National Aeronautics and Space Administration

Earth's Interior Stress Field Perturbed by the Chandler Wobble

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Program: Innovative Spontaneous Concept

Project Objectives

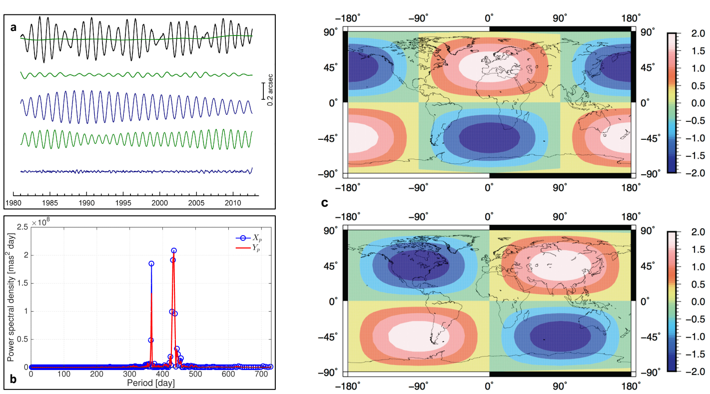
Background: The Chandler wobble is a Eulerian free rotational mode of the Earth. This free mode has a periodicity of 434 days and varies in amplitude, but is generally about 100-200 millisecond of arc (mas; 1 mas ~3.1 cm on the Earth's surface). It is primarily excited by a combination of atmospheric and oceanic mass and momentum transport processes [1]. As the spin axis moves, it produces a centrifugal force that has the same radial and angular dependence as the luni-solar tidal potential. The rotationally induced centrifugal potential may be treated as a tide. In fact, both the body and ocean load components are formally termed "pole tides". The largest among the pole tides are at periods of 14 (free Chandler wobble) and 12 months (forced annual wobble). Pole tides deform the solid Earth and the equipotential surface, causing the redistribution of ocean mass with a near-instantaneous equilibrium response [2]. The 14-month signal is significant enough to manifest itself in ocean satellite altimetry data [3]. The surface forcing of potential and associated ocean load induced by the Chandler Wobble perturbs Earth's interior stress field. To our knowledge, no rigorous computational model of these stresses is available as yet.

Goal: To compute all six scalers of 3-D stress tensor in the interior of the solid Earth induced by the Chandler wobble for the period 1994 to present.

Significance

One of many implications of this project is to quantify the pole tide modulation of the episodic tremor and slow slip events along the Cascadia subduction zone [4]. It has been well documented that stress accumulates episodically across the deeper (25-45 km) plate in Cascadia and is relieved every 13-16 months, a periodicity strikingly similar to that of Chandler wobble [5]. Accurate quantification of the Coulomb stress change induced by both the body and ocean pole tide may shed light on the interior stress environment in the Cascadia megathrust earthquake zone. The topic of this project is in direct concert with some of the priority questions set forth in the 2016 NASA CORE report.

Chandler Wobble and Potential Forcing



Components of polar motion and degree-2 order-1 Spherical Harmonics. (a) x-component of polar motion. From top to bottom of the panel, we show the observed data with a trendline, low frequency, Chandler, annual, and high frequency signals. Notice, in the middle panel, the variability in amplitude of Chandler wobble. **(b)** A simple spectral decomposition, highlighting the unambiguous presence of Chandler and annual wobbles in both x- and y-components of polar motion, with respective periodicities of 433 and 365 days. **(c)** Cosine (top) and sine (bottom) components of degree-2 order-1 Spherical Harmonics: $C_{21}(\theta,\phi)$ and $S_{21}(\theta,\phi)$. These serve as "physical basis function" that can be used in concert with the time series of Chandler wobble in order to derive the time series of associated potential field, $L(\theta,\phi,t)$, such that $L(\theta,\phi,t) = X(t)C_{21}(\theta,\phi) + Y(t)S_{21}(\theta,\phi)$, where $X(t)$ and $Y(t)$ are the amplitudes of x- and y-components of the Chandler wobble (see, for example, middle panel in **a**).

