

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



Eliška Zábranová*, Ctirad Matyska

Department of Geophysics, Faculty of Mathematics and Physics, Charles University in Prague, V Holešovičkách 2, CZ-18000 Prague, Czech Republic

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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} , $(M_{\theta\theta} - M_{\phi\phi})/2$ and $M_{\theta\phi}$, 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.

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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 submillihertz 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

* Corresponding author.

E-mail address: zabrana@karel.troja.mff.cuni.cz (E. Zábranová).

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.

Zábránová 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,

$$\mathbf{a}(\mathbf{x}_r, \mathbf{x}_s, t) = \text{Re} \left[\sum_k \mathbf{A}_k(\mathbf{x}_r, \mathbf{x}_s) \exp \left(i\omega_k t - \frac{\omega_k t}{2Q_k} \right) \right], \quad (1)$$

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, $\mathbf{e}_k = \frac{1}{2} [\nabla \mathbf{s}_k + (\nabla \mathbf{s}_k)^T]$ is the strain and

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

$\mathbf{s}_k(\mathbf{x}_s)$ 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 (Zábránová 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.

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 $M_{rr}, \dots, M_{\vartheta\varphi}$ are its spherical components, into five suitable base moment tensors,

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

where

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

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 $-3 \text{ nm/s}^2/\text{hPa}$ (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.

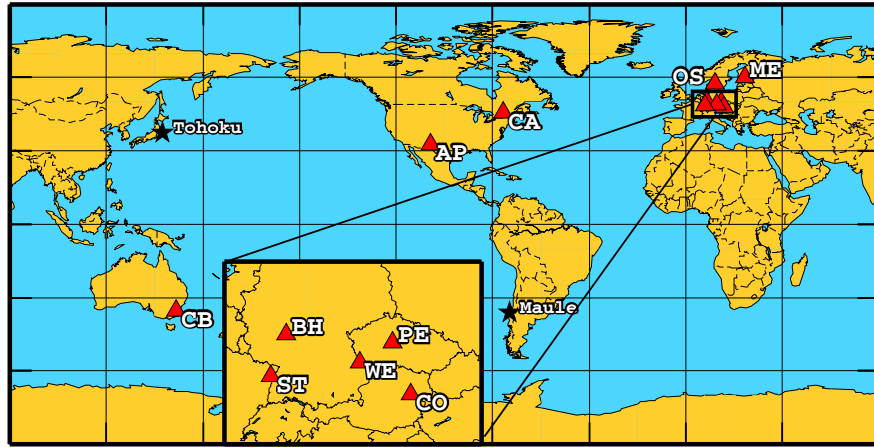


Fig. 1. GGP stations used in this study.

The quality factors Q of individual modal multiplets are key parameters, and their values used in synthetic calculations can substantially influence the results. We determined the Q s by their simultaneous inversion together with the three CMT components M_{rr} , $(M_{\theta\theta} - M_{\phi\phi})/2$ and $M_{\theta\phi}$. In all calculations two “low-sensitive” remaining components of $\mathbf{M}$ were fixed on the Global CMT solution, i.e. $M_{r\theta} = 0.23 \times 10^{22}$ Nm, $M_{r\phi} = -1.51 \times 10^{22}$ Nm for the 2010 Maule earthquake (Ekström and Nettles, 2010) and $M_{r\theta} = 2.12 \times 10^{22}$ Nm, $M_{r\phi} = 4.55 \times 10^{22}$ Nm for the 2011 Tohoku earthquake (Nettles et al., 2011). It is clear from Table 1 that such a choice of $M_{r\theta}$ and $M_{r\phi}$ influences amplitudes of all studied fundamental modes negligibly when the remaining components of the CMT are of the same order. The overtone ${}_1S_2$ is the only exception but still these two components generate much weaker ${}_1S_2$ signal than the remaining considered components of the CMT. Since the total amplitude of this overtone is about one order of magnitude smaller than the amplitudes of the other modes, its role in the CMT inversion is very small.

We define the misfit function calculated for each station s and each mode m as the square of the difference between the data and synthetic-signal-amplitude spectra averaged over a narrow frequency range δf_{sm} covering all singlets, where the amplitudes are above noise level, i.e. we minimize the functional

$$\sum_{sm} \frac{1}{\delta f_{sm}} \int_{\delta f_{sm}} \left(A_s^{(d)}(f) - A_s^{(c)}(f) \right)^2 df,$$

where $A^{(d)}$ ($A^{(c)}$) is the amplitude spectrum of the data (calculated synthetic signal). We do not employ the phase spectra since they are sensitive to the source finiteness and duration, noise and aftershocks (Lambotte et al., 2007; Bogiatzis and Ishii, 2014). We calculated the misfit from the optimal record lengths according to Dahlen (1982), see the last column in Table 2, derived for the case

Table 2

Periods T of the modes, their quality factors Q used in this study and optimal lengths of the signals according to Dahlen (1982). Q_0 was calculated from the PREM, Q_1 is our estimate contained by averaging over 4 inversion results: inversions started from the Q -values of the PREM and were performed for the centroid depth of 10 and 20 km for the 2010 Maule (20 and 30 km for the 2011 Tohoku) earthquake, Q_2 was estimated by Tanimoto et al. (2012) and Q_3 by Deuss et al. (2013).

