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A 6-year westward rotary motion in the Earth: Detection and possible MICG coupling mechanism

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ABSTRACT

Seeking geophysical explanations for the periodic ∼six-year oscillation (SYO) previously found in the Earth's length-of-day variation (ΔLOD), we analyze the global GPS displacement and geomagnetic data using the array processing technique of OSE (Optimal Sequence Estimation), and find clear evidences of the 6-yr signals which manifest as a westward rotary propagating wave of the sectoral spherical-harmonic pattern of degree-2 order-2 (Y_{22}). Based on the period, the spatial pattern, and the amplitudes and the estimated phases that exhibit consistent synchronicity among the three datasets, we propose the following scenario: The mantle-inner core gravitational (MICG) coupling gives rise to a 6-yr axial torsional libration of the inner core controlled by the sectoral Y_{22} density anomalies, or the equatorial ellipticities, in the inner core and the (lower) mantle, the angular momentum exchange between which manifests as the SYO in ΔLOD. It forces into action a pressure wave-2 cyclic in 6 yr through the fluid outer core, which in turn produces the corresponding GPS and geomagnetic variations. Our findings provide insight into the dynamics of the deep Earth, and corroborate a positive density anomaly for the lower-mantle Large Low-Shear-Velocity Provinces.

1. Introduction

A steady six-year oscillation (SYO for brevity), more precisely determined here to be of period 5.9 ± 0.04 yr, has previously been observed in the solid-Earth's spin rate or length-of-day (LOD) variation ΔLOD (Abarco del Rio et al., 2000; Mound and Buffett, 2006; Holme and de Viron, 2012; Chao et al., 2014; Duan et al., 2018). The stable periodicity of SYO is irreconcilable to the Earth's large-scale visco-elastic behavior manifesting in the gravest modes of free oscillation that have periods no longer than 1 h. The angular momentum (AM) conservation relation $\Delta AM_{\text{fluid}}/AM_{\text{mantle}} = \Delta\text{LOD}/\text{LOD}$ (where LOD $= 86400$ s) for the polar or axial component of AM dictates that the observed ΔLOD SYO amplitude of $\sim\pm 0.13$ ms amounts to $\sim 10^{-9}$ mantle's total AM to be exchanged with the fluid parts of the Earth. That amount would be equivalent to an east–west wind field of magnitude comparable to that of the stratospheric quasi-biennial oscillation (Chao, 1989), or a (fictitious) oceanic circum-globe equatorial ocean current the size of Kuroshio of flux $\sim\pm 25$ Sv (where 1 sverdrup Sv $= 10^6$ m^3/s, about the total flux of world river runoff), flip-flop every 3 yr. Likewise, if placed in the fluid outer core (of heavy material) it would be equivalent to an equatorial current of alternating flux as large as $\sim\pm 10$ Sv. However, if the SYO in ΔLOD comes from the AM exchange between the solid inner core and the mantle, given their moments of inertia, the solid inner core as a whole would only need to undergo a torsional oscillation around its spin axis, or libration, of ±0.27° during the 6-yr cycle to enable the required AM exchange (Chao, 2017).

Gillet et al. (2010) found a ∼5–8 yr signal in the geomagnetic field, and postulated a torsional oscillation giving rise to a ∼6-yr geostrophic oscillation in the fluid outer core in light of the Taylor Proudman theorem (Taylor, 1963); Teed et al. (2015) suggested that it may be driven by the Lorentz force at the tangent cylinder in the fluid core. Silva et al. (2012) and Holme and de Viron (2012) (see also Chulliat et al., 2015) characterized the geomagnetic spatial behavior and suggested that the SYO in ΔLOD be closely related to or excited by geomagnetic jerks, whilst Soloviev et al. (2017) further suggested some relationship of SYO with the 1996, 1999, 2002 and 2014 geomagnetic jerk events.

