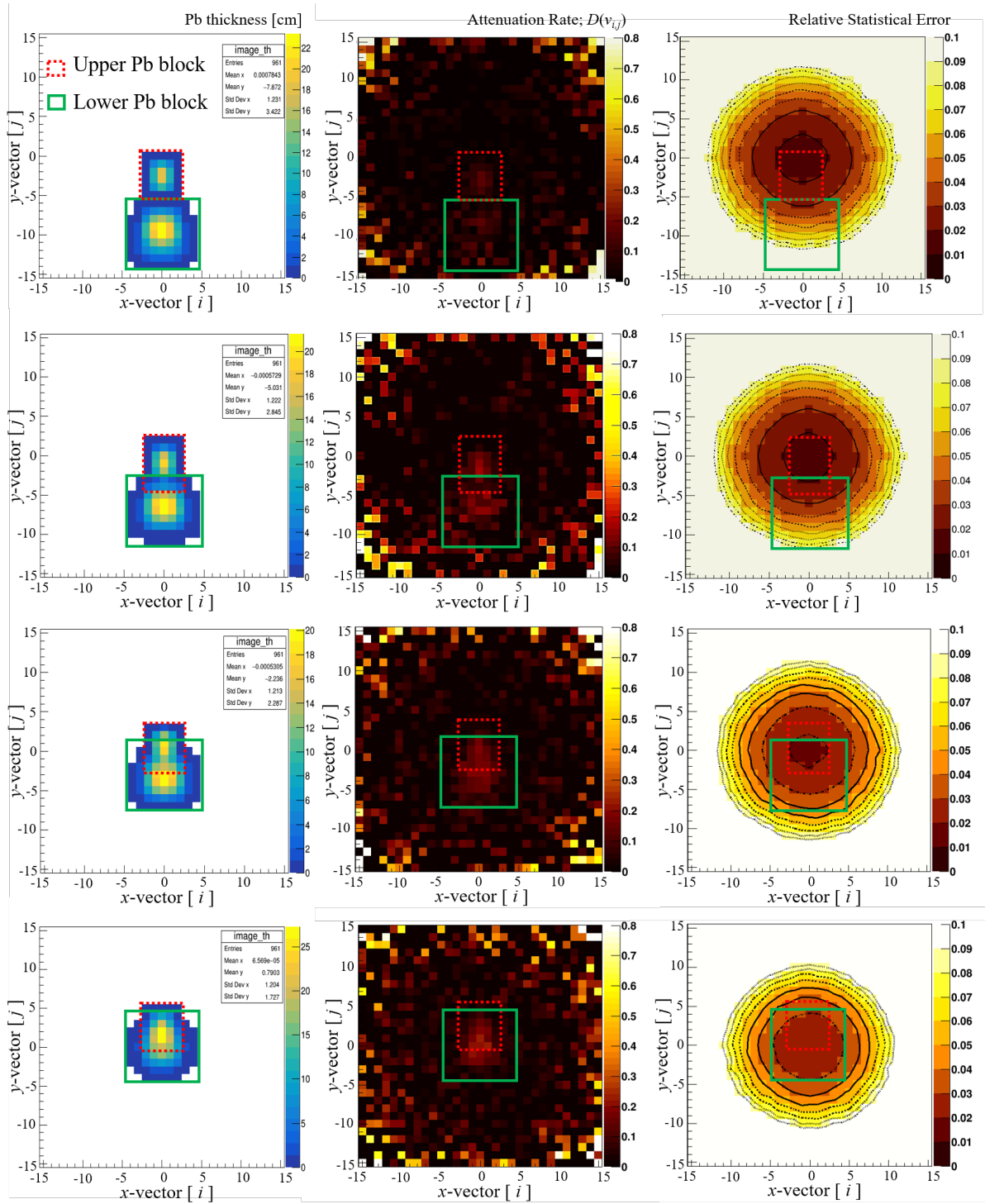


Figure 6.11: Muography 2D projection at detection position from “0” (top) to “3” (below), included the thickness projection simulation result (left column), the measurement result (middle column) and the relative statistical error from measurement (right column).