	T [s]	Q_0	Q_1	Q_2	Q_3	$Q_0 T/2$ [h]
${}_0S_2$	3234	510	496 ± 16	525	477 ± 177	230
${}_0S_3$	2135	417	409 ± 11	380	405 ± 14	124
${}_0S_4$	1546	373	394 ± 27	365	373 ± 9	80
${}_0S_5$	1190	356	350 ± 16	350	364 ± 5	59

when amplitudes for the retrieval of source mechanism and the Hann taper for spectra calculations are utilized. All records started two hours after the origin time of the earthquakes and the synthetic calculations were performed for the two centroid depths, see Table 3.

We have used two-step iterative inversion procedure starting from the Q -values of the PREM: in the first step all quality factors are fixed and the three CMT components are inverted, in the second step the obtained CMT is fixed and the quality factors are inverted. The first step is then repeated with the new quality factors, then we continue with the second step etc. The convergence is very fast and only several loops (up to ten) of both steps are needed to reach misfit minimum. Note that we use grid-search in both steps with higher accuracy than 10^{20} Nm in the first step and 1 in the second step. Since the studied modes are isolated in the spectrum, the quality factor of each mode can be inverted separately in the second step. The first step could be solved as an linear inverse problem but the direct linear problem is extremely fast and thus this straightforward minimization method can be easily implemented.

Obtained quality factors in our inversion procedure are almost independent of changes in the source depth and the choice of the earthquake. Fig. 2 shows the amplitude spectra of synthetic and measured signals averaged by the time-window lengths to demonstrate data fitting reached in our inversion procedure. We obtained excellent fit for the modes ${}_0S_2$, ${}_0S_3$ and ${}_0S_5$ but worse results for the mode ${}_0S_4$.

In order to estimate the errors of our inversion procedure, we performed single-record inversions and then calculated the standard deviations of inverted parameters from the resultant set of these individual inversions. We first determined the quality factors from the records separately for each station (fixing the CMT components on all-station inversion values) and then obtained the CMT independently for each station (fixing the quality factors on all-station inversion values).

In Table 2 we compare our Q values of fundamental modes averaged over performed inversions for both earthquakes with the results obtained by Tanimoto et al. (2012) from cross-correlations in the time domain, by Deuss et al. (2013) performing splitting function inversions, as well as with those from the PREM (Dziewonski and Andersen, 1981). The fundamental-mode-quality factors of the PREM and almost all of Deuss et al. (2013) lie within the obtained confidence interval but the results of Tanimoto et al. (2012) differ more. The highest standard deviation was obtained for the mode ${}_0S_4$ which corresponds to the problems with its fit as demonstrated in Fig. 2. We also tried to determine the quality

Table 3

The CMT components obtained from the joint inversion with the quality factors of the records from the stations AP, BH, CA, CB, CO, ME, PE, WE (2010 Maule) and AP, BH, CA, CB, CO, ME, OS, PE, ST (2011 Tohoku), see Fig. 1 and Q_1 in Table 2.

Centroid depth [km]	M_{rr} [10^{22} Nm]	$(M_{\theta\theta} - M_{\phi\phi})/2$ [10^{22} Nm]	$M_{\theta\phi}$ [10^{22} Nm]
2010 Maule			
20	1.10 ± 0.01	0.55 ± 0.19	-0.09 ± 0.09
30	1.05 ± 0.01	0.54 ± 0.20	-0.10 ± 0.09
2011 Tohoku			
10	1.61 ± 0.02	0.63 ± 0.16	-0.52 ± 0.10
20	1.70 ± 0.02	0.60 ± 0.17	-0.56 ± 0.10

factor of the mode ${}_1S_2$ and attained its reasonable value of $Q \approx 310$ for the 2010 Maule earthquake but most of individual-station inversions of this quality factor were unstable; therefore, we were not able to obtain standard deviations. Moreover, the data for the Tohoku 2011 earthquake exhibit much higher values ($Q \geq 340$). These two analyses are not consistent, and we decided not to deal with this mode.

The review of the obtained CMT components is in Table 3; we used Global CMT source location. Our M_{rr} component for the 2011 Tohoku earthquake is in good agreement with the recently published low-frequency-normal-mode inversion based on Global Seismographic Network data, see Table 2 in (Bogiatzis and Ishii, 2014), but the remaining components are in better agreement with the Global CMT solution (Nettles et al., 2011), the USGS CMT solution (Polet and Thio, 2011) as well as the USGS Wphase

solution (Duputel et al., 2011). Note that the dependence on a source depth (mainly that of the component M_{rr}) is primarily due to the changes of the model elastic parameters. On the other hand, inversions of individual records yield almost identical values of the M_{rr} component for fixed depths that are, moreover, in a very good agreement with the M_{rr} estimates obtained from the radial mode ${}_0S_0$ inversion, see (Zábánová et al., 2012).