Stress Modulation at the Planetary Interior

Step 1: Solve the y-system equations, and generate Green's functions for all six scalars of 3-D stress tensor at a specified depth.

Step 2: Convolve these Green's functions with the potential forcings to retrieve the stress field.

Theory and Methods

- Perturbation equations of motion and gravitation for a viscoelastic Earth:

$$\rho_1^e + \nabla\cdot(\rho_0 \boldsymbol{u}) = 0$$
$$\rho_0 d^2\boldsymbol{u}/dt^2 = \nabla\cdot\sigma_1^e + \rho_0\nabla\Phi_1^e + \rho_1^e\nabla\Phi_0 + \rho_0\nabla V$$
$$\Delta\Phi_1^e = -4\pi G\rho_1^e$$

- Variables are decomposed in a vector Spherical Harmonic space

$$\boldsymbol{u}(r,\theta,\varphi) = \sum_{n=0}^{\infty}\sum_{m=0}^{n}\left(u_{rnm}^{c,s}Y_{nm}^{c,s}\boldsymbol{e}_r + u_{snm}^{c,s}r\nabla Y_{nm}^{c,s} + u_{tnm}^{c,s}\boldsymbol{r}\wedge\nabla Y_{nm}^{c,s}\right)$$

- Field equations reduce to a linear "y-system" of equations, e.g.

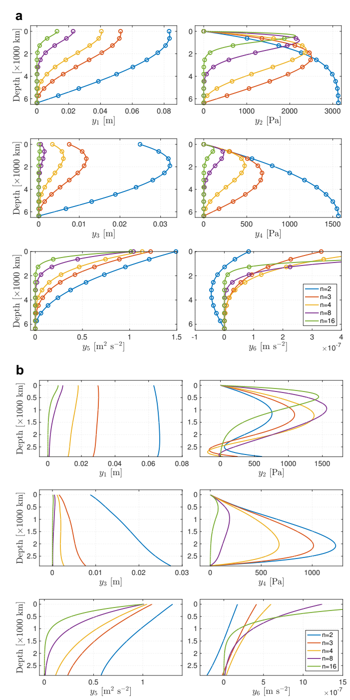
$$\dot{y}_1 = \frac{-2\lambda}{\lambda+2\mu}\frac{y_1}{r} + \frac{1}{\lambda+2\mu}y_2 + \frac{\lambda n(n+1)}{\lambda+2\mu}\frac{y_3}{r}$$

- Boundary conditions: $y_2(a) = -P_n$; $y_4(a) = 0$; $\boldsymbol{u}(0,\theta,\phi) = 0$; and $y_6(a) + \frac{n+1}{a}y_5(a) = \frac{2n+1}{a}V_n$.

- Given $\rho(r)$, $\lambda(r)$, $\mu(r)$, we solve the BVP for $y_i(r)$. See example results =>

- We convolve $y_i(r)$ with applied surface forcings, $L(\theta,\phi)$, e.g.,

$$\mathcal{G}_1(\alpha,r) = \sum_{n=0}^{\infty} y_{1n}(r)\mathcal{P}_n(\cos\alpha)$$
$$u_1(r,\theta,\phi) = \int \mathcal{G}_1 L(\theta,\phi)\mathrm{d}\mathcal{S}$$



Solutions of y-system of equations. (a) Analytic (circle) versus predicted depth profiles for select wave numbers of y's. A homogeneous incompressible Earth is considered. **(b)** Predicted depth profiles for select wave numbers of y's for the Preliminary Reference Earth Model [6]. Green's functions associated with these solutions will be convolved with the time series of potential field associated with the Chandler wobble. Results are adapted from [A].

Publications

A. S. Adhikari, L. Caron, E.R. Ivins, E. Larour, P. Lundgren, 2019: Computation of high-resolution planetary interior displacement and stress fields in the ISSM framework, to be submitted to *Geoscientific Model Development*.

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