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In situ Lunar Orientation Measurement (ILOM): Simulation of observation

H. Noda [a,*], K. Heki [b], H. Hanada [a]

[a] National Astronomical Observatory of Japan, Hoshigaoka 2-1, Mizusawa, Oshu 019-0238, Japan
[b] Hokkaido University, Kita 10, Nishi 8, Kita-Ku, Sapporo 060-0810, Japan

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Abstract

The measurement of the rotation of the Moon is one of the key techniques to get the information of the internal structure. For this purpose, we proposed a small telescope experiment on the surface of the Moon in which motion of stars are utilized for the estimation of the rotation parameter. This paper describes results of simulation of observation, in which star trajectories observed are decomposed to librations, polar motion, and the precession and the amplitude and phase of each component are estimated. The standard deviation of the parameter estimation becomes nearly 1 ms of arc, which will be better than the Lunar Laser Ranging observation. From the viewpoints of accuracy of observation, thermal condition, and electric power generation, the instrument should be placed where the much sunshine is achieved on the lunar polar region.

Keywords: ILOM; Lunar observatory; Lunar librations

1. Introduction

One of the unsolved big questions about the Moon is how it was made and evolved to the present state. There are four major candidates for the origin of the Moon, and among them the giant impact hypothesis is regarded as the most promising scenario. Study of the internal structure provides us of key information of the evolution. The measurement of the rotation of planets is one of techniques to get the information of the internal structure of planets. The Lunar Laser Ranging (LLR) (Dickey et al., 1994) has 30 years history of observation since both the Apollo and the Lunokhod mission placed retrograde reflectors on the Moon in 1960'. The LLR has given unprecedented data on the lunar rotation, and gives some proposals of the state of the core. For example, Williams et al. (2001) discussed the dissipation between the solid-body and a fluid core by analyzing LLR data.

The Moon revolves around the Earth once in a month, while it rotates once in the same period. Therefore, one face of the Moon is always seen from the Earth, which is called near-side of the Moon. However, because the orbit of the Moon around the Earth is an ellipse and that the orbit plane has small inclination to the Earth equator, the face of the Moon changes in a small amount. This phenomenon is called the optical libration, because it is simply due to the geometric effect between the Earth and the Moon. Viewing the Earth from the near-side of the Moon, the Earth changes its position in the celestial sphere also in the small amount. This movement of the Earth to the Moon excites tidal forces to the Moon, causing deformation of the solid Moon. As a result, the deformation excites irregular motion of the Moon with small amplitude, which is called forced librations. Adding to them, free librations were found by analyzing a lunar ephemeris which contains lunar libration terms (Newhall and Williams, 1997). They might be excited by a fluid core (if any), passage through resonance, or impacts by a large body. More accurate observations of the librations will provide us of the internal

* Corresponding author.
E-mail address: noda@miz.nao.ac.jp (H. Noda).

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information of the Moon, especially the state of the core and interaction between the core and the mantle.

The In situ Lunar Orientation Measurement (ILOM) (Hanada et al., 2004) is an experiment to measure the lunar physical librations in situ on the Moon with a small telescope which tracks stars. While the LLR inevitably has the effect of the motion of the Earth (both orbital and rotational), in situ observation is free from them, and the understanding of the inner structure of the Moon will be improved.

In this paper, we show results of the simulation of observation by the ILOM. In chapter 2 the instrumentation is shortly mentioned, followed by the simulation results in chapter 3. Chapter 4 describes the ideal landing site for the ILOM. The effect of the tidal motion which is not included in the calculation will be addressed as concluding remarks.

2. Instrumentation

Assuming that the telescope will be put on the Moon without humans, the structure should be simple and no moving parts are preferable. As of 2006, we propose a kind of refractor with a mercury pool mirror shown in Fig. 1. The mercury pool is put at the half of the focal length so that the ray converges just under the objective lens. Star images are detected by a CCD array beneath the objective lens. This type of telescope is called the photographic zenith tube (PZT), which was once used for the latitude observation on the Earth for the study of the Earth rotations in 1980s. The tilt of the tube is nearly cancelled because the surface of the mercury pool becomes parallel to the geoid surface.

The diameter of the objective lens is 20 cm and its focal length is 200 cm, which gives the Airy disk of 10 μm. Assuming 4k × 4k CCD array with pixel size of 10 μm, one pixel becomes 1 s of arc, and the field of view becomes 1° According to the ray optics calculation, the position of stars on the CCD array changes less than 1 ms of arc due to tilt of the tube of 10 ms of arc.

