In Situ Measurements of Lunar Rotation for the Study of the Interior of the Moon

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Measurements of physical and free librations of lunar rotation are important because they provide information of the physical state of the lunar interior. For example, we can discuss if the lunar core is molten from the amplitudes of libration terms. Previously only passive LLR (Lunar Laser Ranging) using CCR (corner cube reflectors) has been applied for the detailed study of lunar librations. As for candidate instruments for SELENE-II (forthcoming lunar landing mission by JAXA), we propose detailed measurements of lunar rotation by ILOM (In-situ Lunar Orientation Measurement) and IVLBI (Inverse-VLBI) in addition to LLR.

Key Words: Libration, Lunar Rotation, Lunar Laser Ranging, VLBI, ILOM

1. Introduction

The precise measurement of the rotation of planets is one of techniques to obtain the information of the internal structure of planets. The Moon revolves around the Earth once in a month synchronously with a small eccentricity. The Moon is tidally deformed by the Earth and the deformation excites irregular motion of the lunar rotation with small amplitude, which is called forced librations. Moreover free libration would be excited by impacts, fluid core (if exist), and orbital resonance. Dissipation of the libration terms of lunar rotation may depend on the interior structure of the Moon, especially the state of the core and lower mantle1-3).

As for candidate instruments for SELENE-II (forthcoming lunar landing mission by JAXA), we propose detailed measurements of lunar rotation by ILOM (In-situ Lunar Orientation Measurement) 2,4), LLR (Lunar Laser Ranging) 1,3,5-7) and IVLBI (Inverse-VLBI) 8). Table 1 shows the comparison between those methods.

Conventionally LLR has been studied for evaluating lunar librations. Apollo and the Lunokhod settled 6 (5 being useful) retroreflectors on the surface of the Moon. Since then, more than 40 years, lunar rotation data have been accumulated. However, LLR data involve not only lunar rotation but also orbital motion. Moreover, in order to obtain sub-milliarcsecond accuracy for rotation measurement, some novel methods should be necessary. Here we are proposing ILOM and Inverse-VLBI in addition to LLR. Inverse-VLBI is useful also for precise gravity measurement.

2. ILOM (In-situ Lunar Orientation Measurement)

The ILOM (In-situ Lunar Orientation Measurement) is an experiment to measure the lunar physical librations in situ on the Moon with a small telescope 2,4). Since ILOM on the Moon does not use the distance between the Earth and the Moon, the effect of orbital motion is clearly separated from the observed data of lunar rotation. This is the advantage of ILOM over the Earth-based methods such as LLR and VLBI.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Sensitivity for Rotation</th>
<th>Sensitivity for Distance</th>
<th>Mission Constraints</th>
<th>Number of landers</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILOM</td>
<td>&lt;1 mas (milli-arcsec)</td>
<td>N/A</td>
<td>Overnight survival</td>
<td>1 (or more)</td>
</tr>
<tr>
<td>LLR</td>
<td>1 mas</td>
<td>A few mm</td>
<td>Attitude at deployment.</td>
<td>1 (or more)</td>
</tr>
<tr>
<td>IVLBI(S/X)</td>
<td>0.05-1 mas</td>
<td>0.1 mm</td>
<td>Overnight survival</td>
<td>2 (or more)</td>
</tr>
<tr>
<td>IVLBI(Ka)</td>
<td>0.01-1 mas</td>
<td>0.03 mm</td>
<td>Overnight survival</td>
<td>2 (or more)</td>
</tr>
</tbody>
</table>

*1 The value depends on the positions of landers.
*2 The latest observations attained 1-3 mm level.
*3 There are five useful reflectors on the lunar surface.

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The ILOM will observe the lunar physical and free librations from the lunar surface with an accuracy of 1 milli-arcsecond. If ILOM telescope is put on the lunar polar region, it can detect spiral trajectories of the stars. If a telescope is put on mid-to-low latitude on the Moon, it can still derive information of lunar rotation from the motion of the stars. Long-term (possibly longer than a half year) data will provide information on various components of the physical librations, and possibly that on the lunar free librations. The information is used to discuss the lunar mantle and the liquid core. A photographic zenith tube (PZT) telescope, which is similar to ones used for the international latitude observations of the Earth, is applied to ILOM. Although ILOM optical telescope is small in size (20 cm in diameter), it is positioned as a precursor for the future larger telescope on the Moon.

Noda et al. (2008) simulated the ILOM observation assuming that the telescope would observe stars in the vicinity of the lunar north pole (Fig. 2). Shown in the left figure, the spiral star trajectory is mainly due to the precession. Observation at the place of lower latitude (89 deg) shows more linear trajectory as shown in the right figure. In general, observed stellar trajectories are decomposed to librations, polar motion, and the precession, where the amplitude and phase of each component are estimated. The standard deviation of the parameter estimation becomes nearly 1 milli-arcsecond, which will be better than the Lunar Laser Ranging observation. More theoretical study in relation to the interior structure is being developed by Petrova et al.9).

