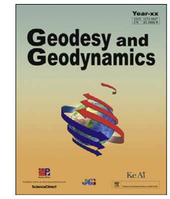
Geodesy and Geodynamics xxx (2017) 1–7

Contents lists available at ScienceDirect

Geodesy and Geodynamics

journal homepages: www.keaipublishing.com/en/journals/geog; http://www.jgg09.com/jweb_ddcl_en/EN/volumn/home.shtml



Understanding the effects of the core on the nutation of the Earth

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A R T I C L E I N F O

Article history:
Received 29 December 2016
Received in revised form
18 April 2017
Accepted 21 April 2017
Available online xxx

A B S T R A C T

In this review paper, we examine the changes in the Earth orientation in space and focus on the nutation (shorter-term periodic variations), which is superimposed on precession (long-term trend on a timescale of years). We review the nutation modelling involving several coupling mechanisms at the core-mantle boundary using the Liouville angular momentum equations for a two-layered Earth with a liquid flattened core. The classical approach considers a Poincaré fluid for the core with an inertial pressure coupling mechanism at the core-mantle boundary. We examine possible additional coupling mechanisms to explain the observations. In particular, we examine how we can determine the flattening of the core as well as information on the magnetic field and the core flow from the nutation observations. The precision of the observations is shown to be high enough to increase our understanding on the coupling mechanisms at the core-mantle boundary.

1. Introduction

The relationship between the celestial frame and the terrestrial frames is complicated by the fact that the rotation and orientation of the Earth is subject to irregularities. The paper examines developments for improved model of Earth rotation and orientation at the sub-centimetre level.

The changes in the Earth orientation are caused by the gravitational attraction of the Sun and the Moon on the Earth, as well as many other factors that are progressively being identified by geodesists and geophysicists (in particular, the existence of a liquid core inside the Earth plays an important role). Because the Earth's shape can approximately be described as an ellipsoid flattened at its poles, the combined forces acting upon the Earth produce changes in both the speed of rotation and the orientation of the spin axis (Fig. 1). The term 'precession' describes the long-term trend of this latter motion (as seen on a timescale of several years), while 'nutation' is the name given to shorter-term periodic variations. These are the prime focus of the present paper. The precession of the Earth in space corresponds to about 50 arc seconds per year and the nutation amplitude is at the level of a few tens of arc seconds. The rotation axis of the Earth is moving in space at the speed of 1.5 km/year due to precession and has periodic variations with amplitudes at the level of 600 m (as seen from space in a plane tangent to the terrestrial pole). The present observations allow scientists to measure these at the sub-centimetre level.

Earth rotation changes, precession, and nutation are measured using Very Long Baseline Interferometry (VLBI), a technique that employs radio telescopes (Fig. 2) to observe extra-galactic radio sources such as quasars, which allows us to establish a celestial reference frame.

This geodetic technique is based on simultaneous recordings of radio emissions received from extra-galactic radio sources by a number of radio telescopes (5–20). The radio dish antennas, ranging from 3 to 100 m in diameter, form part of a worldwide VLBI network. They are situated at distances of hundreds to many thousands of kilometres from each other's. Each recording, electronically captured during the observation session, carries also, along with the radio emission received at the VLBI station, a time signal from the "station clock". These clocks are very high accuracy and stability atomic clocks, such as hydrogen maser clocks. Each

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Peer review under responsibility of Institute of Seismology, China Earthquake Administration.

ELSEVIER Production and Hosting by Elsevier on behalf of KeAi

http://dx.doi.org/10.1016/j.geog.2017.04.005

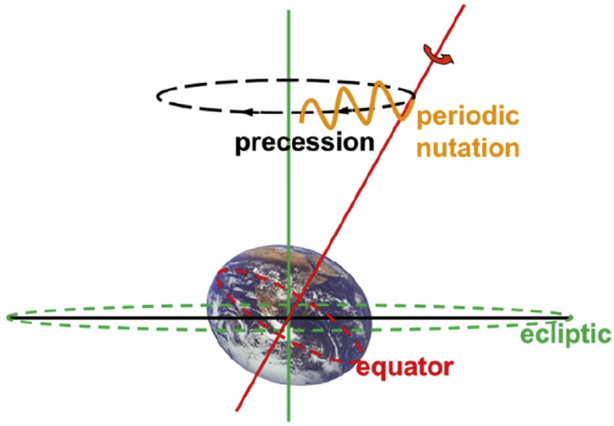

Fig. 1. Representation of precession and nutation of the Earth.

Fig. 2. VLBI antenna of Shanghai, China.

