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Low-frequency centroid-moment-tensor inversion from superconducting-gravimeter data: The effect of seismic attenuation

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ABSTRACT

After the 2010 Maule and 2011 Tohoku earthquakes the spheroidal modes up to 1 mHz were clearly registered by the Global Geodynamic Project (GGP) network of superconducting gravimeters (SG). Fundamental parameters in synthetic calculations of the signals are the quality factors of the modes. We study the role of their uncertainties in the centroid-moment-tensor (CMT) inversions. First, we have inverted the SG data from selected GGP stations to jointly determine the quality factors of these normal modes and the three low-frequency CMT components, $M_{rr}, (M_{\vartheta\vartheta} - M_{\varphi\varphi})/2$ and $M_{\vartheta\varphi}$, that generate the observed SG signal. We have used several-days-long records to minimize the trade-off between the quality factors and the CMT but it was not eliminated completely. We have also inverted each record separately to get error estimates of the obtained parameters. Consequently, we have employed the GGP records of 60-h lengths for several published modal-quality-factor sets and inverted only the same three CMT components. The obtained CMT tensors are close to the solution from the joint Q-CMT inversion of longer records and resulting variability of the CMT components is smaller than differences among routine agency solutions. Reliable low-frequency CMT components can thus be obtained for any quality factors from the studied sets.

Introduction

CMT inversions of giant earthquakes in the frequency range below 1 mHz are based on normal-mode calculations where fundamental parameters are the quality factors of the modes. Although free oscillations of the Earth have been observed for decades, precise determination of the ultralong-period-mode quality factors is still discussed (e.g., Roult et al., 2006; Okal and Stein, 2009; Tanimoto et al., 2012; Deuss et al., 2013; Ding and Shen, 2013). The modal quality factors can be estimated directly from the observed signal attenuations. Very long high-quality records are needed because multiplet splitting into singlets of near frequencies causes complicated decrease of signal amplitudes with time, but continuous non-disrupted SG records lasting several weeks are rather rare. Determination of ultra-long-period-mode-singlet attenuations from SG and seismic data yields relatively broad ranges of values (Ding and Shen, 2013), probably due to the noise in available signals. However, in quasi-spherical approximation, when only splitting due to the Earth's rotation and ellipticity is considered, the quality factors of individual singlets should be very close (e.g., Dahlen and Tromp, 1998).

The other way how to obtain the modal quality factors is, therefore, based on an inversion procedure when calculated synthetic signals are compared with the observed data provided one quality factor for all singlets of a mode is to be determined. Synthetic calculations cannot be performed without a model of earthquake source which should thus be simultaneously added into the inversion procedure to obtain self-consistent results.

Here we first deal with the problem of joint determination of both the modal quality factors and the CMT components from the spheroidal-mode observations up to 1 mHz. Since they are isolated in the spectrum, influence of mode couplings and 3-D structures to amplitude spectrum is not substantial (e.g., He and Tromp, 1996), it is sufficient to calculate multiplets splitting due to the rotation and ellipticity. The observations after the 2010 Maule and 2011 Tohoku earthquakes within the GGP framework provide high-quality data that exhibit lower noise level in submilihertz frequency range than broadband seismometer data; detailed discussion can be found in, e.g., Ferreira et al. (2006).

Ultralong-period-normal modes were employed in several earthquake-source studies (e.g., Okal and Stein, 2009; Okal et al., 2012; Okal, 2013; Tanimoto and Ji, 2010; Tanimoto et al., 2012) to reveal potential ultraslow components to the seismic source of

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giant earthquakes by evaluating low-frequency estimates of the scalar moment M_0 when the strike, dip and rake were fixed in agreement with the Global CMT double-couple-focal mechanisms. The one parameter was thus inverted using a priori estimates of the remaining source parameters (and quality factors). It is clear that such an approach stabilizes inversion of M_0 but the question arises whether the influence of errors in determination of the strike, dip and rake (Duputel et al., 2012; Tanimoto et al., 2012; Valentine and Trampert, 2012) is negligible. Moreover, potential usage of very long records (up to several weeks) require precise knowledge of the modal quality factors.

