COMPACT MUOGRAPHY INSTRUMENT FOR FUTURE MARS EXPLORATION: EXPERIMENTAL DEMONSTRATIONS. H. Kamiyoshihara[1], K. Shimazoe[1], T. Ninomiya[1], H. Tanaka[1], H. Takahashi[1], H. Miyamoto, [1]University of Tokyo (7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan; kamiyoshihara@seed.um.u-tokyo.ac.jp).

Introduction: Muography (muon radiography) is a technique that uses cosmic ray muons with high penetrating power and determines the density structure of kilometer-sized objects. Given the recent success of terrestrial applications of muography [e.g., 1, 2], several targets have already been proposed for muography observations, including the Martian surface [3], Phobos [4], and small bodies [5]. Although those studies suggest that the subsurface structures acquired by muography will provide crucial information about the origins and evolutional histories of the target bodies, muography instrument for planetary missions has not been developed.

In order to operate muography at extraterrestrial bodies, we need to understand the radiation environment of the target bodies to determine the decent size of the instrument. Previous studies have estimated these radiation environments mostly based on calculations using particle transport models, due to lack of detailed observations of radiation particles until recently. Therefore, the results of those estimations have not been validated. Moreover, conventional muography instruments are so large (about 1m^2 detection area) that they are not suitable to mount on a spacecraft. In this study, we discussed the radiation particle spectra on the Martian surface based on the studies related to the Radiation Assessment Detector on the Mars Science Laboratory (MSL-RAD) [6]. Then, we designed and developed a muography instrument prototype for Mars exploration, applying the knowledge of compact gamma-ray detectors for nuclear medicine imaging.

Radiation environment on the Martian surface: MSL-RAD is the first instrument to provide detailed information about radiation particle spectra on the Martian surface. The observed particle spectra were compared with the simulation results of several particle transport models (GEANT4, PHITS, HZETRN, and OLTARIS) [6]. Although good agreement was found in many cases, GEANT4 showed the best agreement in the four models. Thus, we discussed the radiation environment on the Martian surface based on the results of the GEANT4 simulation.

One of the calculated charged particle flux using GEANT4 simulation is shown in Table 1. The table suggests that muon flux on the Martian surface is almost the same as on the Earth's surface (~ 25.0 /m^2/s/sr). However, the flux of primary cosmic ray protons, which hardly exists on the Earth's surface, is much higher than the muon flux on Mars. One solution to remove these unwanted proton signals is utilizing Pulse Shape Discrimination (PSD). Although PSD is often used in the field of particle physics, this technique is not realistic for the muography instrument due to the size and complexity of the electric circuit. An alternative solution this study applies is removing vertical flux utilizing multiplicity analysis and shielding horizontal flux by the target structure itself [3].

Table 1 Particle flux on the Martian surface (calculated from [7]). The fluxes are integrated with energy and averaged with zenith angles.

Particle	Muon	Electron Positron	Pion	Proton
Flux (/m^2/s/sr)	33.0	17.0	4.2	908.3

Development of a compact instrument: The compact muography instrument consists of two 64-channel silicon photomultipliers (SiPM, Hamamatsu S13361-3050AE-08), plastic scintillators (EJ-200) with a size of 2 × 2 × 30 mm^3, dynamic Time-over-Threshold (dToT) boards [8], a temperature sensor, high-voltage power supply units, and data acquisition (DAQ) board. Incident muons react with the scintillator to emit weak light, and the light is amplified by SiPM and is converted into digital data with the dToT board. The DAQ board readout and store the data. The size of the active area of one layer is 26 × 26 × 30 mm^3. The SiPM performs with 57.0 V of supply voltage and 1 mA of current, and dToT performs with 3.3 V of supply voltage and 70 mA of current, resulting in power consumption of 0.3 W.

After the development, we observed the sensitivity and the temperature dependence of the detector using gamma-ray sources (^{241}Am, ^{22}Na, ^{137}Cs, ^{60}Co). Because the responses of the plastic scintillator to gamma-rays are almost free of any photopeak, we analyzed the energy of Compton edge using the differentiation method [9]. Low data acquired by DAQ board were calibrated using the results of this observation.

Data analysis method: Muons track were computed by identifying simultaneous (in 100 ns) and the same channel signals from two different detector layers. Assuming that we remove the signals of vertical protons

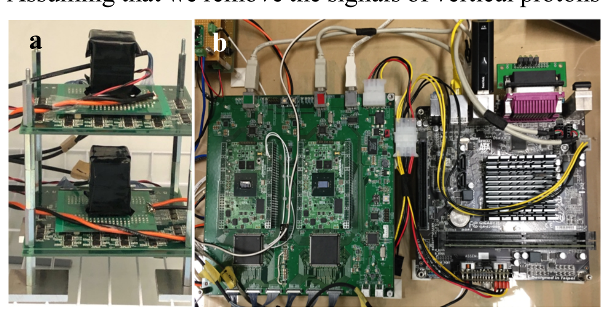

Fig. 1 (a) Photo of the compact scintillation detector attached to the dToT board (size: 10 × 10 × 15 cm^2). (b) Photo of the DAQ board (size: 20 × 40 × 5 cm^2).

on the Martian surface, we eliminated the events when more than one signal from the same layer coincides in a time gate of 100 ns (multiplicity cut [10]). As shown in Fig. 2, this detector observes muons flying from one direction with a very narrow viewing angle.

