Constraints on the Rheology of the Earth’s Deep Mantle from Decadal Observations of the Earth’s Figure Axis and Rotation Pole

A. Couhert[1,*], C. Bizouard[2], F. Mercier[1], K. Chanard[3], M. Greff[4], P. Exertier[5]

[1] Centre National d’Etudes Spatiales, Toulouse, France
[2] Observatoire de Paris–SYRTE, Paris, France
[3] Institut National de l’Information Géographique et Forestière–LAREG, Paris, France
[4] Institut de Physique du Globe de Paris-Sorbonne Paris Cité–UMR CNRS 7154, Paris, France
[5] Observatoire Midi-Pyrénées–GET, Toulouse, France

*Mail : alexandre.couhert@cnes.fr

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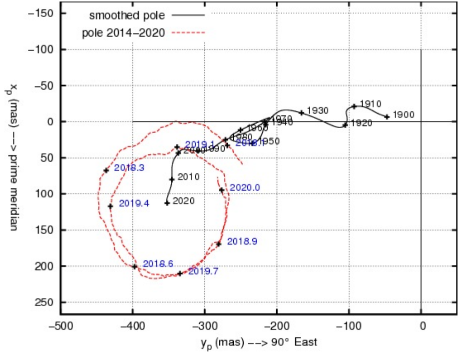
INTRODUCTION

1. Background
2. Mean figure and rotation axes
3. Modeling the Earth viscoelastic response
4. Derived model versus previous theories
5. Conclusions

Definitions

- *Polar motion* : displacements (> 2 days) of the rotation pole from the geographic North pole.



Beating Chandler wobble (435 days) and annual oscillations superimposed on the low-frequency (> 10 years) polar motion [`https://hpiers.obspm.fr`].

- *Figure axis* : mean axis of maximum inertia, whose terrestrial coordinates can be derived from the degree-2 order-1 geopotential terms : $x_I = -\sqrt{\frac{5}{3}}\frac{MR_e^2}{C-A}\overline{C}_{2,1}$ & $y_I = -\sqrt{\frac{5}{3}}\frac{MR_e^2}{C-A}\overline{S}_{2,1}$.

1. Background

❖ Three independent data sources

➢ Space geodetic *measurements*

1. (x, y) Earth orientation parameters (mainly from GPS & VLBI) : IERS 14C04 (Bizouard et al., 2019).
2. SLR observations to geodetic spheres (Starlette/Stella, LARES, LAGEOS-1/2, Ajisai) makes it possible to measure the long-term displacement (34-year period 1984-2017) of the figure axis,

$$\begin{cases} \overline{C}^{*}_{21}(t) = \overline{C}_{21}(t_0) + \Delta\overline{C}^{\text{solid Earth tide}}_{21} + \Delta\overline{C}^{\text{ocean tide}}_{21} + \Delta\overline{C}^{\text{solid Earth/ocean pole tide}}_{21} + \Delta\overline{C}^{\text{dealiasing}}_{21} + \Delta\overline{C}^{\text{load}}_{21} \\ \overline{S}^{*}_{21}(t) = \overline{S}_{21}(t_0) + \ldots, \end{cases} \quad (1)$$

where blue terms are left unmodeled to observe the full GIA, changes in the continental hydrology/ice sheets, pole tide and non-tidal hydro-atmospheric mass-related long-term excitations of polar motion.

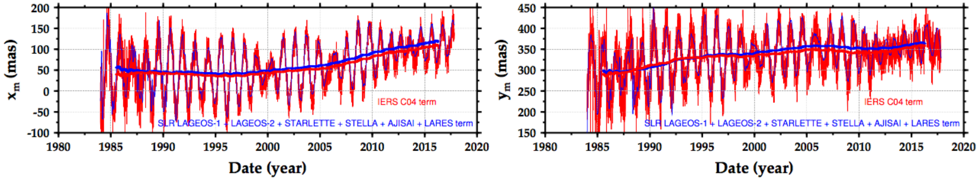
Starlette/Stella, LARES, LAGEOS-1/2, Ajisai (the proportion of the scale is kept).

➢ Geophysical excitation *models* of polar motion

3. Hydro-atmospheric angular momentum functions $(\chi_1^{\text{ma+mo}}, \chi_2^{\text{ma+mo}})$ from Dobslaw and Dill (2018).

Long-term behavior of the independent time series

- The rotational axis has a circular motion around the figure axis at seasonal time scales.
  - *What happens at decadal time periods and how well the two axes are aligned ?*



Rotation pole and mean figure axis coordinates x_m (left) and y_m (right), in mas.