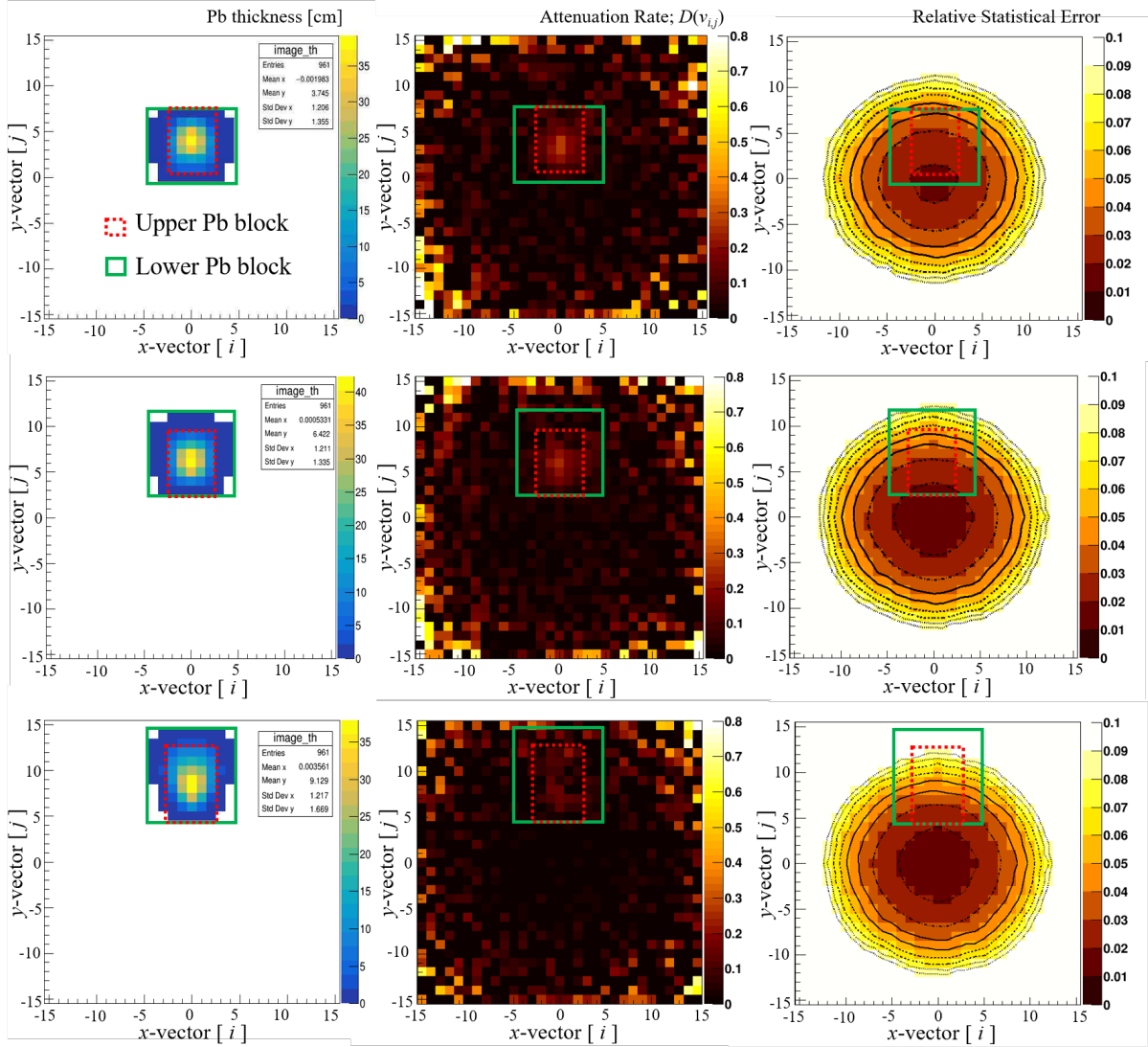


Figure 6.12: Muography 2D projection at detection position from “4” (top) to “6” (below), included the thickness projection simulation result (left column), the measurement result (middle column) and the relative statistical error from measurement (right column).

