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Fictitious orbital anomalous secular and abrupt changes in the lunar orbit semi-major axis and eccentricity established by modern-era laser measurements

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It is shown that the anomalous effects (secular changes of semi-major axis and eccentricity of the lunar orbit), which are widely discussed in scientific literature, are fictitious and do not exist for the spatial orbit of the Moon. They are a reflection of the relative displacements of the center of mass of the Moon relative to its crust or relative to the system of laser reflectors mounted on the lunar surface and the observations which they have identified in recent years. The mechanism of forced relative displacements of the core and mantle of the Moon is crucial for the studied effects. As a result of the analysis of these effects we have obtained their explanation and interpretation in good agreement with laser observations.

Keywords: Lunar orbit, semi-major axis and eccentricity, fictitious changes

1 Introduction

It would seem to celestial mechanics that there is no limit to the knowledge of the motion of celestial bodies, their predictions and forecasts. But the motion of the Moon, which is the nearest celestial body to us, shows some additional effects in rotational and orbital motion, the nature of which is not explained [1]. In particular some rough estimates of abnormal changes in the age-old semi-major axis and eccentricity of the lunar orbit, according to the author, were found to be $\dot{e} = (0.9\pm0.3)\cdot10^{-11}$ 1/yr, $\dot{a} = 6$ mm/yr [1]. The history of (unsuccessful) attempts to explain these anomalous orbital effects is considered in [2–4]. In these modern papers the secular anomalous effects in the orbital motion of the moon were studied. Studies of the Moon, thanks

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to NASA and Johnson Space Center have quantified an anomaly in the measurements of lunar orbital evolution. The Lunar Laser Ranging Experiment (LLRE) from Apollo reports the Moon's semi-major axis increasing at a rate of 3.82±0.07 cm/yr, which is anomalously high. LLRE bounces laser light off corner reflectors placed on the Moon's surface. On the other hand, sedimentary data indicate a rate of only 2.9±0.6 cm/yr. From historical eclipse records we can accurately calculate a rate of 2.82±0.08 cm/yr. A detailed numerical simulation of lunar orbital evolution predicts 2.91 cm/yr. LLRE's laser light differs from independent experiments by up to 12σ. This predicts that LLRE will differ by 0.935 cm/yr, precisely accounting for the lunar anomaly. In the recent years various authors suggested several possible explanations of indicated anomalous effects in orbital lunar motion. In the opinion of Riofrio this anomaly or phenomenon can be caused by a secular change in the speed of light decreasing at a rate of $(dc/dt)/c = -0.24 \cdot 10^{-10}$ yr^{-1} and may have significance for cosmology. In [4], similar results were presented for acceleration of the Moon but new ideas about the variations of the velocity of light by the leading scientists on LLRE was not accepted. Tides induce a semi major axis rate of 38.08±0.19 mm/yr, corresponding to an acceleration of the Moon's orbital mean longitude of $l = -25.8 \pm 0.13''/\text{cent}^2$, as determined by the analysis of 43 yr of Lunar Laser Ranging (LLR) data [4]. The LLRE result is consistent with analyses made with different data spans, different analysis techniques, analysis of optical observations, and independent knowledge of tides. Plate motions change ocean shapes, and geological evidence and model calculations indicate lower rates of tidal evolution for extended past intervals. The rotation of the Earth has long-term slowing due to tidal dissipation, but it also experiences variations for times up to about 10^{-5}/yr due to changes in the moment of inertia. An analysis of LLRE data also tests for any rate of change in either the speed of light c or apparent mean distance. The result is $(-2.8 \pm 3.4) \cdot 10^{-12}$/yr for either scale rate or $-(\mathrm{d}c/\mathrm{d}t)/c$, or equivalently –1.0±1.3 mm/yr for apparent distance rate. So the lunar range does not reveal any change in the speed of light [4].

