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Low-Frequency Centroid Moment Tensor Inversion of the 2015 Illapel Earthquake from Superconducting-Gravimeter Data

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Abstract—After the 2015 Illapel earthquake the radial and spheroidal modes up to 1 mHz were registered by the network of superconducting gravimeters. These data provide unique opportunity to obtain ultralow-frequency estimates of several centroid moment tensor components. We employ the superconducting-gravimeter records of 60-h lengths and perform the joint inversion for M_{rr}, $(M_{\vartheta\vartheta} - M_{\varphi\varphi})/2$ and $M_{\vartheta\varphi}$ centroid moment tensor components from spheroidal modes up to 1 mHz. The M_{rr} component is also obtained from independent inversion of the radial modes $_0S_0$ and $_1S_0$. Our results are consistent with the published solutions obtained from higher frequency data, suggesting thus negligible slow afterslip phenomenon.

Key words: 2015 Illapel earthquake, superconducting-gravimeter data, normal modes, CMT inversion.

1. Introduction

The 2010 Maule and 2015 Illapel earthquakes are the biggest Chilean events of the last decade. It is of interest that the strain accumulation in the Illapel region was measured by GPS and the preparation of such an event had thus been described before (Vigny *et al.* 2009). In addition to standard seismometer networks, the observations after megathrust earthquakes are performed by superconducting gravimeters (SG) (Fig. 1). The superconducting gravimeters provide high-quality data that exhibit low noise level in submillihertz frequency range (Rosat *et al.* 2004, 2015; Rosat and Hinderer 2011) and can thus be employed in earthquake source studies.

Ultralong-period-normal-mode inversions are needed to reveal potential ultraslow components of the seismic source. Several such inversions were performed to study frequency dependence of the scalar moment M_0 (Okal and Stein 2009; Okal *et al.* 2012; Okal 2013; Tanimoto and Ji 2010; Tanimoto *et al.* 2012), complementary approach can be based on amplitude ratios of these modes (Braitenberg and Zadro 2007). However, a one-component inversion requires to fix other quantities determining seismic double-couple source (strike, dip and rake) on some a priori chosen values. Our approach is different and is based on direct inversion of several components of the centroid moment tensor (CMT) independently on remaining ones without an a priori assumption about the source mechanism, except the condition of zero isotropic part of the CMT. For shallow earthquakes the M_{rr} component of the moment tensor can be obtained by inverting the amplitudes of the radial modes (Zábranová *et al.* 2012) and the M_{rr}, $(M_{\vartheta\vartheta} - M_{\varphi\varphi})/2$ and $M_{\vartheta\varphi}$ CMT components result from joint inversion of spheroidal modes (Zábranová and Matyska 2014). The aim of this study is to perform inversion of these CMT components for the 2015 Illapel earthquake from the registered modes with eigenfrequencies lower than 1 mHz and compare the obtained results in such an ultralong-period range with solutions routinely obtained from higher frequency data.

We apply inversion procedure to SG data registered after the 2015 Illapel earthquake adopting quality factors of the employed modes from our previous studies (Zábranová *et al.* 2012; Zábranová and Matyska 2014). In the case of the spheroidal modes inversion, the record lengths of only 60-h length is sufficient (Zábranová and Matyska 2014).

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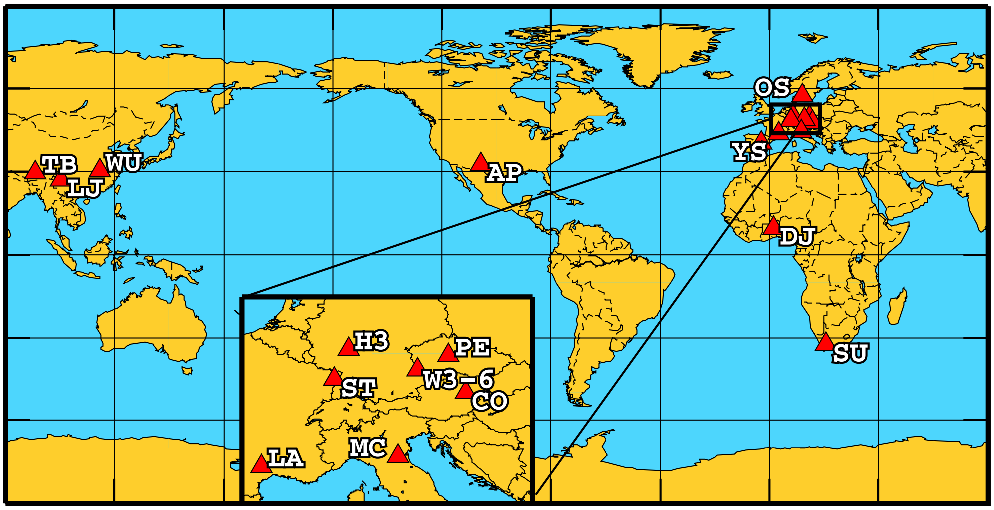