Alternatively, Buffett (1996a, 1996b) and Mound and Buffett (2006) suggested that the SYO in ΔLOD may come from the mantle-inner core gravitational (MICG) coupling, with the coupling strength of $\widetilde{\Gamma} = 3.0 \times 10^{20}$ Nm. Davies et al. (2014) estimated that

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$\widetilde{\Gamma} = 3.0 \times 10^{19}$-$2.0 \times 10^{20}$ Nm based on a broad range of viscous mantle flow models with density anomalies inferred from seismic tomography, while Chao (2017) estimated that $\widetilde{\Gamma} \sim 6.5 \times 10^{19}$ Nm for the inner-core's axial torsional libration under MICG coupling to accommodate the SYO of ΔLOD. Adopting the latter scenario, in the present study we suppose this libration of the inner core sets off a rotary pressure wave through the fluid outer core, inducing deformations in the mantle (cf. Fang et al., 1996; Greff-Lefftz et al., 2004) and in turn causing geophysical changes (admittedly small) which get observed at the Earth's surface.

Thus, we shall report the positive detection of the SYO signals in two global geophysical datasets, namely the GPS (Global Positioning System) 3-D surface deformation field and, to a lesser degree, global geomagnetism. This finding is obtained upon using the array-processing method of the Optimal Sequence Estimation (OSE; Ding and Shen, 2013; Ding and Chao, 2015, 2017), which constructs from all array records the optimal composite time series of certain targeted spatial signal in the least-squares sense, solved along with other possible signals that are orthogonal to the target signal to absorb untargeted signals when feasible. In terms of the behavior of the GPS deformation and the geomagnetic fields, we report, and hence propose an explanation, that our findings are well consistent with the above scenario of inner core's axial libration under the MICG coupling.

2. Data

The main dataset used in the present study is the surface deformation obtained from the global GPS array; the secondary dataset is the geomagnetic field variation from global geomagnetic records. We also report data analysis of six other ancillary global datasets in the Supplementary Information (Figs. S1–S6).

The continuous GPS 3-D surface deformation data are acquired from the Jet Propulsion Laboratory (JPL) website release. We select 38 records of timespan longer than 3 cycles of SYO (1995/01/01–2015/04/02) for the vertical up- or U-component, and 31 records for the horizontal north N- and east E-components (see Supplementary Information, Table S1), all the selected records with data gaps no longer than 180 days. The JPL-released data already removed of the seasonal (annual and semi-annual) terms and the solid and ocean tidal signals, we further remove the spikes and prominent steps in the data series as well as the equilibrium ocean pole tide effect (although small). We also interpolate the data gaps by spline interpolation. The resultant residual, broad-band time series are subsequently subjected to the OSE analysis below.

The global geomagnetic records are provided by the World Data Centre for Geomagnetism. We first de-spike and de-step the original data and interpolate through short data gaps as above, and decimate (after proper low-pass filtering) them from hour to daily sampling. For the records that are several decades long, we empirically remove the effects of signal powers of periods much longer than 6 yr by least-squares fitting of long-period sinusoidal terms nominally at 93 yr, 186 yr and 280 yr, or alternatively polynomial of degrees up to 10. We then select the timespan 1990–2010.5 to be our data span and wind up with 31 worldwide records. We convert the provided geomagnetic intensity F, declination D, and inclination I into the U, N, and E components by $\mathrm{U} = -F \cdot \sin I$, $\mathrm{N} = F \cdot \cos I \cdot \cos D$ and $\mathrm{E} = F \cdot \cos I \cdot \sin D$.

In an effort to put the SYO signal in geophysical perspective, we further analyze six other global datasets: the ΔLOD, the Earth's oblateness (J_2) variation, the polar motion, the time-variable gravity field (from GRACE satellite), the superconducting gravimetry records, and the global mean sea-level variation. Those results are presented in the Supplementary Information.

3. Method

The method of OSE aims to retrieve spatially coherent signals of known mathematical form among multiple records, by way of a matrix inversion simultaneously with a set of non-target functions that are orthogonal to the target function to absorb the possible presence of such signals. In the present case, the targeted signal is in the form of vector spherical harmonics of specified degree l and order m, for which we speak of the OSE "$[l, m]$ stack" time-series. The non-target signals are other, orthogonal spherical harmonics of some neighboring l or m. The stack greatly enhances and facilitates the detection of the (subtle) targeted signal, as demonstrated in Ding and Chao (2015, 2017).

