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Analysis of topocentric and gravimetric data from modern space missions

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Abstract. The present paper focuses on the analysis of modern lunar missions and ground-based projects, such as “Chandrayaan -1”, “Chandrayaan -2”, “Chang’e 1”, “Chang’e 2”, “Chang’e 3”, “Clementine”, “GRAIL”, “KAGUYA”, “LRO/LCROSS”, “LRO”, Lunar Laser Ranging, “Lunar Prospector”, “SMART-1”. The methods and algorithms of constructing a dynamic model of the lunar physical surface as well the results are considered. A particular attention is given to the “LRO” project which was the first step towards implementation of the long-term program on creating manned lunar bases. Essential information on lunar dynamics was provided by observations of the Moon’s physical libration, since the study of celestial objects’ rotation allows for understanding their complex internal structure, particularly, when there is no opportunity to use other methods.

1. Introduction

In the new millennium the global investigation of the Moon with the space methods started with a series of space missions on the study of lunar topography, internal structure, and gravitational field (“Clementine” [1]; “Lunar Prospector” [2]; Lunar Laser Ranging (LLR) [3]; “SMART-1” [4]; “KAGUYA” [5]; “Chang’e 1”, “Chang’e 2”, “Chang’e 3” [6]; “Chandrayaan-1”, “Chandrayaan-2” [7]; “LRO/LCROSS” [8]; “LRO” [9]; “GRAIL” [10]). Particularly important contribution to learning selenophysical parameters was made by “Clementine”, “LRO”, “GRAIL”, “SELENE” (KAGUYA). “SMART-1” lunar mission with its new technological capabilities for obtaining a wide range of the lunar data should also be mentioned. “LRO” mission provided the unique high-resolution images of the lunar surface. “LRO” mission was the first serious step towards the implementation of the long-term program on the creation of manned lunar bases which are planned to be developed in 2020s. “LRO” mission had been supposed to help select the areas most suitable for landing on the Moon. With this purpose, the sources of oxygen and water were searched for; the radiological situation near the Moon was investigated as well. These tasks were solved with the six scientific tools of “LRO”. 2007 was the year when the space projects of Japan, China, and India were launched. In this regard, “SELENE” (KAGUYA) Japanese mission should be mentioned as it provided highly accurate topographic and gravitational observations of the entire surface of the Moon including its far side and Poles. Chinese “Chang’e 1” and Indian “Chandrayan-1” gave some new data on the lunar gravitational field, mascon, crust, and geochemical composition. It should also be noted that some important information concerning the Moon may be obtained through observations of the physical libration of the Moon (PLM) from the lunar surface using the lunar telescope as well as through the theoretical simulation of PLM. The study of rotation of celestial bodies allows understanding their complex internal structure, particularly, if there is no opportunity to apply the other methods [11].

2. The multi-layered modes of Moon

When studying the inner structure of the Moon, the investigation of its free libration is of particular importance. This type of libration would take place even if the Moon were not affected by other external perturbations. For instance, free libration occur after the “free” Moon is excited by the fall of large meteorites. On the one hand, the noticeable dissipation of the lunar rotation was discovered from



PLM observations and, as a result of this, free oscillations should have been faded by now. On the other hand, the same observations point at the presence of free libration in the modern lunar rotation. This contradiction has led to the conclusion that the traditional homogeneous solid-body model of the lunar body is inaccurate. The Moon not only “breathes” under the influence of solar and terrestrial tides, but also probably contains the liquid melting core inside. This is why, it is necessary to take into account the subtle spin-orbital effects in Moon-Earth and Moon-Sun interactions, resonant interaction of the Moon’s rotation with Venus, and two- or three-layered models of non-solid Moon with tidal and turbulent dissipation in the mantle and core. This may be implemented within the Hamilton’s approach developed by the authors of the present paper and applied for the Earth’s rotation description [12]. The analytical Hamilton’s method applied in calculation of celestial body’s rotation with the layered structure [13] reveals a few features of the normal rotational modes. The model of the Moon is constructed as a three-layered body with three ellipsoidal layers: solid mantle, liquid outer core, and solid inner core. Thus, during the lunar polar rotation the four types of oscillations are supposed to be observed. The values of these oscillations’ frequency are determined from the corresponding equations and depend on the thickness of the core’s layers, their chemical composition, and dynamical flattening [14]. As for the amplitudes of free modes, they cannot be calculated theoretically. Their values can only be determined from the comparison with observations or roughly estimated from the geophysical models of free modes excitation.

