Japan Geoscience Union Meeting 2015
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PPS03-01 会場:A03 時間:5 月 28 日 14:15-14:30

月マントル下部の低速度層について
On low-velocity zone at the bottom of the lunar mantle

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Introduction: The knowledge of internal structure of the Moon is a key to understand the origin and the evolution of our nearest celestial body. Some analyses of the Apollo seismic data have indicated the existence of low-velocity zone (LVZ) at the bottom of the lunar mantle, e.g., [1], [2], but some models do not include the LVZ, e.g., [3]. The recent Gravity Recovery and Interior Laboratory (GRAIL) mission has provided a degree-2 potential Love number k_2 accurate to 1% [4], [5]. This level of k_2 accuracy has a potential to better characterize the lunar deep interior [6]. One of the recent studies which used the GRAIL-derived k_2 indicates the existence of the LVZ [7].

Data and inversion: In order to infer the deep structure of the Moon, we employed four selenodetically observed data of mean radius (R), mass (M), normalized mean solid moment of inertia (I_s/MR^2), and the GRAIL-derived k_2 which are recently summarized by [8], together with the seismic travel time data which are selected by [9], i.e., 318 data (183 P-wave and 135 S-wave) from 59 sources (24 deep quakes, 8 shallow quakes, 19 meteoroid impacts, and 8 artificial impacts). The Love number k_2 is corrected for the anelastic contributions following [7]. We used Markov chain Monte Carlo (MCMC) algorithm to infer the parameters of the lunar internal structure. The solutions of the parameters and their uncertainties are obtained from the posterior distribution which is sampled by the MCMC algorithm.

Results: The inferred mean crustal and mantle structures are basically consistent with previous studies (e.g., [2], [3], [10]). Our model, however, has larger lower-mantle density. P and S wave velocities in the LVZ are estimated to be 6.9 +0.9/-0.5 km/s and 2.6 $\pm$ 1.4 km/s, respectively. A two-dimensional posterior probability function clearly shows a negative correlation between the outer core size and the LVZ thickness; a smaller outer core should be accompanied by a thick LVZ and vice versa. The outer core radius is estimated to be 310 +90/-200 km. The thickness of the LVZ is inferred as 220 $\pm$ 170 km, so provided that the anelastic correction is appropriate, the LVZ is required from the observations. The plausible inference from the existence of the LVZ is that the LVZ is partially molten where viscosity is also low and most of the tidal dissipation occurs [11, 7]. Although the uncertainty is large, the estimated LVZ density at the pressure near the core mantle boundary ($\sim$4.5 GPa) indicates that this zone is typically high-Ti basalt which might have originated black glass with TiO2 content $\sim$16 wt% [12]. The deep Ti-rich composition is consistent with a lunar evolution model involving lunar mantle overturn in which ilmenite-bearing cumulate layer sank with trapped incompatible heat-producing elements [13]. The above discussions support the idea that both tidal heating and radiogenic heating have maintained the partially molten region up until the present.

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キーワード: 月, 低速度層, エネルギー消散, ラブ数, 内部構造
Keywords: Moon, low-velocity zone, energy dissipation, Love number, internal structure

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PPS03-02 会場:A03 時間:5 月 28 日 14:30-14:45

月核マントル境界直上の超低粘性領域内部の強い潮汐加熱
Strong tidal heating inside an ultralow-viscosity zone over the lunar core-mantle boundary

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Tidal heating due to viscous dissipation in a planetary body is an important energy conversion process, depending on its internal structure, and connected to its thermal and orbital states. Our moon is not an exception. Previous studies have calculated the tidal response including dependence of the dissipation on the lunar interior structure, but these studies did not completely explain the geodetically-observed dependence of the dissipation on the lunar tidal period. One possibility to interpret this frequency-dependence is a low-viscosity layer inside the mantle as a natural consequence of the strong seismic attenuation zone, because such a viscosity contrast affects this dependence. However, previous studies have not considered its potential impact. Here we show that the explicit influence of the low-viscosity zone successfully provides the frequency-dependent dissipation on the Moon consistent with the geodetic observables. We found that the above-mentioned high attenuation zone is equivalent to the low-viscosity layer. Furthermore, we also found that the resultant viscosity value is remarkably low, signifying a relaxation time close to the tidal period. This ultralow viscosity implies partial melting as formerly suggested. Our result demonstrates that the most effective dissipation is localised to this layer, indicating a blanket effect on the core. We anticipate that such tidal heating, balanced against convective cooling, maintains this layer over the course of the lunar tidal history.