In order to study potential trade-off between the CMT components and the quality factors, we chose the quality factors by Tanimoto et al. (2012) and Deuss et al. (2013) in the role of starting models and repeated the simultaneous inversion of all records. The results obtained from the joint inversions starting from the different quality factors lie within the confidence intervals obtained in the inversion starting from the PREM quality-factor set Q_0 . Then we computed the CMT components for the fixed quality-factor sets (Q_0 – Q_3) for both the 2010 Maule and 2011 Tohoku earthquakes assuming the depth of 20 km. The lowest values correspond to the Q_0 quality factors ($M_{rr} = 1.06 \times 10^{22}$ Nm for 2010 Maule; $M_{rr} = 1.70 \times 10^{22}$ Nm for 2011 Tohoku) and the highest values correspond to the Q_2 quality factors ($M_{rr} = 1.11 \times 10^{22}$ for 2010 Maule; $M_{rr} = 1.77 \times 10^{22}$ for 2011 Tohoku). The spans of the remaining two CMT components are within the confidence intervals. The trade-off between the quality factors and M_{rr} is demonstrated in Fig. 3. One can clearly recognize that an increase of the M_{rr} component is connected with decreases of the quality factors and the “minima valleys” are shallow. Since the trade-off between the CMT and quality factors complicated the joint Q-CMT inversion although relatively long records were utilized, we will continue with the CMT inversion of short records fixing the quality factors.

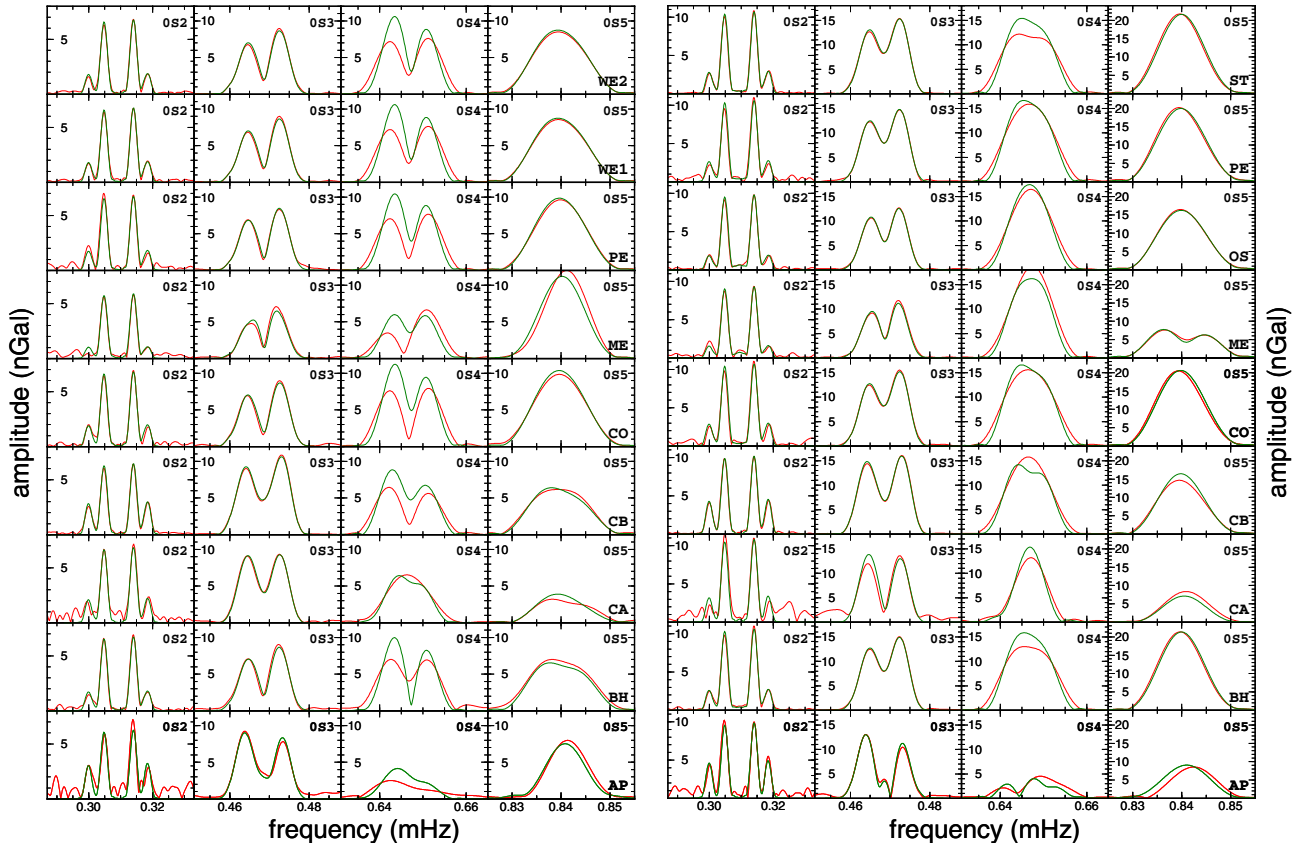


Fig. 2. Vertical acceleration amplitude spectra of the studied modes from the SG data (red) and synthetics (green) after the 2010 Maule (left panel) and 2011 Tohoku (right panel) earthquakes. The synthetic signal was calculated for the solution of joint inversion at the depth 20 km (10 km) for the Maule (Tohoku) earthquake. A Hann filter and Fourier transform were applied to the time series of the length shown in the last column of Table 2 starting 2 h after the origin times and averaged by the length of the time windows. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

CMT inversion from short time series for fixed quality factor sets

We will demonstrate now that relatively short SG records can be employed to obtain reasonable low-frequency CMT parameters provided the quality factor set is fixed on “reasonable” values. From the point of view of mode-amplitude attenuation with time, the optimal length of a signal to determine the amplitude of a mode is given by its Q multiplied by half of the period (Dahlen, 1982). Therefore, when all studied modes are used in the inversions together, it is important to employ signals where neither of the modes is too much attenuated. This is the reason why we used only 60 h-long signals; the Hann taper and Fourier transform were applied to the time series starting again two hours after the earthquake-origin time. In principle, even shorter records could be employed but too short time series would not lead to narrow spectral peaks and an approach in the time domain would have to be applied (Tanimoto et al., 2012).