Free modes occur due to the mantle’s axes of rotation do not coincide with the ones of outer and inner cores. The detection of those modes from observation allows concluding that the body contains a homogeneous eutectic liquid or liquid-solid core inside. Moreover, the free modes’ parameters will allow determining the important characteristics of internal structure, such as nuclear radius and its flattening as well as density leap at core-mantle boundary.

We derived the modes of the two-layered moon from the lunar free rotation equations [15]. First of all, chandler-like mode is considered (Chandler Wobble, CW) whose frequency is given by equation:

$$\sigma_1 = n \frac{A}{A_m} \sqrt{k \frac{(C-A)(C-B)}{AB}} = n \frac{A}{A_m} \sqrt{k\alpha\beta}.$$

Here, n is lunar average rotational speed; A, B, C – main moments of inertia of the entire Moon; A_m – corresponding moment of inertia of lunar mantle; α, β – dimensionless coefficients of moments of inertia. The value of k is close to 4 for the Moon. The coefficient arises, since when making up the Hamilton’s equations it is necessary to take into account the fact that the Moon is captured into the resonant rotation of 1:1 type. This is why, the term “chandler mode” is not so suitable for this kind of libration. The Moon is not in the free Euler’s rotation, as the Earth and other planets that have rotational type of motion. Therefore, this type of libration should not be called “free”, i.e. occurring in the absence of external perturbations. The modern Moon with its evolved rotation moves in the gravitational field of the Earth, and when constructing librational equations for the “freely” rotating Moon this fact should be taken into account.

The mode σ_1 corresponds to the period of 74.6 years determined in the Cartesian coordinate system (CCS) and describes the direct movement of the axis of rotation along the ellipse of 3” by 8”. The values of the axes of the ellipse were obtained from the PLM theory with LLR data [16]. The characteristic time of this mode’s fading is estimated to be about $2 \cdot 10^6$ years.

When there is the liquid core, another mode of σ_2 frequency arises in the movement of the axis of rotation of the free Moon, i.e. without any other external perturbations:

$$\sigma_2 = -n \left[1 + \frac{A}{2A_m} \left(\frac{C_c - A_c}{A_c} + \frac{C_c - B_c}{B_c} \right) \right] = -n \left[1 + \frac{A}{A_m} (e_{ca} - e_{cb}) \right].$$

Here, the index c describes the corresponding lunar core's parameters with e_{ca} and e_{cb} equatorial ellipticity. This type of libration is called free core nutation (FCN). This mode arises due to the differential rotation of the core and mantle and exists only in case of liquid core. The mode describes the lunar axis of rotation's reverse motion.

The period corresponding to FCN is close to the duration of lunar month:

$$\sigma_2 = - \left[\frac{1}{1 \text{ month}} + \frac{1}{P_{FCN}} \right].$$

Value $P_{FCN} = - \frac{P_{rot}}{2(e_{ca} + e_{cb})} \frac{A_m}{A}$ is period of free nutations in the inertial coordinate system. This value, by our estimates, varies between 144 and 186 years depending on the ellipticity of the lunar core accepted. Compared with FCN of the Earth and Mars, the Moon has a large period of free core nutations. This is caused by the slow lunar rotation and small size of the core. Free core modes' inclusion into the analytical solution of physical libration theory is described in [17].

3. The free librations geometrical interpretation

Hetino et al. [13] developed a canonical theory of the two-layered Earth's free rotation. Petrova [15] used Hetino' method to describe the two-layered Moon's rotation. As a result, for case of lunar polar rotation the solution for projections of rotational speed on the axes of CCS was obtained (ω_A , ω_B , ω_C).

