Radio Navigation Beacons on the Moon, Lunar Geodetic VLBI System, Physical Libration of the Moon for Chang'E-3/4, Luna-Glob, Luna-Resource and SELENE-2 Projects

Alexander Gusev[1,2], Jinsong Ping[2], Hideo Hanada[3], Fuyuhiko Kikuchi[3], Alexander Kosov[4], Jinling Li[5], Oleg Titov[6]

Abstract The future lunar missions of Chang'E-3/4, Luna-Glob, Luna-Resource, and SELENE-2 will consist of a lander and an orbiter. Using the Lunar Same Beam, Differential and Inverse VLBI technologies, we anticipate to determine the coordinates of the radio beacons on the lunar surface with an accuracy of 1 mm for various space projects on the Moon. Small radio telescopes being installed on the surface of the Moon and incorporated into the existing network will help to improve the traditional IVS products by a factor of ten or even more. The model of the two-layer Moon gives several normal rotational modes—Chandler Wobble and Free Core Nutation. They can play an important role in the determination of the core parameters.

Keywords Lunar SBI, geodetic VLBI, lunar libration

1 Introduction

Many space agencies are planning lunar missions, including scientific observations in close proximity to and/or on the surface of the Moon. One of these experiments proposes to place two landers with radio beacons onto the lunar near side and to launch one or more orbiters into a lunar orbit. The difference of the distances between two radio beacons and Earth will be assumed to be measured by the methods of Inverse VLBI: the radio signal from various radio beacons will be sent to Earth antenna systems using the orbiter. The estimation of the physical libration angle accuracy is made for various locations and configurations for the radio beacons.

The geodetic VLBI network managed by the IVS provides high accurate positions of the reference radio sources, radio telescope coordinates, Earth Orientation Parameters (EOP), and so on. A small radio telescope being installed on the lunar surface (by the year 2020) and incorporated into the existing network will help to improve these traditional IVS products by a factor of ten or even more. This new instrument will be able to detect some known effects with an unprecedented accuracy as well as new effects, which are not available for other ground-based instruments or space missions.

2 Same Beam, Differential and Inverse VLBI for Lunar Space Projects

The future lunar missions of Chang'E-3/4, Luna-Glob, Luna-Resource, and SELENE-2 will consist of a lander and an orbiter. Using the Lunar Same Beam, Differential and Inverse VLBI technologies, we anticipate to be able to determine the coordinates of the radio beacons on the lunar surface with an accuracy of 1 mm for various space projects on the Moon. The radio sources installed on the orbiter and the lunar landing unit (lander or survival module) transmit three S-band signals (SELENE-2; Kikuchi, 2014; Sasaki, 2012) or an X-band and a Ka-band signal (Luna-Glob; Kosov, 2011) to the Earth. The double difference range between two lunar radio sources and the VLBI stations is measured with an error of less than 1 mm. This mea-

1. Kazan University
2. NAOC CAS
3. NAOJ
4. ISR(IKI)
5. SHAO CAS
6. Geoscience Australia

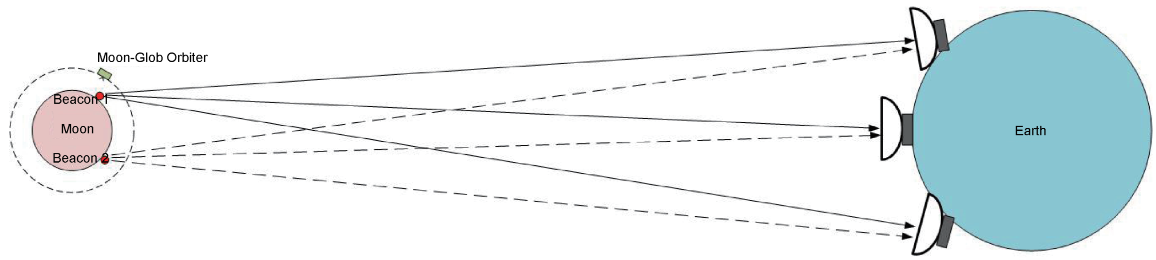

Fig. 1 Moon-Glob radio science experiment (2017).

surement will contribute to the determination of the position of the orbiter and the lunar landing unit.