VLBI observing session lasts typically for a few hours to about 24 h. Emissions from many different radio sources (typically 100 sources) are recorded during one such session. The data are put on recording discs that are shipped, if not directly electronically transmitted, to a central processing site for analysis. One then evaluates the delay between the two arrival times of the same signal based on the expected identity of the temporal variations of the emissions recorded at two different stations. This determination is done by using a correlator/processor measuring with a precision at the level of 10 ps.

The VLBI observations are then compared with a model of the Earth orientation and rotation. The data have now been cumulated for over about 30 years. The data were showing large differences compared to theoretical nutation models at the beginning of the technique, leading to re-evaluation of the model. At present, they still show significant differences at the centimetre level (1 mas ≅ 3 cm). Fig. 3 show the differences between the VLBI observations and the results obtained from applying a theoretical model adopted by the International Astronomical Union (IAU) in 2000 (nutation) and 2006 (precession) and by the International Union of Geodesy and Geophysics (IUGG) in 2003 (see IERS Conventions [1–3]). If eventually corrected for the free FCN (Free Core Nutation) contribution, these differences are presently at one third of a mas level.

The adopted model depicts the Earth as a deformable object with a deformable inner core (viscoelastic central part of the Earth composed of a solid iron alloy), a liquid core (also composed of iron alloy), a deformable viscoelastic mantle (composed mainly of olivine and perovskite) (see Fig. 4), as well as oceans and an atmosphere. The adopted theoretical model is almost perfect as seen from the observed residuals. The gravitational torques exerted by other solar system bodies on the Earth are the cause of the nutations and can be precisely computed [4–6]. The response of the Earth to this forcing allows us to constrain interior properties and is modelled in terms of a transfer function [7–10]. The transfer function is the ratio between the amplitudes of the circular wobbles for the non-rigid and rigid Earth models and is independent of the amplitude of the torque. We may compute these ratios for the different frequencies of the forcing. The ratios are defined only for circular motions and are determined solely by the structure and properties of the non-rigid Earth. Transfer functions are of considerable utility as the nutations of the rigid Earth have been studied extensively in the literature [4–6] and highly accurate results are available. Once the transfer function is computed for the chosen non-rigid Earth model for any frequency of the excitation, the non-rigid Earth amplitude is simply obtained as the product of the transfer function with the rigid-Earth response at some chosen excitation frequency. The rigid Earth amplitudes (for an axially symmetric ellipsoidal model) depend on the dynamical ellipticity. A re-scaling according to the true non-hydrostatic dynamical ellipticity to be used can always be done as well. This computation ignores the external geophysical fluids and the small contributions from the oceans and atmosphere [11–15] have to be accounted for through further refinement of the model (for more detail, [16,17]). The coupling mechanisms at the boundaries between the inner core, the liquid outer core, and the mantle are not yet understood or modelled accurately enough to be properly included inside a complete nutation model. The aim of our paper is to show, with a simple approach, how to get further insight into the Earth's interior, by coming up with a new model for nutation considering new advanced theories involving physical concepts for the non-rigid Earth that have not been taken into account previously.

The paper revisits the simple two-layer semi-analytical approach for better understanding and modelling the physical processes inside the Earth's core associated with Earth nutation and in particular at the core-mantle boundary (CMB) where uncertainties remain. The existence of a liquid core inside the Earth and all the coupling mechanisms at the core-mantle boundary play indeed an important role in nutation amplitudes. A mundane demonstration of the influence of the physical state of the interior on the rotation is that raw (liquid) and cooked (solid) eggs rotate differently. For the Earth, the identified mechanisms considered in the previous nutation model involve the flattening of the core and the fluid pressure and gravitational effect on that flattened boundary (see Ref. [18]) as well as a simple dipole and uniform magnetic field effect [10,19–21], because of their role in transferring angular momentum from the core to the mantle. By now we have understood that there are important roles from other components of the magnetic field [22–29], and possibly from the viscosity of the inner core [30–37], from the viscosity of the outer core [27–29], or from the core stratification [38–42] could have significant contributions to nutation, and that topography at the core-mantle boundary at the kilometre level plays an important role as well [43–45]. Seismic tomographic data have indeed pointed out the existence of valleys and mountains at the interface between the liquid core and the viscous deformable mantle down at about 2900 km below the surface. We also point out that the inertial waves associated with the topography at the core-mantle boundary may interact with the core flow produced by nutations, and may

Please cite this article in press as: V. Dehant, et al., Understanding the effects of the core on the nutation of the Earth, Geodesy and Geodynamics (2017), http://dx.doi.org/10.1016/j.geog.2017.04.005