On the possible detection of inter-annual deformation signal at the Earth’s surface due to the fluid core dynamics

Length-Of-Day variations and Torsional waves

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Journées 2019 - Astrometry, Earth Rotation and Reference Systems in the Gaia era
**LOD changes**

In terrestrial reference system,

\[ \omega = \Omega(m_1, m_2, 1 + m_3) \]

\[ \Delta LOD = -LODm_3 \]

<table>
<thead>
<tr>
<th>Processes</th>
<th>Time scale</th>
<th>Amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tidal friction, GIA, present-day ice melting, tectonics, etc.</td>
<td>secular</td>
<td>&lt; 2 ms/cy</td>
</tr>
<tr>
<td>Core-Mantle interactions</td>
<td>decadal</td>
<td>(\sim 2) ms</td>
</tr>
<tr>
<td>Atmospheric, oceanic and hydrologic</td>
<td>interannual</td>
<td>(\sim ms)</td>
</tr>
<tr>
<td>Core-Mantle interactions</td>
<td>interannual ((\sim 6) yr)</td>
<td>(\sim 0.12) ms</td>
</tr>
<tr>
<td>Atmospheric, oceanic and tides</td>
<td>seasonal</td>
<td>(\sim 0.5) ms</td>
</tr>
<tr>
<td>Tides</td>
<td>monthly &amp; fortnightly</td>
<td>(\sim 0.5) ms</td>
</tr>
</tbody>
</table>
A 5.9-yr oscillation in LOD


Holme & de Viron (2013)

Figure 2 | Decadally detrended LOD data (with 6-month running average), plotted with 5.9-year oscillation fit (dashed line). Vertical lines show best determinations of geomagnetic jerk timings.

↓

5.9-year oscillation
A 5.9-yr oscillation in LOD: Mechanism?

Mantle-Inner Core Gravitational coupling (MICG)

Chao (2017)

Unlikely alone: strength of gravitational coupling too small (Davies et al. 2014)

Torsional waves
Gillet et al. (2010; 2017)

Teed et al. (2019)

→ Traveling Waves break upon CMB
Core-Mantle Angular Momentum exchanges

axial invariance (quasi-geostrophy) in numerical geodynamo simulation

Schaeffer et al. (2017)

if axially invariant: only concern $t_1^0$ and $t_3^0$ "zonal" coefficients

Jault et al. (1988); Jackson et al. (1993); Jault & Finlay (2015)
Core-Mantle Angular Momentum exchanges

Variations in core angular momentum caused by time changes of geostrophic velocity are compensated by variations in mantle angular momentum and thus in LOD.

- Geostrophic flow velocity:
  \[ U_G = - \sum_{n=0}^{\infty} t_{2n+1}^0 P_{2n+1} \]

- Core angular momentum (\( C_c \) core moment of inertia):
  \[ H_c \simeq C_c \left( t_1^0 + 1.776 t_3^0 + 0.0796 t_5^0 + 0.002 t_7^0 + 4.10^{-5} t_9^0 + \ldots \right), \]

- Conservation of total angular momentum of Earth:
  \[ \Delta LOD = -H_c \frac{2\pi}{\Omega^2 C_m} \simeq 1.232 \left( \delta t_1^0 + 1.776 \delta t_3^0 \right) \]

(LOD in ms, flows in km/yr) 

Jault & Finlay (2015)
(top) Flow coefficient $t_0^1$ (km/yr)
(middle) predicted (black) and observed LOD changes (red) (ms)
(bottom) LOD band-pass filtered between 4 and 9.5 years.

→ inter-annual LOD changes well-explained by core flow models inverted from (independent) geomagnetic data

(Gillet et al. 2015)
A 5.9-year signal in GNSS and magnetic data?

Ding & Chao (2018): $Y_2^2$ pattern, linked to MICG coupling

amplitudes a few mm (on Z) and 5-10 nT (on $B_r$) (Ding & Chao 2018)
A 5.9-year signal in GNSS data?

Watkins et al. (2018):
• stacked spectra (BUT only 12-years of time-series)
• a 5.9-year signal detected in GNSS data but not conclusive

→ Is the observed 5.9-yr oscillation compatible with core flows models?
→ Can we reproduce previous results?
Surface deformation and core flows

- Vertical displacement at the Earth’s surface:

\[ u_r = \sum_n \bar{h}_n \frac{\Delta P_n}{\rho g_0}, \]

- \( \bar{h}_n \) degree-\( n \) Love numbers \((h_2, h_4, h_6) \approx (0.23, 0.05, 0.01)\)
- Geostrophic pressure \( \Delta P_n = 2\rho_c \Omega U_n L_n \), with \( L_n \approx 2\pi r_c/(2n + 1) \)

Ding & Chao (2018):
- Vertical surface displacement of 4.3 +/- 1.7 mm \( \rightarrow \Delta P \sim 1000 \) Pa
  \( \rightarrow U_Z \sim 10^{-4} \) m/s \( \sim 3 \) km/yr

... good order of magnitude?
**Zonal and non-zonal motions**

Only **zonal toroidal** motions of the core wrt mantle contribute to axial component of angular momentum of the core.

\[
|U_{NZ}| = O(2) \text{ km/yr} \\
|U_{Z}| = O(0.6) \text{ km/yr} \\
\rightarrow |U_{NZ}| \approx 3|U_{Z}|
\]

(Gillet et al. 2015)

5.9-year oscillation: weak in zonal flows (torsional waves), absent in non-zonal flows

\[
\rightarrow \text{do not expect strong 5.9-year signal: 0.2-1 mm vertical displacement}
\]
GNSS data analysis: vertical displacement

International GNSS Service (IGS) solutions from 2nd data reprocessing campaign in ITRF2014 with geophysical corrections (tides, ocean loading, non-tidal atmospheric loading) after IERS Conventions (2010) (Rebischung et al. 2016)

Stacked FFT of solutions from 63 stations with duration 18.5 years (band-pass filtering [2 - 12] yr) → 0.4 mm on Z at ∼ 6-year
GNSS data analysis: vertical displacement

Optimal Sequence Estimate as in Ding & Chao (2018) applied on IGS Repro2 solutions from 63 stations with duration 18.5 years
GNSS data analysis: vertical displacement

Peak at 6-year period in hydrological loading predictions?

\[
\downarrow 6 \text{ year}
\]

Optimal Spectral Estimate on GLDAS predictions at GNSS sites

http://loading.u-strasbg.fr/

→ 1 mm vertical displacement at 6-year in GLDAS predictions
Summary

- 6-year oscillation in LOD well-explained by torsional waves in fluid core
- if detected 6-year oscillation in vertical GNSS data originates from fluid core, then associated core flows of the order of 3 km/yr ($\gg 0.6$ km/yr from torsional waves obtained from geomagnetic observations)
- if $Y_2^2$ pattern confirmed, then non-zonal flows should play a major role, but no peak at 6-year period in reconstructed non-zonal flows
- even with non-zonal flow 3 to 5 times larger than zonal flows, associated pressure flows (in quasi-geostrophic approximation) similar to zonal ones $\rightarrow$ not enough to induce 1-mm vertical displacement at surface
- our attempts have not yet confirmed previous detection: a peak present at $\sim$ 6-year with amplitude 0.4 mm
- but hydrological loading signal also has a peak at $\sim$ 6-year with similar amplitude...
- effect on polar motion known to be small (e.g. Dumberry (2008); Greff-Lefftz & Legros (1995))...

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Acknowledgments

Thank you for your attention