Different sources for different time scales have been proposed for lunar orbit anomalies. The lower recession rate found in sedimentary data has been attributed to increasing tides over millions of years. This inference has not been independently verified. For the Moon's recession to vary so greatly, tidal heights would have to increase enormously over time. But Mansfield sedimentary data and other sediments do not differ significantly from current tidal heights. This predicts that LLRE will differ by 0.935 cm/yr, precisely accounting for the lunar anomaly. Scientists have actively analyzed different possible factors for the origin of lunar anomalies from Cosmology, Laser ranging, Lunar orbit, Relativity, Speed of light and others. Thus, Riofrio [3] proposes the hypothesis that the speed of light decreases at a rate of $\dot{c}/c = -0.24 \cdot 10^{-10}$ yr^{-1}. Unfortunately, all very intensive attempts to explain the anomalous increase in the semimajor axis and eccentricity of the Moon's orbit have been unsuccessful.

However, in 1996–2002 a new mechanism of excitation of endogenous activity of planets and satellites (shell dynamics) was proposed [5], which in principle solves the age-old challenge of abnormal changes in the Moon's orbit. In accordance with this mechanism, which is universal for all celestial bodies in solar and other planetary systems, the main shells of planets and satellites (in particular the Moon): cores, mantle, crust execute small forced relative displacements due to the gravitational action of the surrounding celestial bodies. In this short paper, we present the introductory part of

the planned solution of the fundamental problem. Namely, we discuss the mechanism for a drift of the center of mass of the Moon with respect to its crust. Based on the completed analysis, we obtained estimates of velocities of secular trends of semi-major axis and eccentricity of the orbit in good agreement with current observations and especially its tectonic evolution.

2 The mechanism of secular relative displacements of the Moon shells and drift of its center of mass relative to the crust. Anomalous effects in the orbital motion of the Moon

We have shown that unexplained secular effects in the orbital motion of the moon are the consequences found in recent years of the phenomenon of removal of the center of mass of the Moon relative to its mantle and crust in the direction of the Earth [6]. Secular variations of the semi-major axis and eccentricity of the lunar orbit, which is actively discussed in the current literature, are treated as fictitious phenomena. They are due to secular drift of the center of mass of the Moon relative to the lunar crust and mantle in the direction of visible side of the Moon. An approximate estimate of the drift velocity of the center of mass in accordance with our first results are about 8–12 mm/yr [6]. This effect and the secular anomalous changes in the eccentricity of the lunar orbit contains only data of precision laser observations of the Moon (with reference to positions of the laser reflectors), not to the dynamic characteristics of the center of mass of the Moon in space. Abnormal secular variation of the eccentricity of the orbit of the Moon are associated with spatial character of shifts of the center of mass of the Moon relative to the system of reflectors on its surface. These effects are not real for lunar orbit secular and abrupt changes but they are results of incorrect interpretation of laser observations of laser range in long period (Figs. 1, 2).

In other words these observed and discussed anomalous orbital effects are not real for center of mass but fictitious and are caused by relative displacements of the Moon (crust) relative to its center of mass. It means that all attempts to discover new physical and celestial mechanical effects in the Moon motion are not serious. But they can be useful for estimations of possible very small orbital effects for future studies of the motion of the Moon. It concerns practically all studies and papers on anomalous effects. This is the main reason that all the work on this problem was unsuccessful. All subsequent works and researches will also be unsuccessful if they do not rely on the modern geodynamic model [5]. This conclusion applies to almost all planetary problems in geosciences and planets that have received extensive application and confirmation.

Our preliminary conclusion is: due to forced relative displacements, oscillations and abrupt (step) displacements of the shells of the Moon (the core, the mantle, the crust), the center of mass of the Moon makes similar motions relative to the crust (and reflectors). It is noted that one should observe a class of motions and oscillations of center of mass of the Moon on its crust, and the secular trend is just one of the major motions. These motions can be studied with the help of laser observations. And the signs of a trend in the range of its abrupt changes in 1997–1998 as well as a number of cyclical fluctuations have been confirmed in these modern laser observations (Figs. 1, 2).