To achieve accuracy of 1 ms of arc for position detection of the star position on the CCD array, the center of the star image should be determined with 1/1000 pixel size. Detection of the centroid of a star with 1/300 pixels has been achieved (Yano et al., 2004), and study for the improvement of accuracy is progressing.

3. Simulation of ideal observation on the North Pole

Fig. 2 shows the position of the lunar North Pole direction on the celestial sphere. Lunar orientation data (Euler angles of the North Pole) are taken from the DE405 ephemeris which contains lunar librations. The direction changes in 18.6 years because of the precession with amplitude of about 1.5°. Small rotations of the pole direction with a period of one month (27.6 earth days) are embedded to it. It is noted that the instantaneous North Pole direction changes within a month, which means that the lunar "polar star" changes in a short time. The amplitude of the small rotations changes in 6 years due to the resonance between two libration terms whose period are close to each other.

If the telescope is put on the pole, the star trajectory draws spiral (left in Fig. 3) mainly due to the precession. Observation at the place in lower latitude causes the trace more linear as shown in the right in Fig. 3 (latitude of 89°).

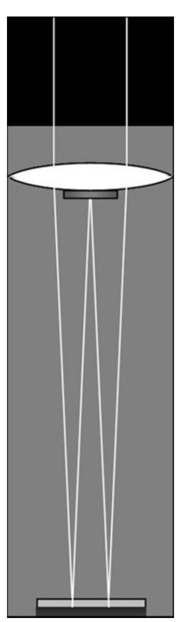

Fig. 1. PZT telescope. A mercury pool is put at the half of the focal length so that the focus comes near the objective lens.

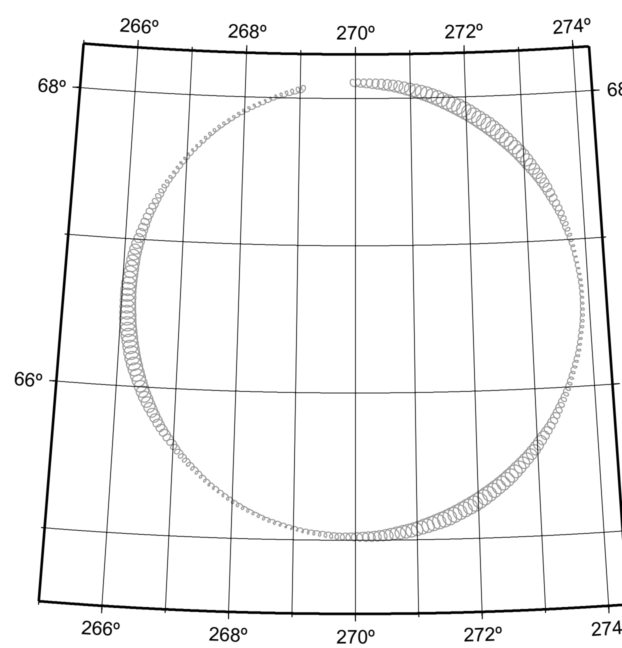

Fig. 2. The trajectory of the lunar North Pole direction in the celestial sphere. The unit of axes is degrees.

Fig. 4 shows an example of the decomposition of the star trajectory appeared in the left panel of Fig. 3. We took three largest terms of librations (the amplitude is more than 10 s of arc), polar motion, rotational phase, and precession, and fitted the star trajectory by a least-square method. Given periods for longitudinal libratoins are 27.555 days (anomalistic month), 27.212 days (draconic month), and 13.61 days (draconic half month). The parameters estimated and resulting standard deviations are listed in Table 1. Parameters are expressed as both retrograde and prograde trajectory because any ellipse can be expressed with them. It is noted that the standard deviations become comparable to or smaller than the aiming 1 ms of arc. The accuracy of the rotation phase is worse than others, because observation of the polar direction is less sensitive to the rotation motion. If we introduce half mirror above the objective lens so that it observes stars in the horizontal direction together, the estimation of the rotation phase will be much better. This will be left for the future work. Results for the case of right panel of Fig. 3 (latitude of 89°) becomes much worse than this case (not shown), especially rotation phase, because data in much of the rotation phase are absent.

Fig. 5 shows the dependence of the accuracy on the observation period (top) and number of stars (bottom) for a parameter for the case of observation at the pole. The accuracy improves as the number of stars or the observation period increases. The powers are −0.5 and −2.5, respectively. It means that the accuracy more strongly depends on the observation period than the number of the stars observed.