キーワード: 月, 核マントル境界, 低粘性領域, 潮汐加熱
Keywords: the Moon, core-mantle boundary, low-viscosity zone, tidal heating

Japan Geoscience Union Meeting 2015
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PPS03-03 会場:A03 時間:5 月 28 日 14:45-15:00

Precession, nutation, pole motion and variations of LOD of the Earth and the Moon
Precession, nutation, pole motion and variations of LOD of the Earth and the Moon

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The theories of precession, nutation, pole motion and variations of LOD of the Earth and the Moon are developed on the base of unified approach. The Earth and the Moon are modeled as non-spherical bodies with ellipsoidal liquid core.

The base of studies is the Hamiltonian formalism with application of Andoyer's and Poincare's variables.

New analytical theory of Earth's rotation. The theory of non-spherical Earth's rotation with an elastic mantle, with variable outer shell and with ellipsoidal liquid core in the gravitational field of the Moon, the Sun and planets are developed. As the base the equations of motion have been used equations in Andoyer's variables. We take into account the second harmonic of the geopotential for high-precision orbital description of the motion of the Earth and the Moon. We take into account variations of the components of the inertia tensor of the Earth. They are based on the modern satellite data about secular, annual and semi-annual variations of geopotential. An approximate solution of the problem of the rotation of the Earth is constructed using the small parameter method in Andoyer variables, as well as projections of the angular velocity of rotation of the Earth and its core. It is assumed that the core is an ideal fluid undergoing a simple Poincare's motion. As unperturbed rotational motion of the Earth is taken no axial rotation (rotation around the polar axis of inertia of the planet), and a conical Eulerian ? Chandler motion (Barkin Yu., Barkin M., 2014). The tables of precession, nutation, polar oscillations axis of rotation of the Earth and others perturbations of the Earth rotation have been constracted. They show the good agreement between the developed theory and previously developed theories of the Earth's rotation (Kinoshita, 1977; Getino, Ferrandiz, 2001 et al.).

New analytical theory of lunar rotation. In our work the analytical theory of lunar physical libration based on its two-layer model consisting of a non- spherical solid mantle and of the ellipsoidal liquid core has been developed. On the base of analytical solution for two layers model (the Moon with liquid core) and empirical theory of the Moon's rotation (Rambaux, Williams, 2011), we have identified period, amplitude, and the initial phase of the forth mode of free libration of the Moon, caused by liquid ellipsoidal core. The plans for future studies of the Moon rotation are discussed. On the base of two layers model of the Moon we have fulfilled systematic studies of the Moon physical librations. And in first we have presented a solution of the problem in components of vector of angular velocity of the Moon. An analytical presentation of LOD of the Moon with high accuracy in form of trigonometric series has here the progressive value. In first we have determined the fourth mode of free libration of the Moon caused by the influence of the liquid core oscillations of pole axis of rotation of the Moon (its mantle), with a long period in 205.7 yr, with an amplitude of 0?0395 and the initial phase of -134 o (for the initial epoch 2000.0). The estimates for the dynamic (meridional) oblatenesses of the ellipsoidal liquid core of the Moon: 0.000442 and 0.000283 have been obtained (Barkin et al., 2014).

キーワード: Moon rotation, free libration, liquid core, solid core
Keywords: Moon rotation, free libration, liquid core, solid core

Japan Geoscience Union Meeting 2015
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PPS03-04 会場:A03 時間:5 月 28 日 15:00-15:15

Improvement of the Earth rotation theory: recent advances and prospects
Improvement of the Earth rotation theory: recent advances and prospects

FERRANDIZ, Jose M.[1*] ; GETINO, Juan[2] ; ESCAPA, Alberto[1] ; BARKIN, Yuri V.[3] ; NAVARRO, Juan F.[1]
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Earth rotation is considered as one of the three pillars of modern Geodesy and is presently a very active field of research, due to the very stringent demands of accuracy resulting from a broad set of applications to various fields. The most stringent ones are those related with the monitoring of sea level, which is tightly linked to the climate change and related prevention policies, having both a big economic and social impact.