Figure 1
SG stations providing data after the 2015 Illapel earthquake

The influence of potential quality factor inaccuracies is thus suppressed because fundamental spheroidal modes are only slightly attenuated during such a relatively short time interval and their signal is sufficiently above noise level at many stations registering normal modes generated by the 2015 Illapel earthquake (Fig. 2). Note that longer records must be used to deal with the radial modes as they are weak but their quality factors are high. Typical situation is, however, that parts of the submillihertz spectra are corrupted on several records, see, e.g., the spectrum of the ${}_0S_2$ mode obtained from the records at the stations SU (Sutherland, South Africa), DJ (Djougou, Benin), AP (Apache Point, US) and PE (Pecny, Czech Republic). We include also the synthetic spectra calculated for several published solutions. One can clearly see that the synthetic spectra exhibit similar behavior but differences are visible and the inversion of data can, in principle, yield results slightly different from these solutions.

2. Method

We obtained the fundamental eigenfrequencies and eigenfunctions of the modes by means of the pseudospectral finite-difference matrix-eigenvalue approach (Zábranová *et al.* 2009) applied to the PREM (Dziewonski and Andersen 1981). Consequently, we include the potential perturbation, free air and tilt corrections to model a realistic device response (Dahlen and Sailor 1979), as well as the Earth's ellipticity and rotation (including second-order Coriolis corrections) leading to modal-multiplets splitting (Dahlen and Sailor 1979), similarly as in Zábranová *et al.* (2012) and Zábranová and Matyska (2014).

In general, there are six independent spherical components of the moment tensor $\mathbf{M} = (M_{rr}, M_{\vartheta\vartheta}, M_{\varphi\varphi}, M_{r\vartheta}, M_{r\varphi}, M_{\vartheta\varphi})$. However, the isotropic component of the source of shallow subduction earthquakes is commonly assumed to be negligible and thus we can use a straightforward decomposition of the moment tensor into the five base moment tensors:

$$\mathbf{M} = M_{rr}\mathbf{G}_1 + \frac{M_{\vartheta\vartheta} - M_{\varphi\varphi}}{2}\mathbf{G}_2 + M_{r\vartheta}\mathbf{G}_3 + M_{r\varphi}\mathbf{G}_4 + M_{\vartheta\varphi}\mathbf{G}_5, \quad (1)$$

where

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

We use this representation of the CMT because radial modes are generated by the M_{rr} component only. The