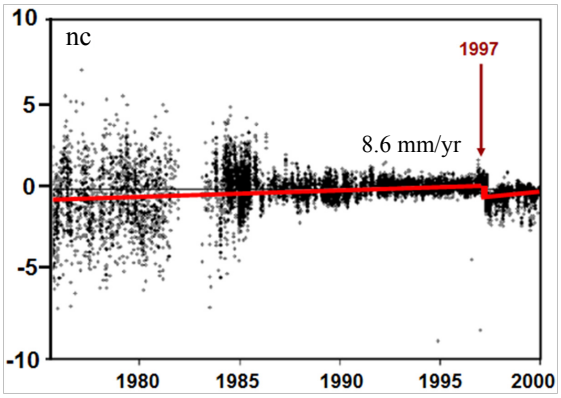


Figure 1 The residual difference of laser distances to the Moon during the period 1970–2000. Solution A) from the work by Krasinsky [7]. The ordinate axis indicated nanoseconds. Jump in laser ranges in 1997 approximately 0.48 ns = 15 cm.

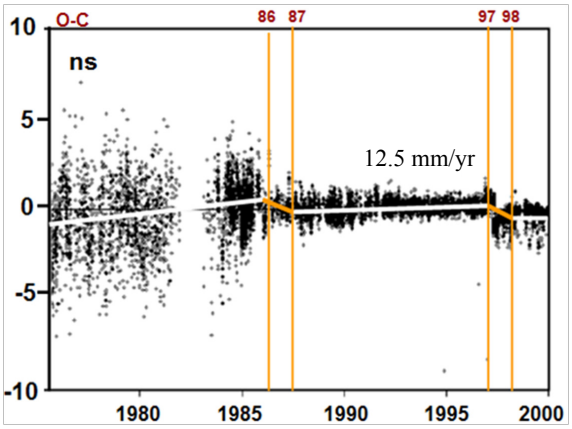


Figure 2 The residual difference of laser ranges in Krasinsky work [7]. Possible interpretation of jumps and trends in irregular distances to the Moon in 1986–1987 and 1997–1998 [6]). Trend and steps of center of mass of the Moon relative to its crust.

3 The drift of the center of mass of the Moon relative to its mantle and the explanation of the anomalies of the orbital motion

In this work, for the first time, an assessment can be made of the possible velocity of the secular drift of the center of mass of the Moon on its crust and mantle in the 10–15 mm/yr towards to the Earth. This secular drift of the center of mass of the Moon should be taken into account in the study of the orbital motion of the moon based on laser observations and adds to the value obtained by laser observations.

The resulting estimates of tidal change in semi-major axis of the Moon's orbit have a considerable scatter. Therefore, these results should be considered preliminary and

should be confirmed in future studies. For the selected period of acceleration detection of Moon using single method based on laser observations, we obtain the average value –24.6″ 1/cy^2 (36.4 mm/cy). This allows us to estimate the drift velocity of the center of mass of the Moon at a rate of 8–12 mm/yr towards the visible side of the Moon. In these determinations, it is assumed that the center of mass does not change its position relative to the laser reflectors. However, from our studies it is an artificial constraint, and in fact the center of mass of the Moon drifts at a rate of about 5–15 mm/yr in the direction to the Earth with respect to the Moon. These results should be considered as preliminary and they need to be further clarified with the involvement of a wider series of observations: laser, and the classic astrometric and satellite observations. Similar effects are abnormal secular distance from the perigee and apogee and eccentricity. In the model they are, correspondingly, 4.65 mm/yr (for the perigee) and 14.95 mm/yr (for the apogee) (Table 1). That is, secular decrease in the distance to the perigee occurs at a slower rate than the increase in the distance to the eccentricity peak; a similar effect is mentioned in [1]. The cyclic variations of residuals of laser ranges outlined variations with periods (in days) and amplitudes about 1–3 mm: 18.6 years (3.25 mm), 3 years (3.45 mm), 365 days (2.80 mm), 206 days (2.90 mm) and others.

