

# Moonlight project - Observations of Lunar rotation and Ephemeris by optical methods on the Moon

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**Abstract.** A PZT (Photo Zenith Tube) telescope together with an active transponder for lunar laser ranging on the Moon can observe lunar rotation and lunar ephemeris with one order higher accuracy than the observations made so far and will try to detect the lunar free librations as well as the lunar physical librations in order to investigate the lunar mantle and the liquid core, and is applicable not only to lunar science but also general relativity and communication engineering.

## INTRODUCTION

The Moon is the object of interest not only for scientists of planets, astronomy, space geodesy, but for engineers who is going to use the Moon as a new habitation space or a new factory. The Moon is not fully known for either case. Our present understanding of the internal structure of the Moon is based mainly on selenodetic, seismic and surface observations made by past lunar missions and LLR (Lunar Laser Ranging) observation and on theories extrapolated from the Earth. We hardly know the interior of the Moon, especially the deep interior near the core and the deep mantle, from the viewpoint of science.

Although the long-time observation of LLR have contributed to improvement of the accuracy of the rotation and the evolution of the Moon, it is difficult to improve the accuracy more with the present condition. One possibility to exceed the limit of accuracy is to increase the intensity of a laser power, which brings about improvement of the signal to noise ratio and increase of the number of LLR stations on the Earth. Another possibility is to add a new observation to LLR. We can investigate the possibility of the existence of a systematic error and distinguish a parameter from the other parameters with plural kinds of observations and it results in the improvement of the accuracy of each parameter. It is necessary to develop a communication line between the Moon and the Earth for huge amount of data as well as to improve the accuracy of the observations. Optical communication is expected as a means of this purpose from a viewpoint of an amount of data and easiness of installation of communication equipment.

We have a plan to observe the rotation and the revolution of the Moon by a combination of in-situ lunar orientation measurements by a telescope and active LLR in order to improve both accuracy dramatically and to elucidate the deep interior, to verify the theory of general relativity, to build a new ephemeris, and also to develop optical communication technology between the Moon and the Earth.

## MOONLIGHT PROJECT

It is an essential problem whether the lunar core is mainly composed of metal or not or whether it is liquid or not when we understand the origin and evolution of the Moon through its internal structure and the property. The key to solving the problem lies only in a slight change of rotation of the Moon of about a few milliseconds of arc which is almost the same level as the error included in the past observations. On the other hand, there is still a possible theory of gravitation where acceleration of an object decreases by own gravitational binding energy (Nordtvet effect), besides Einstein's general theory of relativity (all objects have the same acceleration in a gravitational field), and the difference of the accelerations predicted by the theories can be only detected through the huge object such as the Earth and the Moon. It is verified that there is a phenomenon which the Einstein's theory of relativity can not explain if there is difference between the acceleration of the heavier Earth and that of the lighter Moon both of which receive the same acceleration from the Sun. There was no evidence of the new effect exceeding a few tens of centimeters in the difference between the predicted and the observed orbits of the Earth and the Moon.

It is necessary to improve the accuracy of the measurements of rotation of the Moon by more than 10 times in order to conclude the problems. We can know the direction of the axis of rotation by observing stars through a telescope on the lunar surface. LLR (Lunar Laser Ranging), on the other hand, measures distances between observation stations on the Earth and several reflectors on the lunar surface, and they include information of Earth's rotation, lunar ephemeris, lunar rotation and other disturbing factors such as the effect of general relativity. A combination of LLR and the astrometry on the Moon will improve the accuracy of both the lunar ephemeris and the lunar rotation since the parameters are separated well.

The moonlight project measures the orbital motion of the Moon relative to the Earth by the active LLR where the effect of the rotation of the Moon above-mentioned is corrected. Since the ephemeris of the Moon gives basis for the astronomical observation from the moon and verification of the theory of relativity, we must improve the accuracy of the ephemeris in order to attain the purposes of the moonlight project. The present ephemeris, which is mainly based on LLR observations, has a problem that only very small number of stations on the Earth can detect very weak signal. The moonlight project aims at development of a higher precision ephemeris by increasing the number of observations with the active LLR and by adopting a precise models of lunar rotation and tidal friction based on the observation of the telescope on the Moon.

## A PZT TELESCOPE ON THE MOON

If a telescope installed on the lunar surface observes position of many stars over one year or more, the difference between the observed and the predicted position of the stars gives information of lunar rotation parameters (inclination of the axis of rotation or latitudinal component, and change of spin rate or longitudinal component). A PZT (Photographic Zenith Tube) or astrolabe is assumed as the telescope for this purpose. Fluctuations in rotation of the Moon consists of the physical librations and the free librations. Since the physical librations are caused by the attraction of the Sun and the Earth, the period is the combination of the period of rotation or revolution of them. On the other hand, the free librations, which also have longitudinal and latitudinal components, change the attitude of the Moon with respect to the axis of rotation with own natural period excited by some sources. The longitudinal and the latitudinal components have the period of about 2.9 years and 75 years, respectively, and the latter is difficult to be a candidate for the observation since the period is too long compared with the observation period of one year.