In 2013 the International Astronomical Union (IAU) and the International Association of Geodesy (IAG) approved the creation of an IAU/IAG Joint Working Group on Theory of Earth Rotation (JWG_ThER) chaired by the first author. This group has a singular structure since comprises 3 sub-working groups. Its purpose is promoting the development of theories of Earth rotation that are fully consistent and that agree with observations and provide predictions of the Earth orientation parameters (EOP) with the accuracy required to meet the needs of the near future as recommended by GGOS, the Global Geodetic Observing System of IAG. Such accuracy is of the order of 1 mm in position, measured on the Earth surface, which corresponds roughly to an angle of 30 micro arc seconds from the Earth's centre.

Those extreme requirements of accuracy challenge all of the theories that have been devised and used up to the date and demand their improvement, paying especial attention to the achievement of a level of consistency appropriate to the pursued accuracy not only in the internal construction of theories but in the realization of the celestial and terrestrial frames related to which the EOP are referred.

This presentation emphasizes the recent advances in the Hamiltonian approach to Earth rotation developed by the authors, since they provide a systematic and consistent way of treating a variety of Earth models and physical second order effects and derive accurate enough mathematical solutions, mainly by means of analytical perturbation methods.

キーワード: Earth orientation parameters, precession, nutation, second-order effects
Keywords: Earth orientation parameters, precession, nutation, second-order effects

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PPS03-05 会場:A03 時間:5 月 28 日 15:15-15:30

Nature of contrasting changes in sea level in the northern and southern hemispheres of the Earth

Nature of contrasting changes in sea level in the northern and southern hemispheres of the Earth

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S/N oceanic secular tide. South-north a ocean secular tide in the present epoch has been found in 2007 and was analytically described the quasi-static approximation by the author (Barkin, 2011). This tide of a different nature compared with the lunar-solar tides. It is caused by the gravitational attraction of Earth's core shifting to the north.

Displacement of the core (and as consequence of the center of mass of the Earth) relative to its mantle generates a slow tide of oceanic and atmospheric masses from the southern hemisphere to the northern (Barkin, 2011). Similar phenomena are also observed on Mars, Titan and other bodies of the solar system. Along with the fundamental core of the tide, we studied other phenomena that determine the secular changes in sea level. Deformation changes the Earth's surface that are installed on the GPS satellite observations. The role of the asymmetric arrangement of the continents in relation to the northern and southern hemisphere. The modern thermal factors of the ocean volume and its thermal expansion. All these factors, taken together, made it possible to explain the observed increase in global average sea level. The result revealed contrasting changes its average levels in the northern and southern hemispheres. In the northern hemisphere the average sea level increases at a rate of about 2.45 ± 0.32 mm / year, and in the southern hemisphere, the average sea level rises with a much lower average rate of 0.67 ± 0.30 mm / yr (Barkin, 2011). I.e. the contrast change NS levels of ocean is 1.78 mm / year.

Confirmation of S/N tide. Revealed asymmetric ocean tide towards south-north also has obtained a clear confirmation in modern observations on the coastal tidal stations in the past 30 years (Evreeva et al., 2007). The theoretical value of the rate of rise of the global sea level was 1.61 ± 0.36 mm / yr (Barkin, 2011). This value agrees well with the modern determinations of its characteristic obtained from the coastal tidal observations at stations including taking into account the vertical geodetic displacements of coastal tide stations. In a recent paper Woppelman et al. (2014), this effect was more evidence. Contrast rates of change mean sea level over the past 100 years was approximately 0.9 mm / year. The authors used data from tide gauges and GPS data to identify the vertical displacements of coastal stations themselves. As a result, by strict selection criteria have been studied in detail data on 76 stations. Estimates of the average velocity change in sea level have been obtained for the entire 20th century. For the northern and southern hemispheres, they amounted to (2.0 ± 0.2) mm / year and (1.1 ± 0.2) mm / year (Woppelmann et al., 2014). In my work in 2007 were received related values (2.45 ± 0.30) mm / year and (0.67 ± 0.30) mm / yr (Barkin, 2011). This match could be more expressive if the studies undertaken to take into account data on some tidal stations located at higher latitudes 60 - 90o in the southern and northern hemisphere. In the paper (Barkin, 2011) we have considered a shorter time interval of about 30 years, at which the contrast of mean sea levels in S/N hemispheres is represented by more expressive. We also note that according to our research post glassial rebound effects and the effects of vertical displacement observation stations (in average sense) do not provide a significant contribution to the parameters studied changes in sea level (Shen et al., 2015). Studies of South - northern secular tide require additional intensive research. The work was accepted by grant of RFBR N 15-05-07590 A.

