Seismic Observation by the seismometer on board the penetrator for lunar exploration. Ryuhei Yamada[1,4], Isao Yamada[2], Hiroaki Shiraisi[1], Naoki Kobayashi[3], Nozomu Takeuchi[4], Hideki Murakami[5], Satoshi Tanaka[1], Akio Fujimura[1] [1] Institute of Space and Astronautical Science (ISAS/JAXA) (Sagamihara, 229-8510) (e-mail address: ryamada@planeta.sci.isas.jaxa.jp), [2] The University of Nagoya (Chikusa-ku, Nagoya, 464-8602) [3] Tokyo Institute of Technology (Ookayama, Meguro-ku, Tokyo, 152-8551) [4] The University of Tokyo (Hongo, Bunkyo-ku, Tokyo 113-0033) [5]Kochi University (Akebono-cho, Kochi, 780-8520)

1. Introduction

In the past, some attempts had been made to deploy the seismometers on the moon, example for Ranger, Surveyor and Apollo missions. Only through the series of Apollo missions, a seismic network had been constructed on the nearside of the moon. The seismometer system installed on each station consisted of three orthogonal long-period seismometers (LP) and one component short-period seismometer (SP). The seismic observation by Apollo seismometers had provided us highly useful data relevant to the seismic activity of several types of moonquakes and unique character of them as well as internal structure of the moon. However, the seismic velocity structure below the depths of source regions of deep moonquakes, which is the most abundant types of moonquakes that occur at depth of about 600~1400km from the lunar surface, is not well determined because few ray passes of seismic events travel deeper than the depths of their hypocenters[1].

To get more information on the deep interior of the moon, we need much more deep moonquakes data. The deep moonquakes have the predominant frequency of about 1Hz [2] and are very small in magnitude. This means that the seismometer should have higher sensitivity around 1Hz than that of the Apollo seismometers to detect the much more waveforms of deep moonquake with high quality.

On the other hand, to give a more definitive answer, all we need is a seismic station near the antipode of known deep moonquake hypocenters. In Japanese LUNAR-A Mission, a penetrator-based deployment of a seismic station is planned [3]. The hard landing probe 'penetrator' is more useful tool to deploy on the antipodes and/or multi-point stations and to constitute of a geophysical network than soft landing system.

Through a lots of tests and inspections, we developed the newly seismometer on board the penetrator, which had higher sensitivity than those of the Apollo seismometers at a frequency of around 1Hz for future lunar explorations. In this study, the seismic observations by the seismometers on board the penetrator after the penetration into the simulant of lunar regolith were made. We will report about the results of these tests.

2. Description about the seismometer

Science instruments on board the penetrator must have impact durability to retain their characteristics after the penetration and they are required to be small in size, light in weight and low in electrical power because of the limitation of the battery and the total mass budget of the penetrator. The newly developed seismometer is a short-period electromagnetic sensor with velocity transducers. It doesn't require additional electrical power. Table.1 shows the size, the weight and the sensitivity of three short period seismometers for comparison. Our seismometer has much higher sensitivity and is smaller and lighter than other sensors, while they have all same resonant frequency of 1Hz.

	Penetrator	Ranger [4]	Surveyor [5]
natural frequency(Hz)	1.0-1.2	1.0	1.0
sensitivity (KV/m/sec)	1.050	0.340	0.200
Diameter(cm)× Height(cm)	5×5	11×15	10×11
Weight of Mass(Kg)	0.046	1.45	1.65

Table.1 Specification of three short-period seismometers for moonquake explorations

Inside of the penetrator, two components seismometers, the vertical and the horizontal, are suspended by the gimbals mechanism to reorient them to the desired direction by two-axes motors. The seismometers are sustained by friction wheels of the rotation mechanism and two opposing bearings of the gimbals mechanism. The seismometers may be affected by the properties of the gimbals, especially of the friction wheels and of the bearings, other than the ground motion. The seismic data through the seismometer system (or sensor, gimbals and electronics) of the penetrator will include the effects of gimbals mechanism and system electronics.