We need to determine the centroid of star image with an accuracy of 1/1000 pixels which corresponds to a 1 milli-second of arc if we adopt a telescope with 1 m focal length and a CCD with a pixel of 10  $\mu\text{m}$ , and to determine the amplitude and the phase of the physical librations with an accuracy ten or more times higher than that attained by LLR, by analyzing the trajectory of star images for one year or more recorded on CCD. High precision observation of rotation of the Moon is important not only for the science of the Moon, but also for establishing the lunar coordinate system which will be the basis for a future astronomical observatory on the Moon.

The latitude at which we observe on the Moon, the method which we adopt for the observation, and the accuracy which we expect are the most important when we plan the observation on the Moon. It is also important to take an environmental condition into consideration which may affect the accuracy indirectly such as the temperature, the sunshine condition, and the foundation or dust. There are two kinds of observation method, the trajectory method which determines the rotation parameters from the trajectory of the star within a telescope view and the time-

position method which measures time and zenith distance of a star when it passes the meridian of the observation point. Time measurements are not necessary in the trajectory method, although it can be applied only near the pole since a trajectory of a star needs to be within a field of view. On the other hand, the time measurements are inevitable in the time-position method, although it is possible at every latitude.

It is usually difficult to separate two parameters from one observation. Observation of rotation is not the exception and the time-position method requires plural stations like the observation on the Earth, in order to separate the physical librations and the free librations. A latitudinal component of the free libration moves the pole relative to the Moon and the physical librations moves the axis of rotation relative to the space although both make a change in an apparent position of a star. It is possible to separate the two components by the observations at one station if we assume the latitudinal component of the free libration, which has the period of 75 years, be constant for the observation period of one year. The trajectory method, on the other hand, can separate all parameters from observations at one station (Heki, 2003). It is because the center of trajectory is estimated at every moment from the curvature of the trajectory. Estimated accuracy of each parameter should be almost the same also in the trajectory method or in the time-position method if observation conditions such as the latitude and the observation period are the same, although a simulation is required for further details.

It is difficult to separate the effect of proper motion of stars from the rotational fluctuations by either method. We need to correct the effect using a star catalog, and the residuals will remain in the long periodic component of the free librations. Required accuracy of time measurements in the time-position method is about  $4 \times 10^{-10}$  if we want to attain the positioning accuracy of 1 milli-second of arc, since the lunar rotation of 1 milli-second of arc takes 2 milli-second and the rate of 2 milli-second to the observation period of 1 year corresponds to  $4 \times 10^{-10}$ . This accuracy can easily be attained if time comparison between the Moon and the Earth is periodically made.

Sensitivity of the telescope observation to the physical librations changes according to latitude. The sensitivity of the latitudinal components is the maximum on the pole and that of the longitudinal one is the maximum on the equator in principle. The sensitivity at a middle latitude is lower than the maximum by a cosine of the latitudinal difference from the pole or the equator. The trajectory method has no sensitivity to the longitudinal component

## **AN ACTIVE TRANSPONDER ON THE MOON**

An active lunar laser ranging and optical communication mission on the moon include the technologies to be able to apply for the both science (LLR) and engineering (communication). The technology for LEO (Low Earth Orbit) inter-Satellite communication has been designed and developed in NeLS (Next-generation LEO System). We have already made a thermal structure mathematical model, and simulated temperature change in latitudes 28 and 98 degrees south on the Moon for two months as preliminary experiments.

A simple structure composed of a CCR (Corner Cube Reflector) is used as a reflector and an amplifier/repeater are proposed. To investigate the Nordtvet effect, the LLR observation in new moon and full moon is important. So far, however, it is impossible to conduct the observation by passive CCR in such light background condition. The amplifier/repeater is indispensable for conducting the LLR observation in the case of new moon and full moon.

An optical transponder used for the active LLR is collaborated with the usual passive CCR (Corner Cube Reflector) and a calibration is necessary. The lifetime of the transponder should be as long as possible for the scientific objectives. An observation for longer than 13 months is necessary for determination of physical parameters related to the theory of general relativity. The passive CCR will be substituted to the active one after finish of the life.

The active transponder is composed of an OCR (Optical Communication Repeater) of small size and of low power consumption. The process to landing is as follows: 1) the main orbiter is tracked and controlled based on laser ranging of the OCR from the Earth, 2) the status of the main orbiter is sent to the Earth using a carrier wave modulated by the OCR, 3) after landing, laser ranging using the OCR is performed by an international network.

## CONCLUSIONS

We propose a lunar mission composed of an optical telescope for positioning and an active transponder for LLR and a combination of the two instruments will greatly improve the accuracy of the rotation and revolution of the Moon. It also contribute to development of the optical communication between the Moon and the Earth.

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