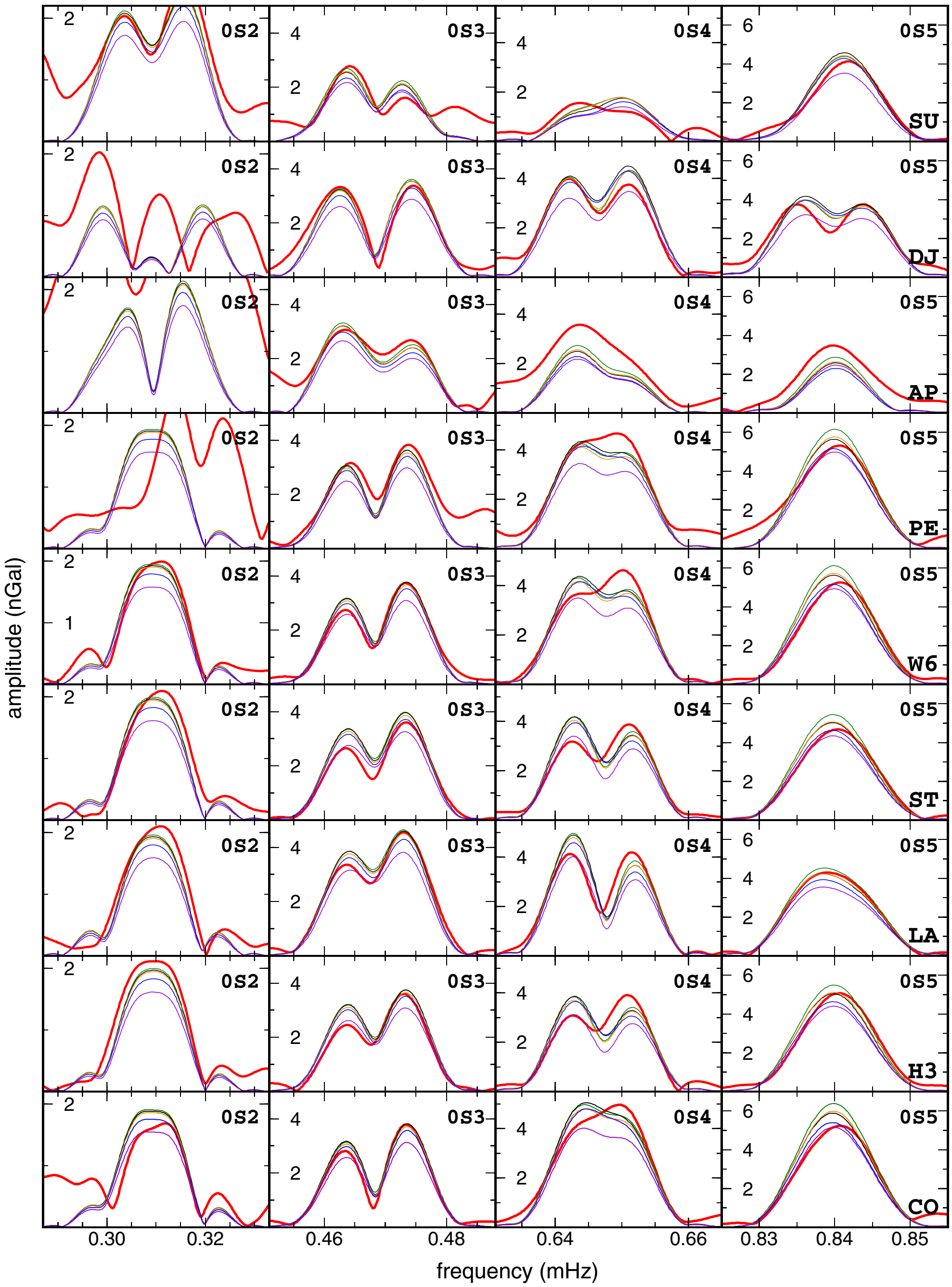

Figure 2

Vertical acceleration amplitude spectra of the studied modes from the SG data (red) and synthetics calculated for several published solutions at several SG stations; (*green*—GCMT, *black*—USGS, *violet*—GFZ, *orange*—Strasbourg, *blue*—IPGP). A Hann filter and Fourier transform were applied to the time series of the 60-h length starting 20 hrs after the origin times and averaged by the length of the time windows

spheroidal 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}. In the case of shallow earthquakes, the $M_{r\vartheta}$ and $M_{r\varphi}$ components do not generate any significant vertical acceleration, since tangential stress vanishes near the surface, see also

Dziewonski *et al.* (1981), Ferreira and Woodhouse (2006), Bukchin *et al.* (2010), Bogiatzis Ishii (2014) and Zábranová and Matyska (2014), i.e., we are not able to determine the components of moment tensor corresponding to the linear space with the base $(\mathbf{G}_3, \mathbf{G}_4)$.