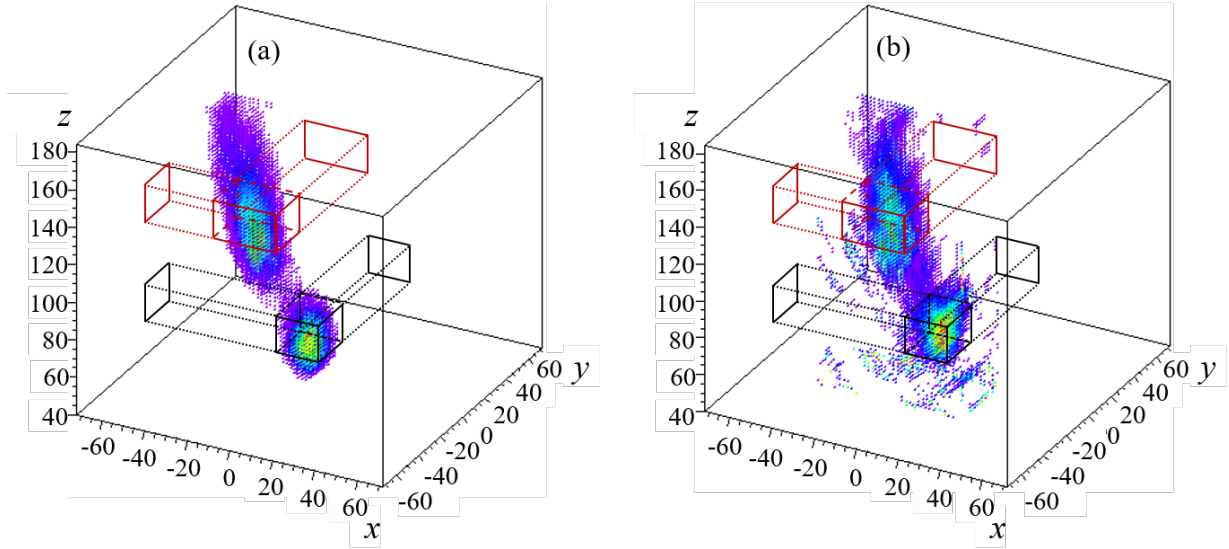


Figure 6.13: 3D muography; (a) from simulation and (b) from experiment

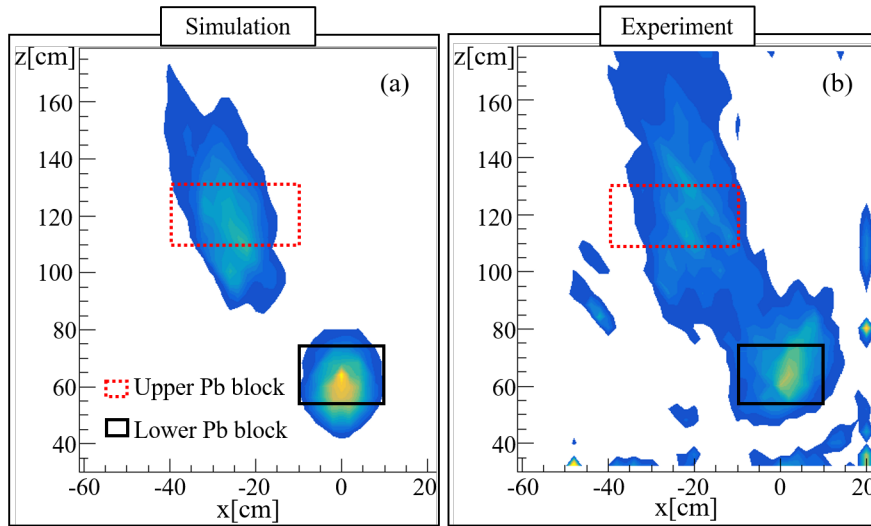


Figure 6.14: Projections of the 3D muography on xz -plane from; (a) simulation and (b) experiment

Chapter 7

Conclusion and Future Prospects

The cosmic-ray muon radiography or muography is one of the effective techniques for nondestructive radiography. The application to degradation survey of civic infrastructures has attracted the research motivation from the viewpoints of their operation and maintenance. The muography has the potential to estimate the density variance caused by the degradation inside of the object structure.