Zábranová et al., 2012 obtained the M_{rr} component of the moment tensor by inverting the amplitudes of radial modes observed after the 2010 Maule and 2011 Tohoku earthquakes by the GGP stations. Again, they had to re-evaluate quality factors of the employed modes to obtain self-consistent results. Since the radial modes are not split, their quality factors can be obtained directly from the records; thus, this source inversion can be done independently and used as a benchmark for the most influential M_{rr} component. For this reason we do not incorporate the radial modes into this study.

Here we show that vertical acceleration of the studied spheroidal modes generated by shallow earthquakes is sensitive to the three components of the CMT, assuming the isotropic component of the source to be negligible: the diagonal terms of the CMT, M_{rr} and $(M_{\vartheta\vartheta} - M_{\varphi\varphi})/2$, and its ϑ-φ component $M_{\vartheta\varphi}$, see Eqs. (1)–(3) and Table 1 below. Quite recently, Bogiatzis and Ishii (2014) tried to invert the whole CMT tensor from the analysis of 15 modes observed by the Global Seismograph Network after the 2011 Tohoku earthquake but the $M_{r\vartheta}$ and $M_{r\varphi}$ components were not resolved. We demonstrate that the three resolvable CMT components can be, in principle, obtained simultaneously with the quality factors of the modes in a joint inversion procedure utilizing long SG records. However, there is still a trade-off between the quality factors and the M_{rr} component of the CMT. Therefore, we deal also with the CMT inversion from short SG records where influence of quality-factor uncertainties is more suppressed.

Synthetic calculations of SG signals

The total ground acceleration at $\mathbf{x_r}(r_r, \vartheta_r, \varphi_r)$ excited by a source situated at $\mathbf{x_s}(r_s, \vartheta_s, \varphi_s)$, is given by a superposition of spheroidal and toroidal modes,

$$\mathbf{a}(\mathbf{x_r}, \mathbf{x_s}, t) = \mathrm{Re}\left[\sum_k \mathbf{A}_k(\mathbf{x_r}, \mathbf{x_s}) \exp\left(i\omega_k t - \frac{\omega_k t}{2Q_k}\right)\right], \qquad (1)$$

where index k contains all degrees (angular order), overtones (radial order) and singlets (azimuthal order), ω_k are angular frequencies and Q_k are quality factors of the modes. The coefficients $\mathbf{A}_k(\mathbf{x_r}, \mathbf{x_s})$ are linearly dependent on $\mathbf{M} : \mathbf{e}_k(\mathbf{x_s})\mathbf{s}_k(\mathbf{x_r})$, where $\mathbf{M}$ is the source moment tensor, $\mathbf{e}_k = \frac{1}{2}\left[\nabla\mathbf{s}_k + (\nabla\mathbf{s}_k)^{\mathrm{T}}\right]$ is the strain and $\mathbf{s}_k(\mathbf{x_s})$ and $\mathbf{s}_k(\mathbf{x_r})$ are eigenfunctions evaluated in a source and a receiver location, respectively. We included the potential-perturbation, free-air and tilt to model a realistic device response (Dahlen and Tromp, 1998), as well as the Earth's ellipticity and rotation leading to multiplets splitting (Dahlen and Sailor, 1979), and calculated the coefficients $\mathbf{A}_k(\mathbf{x_r}, \mathbf{x_s})$ using the formulas that are given explicitly for splitting of an isolated multiplet in (Dahlen and Tromp, 1998; Chapter 14.2 and Appendix D1). We calculate the eigenfrequencies and eigenfunctions by our pseudospectral finite-difference matrix-eigenvalue approach (Zábranová et al., 2009) applied to the spherical equivalent-rock PREM (Dziewonski and Andersen, 1981), where the upper 3-km layer of water is replaced by a 1.2-km-thick rock layer with the same mass. We thus keep the mass of the Earth and avoid calculations in a thin water layer at the surface.