The Radioscience Experiments (Kosov, 2011) will be performed with two lunar radio beacons on the lander and receiver of the "Luna-Glob" orbiter. **Science task 1:** Study of internal lunar motions using the phase-referencing method with support from ground radio telescopes for investigations of the internal structure of the Moon. **Science task 2:** Test the gravitational field (radio science of Lander and Orbiter). **Service task**: Provide radio-beacon service for future Landers and Orbiters. **Navigation task**: Determine the lander's position with an accuracy of 10 cm or better. The method of research will use D-VLBI technology. The planning cyclogram will contain each lunar day for 12–15 lunar days. The main features of the instruments are very high frequency stability and very narrow spectrum line width of the beacons' signals and the orbiter's receiver local oscillator signal. Such performance is possible due to the frequency standard used in the beacons and the orbiter's receiver.

The beacons will irradiate signals at two frequency bands: 8.4 GHz and 32 GHz. The 8.4-GHz signals will be directed to the Earth and, together with the VLBI ground-based network, will be used for celestial mechanics experiments and navigation. It will be possible to measure the beacon's positions with an accuracy of about 1 cm and to register lunar libration. The 32-GHz band will be used for orbiter navigation and gravitation field investigations. The Ka-band signal will be directed to zenith and will be received by the orbiter's receiver. An investigation of the non-uniformity of the lunar gravitation field (experiment INGL) will be performed in the vicinity of the landing regions with an accuracy of 3–5 mGal. The spatial resolution will be about 20 km. The experiment is based on precise Doppler shift measurements. The velocity and the acceleration will be recorded. It is planned to make beacons of an expected life time of five years and more. In first stage the beacons will be powered by solar batteries and then by nuclear power.

3 Lunar Geodetic VLBI

The geodetic VLBI network managed by the International VLBI Service provides high accurate positions of the reference radio sources, radio telescope coordinates, and Earth Orientation Parameters (EOP) (Schuh and Behrend, 2012). A small radio telescope being installed on the Moon surface and incorporated into the existing network will help to improve these traditional IVS products by a factor of ten or even more. In addition, this new instrument will be able to detect some known effects with an unprecedented accuracy and new effects, which are not available for other ground-based instruments or space missions.

3.1 Earth-Moon VLBI Project

The geodetic VLBI technique (Titov and Gusev, 2013) is capable of measuring the group delay between two radio telescopes with a formal error σ_τ of about 20 ps ($\approx$ 6 mm in linear scale). The accuracy of the different parameters (radio source positions, Earth orientation parameters, and VLBI station coordinates) can roughly be estimated as follows: $\sigma \sim \frac{\sigma_\tau}{\tau} = \frac{c\sigma_\tau}{B}$, where B is the length of the baseline between two radio telescopes and c is the speed of light. In accordance with the VGOS plans, the precision is likely to improve to 1 mm in linear scale (3.3 ps) (Petrachenko, 2010).

3.2 Orbital Geocentric Acceleration of the Moon

While the ground VLBI systems are not sensitive to the mutual acceleration between the radio telescopes, for the Earth-Moon baseline the VLBI group delay model must include the barycentric acceleration of the second station (Vlasov et al., 2012). For $B \sim 10^5$ km the time delay is about 1 s. For the precision of 1 mm the acceleration of 2 mm/s^2 must be implemented. The orbital geocentric acceleration of the Moon is about 3 mm/s^2. This means that all variations of the Moon acceleration are essential for accurate reductions. The time delay on the Earth–Moon baseline will be feeling the change of acceleration due to strong earthquakes (up to several m/s^2) and other seismic events. The ability to detect the acceleration of 20 μGal with high temporal resolution provides the opportunity to use this interferometer for gravimetric research.

3.3 General Relativity (PPN Parameters)

A long baseline could be effectively used for studying the propagation of electromagnetic waves in the gravitational field. The post-Newtonian parameters of the General Relativity will be substantially improved. Current LLR observations give an accuracy of the Earth–Moon range of about 1–2 cm. This results in an accuracy for the PPN parameters β and γ of about $\sim 10^{-3}$ and for the Einstein Strong Equivalence Principle (SEP) parameter of $\eta \sim 10^{-4}$ (Turyshev, Williams, 2006).

An improvement of the range measurement of the Earth–Moon VLBI baseline to 1 mm will improve the parameter estimation by a factor of 10, i.e., $\sim 10^{-4}$ for β and γ, and $\sim 10^{-5}$ for the SEP parameter η. In addition, a new set of parameters will be obtained after reduction of the Moon VLBI data (e.g., accurate Moon–Earth distance, Moon rotation parameters, Moon orbit parameters). A bunch of new opportunities for further Moon exploration will result from them (Dehant et al., 2012).