We have inverted three “sensitive” components of the moment tensor M_{rr} , $(M_{\theta\theta} - M_{\phi\phi})$ and $M_{\theta\phi}$ again from the L_2 -inversion with variable source depth. A depth-grid search with 1-km stepping has been applied. The results of inversion are shown in Fig. 4; For the 2011 Tohoku earthquake all inversions yield better misfit than the reference Global CMT solution with the PREM Q -values, i.e., the re-evaluation of the CMT components plays a substantial role in the misfit reduction. Moreover, our new re-evaluation of the

modal quality factors results in further misfit improvement. However, the misfits for the 2010 Maule earthquake were not improved. The probable reason is that the fit of the mode ${}_0S_4$ in the case of the 2010 Maule earthquake is poor for any choice of the quality factors and most of the misfit is thus created by this mode as shown in Fig. 5. The source of this misfit remains unclear but comparing Figs. 2 and 5 one can see that the mode ${}_0S_4$ misfit is lower for shorter time windows. The dependence of the misfit on source depth is rather weak up to 30 km and it gets worse for higher depths for both earthquakes. In principle, it confirms the already published results showing that the centroid was located at shallow depths. The values for the centroid depth 20 km are summarized in Table 4; they are in good agreement with the values in Table 3.

The inversion of M_{rr} from the rather short 60-h signal is only slightly influenced by considered choices of quality factors, and the resultant differences are smaller than differences of the published CMT solutions that are used here for comparison. The Global CMT solution PS1 yields the M_{rr} component in very good agreement with our inversion. This agreement confirms the analyses of frequency dependence of the scalar moment showing that there were no slow components of the two studied earthquake sources (Tanimoto et al., 2012; Okal, 2013). Moreover, there is a good agreement with the independent results of Zábánová et al. (2012) where the value of M_{rr} was obtained directly from the radial modes. Note that M_{rr} is clearly depth-dependent since it is influenced mainly by the shear-modulus profile. The