In this plane the axes (x, y) are parallel to main axes of inertia A and B (figure 1). Then the position of the true rotation pole with respect to the moment of inertia C will be given by coordinates as follows:

$$\begin{aligned} x &= \frac{\omega_A}{\omega_C} = D_1 \cos(\sigma_1 t + d) + F_1 \cos(\sigma_2 t + f), \\ y &= \frac{\omega_B}{\omega_C} = D_2 \cos(\sigma_1 t + d) + F_2 \cos(\sigma_2 t + f). \end{aligned}$$

Here, amplitudes D_1, F_1, D_2, F_2 and phases d and f contain uncertain integration constants whose values are found from observations. According to these equations, the motion of Pole over the lunar surface is going to consist of the movements over two ellipses. The pole moves reversely in a small ellipse with F_1 and F_2 and a period of roughly equal to lunar month. The center of this ellipse moves in another ellipse with D_1 and D_2 semi-axes in the straight direction and a period of 74.6 years. This conforms with the idea that the lunar body fixed by inertia axes oscillates in relation to the axis of rotation.

In the inertial coordinate system, these oscillations overlap with the reverse precession movement of the average angular speed vector $\bar{\omega}$ which is distant from the ecliptic pole for angle $I = 1.53^\circ$.

Calame [18] revealed the greatest modes of free libration from LLR data. The most accurate values of free libration were obtained on the basis of long-term series of LLR observations in work [16]. It was determined that D_1 and D_2 were 3.31" and 8.19" correspondingly, while the period was 74.63 years. This value is close to theoretically predicted one and confirms that the Moon's structure is well described by the model of solid body with very small elasticity. By comparison, the Earth has Chandler period of 433 days which is more than Euler's period (355 days). For the Earth, it is described by the liquid nature of terrestrial core and the presence of the oceans. Generally, FCN forms a blend with libration harmonics having the period of one month and is hard to detect from observations due to FCN has a small amplitude. Nevertheless, the inclusion of FCN harmonics into the PLM theory leads to decrease in the value of residual differences when processing the future highly accurate PLM observations from space data and LLR.

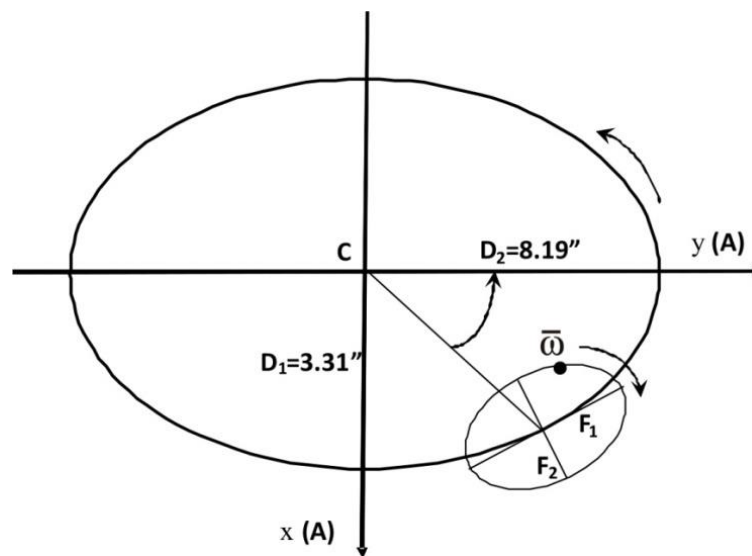


Figure 1. The motion of the axis of rotation of the Moon relative to the dynamic pole of the Moon C due to the free libration of the Moon of two types.

