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Capability of the penetrator seismometer system for lunar seismic event observation

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ABSTRACT

We developed a seismometer system for a hard landing "penetrator" probe in the course of the former Japanese LUNAR-A project to deploy new seismic stations on the Moon. The penetrator seismometer system (PSS) consists of two short-period sensor components, a two-axis gimbal mechanism for orientation, and measurement electronics. To carry out seismic observations on the Moon using the penetrator, the seismometer system has to function properly in a lunar environment after a hard landing (impact acceleration of about 8000 G), and requires a signal-to-noise ratio to detect lunar seismic events. We evaluated whether the PSS could satisfactorily observe seismic events on the Moon by investigating the frequency response, noise level, and response to ground motion of our instrument in a simulated lunar environment after a simulated impact test. Our results indicate that the newly developed seismometer system can function properly after impact and is sensitive enough to detect seismic events on the Moon. Using this PSS, new seismic data from the Moon can be obtained during future lunar missions.

1. Introduction

During the Apollo lunar landing missions (1969–1972), a passive seismic network consisting of four stations (Apollo 12, 14, 15, and 16) was constructed on the nearside of the Moon to investigate lunar seismicity. The network observation continued until 1977, and provided us with information about several types of seismic events (deep moonquakes, shallow moonquakes, thermal moonquakes, and meteoroid impacts) and their unique characteristics, as well as the internal structure of the Moon (Latham et al., 1973; Toksöz et al., 1974; Lammlein, 1977; Goins et al., 1979; Nakamura et al., 1982; Khan and Mosegaard, 2002; Lognonné et al., 2003; Gagnepain-Beyneix et al., 2006). However, we still need a better understanding of the physical mechanisms of moonquakes and the structure and composition of the deep interior of the Moon, since the Apollo data were limited by the small number of stations and their regional locations on the nearside. We require more lunar seismic data from a global seismic network to obtain further information about the whole interior of the Moon, especially the core.

We developed a hard landing "penetrator" probe in the course of the former Japanese LUNAR-A project (Mizutani et al., 2000, 2003) to deploy new seismic stations on the Moon. The cross-sectional diagram of the LUNAR-A penetrator is shown in Fig. 1. The penetrator was designed to be deployed into the lunar regolith at a depth of 1–3 m by free fall from a spacecraft orbiting around the Moon. Hence instruments in the penetrator need to be able to survive the high-speed impact (impact acceleration of about 8000 G) (Mizutani et al., 1999). The penetrator has notable advantages over other types of probes (installed by a soft-lander or by astronauts) in constructing a global geophysical network on the Moon. The principal advantage of the penetrator is that

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multiple stations can be deployed in one flight because the penetrator is smaller and lighter than conventional soft-landers, so a spacecraft can potentially carry a multiple number of probes in a limited weight budget. It is also of lower cost than a human deployment. In addition, the penetrator is placed in a more stable temperature environment compared with deployment on the lunar surface, due to the thermal insulation of the lunar regolith. Lastly, the penetrator's good contact with the regolith provides an ideal environment for seismic observations.

To take advantage of these attributes, we developed a compact seismic sensor for the penetrator. The sensor is combined with the gimbal mechanism for attitude control after penetration, and measurement electronics for recording seismic data in the penetrator. We have already confirmed that the sensor itself has shock durability and works as designed even after an impact penetration (Yamada et al., 2005; Shiraishi et al., 2008). However, we must confirm that the entire penetrator seismometer system (PSS) consisting of the sensors, the gimbal mechanism, and the electronics assembled into the penetrator functions properly and has the signal-to-noise ratio required to detect seismic events in a lunar environment after a hard landing with an impact acceleration of about 8000 G.

In this paper, we describe the current specifications of the PSS—the frequency response, response to ground motion, and noise level—before penetrating into the lunar surface (Section 2). Then, we describe the effects of the lunar temperature and gravity environment (Section 3), and those of the penetrating impact (Section 4) on these specifications. Finally, we discuss whether the PSS developed by our team can satisfactorily detect seismic events on the Moon against the combined effects of the impact and the lunar environment (Section 5).

