The 5th IVS General Meeting Proceedings, 2008, p. 246–250

Earth's Interior from VLBI and Superconducting Gravimeter Data

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Abstract. We analyze VLBI delays back to 1984 from the permanent geodetic network, and ten superconducting gravimeter records from the Global Geodynamic Project spanning more than 7 years. From the former data, we deduce nutation offsets, and from the latter we get gravimetric factors. Comparison of these observed quantities against theoretical expressions of the core and mantle admittance to the tidal potential allows us to estimate Love numbers and resonant frequencies and quality factors of the core. We point out strengths and deficiencies of each technique in their ability to retrieve the Earth's interior parameters.

1. Surface Gravity Changes and Earth's Rotation Variations

The Earth's structure leads to resonance effects that enhance the response of the planet to tidal excitation. The enhancement follows a frequency-dependent resonance law, which resonance frequencies and strength functions are expressed in terms of Earth's structural and rheological parameters. Within the diurnal band, the main resonance is associated with the free wobbling of the core, or retrograde free core nutation (RFCN) which theoretical expression of the frequency in the space-fixed frame of reference $\sigma'_{\mathrm{f}} = -\Omega(A/A_{\mathrm{m}})(e_{\mathrm{f}} - \beta)$. Here, e_{f} is the core flattening, A and A_{m} the equatorial moments of inertia of the Earth and of the mantle, respectively, and β stands for a compliance expressing the deformability of the core-mantle boundary (CMB) under the centrifugal potential due to the core wobble [1].

One phenomenon that undergoes the resonance effects is the surface gravity change given by [2, 3, 4]

$$\Delta g = \left[\delta_2 \left(1 - \frac{Ae - A_{\mathrm{f}}\gamma}{A_{\mathrm{m}}} + \frac{A_{\mathrm{f}}}{A_{\mathrm{m}}} \frac{(e-\gamma)\sigma'_{\mathrm{f}}}{\sigma - \sigma_{\mathrm{f}}}\right) + \delta_1 \frac{A}{A_{\mathrm{m}}} \frac{(e-\gamma)\Omega}{\sigma - \sigma_{\mathrm{f}}}\right] \frac{-2W}{a}, \quad (1)$$

where a is the Earth's radius, W the degree two external gravitational potential, σ the excitating frequency, e the Earth's dynamical flattening, A_{f} the equatorial moment of inertia of the core. The compliance γ expresses the deformability of the CMB under the influence of an external potential. The gravimetric factor δ_2 represents the static response of the Earth to the tidal potential, and δ_1 is the Love number that characterizes the elastic response of the Earth to the inner pressure at the CMB.

Another phenomenon is the celestial motion of the Earth's figure axis, defined by the nutation angles $dY - idX = -\omega(\sigma)/\sigma'$ where the wobble ω of the whole Earth can be expressed in a resonant form as

$$\omega = \left[\frac{Ae - A_{\mathrm{f}}\gamma}{A_{\mathrm{m}}} + \frac{A_{\mathrm{f}}}{A_{\mathrm{m}}}(e-\gamma)\frac{\sigma'_{\mathrm{f}}}{\sigma - \sigma_{\mathrm{f}}}\right]\frac{3W}{\Omega a^2}. \tag{2}$$

The surface gravity changes are measured locally by superconducting gravimeters (SG). These devices can detect variations at the level of 1 nanogal and have been recording data roughly for 10 years. Nutation variations have been densely measured VLBI for more than 20 years. The accuracy now reaches ~0.2 mas. Though VLBI-only data have recenlty led to precise determinations of Earth's structural parameters including the dissipative part of σ_{f} ([5], hereafter referred to as MHB), we address the possibility of using SG measurements as well, since both VLBI and SG observables involve the same geophysical quantities.

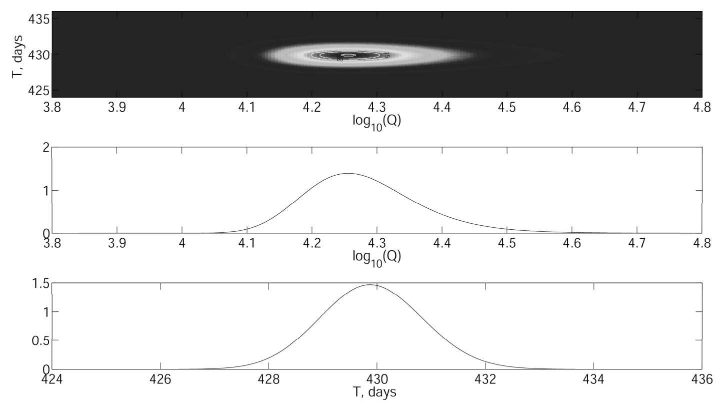

Figure 1. Probability density functions from the analysis of VLBI nutation offsets against the MHB model

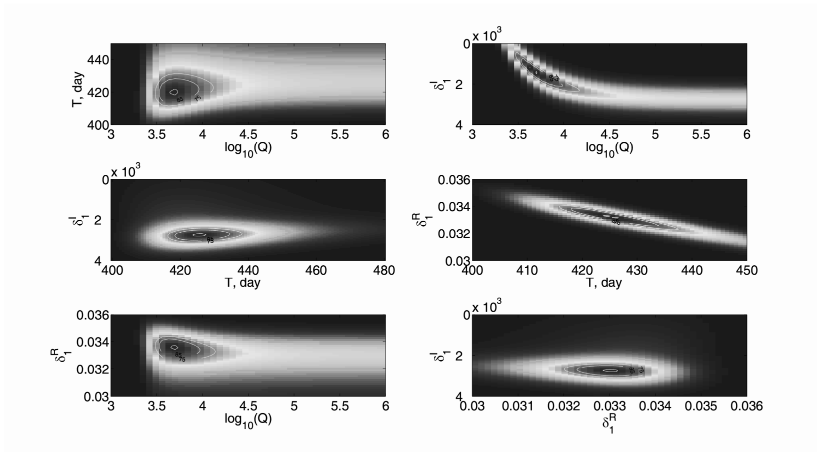

Figure 2. Probability density functions from the analysis of the combination of 7 SG data