Table 1 Anomalous orbital secular effects in the Moon motion in mm/yr.

$\dot{a}$	12.5	9.35	8.6
$\dot{b}$	12.31	9.16	8.41
$\dot{r_p}$	8.35	4.67	5.38
$\dot{r_a}$	16.65	12.53	12.45

Some of these periodicities correlate with cyclical variations in the seismic activity of the Moon, reported previously in our studies [8, 9]. It favors the mechanism of forced relative oscillations of the shells of the Moon [8, 10]. Moreover, this mechanism determines synchronous relative oscillations of the shells of the different bodies of solar system (for example the Moon, the Earth, Mars and others) [11]. The evaluation of the velocity of the secular drift of laser reflectors (away from the Earth) was obtained in a recent paper [6] and was taken to be 12.5 mm/yr (Fig. 2). It also marked a large step of group of reflectors about 12 cm with respect to the center of mass of the Moon in 1997–1998 in direction to the Earth (Figs. 1, 2).

To this data must be added the phenomenon recorded by abrupt (step) changes of the lunar orbit, which are difficult to understand and interpret. These anomalous effects in the orbital motion of the Moon caught the attention of many specialists in celestial mechanics and physics, and have been subjected to scrutiny. A review of work in this direction is, for example, in the article Iorio [2] and Friorio [3]. Unfortunately, all attempts to explain these effects on the basis of classical and modern theories of gravitation have been unsuccessful. This was for us a direct indication that the discussed anomalous effects are fictitious. Their nature is related to the specific features of laser observations and dynamic adjustment of the internal structure of the Moon – with shifts in its center of mass relative to the crust and mantle [8, 10].

Similar offsets and oscillations of the Earth's core and previously studied by us for the planet Earth [6]. For the Moon, these phenomena are discussed practically

for the first time [10]. We only note an important result presented in the paper [7], wherein the laser observations identified a jump in distances to reflectors on the Moon (Figs. 1, 2). Based on data for the study of the residual differences in distances to laser reflectors and our mechanism of relative forced displacements of the shells of the Moon [8], we found abrupt changes in distances to four primary reflector in 1997–1998, as well as in 1986–1987 and also established the existence of linear trends in distances to retro-reflectors in the periods before and after these abrupt changes [10, 11].

A recent analysis of lunar laser ranging (LLR), covering the period of 38.7, revealed an anomalous secular increase in the eccentricity of the lunar orbit at a rate of $(9\pm3)\cdot10^{-12}$ 1/yr [1]. Current models of dissipative phenomena occurring inside the Earth and the Moon are not able to explain this anomalous effect [2]. From our geomodel [5] it also follows that in laser range, along with secular changes in the eccentricity and semi-major axis of the lunar orbit, their abrupt changes should also be observed [6, 8] (Figs. 1, 2). The purpose of the work is to show that all of these phenomena are fictitious and reflect displacements of the center of mass of the Moon relative to the crust in variations of laser ranges.

4 The secular shift of the center of mass of the Moon (and its core) to the Earth and the tension and compression side of the visible side of the Moon

The assumption of secular shift the center of mass of the Moon towards the Earth in the direction of the visible side is confirmed in the analysis of stress and strain fields of the Moon's crust and mantle. Theoretical studies of strains showed that this age-old drift of the center of mass of the moon leads to expansion of the visible side and the compression side of the Moon [6]. These circumstances have a clear confirmation in the surface structures of the satellite. So on the visible Moon grabens are located (white dots in Fig. 3); the geological formation caused by stretching of the satellite's crust. But at far side of the Moon are concentrated compression zones – and there are scarps (Fig. 3).