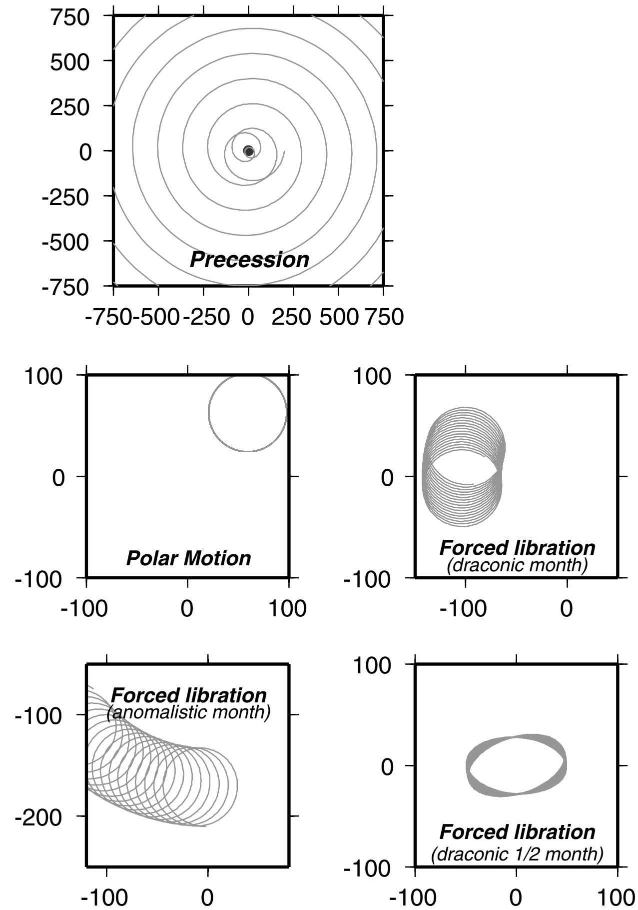

Fig. 4. Decomposition of the star trajectory appeared in the left panel of Fig. 3.

4. Landing site

To obtain well-estimated parameters of librations, observation should be done so that the trace covers all phases of the rotation. This is mainly because periods of both the rotation of the Moon and the drift of the pole direction due to the librations have nearly the same (one month). As the ILOM of PZT type points the zenith direction, it should be placed at the exact pole or places within 0.5° from the pole. In addition, longer sunlit period is needed to make the instrument work as well as to keep operational temperature. For example, rim areas of the Shackleton crater (89.9 S, 0.0 E, its diameter is19 km) in the south polar region, are favorable because the sunlit period becomes more than 70% of a year at certain places (Bussey et al., 1999, 2005).

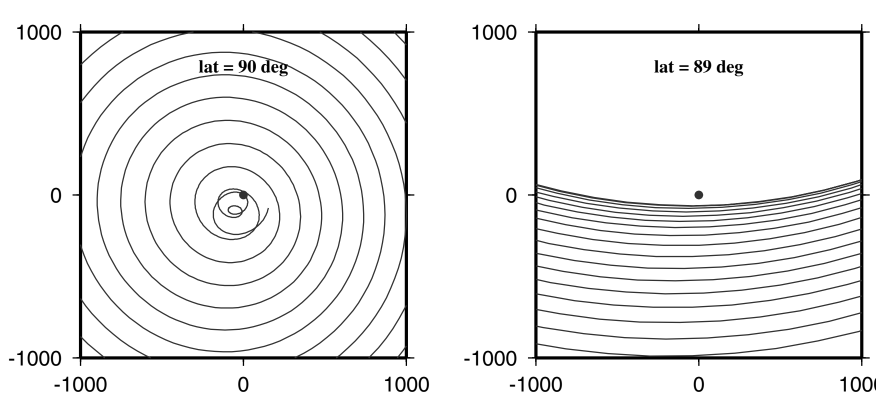

Fig. 3. A simulated trajectory of a star in one year. The telescope is place at the exact North Pole (left) and at latitude of 89° (right). The unit of axes is milliseconds of arc.

Table 1
Estimation of amplitude of libration parameters

#	Amplitude (arcsec)	Std. dev. (milli arcsec)	Terms	
1	−58.96 as	1.74 mas	Polar motion 1	
2	68.10 as	1.75 mas	Polar motoin 2	
3	−40312.88 as	7.23 mas	Rotation phase	
4	−47.52 as	1.26 mas	Draconic month prograde	Cos
5	90.68 as	1.26 mas		Sin
6	1.80 as	.07 mas	Draconic month retrograde	Cos
7	−2.18 as	.07 mas		Sin
8	172.08 as	.52 mas	Anomalistic month prograde	Cos
9	36.83 as	.52 mas		Sin
10	−3.00 as	.07 mas	Anomalistic month retrograde	Cos
11	1.39 as	.07 mas		Sin
12	−9.05 as	.02 mas	1/2 Draconic month prograde	Cos
13	−5.97 as	.02 mas		Sin
14	.06 as	.02 mas	1/2 Draconic month retrograde	Cos
15	−.16 as	.02 mas		Sin
16	5558.89 as	.04 mas	Precessioin retrograde	Cos
17	−80.08 as	.02 mas		Sin