We have been developing BBM model of ILOM at Iwate University (Fig. 1). This BBM was made for the tests of controllability and optical characteristics. Since the lunar surface is covered with regolith, the precise attitude control of ILOM PZT telescope is inevitable after its deployment on the lunar surface. Even in the case that ILOM would be installed inside the lander, the attitude control should be necessary.

The crucial issues that should be overcome are the survival of lunar night and thermal effect of solar illumination on the zenith tube. The optical pointing would be affected by the change of the solar illumination. If ILOM telescope is put on the lunar polar region and can use stable electric power, those issues can be overcome. If a telescope is put on mid-to-low latitude (as currently suggested by SELENE-II), the lander should have a battery to keep telescope electronics alive during the lunar night for the survival and stellar observation might be limited during daytime when enough electric power can be used.

3. LLR (Lunar Laser Ranging)

The Lunar Laser Ranging (LLR) is the method to measure the distance between the Earth and the Moon using laser beam. For more than 40 years since the Apollo and the Lunokhod mission placed retroreflectors on the Moon, LLR produced data on the lunar rotation as well as the lunar orbital evolution. A strong advantage of LLR over the other methods is the capability of long-term observation, since the retroreflectors need no electric power. On the basis of LLR data, the state of lunar interior is discussed. Williams et al.10 discussed the dissipation between the solid mantle and a fluid core from LLR data. LLR observation has also provided information of moment of inertia and tidal Love number of the Moon.

We are proposing a new LLR on board SELENE-II. Instead of conventional corner cube reflector (CCR) array, we are planning to use a larger single hollow-type reflector. This has an advantage over the conventional CCR array, because a single cube should have smaller distance variation within the reflector upon monthly libration of the lunar rotation.

We are proposing that a new reflector should be somewhere in the southern hemisphere on the nearside Moon (Fig. 3). Then in combination with a powerful A15 CCR, latitudinal component of lunar libration and its dissipation can be measured precisely.
4. Inverse VLBI

Very long baseline interferometry (VLBI) is conventionally used for precise positioning of radio source. Radio signal transmitted from radio source, such as a quasar, is received at two separate ground VLBI stations (Figure 4). These signals are cross-correlated and difference of arrival time of the signal, delay time, is measured. The VLBI technique is applied for navigation of spacecraft since 1960s. Delay time is sensitive to motion of spacecraft in a direction perpendicular to line of sight (LOS) in contrast to range and Doppler that are sensitive to LOS direction. By combing these three-dimensional measurements, precise orbit determination can be possible. In Japanese KAGUYA (SELENE) mission, multi-frequency VLBI observations (S/X bands) are used for the precise orbital determination of satellites in order to increase the accuracy of lunar gravity field.

In the case of inverse VLBI, an artificial radio source is loaded on lunar and planetary vehicle, such as orbiter and lander, and radio signals transmitted from vehicle are received at a ground VLBI station. These signals are cross-correlated and the difference of propagation times from vehicles to the ground station is measured. The desired accuracy of the measurement is predicted to several tens to several pico second.

Figure 5 is a configuration of inverse VLBI for the estimation of the planetary gravity field. The difference of the propagation times between orbiter to ground station and lander to ground station \( T_1 - T_3 \) is measured. Here, 2-way ranging is carried out to compensate for the propagation time between orbiter and lander \( T_2 \). The differential range \( (T_1 - T_3) \times c \) is used to estimated the gravity field of the planet through the precision orbit determination.

Figure 6 is a configuration of inverse VLBI for the estimation of the rotation of the planet. The difference of the propagation times between two landers to ground station \( T_2' - T_4' \) is measured. 2-way ranging is also carried out to compensate for \( T_1' \) and \( T_3' \). The differential range \( (T_2' - T_4') \times c \) changes with respect to time by the rotation of the planet. By monitoring the rotation change, especially libration terms of lunar rotation by inverse VLBI, physical property of the deep internal structure, for example liquid or solid of the core, can be estimated.

Currently SELENE-II will have only one lander equipped with a rover. If a radio source should be on board the rover
moving as far as 100 km, rotation change information could be obtained from the difference of the propagation time between the lander and the rover. A crucial issue for VLBI radio sources is the survival of lunar night. In SELENE-II mission, the lander radio source is installed within the survival unit of thermal blanket using stored heat in regolith. However, thermal control for overnight survival of electronics would be very difficult for the rover. Therefore, we should seek a possibility of simultaneous observation between SELENE-II lander and another lander in the framework of recently discussed ILN (International Lunar Network).

5. Conclusion

Precise measurements of lunar rotation are important for the study of lunar interior, especially the state of the core and lower mantle. To measure very small change of direction and/or distance, instruments on board lunar lander are desirable. As for candidate instruments for SELENE-II (forthcoming lunar landing mission by JAXA), we propose ILOM (In-situ Lunar Orientation Measurement), LLR (Lunar Laser Ranging) and IVLBI (Inverse-VLBI).

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