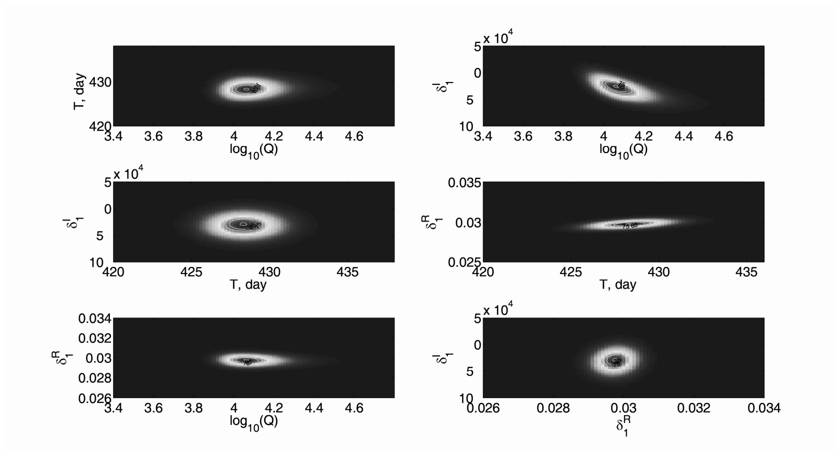

Figure 3. Probability density functions from the analysis of the combination of 16 SG data with the weighting method of Ducarme [12]

2. Data and Results

Nutation offsets since 1984 are obtained by a global inversion of delays accumulated in 3762 diurnal sessions. To maintain the celestial reference frame, a no-net rotation condition has been applied to the coordinates of 247 stable radio sources selected by Feissel-Vernier et al. [6].

The resonance effects on the amplitudes at tidal frequencies are estimated by least-square fits. For SG data, we fit the amplitudes for the following diurnal tidal frequencies: $Q_1, O_1, M_1, P_1, K_1, \Psi_1, \Phi_1, J_1$ and OO_1. It has to be noticed that the error on Ψ_1 and Φ_1 is much larger than for other frequencies. Since these waves are near the resonance, this will have some negative consequences on the ability to determine the resonant frequency with gravity measurements. For VLBI, we fit at the same frequencies in addition to the 18.6-year and 9.3-year terms.

All SG amplitudes have been corrected from local oceanic tidal loading effects using the FES 2004 model [7]. An extra error of 0.3 nm/s^2 has been added in order to account from the error on the oceanic model. VLBI amplitudes have been freed from the effect of non-linear terms [8, 9] so that all effects not directly linked to non-rigidity are removed.

A Bayesian inversion approach [10, 11] has been developped, starting from (1) and (2), to estimate σ_{f} and δ_1 as complex parameters. The latter parameter is estimated from SG only.

First, the algorithm has been tested on VLBI nutation amplitudes in order to get an estimate of the RFCN frequency. Our nutation data set being offsets with respect to the MHB model, we expect the RFCN frequency estimate to be very close to the MHB value. Expressing the RFCN frequency as $\sigma_{\mathrm{f}} = \frac{2\pi}{T}(1 + i/2Q)$, where the quality factor Q expresses the damping with time, we find $T = 429.9 \pm 0.9$ days, and $Q = 19093 \pm 3968$, which is in good agreement with [9] and with MHB within the error bars (Fig. 1).

Fig. 2 shows the probability density functions of the estimated parameters for the combination of 7 European SG records: Bad-Homburg, Moxa and Wettzell (Germany), Membach (Belgium), Medicina (Italy), Strasbourg (France), and Vienna (Austria). One readily remarks the large uncertainties, a low value for Q, and a significant correlation between T and δ_1^{R}, and between Q and δ_1^{I} for lower Q. These results find their origin first in the above-mentioned large error for the amplitude at Ψ_1. Indeed, the diurnal wave most affected by the resonance is Ψ_1. However, Ψ_1 has a weak amplitude and its measurement within SG data is therefore difficult. It results in a poor constraint on the resonance parameters. Incidentally, the dissipation of Ψ_1 should provide a strong constraint on the quality factor. Another factor is the deficient ocean loading correction: gravity measurements are widely affected by oceans, atmosphere and hydrological effects at small wavelengths. It results in noisier time series at high frequencies. For comparison purpose, in VLBI nutation series, the annual retrograde nutation Ψ_1 is well-determined (large amplitude). Moreover, the oceanic, atmospheric and hydrological effects are much lower in nutation than in surface gravity.

Ducarme et al. [12] provided mean values of 16 gravity records as well as a presumably improved ocean loading correction that led to smaller uncertainties on the fitted diurnal amplitudes (especially for Ψ_1). Using this data set, it turns out that we obtain much better constrained parameters and a better agreement with the results from nutations for the RFCN frequency (Fig. 3). Both T and Q now appear to be in agreement with the VLBI within the error bars. Nevertheless, correlations already pointed out in Fig. 2 still show up between δ_1^{I} and Q, but to a smaller extent.

To conclude, it comes out from these preliminary studies that it becomes worth using simultaneously VLBI and SG data, especially since the parameter δ_1 exclusively plays through gravity data. It encourages the use of VLBI for constraining other parameters and strengthening the SG determination of the core potential Love number k_1^{f}. However, some problems do remain, that are linked to local loading corrections at SG locations, although recent attempts to free data from these effects using wise combination methods, look promising.

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