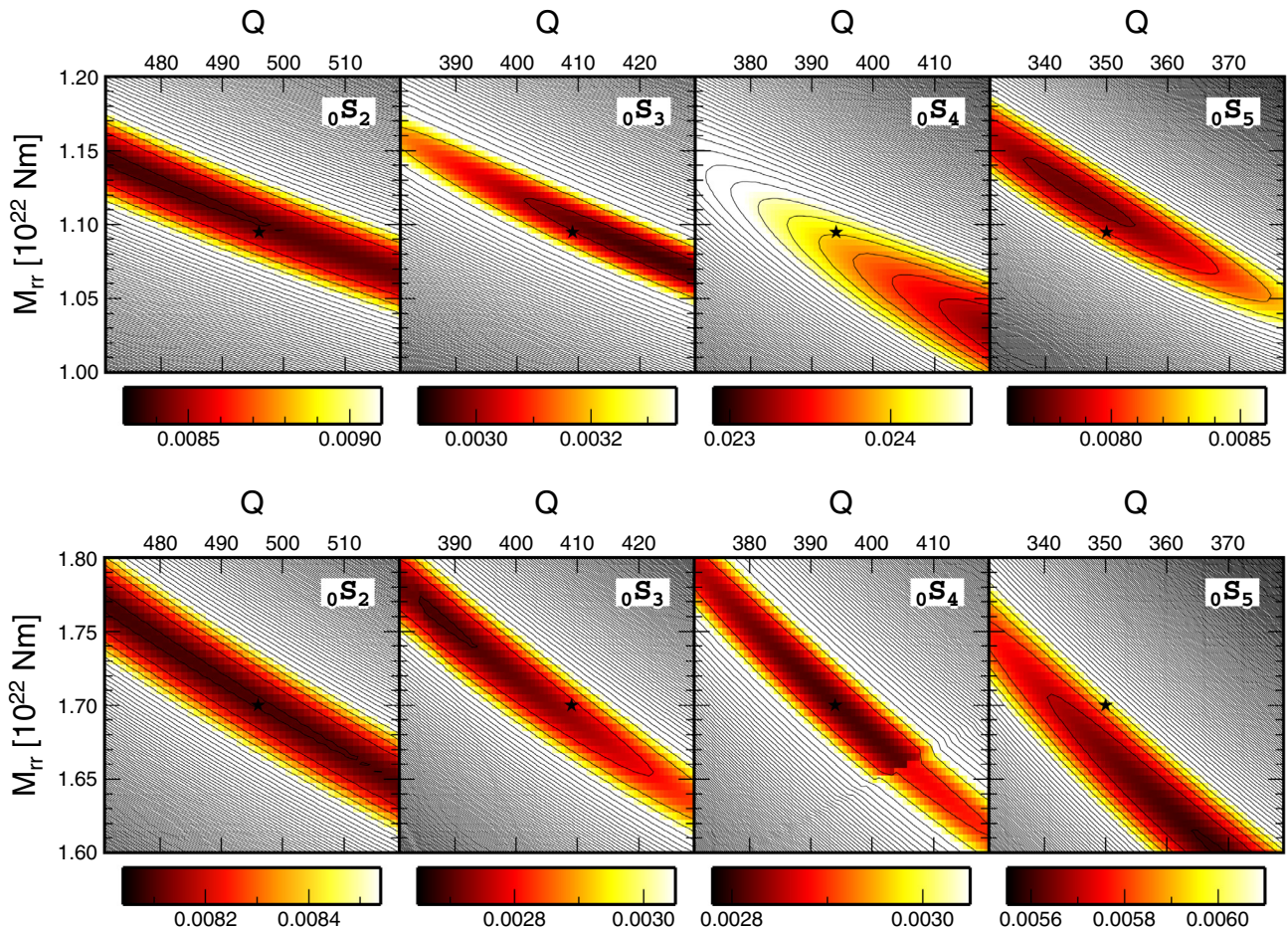


Fig. 3. Relative misfits of individual modes for the 2010 Maule (upper panel) and 2011 Tohoku (lower panel) earthquakes for the centroid depth of 20 km showing the trade-off between the M_{rr} component and quality factors of the modes. The components $(M_{\theta\theta} - M_{\phi\phi})/2$ and $M_{\theta\phi}$ were fixed on their values from Table 3 and the stars denote our solutions presented in Tables 2 and 3. The contour intervals are the same in all panels of a row but the color scales are different. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

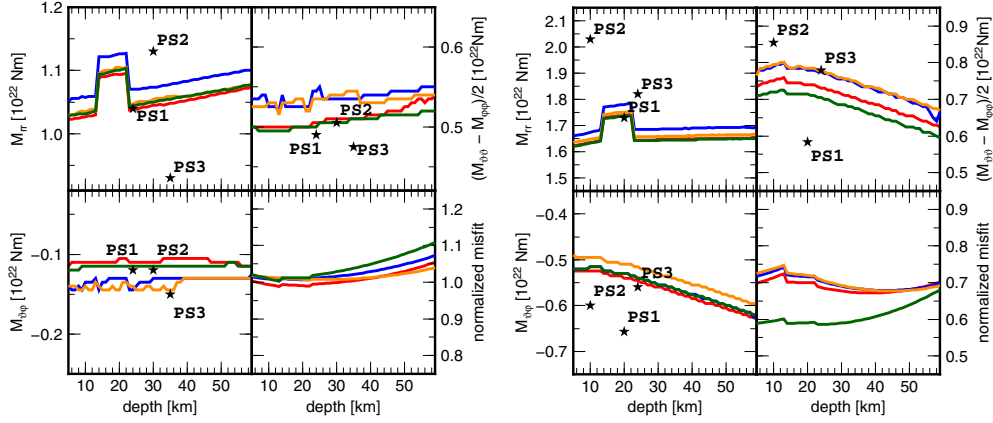


Fig. 4. Dependence of the M_{tr} , $(M_{\theta} - M_{\phi})/2$ and M_{θ} components of the centroid moment tensor on the centroid depth obtained from the inversion of vertical acceleration of the spheroidal modes up to 1 mHz for four sets of Q (red Q_0 , green Q_1 , blue Q_2 , orange Q_3). The left (right) panel is for the 2010 Maule (2011 Tohoku) earthquake. Stars denote published point-source solutions: Global CMT solutions (Ekström and Nettles, 2010; Nettles et al., 2011) (PS1), USGS CMT solutions (Maule: http://earthquake.usgs.gov/earthquakes/eqinthenews/2010/us2010tfan/neic_tfan_cmt.php; Tohoku: Polet and Thio, 2011) (PS2), USGS Wphase solutions (Maule: http://earthquake.usgs.gov/earthquakes/eqinthenews/2010/us2010tfan/neic_tfan_wmt.php; Tohoku: Duputel et al., 2011) (PS3). The last panel shows the relative misfits of inversions as functions of depth normalized by the misfits of the solution PS1 calculated for the PREM quality factors. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

moment-tensor-diagonal term $(M_{\theta} - M_{\phi})/2$ as well as the M_{θ} component are determined well for all the studied quality factor sets. It is of interest that the results of inversions of these two components are almost independent of the choice of the quality factors, and they exhibit sensitivity to the centroid depth for the 2011 Tohoku earthquake.

