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Dynamical model of lunar core and observational constraint from Lunar Laser Ranging

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1. Introduction

Our Moon is one of the most studied objects in the Solar system; we benefit from chemical, geophysical, and geodetical observations achieved by multiple Earth ground based telescopes and in situ missions. However, its deep interior properties remain a puzzle because the lunar core is very small implying weak signature in the observational data set. This paper focuses on the description of a new lunar core rotational model included in INPOP [12] and used to provide a determination of the radius and geometry of the lunar core-mantle boundary (CMB) from the LLR observations. The obtained CMB radius is in full agreement with one seismological model [5].

2. LLR and GRAIL observations

The Moon's rotation is measured with a remarkable accuracy of few milli-arcseconds thanks to the Lunar Laser Ranging (LLR) experiment that has been active since 1969 e.g. [3]. This experiment consists in the measurement of the round-trip travel time of a short laser pulse between an Earth observatory and one of the five corner cube retroreflector arrays settled on the Moon [13, 10, 12]. Earth observatories such as the Apollo station [9] and OCA station [1] regularly range to the retroreflectors in order to obtain echoes and carry on the collection of data. A strong interest from the laser ranging science has led to the emergence of new LLR stations Hartebeesthoek-South Africa [8],Yunnan-China, Wettzell-Germany [4] and next-generation of retro-reflector developments [2]. The LLR data processing is a very sophisticated and challenging task, even after more than 40 years of routine observational operation.

In addition, the Moon has been the target of the space mission Gravity Recovery and Interior Laboratory mission (GRAIL) that determined the gravity field of the Moon at an unprecedented accuracy [6, 7]. It has been obtained with an improved accuracy of 4-5 order of magnitude up to degree and order 660 and higher in spherical harmonics (see e.g. [6]). In addition, the love number k_2 has been improved by a factor 5. Such great accuracy is reached thanks to a mission concept similar to GRACE and the use of a Ka-band transponder instead of S-band transponder (see e.g. [6] and reference therein).

3. Dynamical models and results

Due to the high accuracy of the LLR observations and the large amount of data, the lunar rotation is integrated numerically in INPOP ephemeris and fitted to LLR observations, e.g. [12]. This model is obtained from a joint numerical integration of the orbits of the Moon, the Earth, the planets and asteroids, and of the lunar rotation. The dynamical partial derivatives of the orbits and lunar Euler angles with respect to solution parameters such as moment of inertia, gravity field, tides, dissipation, interaction with a fluid core and initial conditions are computed and the adjustment provides the determination of these geophysical parameters (for a complete description see also [13, 10] and references therein). Here, we have developed a full set of rotational equations for the whole Moon and for the fluid-core that take into accout the pressure torque due to the fluid core on the non-spherical CMB interface and the triaxiality of the interface. This set of equations is also developed for the inner core with pressure and internal gravitational torques. The method is an extension and improvement of the method developed in [11] and here applied to the rotational motion of a differentiated Moon.

This rotation model has been introduced in INPOP. Then, a least-square iterative fit of the dynamical and geophysical model parameters to the LLR data was applied. In particular, by fixing the size of the core, it is possible to determine the flattening of the CMB which optimally adjusts the observations. This was a necessary requirement to maintain the recent (and most accurate) LLR post-fit weighted root-mean-square (wrms) to well-below 2 cm. Then, the size of the core is varied and the fit re-processed. By this method, it is possible to limit a radius interval of the core where the CMB shape corresponds to the hydrostatic case (included in a non-hydrostatic lithosphere). The bounded core size is consistent with the analysis of the seismic data [5] and previous LLR model [13] but the accuracy of the core oblateness and radii of a presently-relaxed lunar core is improved by a factor of 3. This determination brings new constraints on the interior of the Moon and especially for the formation of the Earth-Moon system. Furthermore, this apporach may be applied to other solar system bodies.

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