4. The lunar core existence problem

The question of whether the Moon has the core arose after the seismic experiments on the lunar surface conducted in 1970s. Within the “Apollo” space program, four seismometers were delivered to the Moon in order to detect the seismic activity of the celestial body up to 1977. It appeared that moonquakes occurred much rarely than earthquakes. The fact that the surface of the Earth’s natural satellite is covered by craters left after collisions with small space bodies distorts the signals of the instruments placed on the surface and makes the oscillations of the lunar core less detectable. In this connection, the information on the deep internal structure of the lunar body remained unavailable for the “Apollo” seismic network. As a result, not only the composition and aggregate state were unknown, but even the very existence of the lunar core was in doubt. This is why, the information on the internal structure of the Moon was mainly obtained through the study of the lunar moments of inertia, physical libration, and electromagnetic induction.

One of the most important methods of studying the internal structure of celestial objects, for which the other geophysical methods successfully applied on the Earth are unavailable, is considering the rotation of a celestial body. In this regard, the investigation of the Moon’s internal structure through its physical libration, particularly using LLR and space observations of the gravitational field, is very promising.

The results of LLR could be used to reveal a number of lunar rotation features weakly expressed. One manages to reconstruct the complex structure of the lunar depths through those features. Currently, LLR being implemented for more than 40 years is one of the most efficient sources of information about the Moon. The accuracy of laser measurements achieved the level sufficient for the determination of even relativistic effects in the Earth-Moon system. The analysis of laser data when determining the parameters of lunar rotation allowed not only refining the numerical characteristics of the Moon’s dynamical figure (dimensionless moments of inertia, and etc.) and coefficients of elasticity k_2 and l_2 , but also explicitly determining the amplitudes and phases of chandler-like modes in the free libration and discovering the presence of strong rotational dissipation. The simulation of librational observations allowed obtaining the numerical parameters of the size and chemical composition of the lunar core as well as estimating the probability of the existence of the liquid core according to space gravimetric observations [19]. As a result, on the basis of simulation the following parameters are obtained: radius of lunar disc is either 300 (+90/−100) km on average, if the iron core is considered,

or 400 (+80/−180) km, if the core is described by *Fe-FeS* eutectic composition. These investigations are of great importance in regard to the solution of one of fundamental problems of space studies on the development of the Moon's origin hypothesis. The cosmogonic model shows that if the Moon was formed due to the accretion of the initial matter, then the size of the core is supposed to be more than 360 km. Otherwise, if the Moon is made of the same matter as the Earth's mantle, then the core size could be less than 285 km. The latter is in accordance with the giant-impact hypothesis of the proto-Earth's collision with a celestial body of the size of Mars followed by the emission of large amount of the matter of which the Moon was later formed. Although there are disputes on the reliability of the hypothesis, it remains one of the main ones and therefore cannot be rejected.

The lunar core parameters' estimates from LLR and space observations as well as the very fact of its existence have, however, only indirect proofs. Direct proofs of the presence of the lunar core can only be obtained from free libration parameters determination or seismic investigations.

For a long time, the information received from the Moon has been considered almost useless for scientists. However, for the last 40 years the methods of analyzing the lunar seismic data have dramatically changed. Using the new methods of processing the reflected and transformed seismic energy Veber et al. [20], Garcia et al. [21] reanalyzed the seismograms of the "Apollo" mission. The error occurring due to the craters was taken into account in calculations. As a result, it was concluded that, like the Earth, the Moon does have the melting metal core. Its diameter ranges from about 330 to 360 km, the core is surrounded by the partly melted mantle of 480 km in diameter. Inside the core there is the solid iron heart of about 240 km in diameter. Thus, the first direct proofs of the lunar core and its two-layered structure were obtained.

The seismograms were also analyzed by data processing in groups, which allowed determining the source of the seismic activity's appearance. After the trajectories of seismic waves' passing and the peculiarities of their reflection from the inner layers of the Moon had been determined, the composition and structure of the lunar core layers at various depths were defined. These results of the lunar core investigations once again confirm the hypothesis of the Moon's formation about 4.5 billion years ago as a result of the Earth's collision with the large space object of the size of Mars. Hypothetically, this collision had "knocked out" a piece, consisting of the melted mantle's crust that later formed the Moon, from the Earth. The studies conducted at the Kola Superdeep Borehole established that the rock composition of the peninsula was almost 90% similar to the Moon's one. Thus, we may conclude that the collision had occurred in the place where those layers of the Earth's crust later transformed into the Kola peninsula.