Fig. 6 shows modal-amplitude attenuations with shifts Δt of different time windows (last column in Table 3) applied to the superconducting-gravimeter and synthetic data after the 2011 Tohoku earthquake for mechanisms shown in Table 4. Deviations of the real data from the synthetic curves appear at “critical-time shifts” when modal amplitudes are so small that the role of noise in the signal

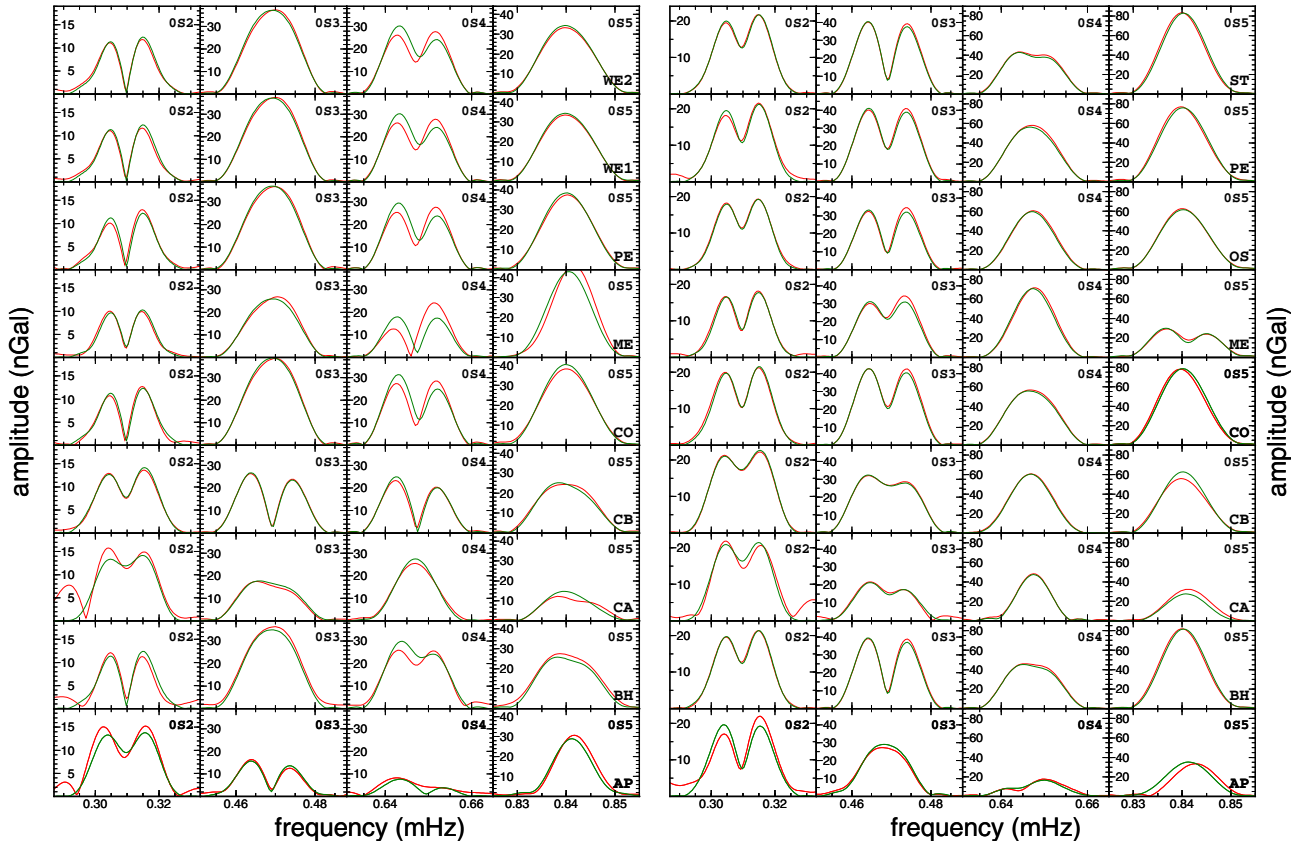


Fig. 5. Vertical acceleration amplitude spectra of the studied modes from the SG data (red) and synthetics (green) after the 2010 Maule (left panel) and the 2011 Tohoku (right panel) earthquakes. The synthetic signal was calculated for the optimal CMT solution at the depth 20 km (10 km) for the Maule (Tohoku) earthquake when the quality factors were fixed at the Q_1 values from Table 2. A Hann filter and Fourier transform were applied to the time series of 60-h length starting 2 h after the origin times and averaged by the length of the time window. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

Table 4

Components of the inverted CMT located in 20 km depth from 60-h-long records.

	M_{rr} [10^{22} Nm]	$(M_{\theta\theta} - M_{\phi\phi})/2$ [10^{22} Nm]	$M_{\theta\phi}$ [10^{22} Nm]
2010 Maule			
Q_0	1.09	0.50	−0.11
Q_1	1.10	0.50	−0.11
Q_2	1.13	0.53	−0.13
Q_3	1.11	0.54	−0.15
2011 Tohoku			
Q_0	1.73	0.74	−0.54
Q_1	1.73	0.72	−0.53
Q_2	1.78	0.78	−0.53
Q_3	1.75	0.79	−0.51

