Lunar Gravity and Rotation Measurements by Japanese Lunar Landing Missions

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Measurements of lunar gravity and rotation are important because they provide information of the physical state of the lunar interior. Previously only passive LLR (Lunar Laser Ranging) using CCR (corner cube reflectors) has been applied for the detailed study of lunar librations, rotation variability. As for candidate instruments for SELENE-2 (forthcoming lunar landing mission by JAXA) and future lunar missions, we propose VLBI (inverse-VLBI and differential VLBI) for gravity measurement to constrain tidal Love number, LLR (Lunar Laser Ranging) and ILOM (In-situ Lunar Orientation Measurement) for libration measurements.

Key Words: Libration, Lunar rotation, Lunar laser ranging, VLBI, ILOM

1. Introduction

In addition to seismic methods, precise measurements of gravity and rotation of planets are important methods to obtain the information of the there internal structure. The Moon revolves around the Earth once in a month synchronously with its rotation 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 exists), 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). Effect of tidal deformation should also appear on gravity. Long-term (> a few months) gravity measurements can provide information of the lunar tidal deformation. One important scale of tidal deformation is degree 2 potential Love number \( k_2 \), which could constrain the state of the core (solid or liquid) and viscosity of the lower mantle of the Moon 4).

Figure 1 shows degree 2 potential Love number \( k_2 \) estimated from LLR and gravity measurements. Also shown are model values from numerical simulation under a priori lunar interior model. There are discrepancies of \( k_2 \) values between gravity and LLR measurements. The estimated value form LLR is low and solid core is more preferable, simply from \( k_2 \) data. On the other hand, estimated values from gravity measurements are higher and they prefer liquid core. But as seen in Fig. 1, \( k_2 \) depends on the core size. We need to determine the \( k_2 \) with errors less than a few per cent and compare it with core size value determined from seismic measurements.

SELENE-2 is planned as a follow-on mission of Kaguya (SELENE). The spacecraft is to be launched before the middle of 2010’s. SELENE-2 lands on the moon and investigates the surface, the rocks, and the interior of the moon. SELENE-2 also has an orbiter for data transmission. As for candidate instruments for SELENE-2 (forthcoming lunar landing mission by JAXA), we propose detailed measurements of lunar rotation by LLR (Lunar Laser Ranging)1,3,3-7) and gravity.
measurement by iVLBI (Inverse-VLBI) and dVLBI (differential VLBI). For a future lunar mission, especially for a lander on the polar region of the Moon, we propose ILOM (In-situ Lunar Orientation Measurement) 2).

2. Inverse and differential 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 2). 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 combining 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. Differential VLBI (dVLBI) data between subsatellites Rstar and Vstar, when both the radio sources were within the beamwidth of the ground antennas (so-called same-beam), were particularly important because they are highly accurate with atmospheric and ionospheric disturbances almost cancelled out by the simultaneous observation. Such tracking data, same-beam differential VLBI data, were used to develop an improved lunar gravity field model SGM100i.

In SELENE-2 missions, we will have VLBI radio (VRAD) sources both in the lander and the orbiter. Then, using VLBI, we will determine the orbit of the orbiter precisely to have very accurate low degree gravity coefficients. The same-beam VLBI observation is only possible when the separation angle between the two radio sources is smaller than the beamwidth of the ground antennas. The relatively large shape of Rstar’s orbit (100 km x 2400 km) did not allow the same-beam observation all the time. But the situation can be improved by adequately setting the orbit. For example, the Vstar-like orbit (100 km x 800 km) will almost always keep the separation angle smaller than the S-band beamwidth of domestic VERA stations since one of the radio sources is fixed on the near-side lunar surface.

In the case of inverse VLBI, radio sources are loaded on the orbiter and the lander. Radio signals transmitted are received at a ground VLBI station. These signals are cross-correlated and the difference of propagation times from the sources to the ground station is measured. The desired accuracy of the measurement is predicted to several tens to several pico second. Figure 3 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 T1-T3 is measured. Here, 2-way ranging is carried out to compensate for the propagation time between orbiter and lander T2. The differential range (T1-T3)*c is used to estimated the gravity field of the planet through the precision orbit determination. Combination between dVLBI and iVLBI should improve the orbital information greatly, which would precisely determine the change of low degree gravity coefficient and constrain potential tidal love number.

A crucial issue for VLBI radio sources is the survival of lunar night. In SELENE-2 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-2 lander and another lander in the framework of recently discussed ILN (International Lunar Network).
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 from the ground station. 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. discussed the dissipation between the solid mantle and a fluid core from LLR data. LLR observation has provided information of moment of inertia and tidal potential Love number of the Moon. Discussion on the potential Love number was already introduced in Section 1.

A new LLR should be on board SELENE-2. Instead of conventional corner cube reflector (CCR) array, we are planning to use a larger single 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.

The new reflector should be somewhere in the southern hemisphere on the nearside Moon. Then in combination with pre-existed reflectors, latitudinal component of lunar libration and its dissipation can be measured precisely.

Apollo and the Lunokhod settled 6 retroreflectors on the surface of the Moon. With newly found Lunokhod 1 reflector, 5 reflectors are useful. Since then, more than 40 years, lunar rotation data have been accumulated. After the start of Apache-point station in 2006, the precision of distance determination has improved to mm level. With a new reflector by SELENE-2 possibly on the southern hemisphere of the Moon, more decadal observations should increase the accuracy of parameters controlling lunar rotation variability.

4. **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, which tracks stars. 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 ground-based methods such as LLR and VLBI.

The ILOM will observe the lunar physical and free librations from the lunar surface with an accuracy of 1 millisecond of arc. 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 in order to investigate 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 can be stated as a precursor for the future larger telescope.

The observed stellar trajectories should be decomposed to librations, polar motion, and the precession, where the amplitude and phase of each component are estimated. Thermal and mechanical perturbations during observation should be suppressed. Simulated standard deviation of the parameter estimation becomes nearly 1 milli-arcsecond, which will be better than the Lunar Laser Ranging observation. The results would constrain the size, density, state of the core (and lower mantle) through the moment of inertia and tidal potential Love number. More theoretical study in relation to the interior structure is being developed by Petrova et al.

We have developed a BBM model of ILOM at Iwate University (Fig. 4). 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.

The crucial issue that should be overcome is the survival of lunar night and thermal effect of solar illumination on the zenith tube which should affect the optical pointing. If ILOM telescope is put on the lunar polar region and can use stable electric power, those 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.
5. Conclusion

Precise measurements of lunar gravity 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-2 (forthcoming lunar landing mission by JAXA) and future lunar missions, we propose VLBI (inverse-VLBI and differential VLBI), LLR (Lunar Laser Ranging) and ILOM (In-situ Lunar Orientation Measurement).

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