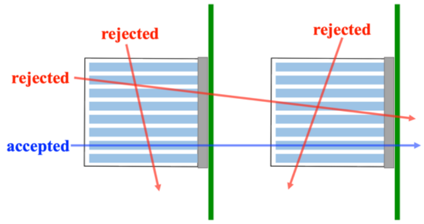

Fig. 2 Schematic diagram of the scintillation detector: scintillator **(**light blue), SiPM (gray), dToT board (green). Only muons flying in parallel with the scintillator are accepted.

Muon detection experiment: We conducted ground-based muon detection experiments to verify the ability of the developed detector. The detector was installed at Tokyo, Japan (35.7ºN, 139.8ºE; 20 m above sea level) and Ibaraki, Japan (36.2ºN, 140.2ºE; 30 m above sea level). Observed vertical fluxes were compared with the result of Geant4 [11] Monte Carlo simulation (Table 2). In all cases, good agreement was found. It was also correctly observed that viewing angle increases as the detector distance is narrowed, which causes the increase of the muon counts.

In addition, we observed the zenith angle dependence of the muon flux. It is experimentally known that the overall zenith angle distribution of muon flux is proportional to $\cos^{1.85}\theta$ at $\theta < 70°$ [12]. The result is plotted in Fig. 3. Note that this analysis was performed by regarding four scintillators as one in order to widen the viewing angle. As seen in the figure, good agreement was found between observed data and $\cos^{1.85}\theta$ fitting. Slight discrepancy may be caused by the modulation of muon flux itself.

Table 2 Comparison of observed vertical muon flux and results of Geant4 simulation.

	Detector distance	Integration time	Muons counts	Count/day
Tokyo	4.5 cm	12.02 days	29	2.4 ± 0.4
Simulation	4.5 cm	17.68 days	75	2.3 ± 0.3
Ibaraki	2.0 cm	7.94 days	66	8.3 ± 1.0
Tokyo	2.0 cm	16.88 days	134	7.9 ± 0.7
Simulation	2.0 cm	17.68 days	142	8.1 ± 0.7

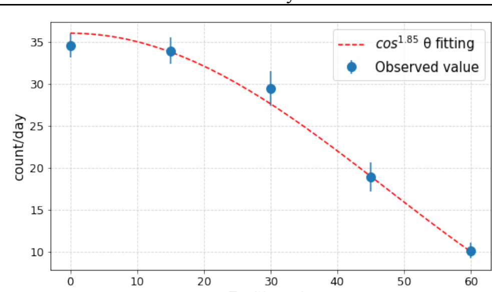

Fig. 3 Zenith angle dependence of the observed muons (blue dots). The dashed line indicates the result of $\cos^{1.85}\theta$ fitting.

Density detection experiment: We also installed the detector in a basement, and observed muons penetrated the soil or rock structure. The zenith angle was set to 60º, and the size of the target structure was 3 m. Table 3 shows the comparison of the muon rate before and after penetrating the structure. The penetrated muon rate decreases by 45 %, which is larger than the predicted decrease rate of 30 % in the standard rock (2.5 g/cm^2). Longer integration time will be needed to discuss the cause of this discrepancy.

Table 3 Comparison of the observed muon rate before and after penetrating the target structure.

	Integration time	Muon counts	Count/day
Before	19.0 days	111	10.2 ± 1.0
After	11.8 days	77	6.5 ± 0.7

Observation accuracy on the Martian surface: We performed a theoretical calculation in order to evaluate the density detection accuracy on the Martian surface. We assumed that our instrument observes the horizontal muons after penetrating 20 m and 50 m size rocks with a density of 2.5 g/cm^2 on Mars. We used the integrated muon flux in Table 1 and estimated the zenith angle dependence using muon flux in the upper Earth atmosphere (see [3]). The energy loss of muons through the rock was calculated based on [1]. Table 4 shows the estimated muon count by our detector and calculated density from the muon count. The error in the muon counts was calculated on the assumption that the muon number follows the Poisson distribution. The result suggests that our compact instrument could detect the density within an accuracy of 2.5 % for 20 ~ 60 days observations on the Martian surface.

Table 4 Estimations of the density detection accuracy.

Size of rock	Integration time	Estimated muon counts	Estimated density
20 m	10 days	37 ± 6	2.50 ± 0.11 g/cm^3
	20 days	74 ± 9	2.50 ± 0.06 g/cm^3
50 m	10 days	9 ± 3	2.50 ± 0.13 g/cm^3
	60 days	54 ± 7	2.50 ± 0.06 g/cm^3

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