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

クラパ, チャイウォンコット

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氏　名：Kullapha Chaiwongkhot
Name

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論文内容の要旨

Thesis Summary

Muography is an effective technique for nondestructive radiography using cosmic-ray muons. The technique has been applied to large objects with the basic principle similar to conventional X-ray radiography imaging. The muography has so far been applied to various fields. Since the cosmic-ray muon has a wide energy distribution from MeV to PeV range, the absorption ratio depends on the density and thickness along the muon trajectory. Based on the principle, various experiments were conducted, such as search of hidden chambers in the Khufu's pyramid in Giza, prediction of volcano eruption and investigation of the volcano inner structure.

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 on the artificial structure were purposed. 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 the field-work of the muography detector. The stability of long-term operation is also required because of the low flux of cosmic-ray muons on the ground.

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 newly designed and fabricated to meet the aforementioned required resolution, and the feasibility of the infrastructure scale muography was demonstrated.

In order to enhance the potential of muography, 3D muography imaging is an innovative way to overcome limitations of the attenuation technique, 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 many limitations in the 3D muography measurement. If an object can be measured from all directions like medical X-ray CT, we can 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, it is strongly required to develop image reconstruction algorithms for the muography.

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.