- The well-known Euler-Liouville equations enable to relate oscillations of the Earth's rotation pole to those of its modeled excitation functions.
  - *Could the elastic Earth approximation be revised to explain the discrepancies between the observed terrestrial path of the rotation pole and our current knowledge of its surface mass-related excitation ?*

Euler-Liouville equations

- Applying the principle of conservation of angular momentum to the Earth system, we have

$$\begin{cases} x + \dfrac{A_m}{\Omega(C-A)}\dot{y} - \dfrac{1}{k_s}\displaystyle\int_{-\infty}^{t} k(t-\tau)x(\tau)\mathrm{d}\tau = \chi_1^{\text{ma+mo}} + \int_{-\infty}^{t} k_2'(t-\tau)\chi_1^{\text{ma}}(\tau)\mathrm{d}\tau \\ -y + \dfrac{A_m}{\Omega(C-A)}\dot{x} + \dfrac{1}{k_s}\displaystyle\int_{-\infty}^{t} k(t-\tau)y(\tau)\mathrm{d}\tau = \chi_2^{\text{ma+mo}} + \int_{-\infty}^{t} k_2'(t-\tau)\chi_2^{\text{ma}}(\tau)\mathrm{d}\tau. \end{cases} \tag{2}$$

  - C and A are the two principal inertia moments of the Earth (composed of the fluid core, mantle, lithosphere and surface fluids), Ω its mean angular velocity, R_e and M its equatorial radius and mass.
  - $k(t)$, $k_2'(t)$, and k_s are the degree-2 effective pole tide (solid Earth and equilibrium ocean), load, and secular Love numbers, respectively.
- Hypotheses
  - The convolution integral of the degree-2 pole tide and load Love numbers (in place of the common multiplication by constant Love numbers) accounts for the viscoelastic deformation of the solid Earth.
  - The introduction of A_m (*extended mantle* without the core) assumes (Sasao and Wahr, 1981) that the Earth core has the same polar motion as the mantle (valid over periods larger than a few days).
  - Other potential sources of decadal motion-related excitations of polar motion, such as climatic oscillation events (e.g., El Niño/La Niña) or the electromagnetic core-mantle interaction are lacking.

A rheology encompassing two different characteristic times

- The response of the Earth's mantle to the *present-day melting of the polar ice sheets*
  - Considering the Earth as incompressible, the short-term (transient) viscoelastic time domain Love numbers $k(t)$ and $k_2'(t)$ can be expressed as an "apparent" normal mode expansion of the form

$$\begin{cases} k(t) = k\delta(t) + qe^{-st}\mathcal{H}(t) \\ k_2'(t) = k_2'\delta(t) + q'e^{-st}\mathcal{H}(t), \end{cases} \tag{3}$$

    in which s is an inverse relaxation time, q and q' viscoelastic amplitude coefficients, k and k_2' the corresponding elastic Love numbers, $\delta(t)$ and $\mathcal{H}(t)$ are the Dirac and Heaviside step functions.
  - This single relaxation time primarily reflects the lower mantle rheological properties, due to its large volume and depth range, as the Earth's rotation depends on the global deformation of the planet.
- The response of the Earth's mantle to the *GIA signal following the last deglaciation event*
  - The long-term viscoelastic behavior of the Earth is introduced through bias and drift terms (D_i, E_i), corresponding to the effects of GIA observed in (x, y) and $(\overline{C}^*_{2,1}, \overline{S}^*_{2,1})$, but lacking in the modeled excitation functions $(\chi_1^{\text{ma+mo}}, \chi_2^{\text{ma+mo}})$.

Problem to be solved

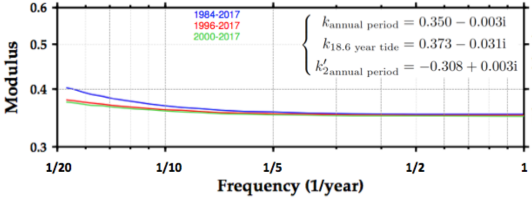
- Adding the previously derived gravity coefficients (mirroring the viscoelastic mass-related excitation of polar motion) yields