キーワード: sea level increase, Southern-northern secular ocean tide, moving core
Keywords: sea level increase, Southern-northern secular ocean tide, moving core

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PPS03-06 会場:A03 時間:5 月 28 日 15:30-15:45

月レーザ測距データ精密解析のためのソフトウェアの開発とその初期成果
Software development for precise LLR data analysis and initial results of parameter estimation for lunar motion

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In order to estimate lunar interior structure from lunar libration and tidal displacement, we are developing new analysis software for precise determination of lunar orbital/rotational motion using lunar laser ranging (LLR) observation data.

As the first step of the software development, we construct an LLR observation model. The model consists of the newest physical models compatible with IERS Conventions (2010) such as Earth orientation, solid tides of the Earth and the Moon, atmospheric delay correction, and some relativistic factors affecting laser propagation delay. For the purpose of calculating these components precisely, we use modules of the geodetic data analysis software ”c5++” [Otsubo et al., JpGU, 2011]. Comparison between observed and calculated ranges is done by combining our own-developed observation model and the lunar orbit/libration obtained from the numerical ephemeris DE430 (provided by NASA JPL). In this calculation, there are 3577 LLR normal points distributed from June 1996 to July 2013, observed at Apache Point, Grasse, Matera and McDonald. The mean value of the residuals of one-way ranges is about 5.7 cm, and the standard deviation is about 4.8 cm.

The following steps are numerical integration of lunar orbit and libration, and the least-squares fitting of integrated ephemeris to observed values. As the date of the submission, only the orbital motion can be determined, and some relating parameters such as positions of retroreflector arrays, lunar mass and the lunar displacement Love numbers are to be estimated. For the models of lunar orbital motion, we implement post-Newtonian EIH equation of motion and perturbations from spherical harmonics of geopotential and J2 term of solar gravity field.

The presentation contains the current status of software development. We will report the results of above-mentioned observation modeling, numerical integration of lunar motion, and estimation of lunar physical parameters.

キーワード: 月, 月レーザ測距, 暦, 秤動
Keywords: Moon, lunar laser ranging; LLR, ephemerides, libration

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月回転観測のための小型望遠鏡の開発のまとめと地上観測の結果
Summary of the development of a small telescope for lunar rotation and the experiments on the ground.

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We have been developing a small telescope like Photographic Zenith Tube (PZT) for observations of lunar rotation since the 1990s. We know the lunar rotation by positioning of stars from the lunar surface, and the accuracy of 1 milli-arc-second (1mas) can detect components of physical librations related to dissipation in the Moon. Observation of lunar rotation is one of the essential and basic observations for investigating the interior of the Moon.

We have already developed a bread board model (BBM) of a PZT type telescope for basic experiments. Technical development for improvement of the accuracy, environmental test of key elements were made by using the BBM. A new tripod makes it possible to set the telescope on the slope of less than 30 degrees, and it keeps the tube vertical within the error of 20 arc-seconds. PZT has a potential to observe deflection of the vertical (DOV) with an accuracy better than 0.1 arc-seconds on the ground. It will be possible to reduce the effect of atmospheric turbulence to be smaller than 0.1 arc-seconds by statistical procedure of observed data. It is also possible to reduce the effect of the ground vibrations to be less than 0.1 arc-seconds judging from the laboratory experiments.

We performed observations on the ground in September of 2014, in order to check the total system of the telescope and the software. It is also important to evaluate the effect of the ground vibrations and temperature change upon the stellar position on CCD. The goal of the observations on the ground is to attain the accuracy of better than 0.1 arc-seconds. The results of the preliminary observations showed that the scatter of stellar positions was about 0.4 arc-seconds, which is a little larger than expected. It is partly due to insufficient signal to noise ratio of star images. Verification of 1 mas on the Moon will be possible in a laboratory equipped with a special space chamber providing the environment on the Moon in the future.

Keywords: libration, PZT, telescope, mercury pool, lunar interior