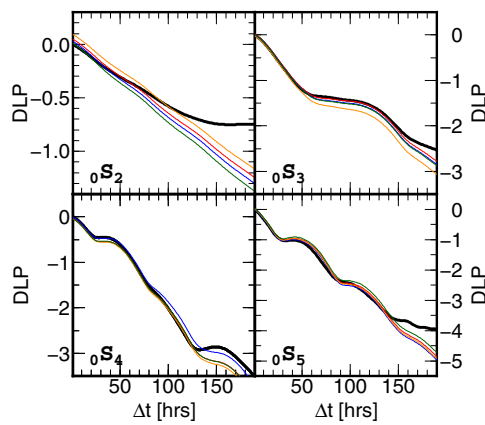


Fig. 6. Decadic logarithm of the powers (DLP) of the studied modes (integral over narrow frequency range covering all singlets for each mode) with time shifts of time windows applied to the data (black lines) and synthetic signals after the 2011 Tohoku earthquake calculated for the four sets of quality factors (red Q_0 , green Q_1 , blue Q_2 , orange Q_3) and for the CMT values from Table 4. All powers are normalized by the powers of data for the time shifts $\Delta t = 0$, i.e. time windows starting 2 h after the origin time. Lengths of time windows are written in the last column of Table 2. The slope of the curves for synthetic data corresponds to the values of the quality factors. Since the modal multiplets consist of several singlets with slightly different frequencies, the curves are oscillating. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this article.)

becomes substantial. Combining these “critical-time shifts” for data from fifteen records with the used lengths of time windows, one can clearly see that maximal length of the signal undisturbed by the noise is only about 200 h for the modes $0S_4$ and $0S_5$ and 280 h for the modes $0S_3$ and $0S_2$. These numbers are only illustrative for this particular earthquake as signal/noise ratio depends on earthquake parameters and the station quality. Nevertheless, we think that they represent typical maximal lengths of the signals from the GGP network that can be used for individual modes after megathrust events. Naturally, one can omit “more noisy” stations to obtain an agreement between data and the synthetics for longer times. This figure clearly demonstrates that applications of very long records, used to determine quality factors of individual singlets, can be affected by noise. On the other hand, if we do not deal with clear separation of multiplets into singlets, e.g., when only the low-frequency components of the CMT are determined, relatively short records are sufficient and they have excellent signal/noise ratio.

Conclusions

In several studies (e.g., Okal and Stein, 2009; Okal et al., 2012; Okal, 2013; Tanimoto and Ji, 2010; Tanimoto et al., 2012)

ultralong-period normal modes were employed to determine only one low-frequency source parameter of giant earthquakes—the scalar moment M_0 —assuming double-couple focal mechanism and fixing the three remaining parameters (dip, strike and rake) by means of values chosen a priori from independent studies. It is well known that there is a trade-off between these parameters; the choice of the dip, strike and rake thus also influences the obtained value of the scalar moment M_0 . We demonstrated here the three low-frequency components— M_{rr} , $(M_{\theta\theta} - M_{\phi\phi})/2$ and $M_{\theta\phi}$ —can be obtained from SG records after the 2010 Maule and 2011 Tohoku earthquakes assuming that the isotropic component of the CMT is negligible, and dealt with their trade-off with the quality factors of the modes. For shallow earthquakes sensitivity of data to the two remaining components— $M_{r\theta}$ and $M_{r\phi}$ —is very weak, these components cannot thus be inverted from the used data, and the results are independent on their choice made a priori, cf. (Dziewonski et al., 1981; Ferreira and Woodhouse, 2006; Bukchin et al., 2010; Bogiatzis and Ishii, 2014).

We first performed inversion of quality factors jointly with the three studied CMT components from long records of optimal lengths to obtain amplitudes for each mode (last column in Table 2). The resulted modal quality factors are in good agreement with the PREM values and the results published by Deuss et al. (2013), however, they differ more from the results by Tanimoto et al. (2012). We then inverted the CMT components fixing the quality factors on these published values. The resultant span of the CMT values is smaller than mutual differences of the Global CMT, USGS CMT and USGS Wphase solutions.

The question thus arises whether it is necessary to use such long records. We thus finally employed only 60 h long records and performed again the CMT inversions for the fixed four quality factor sets shown in Table 2. The best solutions for each quality-factor set are summarized in Table 4. They can be considered as the low-frequency estimates of the CMT components independent of previous results obtained in higher frequency ranges. The optimal centroid depth were located into shallow depths and the differences of the obtained inversion results are again smaller than the mutual differences of the published agency CMT solutions. Problem of proper determination of the modal quality factors in inversion procedures of the low-frequency CMT of giant earthquakes utilizing relatively short records can thus be omitted and the inversion can be, in principle, routinely performed for any of the studied quality-factor sets.

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References

- Bogiatzis, P., Ishii, M., 2014. Constraints on the moment tensor of the 2011 Tohoku-Oki earthquake from Earth's free oscillations. *Bull. Seism. Soc. Am.* 104, 875–884.
- Bukchin, B., Clévédy, E., Mostinskiy, A., 2010. Uncertainty of moment tensor determination from surface wave analysis for shallow earthquakes. *J. Seismol.* 14, 601–614.
- Dahlen, F.A., 1982. The effect of data windows on the estimation of free oscillation parameters. *Geophys. J. Roy. Astron. Soc.* 69, 537–549.
- Dahlen, F.A., Sailor, R.V., 1979. Rotational and elliptical splitting of the free oscillations of the Earth. *Geophys. J. Roy. Astron. Soc.* 58, 609–623.
- Dahlen, F.A., Tromp, J., 1998. *Theoretical Global Seismology*. Princeton University Press, Princeton.