We assume that the U-component of the GPS displacement field under consideration can, as global geophysical quantities often do, be expressed in the spherical harmonic expansion $u_{\mathrm{U}}(t) = \sum_{l,m} A_{lm}(t) Y_{lm}(\Omega)$, where A_{lm} denotes the complex 'excitation' amplitude and $Y_{lm}(\Omega)$ is the complex, fully normalized spherical harmonic function of degree l and order m where the solid angle Ω includes θ (co-latitude) and λ (longitude). Suppose we have K records (having the same timespan) from different stations with $K > 2l + 1$ for a targeted degree l. We assemble the records into a data matrix, $\mathbf{U}_{\mathrm{U}} = \left[u_{\mathrm{U}1}(t) \quad u_{\mathrm{U}2}(t) \quad \ldots \quad u_{\mathrm{U}K}(t) \right]^T$ (T denoting matrix transpose):

$$\mathbf{U}_{\mathrm{U}} = \mathbf{A}\mathbf{Y}, \tag{1}$$

where the $K \times (2l + 1)$ basis matrix

$$\mathbf{Y} = \begin{bmatrix} Y_{l(-l)}(\Omega_1) & Y_{l(-l+1)}(\Omega_1) & \vdots & Y_{ll}(\Omega_1) \\ Y_{l(-l)}(\Omega_2) & Y_{l(-l+1)}(\Omega_2) & \vdots & Y_{ll}(\Omega_2) \\ \vdots & \vdots & \ddots & \vdots \\ Y_{l(-l)}(\Omega_K) & Y_{l(-l+1)}(\Omega_K) & \ldots & Y_{ll}(\Omega_K) \end{bmatrix}$$

and $\mathbf{A} = \left[A_{l(-l)}(t) \quad A_{l(-l+1)}(t) \quad \ldots \quad A_{ll}(t) \right]^T$ is the $(2l + 1)$-vector to be inverted, which can be readily done in the least squares as $K > 2l + 1$. Thus,

$$\mathbf{A} = \left(\mathbf{Y}^T \mathbf{p} \mathbf{Y}\right)^{-1} \mathbf{Y}^T \mathbf{p} \mathbf{U}_{\mathrm{U}}, \tag{2}$$

where the weight matrix $\mathbf{p}$, assuming that all records are independent, is diagonal whose values can be chosen to be inversely proportional to the spectral amplitude SNR of the target signal. A set of composite time series, those contained in $\mathbf{A}$, can thus be constructed, each time series is called the $[l, m]$ *stack*.

The same OSE procedure can be readily applies to the N/E-components only with different basis matrices $\mathbf{Y}$ of relevance for Eqs. (1), (2), now involving the vector spherical harmonics (which form orthogonal sets as Y_{lm} do), specifically $u_{\mathrm{N}}(t) = -\sum_{l,m} B_{lm}(t) \partial_\theta Y_{lm}$ and $u_{\mathrm{E}}(t) = \sum_{l,m} B_{lm}(t) \partial_\lambda Y_{lm} / \sin\theta$ (Ding and Chao, 2017). We do the solutions for both spheroidal and toroidal parts, whereof the two horizontal components are built into one single matrix equation for matrix solutions (cf. Ding and Chao, 2015).

The physical meaning of the stack $A_{lm}(t)$ (or $B_{lm}(t)$) is the excited amplitude at the given moment t, which is normalized to the Greenwich Meridian. Specifically, the amplitude of the $[2, 2]$ stack is normalized to the Y_{22} value at co-latitude $\theta = 90°$ (equator) and longitude $\lambda = 0°$. Note that, in our case of the GPS displacement, this registered amplitude has already been modified by the relevant Lover number h_{lm} (or l_{lm}) of the real Earth. In applications of detecting tides or normal modes of free oscillation, the time series would contain (dominantly) the sinusoidal signal of the relevant periodicity (e.g., Ding and Chao, 2015, 2017). In the present application we shall of course look for the SYO signals in the stacks; we