3. Results of Inversion

We apply the quality factors of the radial and spheroidal modes up to 1 mHz determined in (Zábranová *et al.* 2012; Zábranová Matyska 2014) that are summarized together with their standard deviations in Table 1, and invert these modes to obtain the components of the moment tensor M_{rr}, $(M_{\vartheta\vartheta} - M_{\varphi\varphi})$ and $M_{\vartheta\varphi}$. In Fig. 3 we show the results from the joint L_2-inversion of the fundamental spheroidal-modes amplitude spectra of vertical acceleration in the submillihertz frequency range as a function of the source depth, inferring the 60-h-long signals. We used the records from the stations: CO (Conrad Observatory, Austria), H3 (Bad Homburg, German), LA (Larzac, France), ST (Strasbourg, France), W3–W6 (Wettzell, German). The Hann taper and Fourier transform were applied to the time series starting 20 h after the earthquake-origin time. This time shift of the employed time window suppresses the spectral power of the low-quality factor modes, especially that of the mode ${}_1S_2$ and, subsequently, its influence to the mode ${}_0S_4$ through the coupling that was not included in our calculations. The amplitude spectrum of the mode ${}_1S_2$ is then only slightly above the noise level.

The sensitivity to the centroid depth of the obtained CMT components is very weak except the changes of the M_{rr} caused by jumps of the shear modulus in the PREM. The shaded area shows the uncertainty of the solutions corresponding to ±one standard deviation of the four used modal quality factors. One can clearly recognize that considered errors in the quality factors yield about $\pm 0.03 \times 10^{21}$ Nm deviation of M_{rr}, $\pm 0.05 \times 10^{21}$ Nm deviation of $M_{\vartheta\varphi}$ but slightly more than $\pm 0.2 \times 10^{21}$ Nm for $(M_{\vartheta\vartheta} - M_{\varphi\varphi})$. Variance of the M_{rr} and $M_{\vartheta\varphi}$ of the selected published solutions is higher but, in principle, our results agree with these solutions, although we use only the four modes ${}_0S_2$, ${}_0S_3$, ${}_0S_4$, ${}_0S_5$ and only eight records from the best stations that are not corrupted by noise—the problems with noise have to do mainly with the weakest mode ${}_0S_2$.

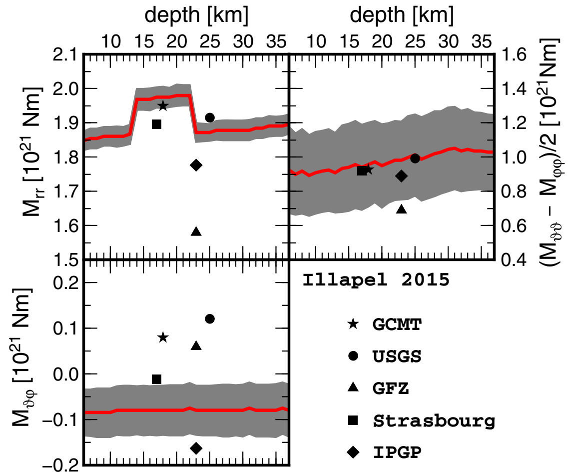

Figure 3
Dependence of the M_{rr}, $(M_{\vartheta\vartheta} - M_{\varphi\varphi})/2$ and $M_{\vartheta\varphi}$ components of the centroid moment tensor on the centroid depth obtained from the inversion of vertical acceleration of the spheroidal modes up to 1 mHz (*thick red line*) from 60-h-long records. The *gray* areas correspond to the errors of the quality factors (Table 1). The several published solutions are denoted by the symbols explained in the last panel

The misfits are shown in Fig. 4. They are similar to the misfits of the published solutions shown in Fig. 2. This is not surprising because our solutions do not deviate from the cluster of these solutions; note that they were already analyzed by Ye *et al.* (2015) with a special emphasize to the need of fast solutions for tsunami warning (Aranguiz *et al.* 2015). One can

Table 1

Periods T of the modes and their quality factors Q according to Zábranová et al. (2012) and Zábranová and Matyska (2014)

	${}_0S_2$	${}_0S_3$	${}_0S_4$	${}_0S_5$	${}_0S_0$	${}_1S_0$
T (s)	3234	2135	1546	1190	1228	613
Q	496 ± 16	409 ± 11	394 ± 27	350 ± 16	5500 ± 140	2000 ± 50