The overview of the cosmic-ray muons at ground level and the muography principle based on an attenuation technique is described. The requirements to construct a muography detector for investigation of infrastructures such as the several tens msr angular resolution, compactness, long-term stability, low electric power consumption and online monitoring system are summarized. The detector should have at least two muon position sensitive detectors to determine the track and flux of muons. Because the detector is dedicated to the infrastructure survey, cosmic-ray muons ranging from 50 MeV to 10 GeV should be measured at zenith angles from 0 to 50 degrees.

A portable muography detector was developed for measuring the degradation of concrete structures. The detector is composed of two position sensitive muon detectors (mu-PSDs), which were fabricated from PSFs and MPPCs. According to the aforementioned requirement of angular resolution, the distance between the two mu-PSDs was set to 10 cm. A solid angle resolution of 7 msr was achieved.

The angular resolution of the detector, the detection uniformity of each MPPCs, and the detection efficiency are discussed for evaluation of the detector performance. The detection efficiency was determined experimentally under the constraints of an external trigger detector. The detection uniformity was confirmed to have a deviation in muon rate detection less than 2×10^{-3} count per second. The detection efficiency of each mu-PSDs layer was also calculated. The efficiency is reasonable under the geometrical conditions of the detector. By direct detection of the cosmic-ray muons without any object, the geometrical conditions are eliminated.

The feasibility of the detector was evaluated with several tests. The detector system was stable over the long duration of an operation. A weak daily deviation of muon flux was observed in both the outdoor and indoor measurements. However, the effect was less than 1.7 % and was negligible for muography. The measurements without the obstruction were also used to derive the intensity distribution of cosmic-ray muons as a function of zenith angle. The resultant zenith-angular spectrum was slightly

different from well-known cosine square distribution but was consistent with the calculation result of the PARMA model which is based on the more precise empirical model.

A measurement of a lead block demonstrated the capability of detecting the target object with the infrastructure scale. The image of the lead blocks was clearly obtained at the expected position and the length of average muon trajectory in the lead block was nearly equal to the real length.

Finally, the detector was placed in the basement of a seven-story concrete building. The structural thickness profile was then obtained from the muon attenuation distribution. This profile was consistent with the structural drawings of the building. Conversion of the attenuation rate of cosmic-ray muons to the concrete thickness demonstrated the potential of this muography system to reconstruct the spatial profile of the concrete building.

This portable muography detector is the initial step of our milestone in the domain of an application of muography for the infrastructure degradation survey. From this achievement on the detection system, the development of the analysis process is required. Cosmic-ray electrons were found to be a major cause of the error. Therefore, the method of filtering out cosmic-ray electron events is being studied. The addition of physics model for precise spatial conversion and the adaption of cosmic-ray muon intensities and zenith angle dependence will improve the accuracy of this muography detector system. The survey for degradation of the core structure (e.g., a furnace in power plant and a bridge) will be done in near future. The new scintillator fiber based portable muography detector with the larger detection area for shorter detection duration is designed and will be constructed. The lower electric power consumption and higher signal to noise ratio are also expected.

For the 3D image reconstruction of cosmic-ray muon tomography based on the attenuation method, the Maximum Likelihood- Expectation Maximization (ML-EM) method was used. The feasibility study was performed under the conditions of limited detection angles and the acceptance of a portable muography detector. A Monte Carlo simulation was carried out for optimization of the measurement duration and confirmation of the accuracy of the ML-EM algorithm. The 3D muography image was reconstructed by applying the ML-EM method to the average thickness projection obtained by the simulation and the attenuation rate projection obtained by the peer setup measurement. By calculating of the center of mass of the reconstructed image, it was found that the image reproduces reasonably well the position of the two blocks. The experimental 3D image confirmed the feasibility of the 3D muography with the portable muography detector developed in the present work on the infrastructure scale target. The iteration stopping criteria of the image reconstruction will be determined in near future.

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