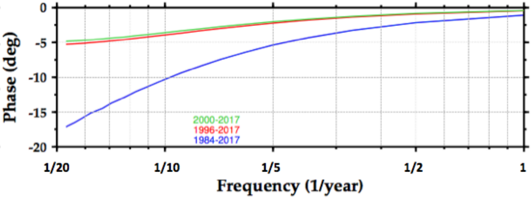
$$\begin{cases} \frac{k_s - k}{k_s} x + \frac{A_m}{\Omega(C-A)} \dot{y} - \frac{q}{k_s} \int_{1984}^{t} e^{-s(t-\tau)} x(\tau) \mathrm{d}\tau = D_1 + E_1 t + \chi_1^{\text{mo}} + (1+k_2') \chi_1^{\text{ma}} + q' \int_{1984}^{t} e^{-s(t-\tau)} \chi_1^{\text{ma}}(\tau) \mathrm{d}\tau + B_1 e^{-st} \\ \frac{k - k_s}{k_s} y + \frac{A_m}{\Omega(C-A)} \dot{x} + \frac{q}{k_s} \int_{1984}^{t} e^{-s(t-\tau)} y(\tau) \mathrm{d}\tau = D_2 + E_2 t + \chi_2^{\text{mo}} + (1+k_2') \chi_2^{\text{ma}} + q' \int_{1984}^{t} e^{-s(t-\tau)} \chi_2^{\text{ma}}(\tau) \mathrm{d}\tau + B_2 e^{-st} \\ -\sqrt{\frac{5}{3}} \frac{M R_e^2}{C-A} \overline{C}_{2,1}^{*} - \frac{q}{k_s} \int_{1984}^{t} e^{-s(t-\tau)} x(\tau) \mathrm{d}\tau - \frac{k}{k_s} x = D_1 + E_1 t + (1+k_2') \chi_1^{\text{ma}} + q' \int_{1984}^{t} e^{-s(t-\tau)} \chi_1^{\text{ma}}(\tau) \mathrm{d}\tau + B_1 e^{-st} \\ -\sqrt{\frac{5}{3}} \frac{M R_e^2}{C-A} \overline{S}_{2,1}^{*} + \frac{q}{k_s} \int_{1984}^{t} e^{-s(t-\tau)} y(\tau) \mathrm{d}\tau + \frac{k}{k_s} y = D_2 + E_2 t + (1+k_2') \chi_2^{\text{ma}} + q' \int_{1984}^{t} e^{-s(t-\tau)} \chi_2^{\text{ma}}(\tau) \mathrm{d}\tau + B_2 e^{-st} \end{cases} \tag{4}$$

  - B_1 and B_2 denote constant viscoelastic initial condition parameters that will be determined with the other *historical terms* (D_i, E_i), as well as the *contemporary terms* of the model (k, s, q, q'), within the constraint that the residuals of the Euler-Liouville equation system are minimized (using least square adjustment).

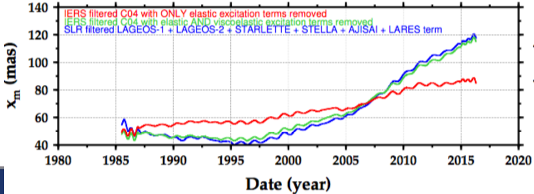
Results

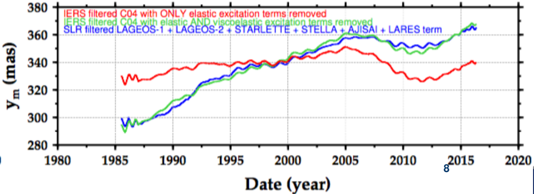
⇒ When starting the estimation after 1996, the derived frequency-dependent Lover number k agrees well with independent values (e.g., $k_{\text{annual/Chandler period}} = 0.353 - 0.003\mathrm{i}$ in Seitz et al. (2012), $k_{im\,\text{18.6 year tide}} = -0.028\mathrm{i}$ in Benjamin et al. (2006), or the R3/R4 models of Nakada and Karato (2012)).





⇒ Agreement between the filtered motion of the Earth's figure axis and the traditional elastic modeling of the mass-related excitation of polar motion and the Earth's viscoelastic response derived from our model.





5. CONCLUSIONS

Summary

Findings

- Polar motion observations (with geophysical excitation models) were used with those of the figure axis variations to constrain Earth's inelasticity at periods till 18.6 years. For this purpose, the *full Stokes coefficients* (including the pole tide effect) were previously derived, not applying corrective models based upon the quasi-elastic approximation of the mantle rheology.
- Nakada and Okuno (2013) showed that the long-term evolution of the polar wander is significantly sensitive to the viscosity of the D'' *layer of the deepest Earth's mantle*, essentially through rotational potential viscoelastic perturbations of the polar motion. Also, our results should mostly be interpreted as constraints on the viscosity of the D'' deeper part of the lower mantle at the decadal time scale.

Recommendations

- Reproducing this type of analysis in the future would enable us to benefit from possibly improved geophysical excitation models and accurate polar motion observations over a long enough time span (at least 1996–2022), to underpin the relaxation time, while validating the derived Love number k value for the 18.6 year tide, in order to infer the viscosity structure of the deep lower mantle, including the D'' layer, a *crucial quantity in discussing mantle dynamics*.
- As it is clear that the Earth behaves differently over different time scales, the viscoelastic contribution to the pole tide perturbation should be further investigated. This is, among other things, *a necessary step to estimate accurately recent ice melting*, and sharpen our knowledge of the Earth's response to present day climate change.