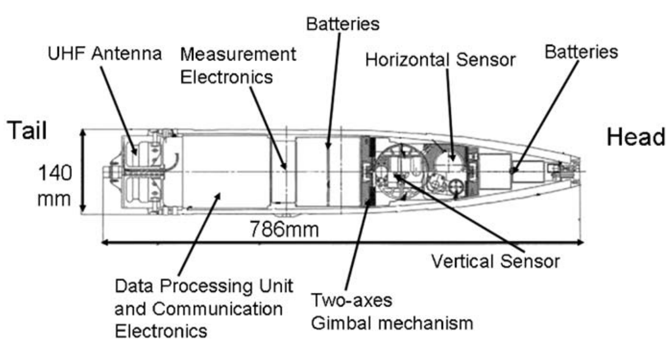

Fig. 1. The cross-sectional diagram of the penetrator. The view is from the lateral.

2. Performance of the PSS before impact

The PSS consists of two sensor components: one horizontal and one vertical, along with a two-axis gimbal mechanism (for orientation) and measurement electronics (amplifiers, filters, A/D converter, and memory). In this section, we describe the current instrument specifications: the frequency response, response to ground motion, and noise level of PSS before penetrating into the lunar surface.

2.1. Frequency response

From previous analysis of three types of lunar seismic events (deep moonquakes, shallow moonquakes, and meteoroid impacts) detected by the Apollo seismometers, it is known that shallow moonquakes and meteoroid impacts typically have higher frequency content and larger amplitudes than deep moonquakes. Many deep moonquakes were detected by the Apollo long-period (LP) seismometer in peaked response mode (Latham et al., 1973), with little energy in the short-period component (Dainty et al., 1975). Some researchers estimated that the dominant frequency of deep moonquakes was about 1 Hz (Lammlein et al., 1974; Goins et al., 1981; Araki, 1994). If the PSS has a better frequency response than those of the Apollo seismometers at 1 Hz and higher, it should be able to detect both deep moonquakes and other higher frequency content seismic events.

The frequency response of the PSS is represented by those of both the sensor and the measurement electronics. The frequency response $T(\omega)$ of the sensor is represented by

$$T(\omega) = G_C\omega^2/(\omega_0^2 - \omega^2 - i2\omega\omega_0 h),\quad \omega_0 = 2\pi f_0, \tag{1}$$

where ω is angular frequency in radian, ω_0 is resonant angular frequency in radian, f_0 is resonant frequency in Hz, h is damping constant and G_C is generator constant in V/m/s (Havskov and Alguacil, 2004). The sensor for the penetrator is a short-period electromagnetic seismic sensor with velocity output, consisting of signal coils as a pendulum suspended by a pair of diaphragm springs, and magnetic circuits fixed to the reference frame (Fig. 2).

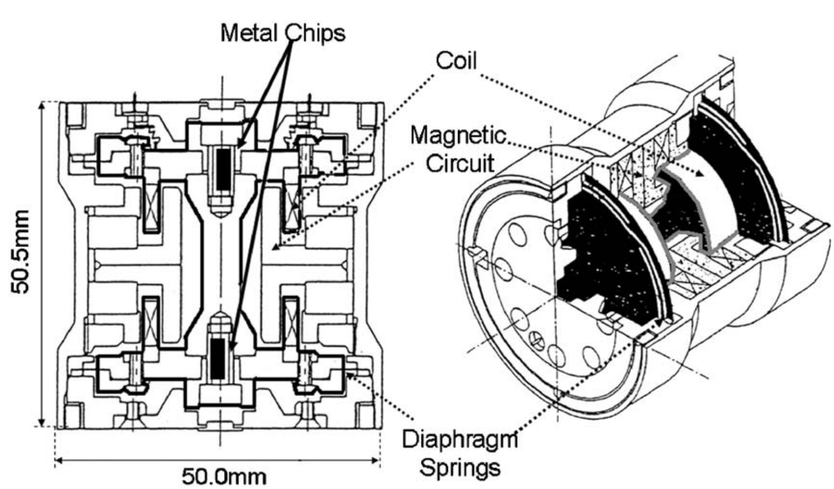

Fig. 2. The cross-sectional diagram and bird-eye view of the sensor for the penetrator. The pendulum of the sensor is surrounded by the bold solid line in the cross-sectional diagram.