3. Seismic observation after the penetration shock

The seismometers on board the penetrator must have impact durability and work well after the penetration shock. To verify the impact durability, the impact test on a qualification level of penetrator including the seismometer system was conducted at Sandia National Laboratory. The penetrator was projected to the simulant of lunar regolith at the velocity of about 330 m/sec with an attack angle of 8.6deg, which are much severer than those of the impact condition of the LUNAR-A penetrator on the lunar surface.

After the impact test, we confirmed the characteristics (resonant frequency and damping constant) and the dynamic response for natural ground motion of the shock-induced seismometers from a series of fields' tests. The seismometer system of the penetrator uses very high gain amplifiers, because very quiet environment has been realized on the moon due to absence of the origin of seismic noise; on the contrary, the winds of atmosphere and ocean waves cause the significant seismic noise on the earth. So, it is very difficult to recognize the seismic signals measured by the seismometer system of the penetrator in the usual laboratory because of their low signal to noise ratios (S/N). In order to avoid this poor S/N, the series of field's test was made at Inuyama Seismic Observatory of Nagoya University. In this site, the amplitude level of micro tremor is as low as that of some large deep moonquakes (1E-8~1E-9 m/sec with velocity of ground movement) at a frequency of around 1Hz.

In Inuyama Seismic Observatory, the calibration waveforms and the micro tremor were measured by the two components shock-induced seismometers on board the penetrator. Using the ground support equipments possessing the similar tele-communication and data handling system as the LUNAR-A spacecraft, we simulated the operation of seismic observations on the moon. The observations of the micro tremor with co-located reference seismometers have been also achieved at the same time for comparison. As the reference, we used two types of seismometers; one is the same type of the seismometer, but it is not loaded into the penetrator, and the other is L-4 sensor (Mark Products Inc.), which is a typical geophone for seismic exploration on the earth. We had confirmed that the dynamic responses of these references are almost consistent with that of STS-2 broadband seismometer for the micro ground motion around 1Hz previously [6].

4. Results

We, first, confirmed the characteristics of the shock-induced seismometers which are set in the gimbals of the penetrator by using calibration waveforms of the vertical and the horizontal seismometers, which were obtained from moving of pendulum by applying the constant electric current to the calibration coil.

Next, we measured the natural ground motions at Inuyama Seismic Observatory. An appropriate correction has been made to the observed data for comparison. Examples of the obtained seismograms for horizontal seismometers during 50 seconds are shown in Figure1. Each waveform is filtered around 1Hz. The correlation coefficients derived from these waveforms are above 0.99 with each other, and they indicate a good correlation among their seismic signals. The observed waveforms by the vertical sensors also show the similar good correlation.

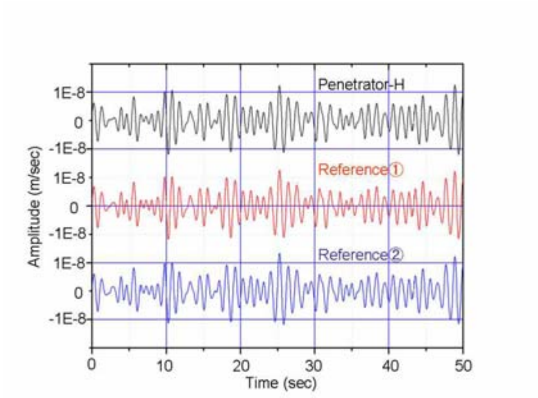

Figure.1 Comparison of waveforms observed by the horizontal seismometers. (Upper line) A waveform by the seismometer on-board the penetrator (Middle line) A waveform by the same type of seismometer without penetrator (Lower line) A waveform by L-4 geophone

Moreover, we have compared the power spectrum and the phase of the observed waveforms in frequency domain in the range from 0.5 to 6.0 Hz that is the designed frequency range for the lunar exploration by the penetrator. From analyses of all data, it is shown that the dynamic responses to the micro ground motion of both the vertical and the horizontal seismometers in the gimbals mechanism and penetrator system are corresponding to those of reference seismometers.

The seismometer system of the penetrator will function well after the penetration and detect more deep moonquakes than Apollo seismometers on the moon.

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