- Deuss, A., Ritsema, J., van Heijst, H., 2013. A new catalogue of normal-mode splitting function measurements up to 10 mHz. *Geophys. J. Int.* 193, 920–937.
- Ding, H., Shen, W.B., 2013. Determination of the complex frequencies for the normal modes below 1 mHz after the 2010 Maule and 2011 Tohoku earthquakes. *Ann. Geophys.* 56, S0563. <http://dx.doi.org/10.4401/ag-6400>.
- Duputel, Z., Rivera, L., Kanamori, H., Hayes, G.P., Hirshorn, B., Weinstein, S., 2011. Real-time W phase inversion during the 2011 off the Pacific coast of Tohoku earthquake. *Earth Planets Space* 63, 535–539.
- Duputel, Z., Rivera, L., Fukahata, Y., Kanamori, H., 2012. Uncertainty estimates for seismic source inversions. *Geophys. J. Int.* 190, 1243–1256.
- Dziewonski, A.M., Andersen, D.L., 1981. Preliminary reference Earth model. *Phys. Earth Planet. In.* 25, 297–356.
- Dziewonski, A.M., Chou, T.A., Woodhouse, J.H., 1981. Determination of earthquake source parameters from waveform data for studies of global and regional seismicity. *J. Geophys. Res.* 86, 2825–2852.
- Ekström, G., Nettles, M., 2010. <http://earthquake.usgs.gov/earthquakes/eqinthenews/2010/us2010tfan/neicftfancmt.php>
- Ferreira, A.M.G., Woodhouse, J.H., 2006. Long-period seismic source inversions using global tomographic models. *Geophys. J. Int.* 166, 1178–1192.
- Ferreira, A.M.G., d'Oreye, N.F., Woodhouse, J.H., Zürn, W., 2006. Comparison of fluid tiltmeter data with long-period seismograms: surface waves and Earth's free oscillations. *J. Geophys. Res.* 111, B11307. <http://dx.doi.org/10.1029/2006JB004311>.
- He, X., Tromp, J., 1996. Normal-mode constraints on the structure of the Earth. *J. Geophys. Res.* 101, 20053–20082.
- Hinderer, J., Crossley, D., Warbuton, R.J., 2007. Gravimetric methods – Superconducting gravity meters. In: Herring T. (Ed.), *Treatise on Geophysics*, pp. 65–122.
- Lamotte, S., Rivera, L., Hinderer, J., 2007. Constraining the overall kinematics of the 2004 Sumatra and the 2005 Nias earthquakes using the Earth's gravest free oscillations. *Bull. Seism. Soc. Am.* 97, S128–S138.
- Nettles, M., Ekström, G., Koss, H.C., 2011. Centroid-moment-tensor analysis of the 2011 off the Pacific coast of Tohoku earthquake and its larger foreshocks and aftershocks. *Earth Planets Space* 63, 519–523.
- Okal, E., 2013. From 3-Hz P waves to ${}_0S_2$: No evidence of a slow component to the source of the 2011 Tohoku earthquake. *Pure Appl. Geophys.* 170, 963–973.
- Okal, E.A., Stein, S., 2009. Observations of ultra-long period normal modes from the 2004 Sumatra-Andaman earthquake. *Phys. Earth Planet. In.* 175, 53–62.
- Okal, E.A., Hongsresawat, S., Stein, S., 2012. Split-mode evidence for no ultraslow component to the source of the 2010 Maule, Chile, earthquake. *Bull. Seism. Soc. Am.* 102, 391–397.
- Polet, J., Thio, H.K., 2011. Centroid-moment-tensor analysis of the 2011 off the Pacific coast of Tohoku Earthquake and its larger foreshocks and aftershocks. *Earth Planets Space* 63, 519–523.
- Roult, G., Rosat, S., Clévéde, E., 2006. New determinations of Q quality factors and eigenfrequencies for the whole set of singlets of the Earth's normal modes ${}_0S_0$, ${}_0S_2$, ${}_0S_3$ and ${}_2S_1$ using superconducting gravimeter data from the GGP network. *J. Geod.* 41, 345–357.
- Tanimoto, T., Ji, C., 2010. Afterslip of the 2010 Chilean earthquake. *Geophys. Res. Lett.* 37, L22312. <http://dx.doi.org/10.1029/2010GL045244>.
- Tanimoto, T., Ji, C., Igarashi, M., 2012. An approach to detect afterslips in giant earthquakes in the normal-mode frequency band. *Geophys. J. Int.* 190, 1097–1110. <http://dx.doi.org/10.1111/j.1365-246X.2012.05524.x>.
- Valentine, A.P., Trampert, J., 2012. Assessing the uncertainties on seismic source parameters: towards realistic error estimates for centroid-moment-tensor determinations. *Phys. Earth Planet. In.* 210–211, 36–49.
- Zábranová, E., Hanyk, L., Matyska, C., 2009. Matrix pseudospectral method for elastic tides modeling. In: Holota, P. (Ed.), *Mission and Passion: Science. Czech National Committee of Geodesy and Geophysics, Prague*, pp. 243–260.
- Zábranová, E., Matyska, C., Hanyk, L., Pálinský, V., 2012. Constraints on the centroid moment tensors of the 2010 Maule and 2011 Tohoku earthquakes from radial modes. *Geophys. Res. Lett.* 39, L18302. <http://dx.doi.org/10.1029/2012GL052850>.