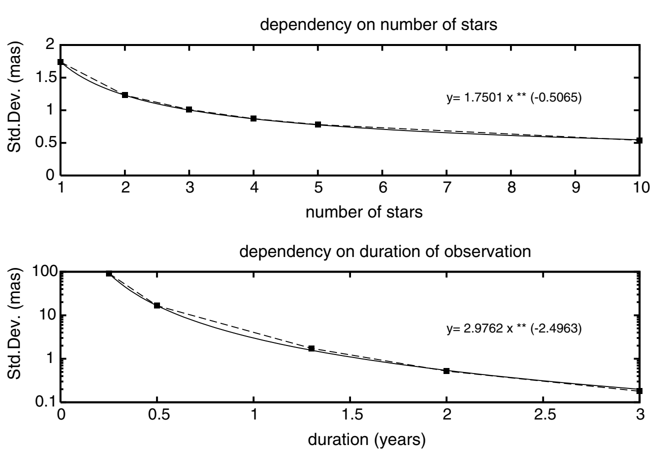

Fig. 5. Dependency on the number of stars observed (top) and period of observation (bottom).

Fig. 6 shows the sunlit condition at the South Pole during 2010–2014. The vertical axis gives the elevation angle of the Sun, and values more than zero mean sunlit periods. In reality, a simulation with local topography with a digital elevation model (DEM) should be done, but it is not taken into account in this paper. In the polar region, especially at the exact pole, the season changes in every half year, which means that the Sun always illuminate the instrument on the pole for at least half year so that the instrument could be kept moderate temperature and electric power could be generated by the solar array panels. As shown in the top panel of Fig. 5, observation period is more important factor than the aperture of the telescope, so the area near the pole is fundamentally necessary for the experiment with a PZT.

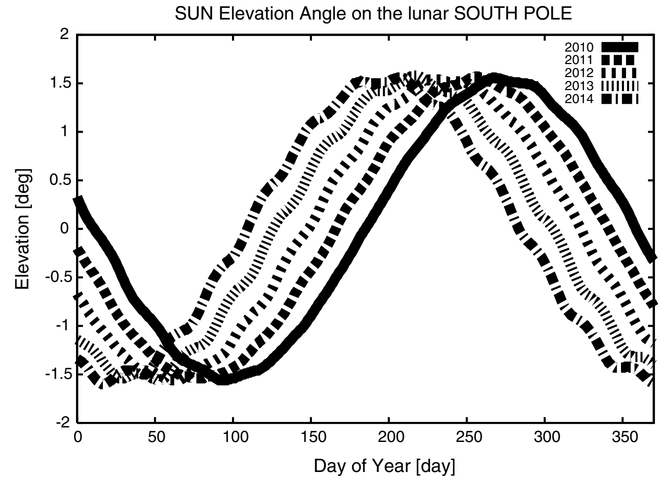

Fig. 6. The elevation angle of the Sun at the lunar South Pole in 2010–2014. Values with more than zero correspond to the sunlit condition. No local elevation information is taken into account.

5. Concluding remarks

In this study, we did not consider the effect of the solid tide to the star traces. As the tidal force by the Earth triggers both the deformation and librations, the periods of the tides are the same as the librations. Therefore basically one cannot separate the effect of tides which appears as deflections of the vertical from librations with same periods. The amplitude of the tide becomes about 0.5 s of arc at the pole. One idea to separate them is that the star trace caused by the deflections of the vertical becomes linear motion on the pole while the librations become circle. The study of the separation between them should be done in the future work.

We did not treat the instrumental error such as deformation of the tube, the position error of the tilt of the CCD supports, or defocus of the star images by the thermal expansion/contraction. They should be included in a more concrete simulation.

In summary, we simulated the trajectory of stars due to the lunar rotation observed by the ILOM on the polar region by using DE405, and split it into the precession, polar motions and three largest librations in the latitude direction. Estimation of amplitudes and phases was successfully done with the aiming accuracy of 1 ms of arc for the calculation for the observation on the exact pole. The accuracy depends more on the observation periods than the number of the stars observed, which means that longer observation is more important than the aperture of the telescope. Therefore the landing site is important in terms of observation accuracy, thermal condition and the electric power supply without a radioactive thermal generator. For example, the limb areas of the Shackleton crater on the lunar South Pole offer ideal place for the ILOM. The beginning of the polar summer is preferable as the arriving period of the year because the summer lasts half year on the pole.

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