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Assessment of the effect of three-dimensional mantle density heterogeneity on Earth rotation in tidal frequencies

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ABSTRACT

In this paper, we report the assessment of the effect of the three-dimensional (3D) density heterogeneity in the mantle on Earth orientation parameters (EOP) (i.e., the polar motion, or PM, and the length of day, or LOD) in the tidal frequencies. The 3D mantle density model is estimated based upon a global S-wave velocity tomography model (S16U6L8) and the mineralogical knowledge derived from laboratory experiment. The lateral density variation is referenced against the preliminary reference earth model (PREM). Using this approach the effects of the heterogeneous mantle density variation in all three tidal frequencies (zonal long periods, tesseral diurnal, and sectorial semidiurnal) are estimated in both PM and LOD. When compared with mass or density perturbations originated on the Earth's surface such as the oceanic and barometric changes, the heterogeneous mantle contributes less than 10% of the total variation in PM and LOD in tidal frequencies. However, this is the gap that has not been explained to close the gap of the observation and modeling in PM and LOD. By computing the PM and LOD caused by 3D heterogeneity of the mantle during the period of continuous space geodetic measurement campaigns (e.g., CONT94) and the contribution from ocean tides as predicted by tide models derived from satellite altimetry observations (e.g., TOPEX/Poseidon) in the same period, we got the lump-sum values of PM and LOD. The computed total effects and the observed PM and LOD are generally agree with each other. In another word, the difference of the observed PM and LOD and the model only considering ocean tides, at all tidal frequencies (long periods, diurnals, and semidiurnals) contains the contributions of the lateral density heterogeneity of the mantle. Study of the effect of mantle density

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heterogeneity effect on torque-free Earth rotation may provide useful constraints to construct the reference earth model (REM), which is the next major objective in global geophysics research beyond PREM.

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1. Introduction

As a vector, the components of the Earth orientation parameters (EOPs) vary in both magnitude and axis orientation. The variation in rotational speed is often expressed in terms of Universal Time (UT1) or in its time derivative the length of day (LOD), while the variation in the rotation axis orientation relative to the terrestrial reference frame is referred to as the polar motion (PM). Two types of precise geophysical data have been available in the last few decades: i) tidal signals in both Earth rotational speed variations and PM extracted from high precision space geodetic measurements such as very long baseline interferometry (VLBI); and ii) the contribution of ocean tides to the above signals as predicted by tide models derived from satellite altimetry observations. The difference of the two at all tidal frequencies (long periods, diurnals, and semidiurnals), reaching a couple of hundred micro-arc-sec in PM and a few tens in LOD, can be reasonably (or at least partially) attributed to the effect of the lateral density heterogeneity of the mantle. In this paper we develop an algorithm and conduct the computation to assess the effect of mantle lateral density heterogeneity to Earth rotation in tidal frequencies. The mantle heterogeneity model is derived from the global seismic shear velocity tomography. With the inclusion of this effect, we can significantly reduce the discrepancy between the observed lump-sum EOP signal and that caused by ocean tides.

Meanwhile, significant advance have also been made in satellite oceanic altimetry. A number of research projects had accounted for the ocean tidal effects on Earth rotation, as ocean tide models continue to be improved on TOPEX/Poseidon data [1]. As a natural extension, this paper accounts for the corresponding effects of the mantle density heterogeneity that has the same type of effects as do oceans. Although the tidal deformation that can be attributed to density heterogeneity is small in magnitude in comparison with that of the ocean, the total mass involved is much larger. The net result therefore could be potentially significant. Mantle heterogeneity models derived by seismology are employed for the computation of their effects on tidal signals in both UT1/LOD and PM for all long-period, diurnal, and semidiurnal tides. Conversely, these signals provide global constraints to (degree-2 harmonics of) three-dimensional (3D) mantle density models for a better understanding of the internal dynamics of the solid Earth, a subject under active development for achieving a new generation of reference earth models (REM) [2].

This paper adds a new dimension of study to understand the variations in the Earth rotation caused by density heterogeneity in the mantle by looking into more subtle causes. This study finds another useful application of seismic velocity tomography results. The rest of the paper is organized as follows. In the next section, we give a brief inventory of the Earth rotation variations in tidal frequencies, including both the external (with torque on the Earth) and internal (torque-free) causes. The focus of this study is then pointed out to put our study in context. In section 3, we layout the theoretical fundamentals by giving a brief theoretic workflow to reach the point we can start the computation. In section 4, we present the observed EOP signals in tidal frequencies in the time window of the VLBI campaign CONT94, as well as the EOP variations caused by the ocean tides based on the ocean tide model. Section 5 describes the approach to evaluate the magnitude of the 3D variation in mantle density based on a seismic shear wave velocity tomography [3]. Finally we discuss the results and conclude by emphasizing the significance of our approach for future studies.

2. An inventory of the effects of the luni-solar tides on Earth's rotation

The luni-solar tides influence the Earth's rotation in a variety of ways. Familiar examples include astronomical precession/nutation and tidal braking. These astronomical effects are caused by direct external tidal torques as the driving force. The tidal effects under consideration in this paper, however, are those caused by the tidal deformation inside the solid Earth acting as an internal source via the conservation of angular momentum.

Table 1 summarizes all tidal influences on Earth's rotation. In this perspective, our study pertains to the item shown in **boldface** type. In an axially symmetric Earth, only the zonal, long-period tidal forcing can affect UT1 (or equivalently LOD) because of symmetry properties (mathematically expressed as the orthogonality of spherical harmonics). The solid Earth is indeed nearly axially symmetric and avails a large quantity of mass for tidal deformation (typically an order of magnitude larger than the ocean tides in terms of mass transport), hence long-period tidal signals are very prominent in LOD records; for example, the M_f amplitude is as large as 350 μs. The discrepancies between the observed and the theoretically predicted amplitudes and phases have been used to constrain core-mantle coupling, ocean tide contribution, and mantle inelasticity, e.g., [4,5], but mantle heterogeneity has not been