3.4 On the Way to ICRF3

Assuming that the precision of 1 mm is achieved for geodetic positions of the ground-based stations for each of the 24-hour sessions, the corresponding formal accuracy of the radio source position will be $\sim$33 μas. A longer baseline will reveal more small details which are not available with a shorter baseline. Variations of the intrinsic structure on the time scale from several days to several years will have the following effects: 1) the long-term effects in the radio source positions (apparent as a fake proper motion), 2) extra random-like noise, 3) correlated noise, or irregular variations of the astrometric positions. The realistic astrometric accuracy of the fundamental catalogs exceeds the formal errors calculated immediately from the global solutions due the reasons mentioned above (Titov, 2010). The Earth–Moon baseline will help to reveal the intrinsic structure variations and improve the final accuracy of the ICRF3 catalog.

3.5 Moon Tides and Other Benefits

It is worth noting that the following factors, which spoil the lifes of the VLBI data technicians and analysts, will be missed with the Moon-based radio telescope: 1) Earth ionosphere delay (if observed far enough from the Earth and Solar disks); 2) Wet troposphere delay with gradients; 3) Ocean loading; 4) Ocean tides; 5) Atmosphere and other non-tidal loading; 6) Tectonic velocities, especially, in the deformation zones; 7) Gravitational deformation of the antenna shape and mount; 8) Gravitational sag; and 9) RFI.

4 Interior Structure and Physical Librations of the Two-Layer Moon

Studies of the rotation of celestial objects give an understanding of their complex internal structure, especially when other (geophysical) methods are inapplicable. Physical libration of the Moon is a deviation of its rotation from uniform rotation described by Cassini's laws, determined by the misalignment of the rotation axis with the axes of inertia, and by perturbations from the Earth, Sun, and planets.

The Chandler Wobble (CW) is a motion of the rotation axis of the Moon around its dynamical figure axis due to the bulges of the lunar body. For the completely solid Moon the CW has a long period of 74.6 years in a frame tied to the Moon and is prograde. This mode was detected from LLR observation as a $3'' \times 8''$ (69×28 m) elliptical component in the oscillation (Rambaux & Williams, 2011).

The Free Core Nutation (FCN) represents a differential rotation of the liquid core relative to the rotation of the mantle. This mode does exist only if the core is liquid. It has a quasi-diurnal period in a frame connected to the Moon and is retrograde (Gusev & Petrova, 2008).

Modeling of Free Periods of the Moon

The dependence on the core's radius is very weak for both periods (CW and FCN), when the radius is set to vary within the range of 300 to 600 km, the periods are changed by less than one percent. Both periods P_{CW} and P_{FCN} depend very weakly on the core density. Only for radii greater than 400 km, the difference in density is observed. The difference in the periods between the eutectic composition with the density 5.5 g/cm^3 and the pure iron core (7 g/cm^3) is very small. The FCN-period is very sensitive to the core ellipticity. This property can be used to impose an additional constraint on the core's parameters, if the expected observation data allows detecting the FCN-mode in the polar motion. The expected amplitudes of the FCN lies at about 16 mas.

Table 1 Free librations of the two-layer Moon (Rambaux & Williams, 2011; Gusev, 2008).

Free modes	Values
Chandler Wobble (arcs) amplitude (m) period	$8.183'' \times 3.306''$ 69×28 m 27,257.27 days = 74.626 years
Precession amplitude period	$0.032''$ 0.27 m 8,822.88 days = 24.16 years
Longitude amplitude period	$1.296''$ 11 m at the equator 1,056.12 days = 2.9 years
Free Core Nutation amplitude P_{FCN} = 27.312 days, LRF	$0.016''$ 0.14 m 67,936 days = 186 years, ICRF

5 Summary

1) Lunar Same Beam, Differential and Inverse VLBI technologies will enable us to determine the coordinates of the radio beacons on the lunar surface with an accuracy of 1 mm for various space projects on the Moon. 2) Small radio telescopes installed on the Moon surface and incorporated into the existing network will help to improve these traditional IVS products by a factor of ten or even more. This new lunar instrument will be able to detect some known effects with an unprecedented accuracy and new effects which are not available for other ground-based instruments or space missions. 3) The model of the two-layer Moon gives several normal rotational modes—Chandler Wobble and Free Core Nutation. They can play an important role in the determination of the core's parameters: radius, density, and geochemical composition. Amplitudes and frequencies of the physical libration depend on the geophysical parameters of the model: the size, thickness, and density of the lunar mantle and core were calculated.

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