Locations of newly discovered young graben (red stars) – trenchlike scars – on the Moon along with recently detected (white dots: Fig. 3) and previously known (black dots in Fig. 3) contractional lobate scarps. The newly found graben are widely distributed and located near lobate scarps. The locations of 26 shallow moonquakes recorded by the Apollo seismic network with stations at the Apollo 12, 14, 15, and 16 landing sites are shown by black triangles (Fig. 3).

The assumption of the secular shift of the center of mass of the Moon towards the Earth with respect to the Moon's crust confirms the analysis of stress and strain fields of the Moon's crust and mantle. Theoretical studies of strains showed that this age-old drift of the center of mass of the Moon leads to expansion of the visible side and to the compression side of the Moon [6, 10]. These circumstances have clear evidence in studies of surface structures of the satellite. So on the visible side of the Moon grabens (white dots in Fig. 3) are mainly located – the geological formations caused by stretching of the satellite's crust. But on the far side of the Moon, the compression zones (scarps) are predominantly located (Fig. 3).

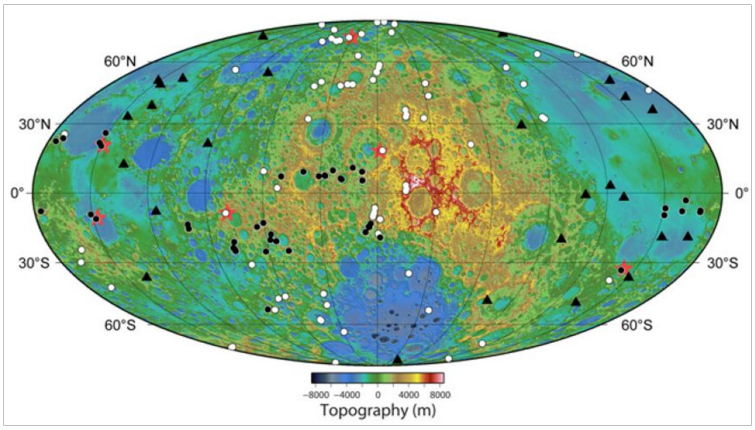


Figure 3 Location of grabens, scarps and pockets of shallow moonquakes. Photo: NASA/GSFC/Arizona State University/DLR/Smithsonian Institution.

Thus the distribution of the deformation field on the surface of the Moon are a direct indication of the drift of the core and the center of mass of the Moon on its mantle predominantly toward the Earth. Also, the distribution of the deformation field on the surface of the Moon are the direct evidence of the mechanism of forced displacements and oscillations relative to the core and the mantle of the Moon. They confirm the expected drift of the core and the center of mass of the Moon (with respect to its mantle) predominantly towards the Earth. On the other hand, the said displacement has the effect of removing the visible side of the Moon from the Earth. What is clearly recorded is a slow increase in the laser distances from Earth (Figs. 1, 2). This effect makes it possible to interpret and explain some of the some observed potential secular changes of the lunar orbit. This predicts that LLRE will differ by 0.935 cm/yr, precisely accounting for the lunar anomaly. This value is very close to our estimates of the rate of increase of abnormal semi-major axis obtained by the residual differences laser ranges from [7] for the time interval of 1978–2011: 1.2 and 0.80 cm/yr.

In Table 1 we present calculated secular variations of elliptic parameters of lunar orbit $\dot{b}$, $\dot{r_p}$ and $\dot{r_a}$ on given base parameter $\dot{a}$ (in first line).

$\dot{r_p}$ and $\dot{r_a}$ are the rates of secular changes of the distances to the perigee and to the apogee. $\dot{a}$ and $\dot{a}/a$ – the linear and relative velocity of secular change of the semimajor axis of the lunar orbit. $\dot{b}$ and $\dot{b}/b$ – the linear and relative velocity of secular change of the lunar minor semiaxis of the lunar orbit. $\dot{e}$ – the rate of the secular change of the eccentricity of the lunar orbit, $\dot{e} = (0.9 \pm 0.3)\ 10^{-11}$ 1/yr.