Table 1

The ratios between maximal $|\mathbf{A}_k|$ of vertical acceleration around the globe for individual base moment tensors and maximal amplitude of a signal generated by the sum of all 5 base moment tensors located at the 20 km depth.

	Relative strength of signals				
	G_1	G_2	G_3	G_4	G_5
${}_0S_2$	0.907	0.045	0.0015	0.0015	0.045
${}_0S_3$	0.670	0.165	0.0000	0.0000	0.165
${}_0S_4$	0.589	0.204	0.0010	0.0010	0.205
${}_1S_2$	0.404	0.282	0.0159	0.0159	0.282
${}_0S_5$	0.553	0.221	0.0024	0.0024	0.221

Assuming negligible isotropic component of the source we decompose the moment tensor $\mathbf{M} = (M_{rr}, M_{\vartheta\vartheta}, M_{\varphi\varphi}, M_{r\vartheta}, M_{r\varphi}, M_{\vartheta\varphi})$, where $M_{rr}, \ldots, M_{\vartheta\varphi}$ are its spherical components, into five suitable base moment tensors,

$$\mathbf{M} = M_{rr}\mathbf{G}_1 + \frac{M_{\vartheta\vartheta} - M_{\varphi\varphi}}{2}\mathbf{G}_2 + M_{r\vartheta}\mathbf{G}_3 + M_{r\varphi}\mathbf{G}_4 + M_{\vartheta\varphi}\mathbf{G}_5, \qquad (2)$$

where

$$\begin{aligned} \mathbf{G}_1 &= (1, -1/2, -1/2, 0, 0, 0), \\ \mathbf{G}_2 &= (0, 1, -1, 0, 0, 0), \\ \mathbf{G}_3 &= (0, 0, 0, 1, 0, 0), \\ \mathbf{G}_4 &= (0, 0, 0, 0, 1, 0), \\ \mathbf{G}_5 &= (0, 0, 0, 0, 0, 1). \end{aligned} \qquad (3)$$

We use this representation of the CMT to distinguish between the CMT components that are able to generate strong vertical acceleration and those of negligible influence. Relative strengths of signals produced by the base moment tensors for the centroid depth of 20 km are shown in Table 1. The $M_{r\vartheta}$ and $M_{r\varphi}$ components do not generate any significant vertical acceleration, i.e., tangential stress vanishes near the surface, see also, e.g., (Dziewonski et al., 1981; Ferreira and Woodhouse, 2006; Bukchin et al., 2010; Bogiatzis and Ishii, 2014). The mode ${}_0S_2$ is generated mainly by M_{rr}, and its sensitivity to the remaining components is weak. Nevertheless, the other modes are sensitive also to $(M_{\vartheta\vartheta} - M_{\varphi\varphi})/2$ and $M_{\vartheta\varphi}$, and these two components can thus be inverted together with M_{rr}. Note that the signal generated by $\mathbf{G}_3$ and $\mathbf{G}_4$ raises with the source depth and, in principal, full CMT of the deepest earthquakes could be achieved from the SG-data inversion.

Determination of quality factors from GGP data and the CMT inversion

We have used GGP data sets registered at the stations AP, BH (averaged from three sensors), CA, CB, CO, ME, PE, WE (averaged from two sensors) after the 2010 Maule earthquake and AP, BH (averaged from three sensors), CA, CB, CO, ME, OS, PE, ST, after the 2011 Tohoku earthquake having neither gaps nor steps in the recordings and with only weak signals from aftershocks (Fig. 1). We have averaged the signals from several sensors located at one station to suppress the noise level and not to increase the weight of such a station in the inversion. After correcting raw gravity data (sampled at 1 s) for atmospheric effects using locally recorded atmospheric pressure data and a standard barometric admittance of $-3\ \mathrm{nm/s^2/hPa}$ (Hinderer et al., 2007), we apply a high-pass Butterworth filter (above 0.1 mHz) to remove local tides. In the studied frequency band, superconducting gravity data are less noisy than seismometer data (e.g. Ferreira et al., 2006), but they provide only the vertical component of oscillations.