5. Dynamic figure and lunar gravitational field

Some of the main tasks on the study of the Moon are investigation and simulation of the lunar dynamic figure [22, 23]. Solution of this problem allows determining structural mass distribution in the lunar body.

The dynamic figure is associated with the ellipsoid of inertia determined by the values of the lunar moments of inertia A , B , C as well as their direction in space. The absolute values and orientation of the moments of inertia A , B , C can be derived neither from space observations nor from ground-based ones. Only the combinations of the moments of inertia may be determined.

At the same time, analysis of orbits variations of lunar orbiters allows obtaining the expansion of the gravitational potential in spherical harmonics (Stokes coefficients). In order to determine dimensionless moments of inertia one uses LLR of corner reflectors installed on the surface of the Moon as well as the physical libration measurements.

Lunar orbiters allow conducting the modern promising studies of the figure and gravitational field of the Moon. The analysis of orbital data of "Apollo", "Clementine", "LRO", "GRAIL", and "KAGUYA" missions allowed determining the coefficients of the lunar gravitational field expansion up to the 165th order with high accuracy. Our analysis of the Moon's gravitational field confirmed the previously obtained results according to which the values of harmonics of the fourth order of expansion were close to the ones of the second order. The only exception is J_2 term. The asymmetry of

the lunar gravitational field on both the near and far sides of the Moon is proved by the fact that the $\bar{S}_{nm}$ with even m and $\bar{C}_{nm}$ with odd m coefficients are not equal to zero. It may be concluded that the real physical figure of the Moon is a more complex system than the one that could be described by the triaxial ellipsoid.

6. Summary and conclusions

New data have been collected by “Lunar Reconnaissance Orbiter” (LRO) robotic spacecraft. “LRO” found traces of hydrogen at southern craters of the South Pole. The latter are in permanent shadow from the sun; therefore, many scientists consider the presence of hydrogen as a sign of water ice presence. According to recent data, temperature in these craters does not rise above approximately 330 K, so theoretically under the given conditions water can be kept for billions years. Within the framework of the project scientists studied craters’ surface with the help of Goldstone Solar System Radar transmitter located in California.

“LRO” has found the coldest site in the Solar system. It is located in the shaded craters near to the South Pole of the Moon. The coldest site has been identified in the course of mapping Moon’s surface temperatures. The temperature inside the craters reaches $-240\text{ }^{\circ}\text{C}$, which is just 33 degrees above the absolute zero. Even on Pluto which is 40 times farther from the Sun, the temperature is several degrees higher. Soon the temperature at the South Pole of the Moon will increase, and the coldest spot in Solar system will “move” to the North Pole. Cold craters may preserve most diverse molecules, such as water or methane. Apart from that, in the course of the study of chemical composition of molecules inside craters astronomers can obtain new information about early stages of formation of the Solar system. It is worth to note that lunar craters are the coldest natural sites of the Solar system.

Among other things, experts are interested in the availability of water too. Delivery of cargoes to the Moon is extremely costly enterprise, whereas lunar base inhabitants would definitely need it, although none has been definitely detected so far. Lunar soil samples delivered to Earth by American and Russian explorers lack any traces of water. Many experts assumed that water ice can be found in always shaded craters’ muzzles.

The task can be solved with regard to relativistic effects of rotation of the Earth-Moon system and recent achievements in geophysics and selenophysics [24]. So far the measurement error is 13 mm. More accurate knowledge of complex laws of rotation of the Moon will allow for clarification of fundamental physical constants of the general theory of relativity, sophisticated structure and composition of the Moon’s core and a viscous-elastic mantle. Realization of research-technical project “Center of space science and technologies” (2015–2020) at Kazan Federal University on the basis of Engelhardt astronomical observatory will become a key element in Russia in terms of achievement of the targeted accuracy in the system of international observations of the Moon [25–27].

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