5 Tectonic processes on the Moon in the present era and their mechanism

Our geodetic studies of the Moon are also in line with the establishment of the regime with reference to stretching of visible side of the crust [6]. This fundamental geological structure of the Moon, its dichotomy and asymmetry, increased endogenous

activity, its energy, as well as the newly discovered tectonic structures on the visible and far side of the Moon (grabens and scarps) and their spatial arrangement allows geodynamic interpretation and explanation on the basis of the mechanism of forced relative oscillations of shells of planet.

The features of the ordered arrangement of the geological formations of the Moon, discovered in modern studies, gives their geodynamic interpretation. The current research of tectonic surface structures on the Moon indicate the action of an unknown mechanism of formation of geological structures on its surface and indicates that the mechanism of action of classical tidal deformation of the Moon is not possible to explain the formation of scarps, cracks, ridges and other structures. This mechanism is too weak for these planetary changes. On the other hand, the said displacement has the effect of proximity of the visible side of the Moon to the Earth. This effect makes it possible to interpret and explain some of the observed potential secular changes of the lunar orbit.

6 The mechanism of tectonic activity of the Moon

Our preliminary studies have shown that all these phenomena can be directly related to the active mechanism of forced displacement and the relative vibration of the planets under the influence of external gravitational attraction of heavenly bodies. For brevity, we will call it a mechanism [5, 8]. In this paper we first discussed the high endogenous activity of Titan. From comparative assessments endogenous activity of planets and satellites, it was found that the activity of the Moon is quite high and does not correspond to popular opinion at the time that the Moon is a totally passive body. In the total value table of endogenous activity of planets and satellites, the Moon won an honorable 10th place [5] (p. 71) and, later this received clear confirmation according to the Cassini space mission. This energy of the Moon in $1.2{\cdot}10^{14}$ Wt is about an order of magnitude inferior to the endogenous energy of the quite active satellite Mimas and is comparable in size to the endogenous energy of satellites like Enceladus and Dione. This mechanism has played an important and decisive role in the formation of surface structures and the structure of its internal structure in the geological history of the Moon [6, 8]. This mechanism is manifested in the present geological epoch, if indeed there is a relative displacement of the shells and, consequently, shifting the center of mass of the Moon relative to the mantle.

We discuss recent data; laser observations of abnormal changes in the residual differences for ranges up reflectors on the lunar surface for the purpose of theoretical study and prediction of shell oscillations of the Moon (core mantle, etc.) and the center of the Moon relative to the crust and mantle of this satellite. The current accuracy of the observations of these methods allows us now to study and discuss these phenomena. In this paper, we make a first and a preliminary assessment of the rate of displacement of the center of mass of the Moon on its mantle of the order of 1 cm/year toward the side of the Moon, and in relation to the crust and mantle of the Moon. The most important feature of this mechanism is offset and oscillations of the center of mass of the Moon on its mantle and crust, as a consequence of forced displacement and the relative oscillations of shells of the Moon (its solid core, the liquid core, crust, the upper and lower mantle). A fundamental role here, apparently,

is played by the core of the Moon (Fig. 1). According to the modern model, the radius of the liquid core of the Moon is 330±20 km, and the solid core of 240±10 km [12].

Thus the assumption of the secular shift of the center of mass of the Moon towards the Earth in the direction of the visible side of it is confirmed in the analysis of stress and strain fields of crust and mantle. Theoretical studies of strains showed that this age-old drift of the center of mass of the Moon leads to expansion of the visible side, and compression of the visible side of the Moon [6]. What is clearly confirmed is that grabens are located on the visible side, that is, this structure corresponds to the area of tension. Scarps are located on the visible back side of the Moon (which correspond to regions of compression) (Fig. 3). These circumstances are confirmed in studies of surface structures of the satellite. On the other hand the said displacement has the effect of removing the visible side of the Moon to the Earth. This effect makes it possible to interpret and explain some of the observed potential secular changes of the lunar orbit.

7 Conclusions

In our opinion, the reason for the abnormal changes in features of the semi-major axis and eccentricity lies in the peculiarities and differences of the satellite method for determining the acceleration of the Moon by laser ranging. The satellite method is more accurate, since it determines the acceleration of the Moon on the satellite orbits, which are attached to the center of mass of the Earth (or Moon). The method of laser ranging is based on the analysis of distances up to certain points on the surface of the moon. But these points can change position relative to the center of mass of the Moon. The author has repeatedly suggested that the center of mass of the Moon oscillates and, generally speaking, makes the secular drift with respect to the mantle of the Moon [6].

Yet in [5], which made a comparative analysis of the endogenous activity of the satellites of the planets, it was noted that the Moon is not a completely passive body (as previously thought), and is characterized by increased endogenous activity. And this prediction also received a clear confirmation in the modern discoveries in the last years of younger geological structures – grabens (Fig. 3). This requires a universal mechanism of active forced buildup, oscillations and rotations of the Moon shells (core, mantle, crust) [5, 6]. And the Moon here is no exception. Clear signs of the mechanism of forced oscillations of the relative core and the mantle of Mercury, Titan, Enceladus, etc., and most recently, Pluto and Charon were confirmed as a result of space missions to these bodies. Thus, it confirmed the existence and active manifestation of the action of the mechanism of excitation the solar system and its universality [5, 8]. The center of mass of the Earth makes a complete oscillation and a secular drift with respect to the mantle (in the respective reference coordinate systems, satellite systems DORIS, GPS and others). Many of geodynamic and geophysical phenomena (their power, cycle, inversion, polar activity, spasmodic, etc.) are direct consequences of the dynamic oscillations of the center of mass of the Earth, and these in turn are related to the relative displacements and oscillations of the shells themselves under the influence of a celestial body outside the differential attraction of celestial bodies

[5]. The above applies fully to the similar phenomena of excitation and relative shell oscillations of the Moon, which will also be accompanied by these phenomena [8].

We emphasize that these effects in the orbital motion of the moon were detected by laser observations. On the other hand, these data actually determine that the secular drift is not the center of mass of the Moon, and the secular motion of the group of reflectors on the lunar surface, located in the region of the pole of main axis of inertia of the Moon, directed to the Earth. The observed acceleration of the orbital motion of the moon contributes significantly to two mechanisms: classical tides in the Earth–Moon–Sun and the mechanism of forced vibration core and the mantle of the Moon. The action of the second mechanism is manifested in oscillations and shifts the center of mass of the Moon on its crust and mantle and deformation of the surface of the Moon, on which the reflectors are placed. Here we have studied only slow secular changes of the center of mass of the Moon, as well as the largest center of mass (relative to the mantle) in 1997–1998. However, the mechanism of involuntary buildup of the shells of the Moon predicts cyclical oscillations in its center of mass with a wide range of frequencies. These are reflected in the cyclical natural processes on the Moon and in particular variations of its seismic activity [9]. These cyclic processes, and some of their derivatives will be found in oscillations in the center of mass of the Moon in the near future. Possible secular drift of the center of mass of the Moon on its crust and mantle toward the visible side. In this work, it is the first time an assessment has been made of the possible speed of the secular drift of the center of mass of the Moon on its crust and mantle in the 10–15 mm/yr towards the back of the satellite. This secular drift of the center of mass of the Moon should be taken into account in the study of the orbital motion of the Moon based on the observations of the distances to the laser reflectors on the lunar surface.

We studied the first rough estimates of the secular drift velocity of the center of mass of the Moon for the periods of 1988–1997 and 1999–2000 and 1985–2013.3 based on laser data. The found offset – the secular drift of the center of mass of the Moon with respect to its mantle (12 mm/yr) is explained by the mechanism of forced excitation and the relative displacements of the shells of the Moon (solid core, liquid core, mantle) in the direction of the Earth [5, 8].

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