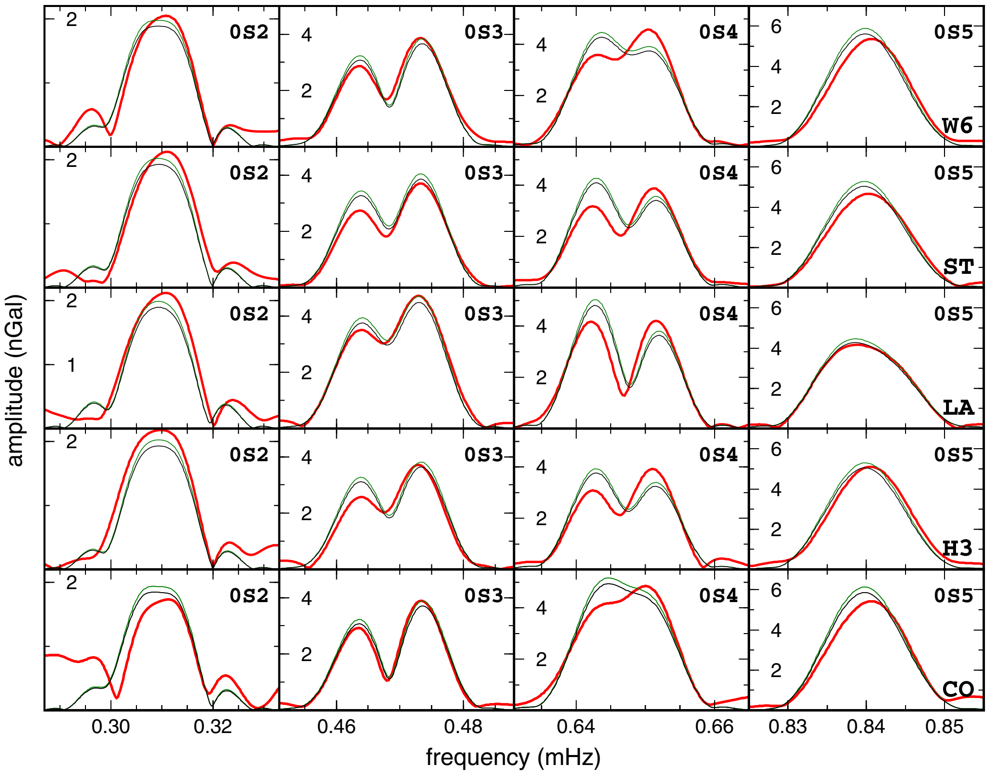

Figure 4
Vertical acceleration amplitude spectra of the studied modes from the SG data (*red*) and synthetics calculated for our solution located at 19 km depth (*green*) and 26 km depth (*black*). A Hann filter and Fourier transform were applied to the time series of the 60-h length starting 20 h after the origin times and averaged by the length of the time windows

recognize that a substantial part of the misfit is due to the mode ${}_0S_4$. It is of interest that a fit of this mode was also rather problematic in inversions of data recorded after the Chilean 2010 Maule earthquake but the fit of ${}_0S_4$ after the Japanese 2011 Tohoku earthquake was better (Zábranová *et al.* 2012). As mentioned above, our rather poor fit of the mode ${}_0S_4$ could be related to the coupling with the mode ${}_1S_2$; however, this mode was suppressed in the employed part of the records, and thus this problem remains opened.

The M_{rr} component can be obtained independently from the radial modes, e.g., (Zábranová *et al.* 2012). For comparison, we show in Fig. 5 the M_{rr} component inverted independently from the modes ${}_0S_0$ and ${}_1S_0$ using the records of 325- and 170-h length, respectively. For each depth we have obtained an interval of M_{rr}-values corresponding again to $\pm$ one standard deviation of each mode quality factor. These values are slightly lower by about $\pm 0.1 \times 10^{21}$ Nm than those obtained from the spheroidal modes but still close enough to confirm self-consistency of the two performed inversions. The mode ${}_1S_0$ is more sensitive to the source depth than the mode ${}_0S_0$, one can thus clearly recognize that the centroid depth can be maximally 40 km since for greater depths inversion of the ${}_1S_0$ mode yields significantly higher values than those obtained from the inversion of the ${}_0S_0$ mode.

4. Concluding Remark

Although the normal-mode inversion in the frequency range below one millihertz is based on only a few modes, it is robust enough to yield relevant results, especially of the values of the M_{rr} component of the centroid moment tensor. Errors in the quality factors of these modes result in the errors of the CMT components that are smaller than the variance of the

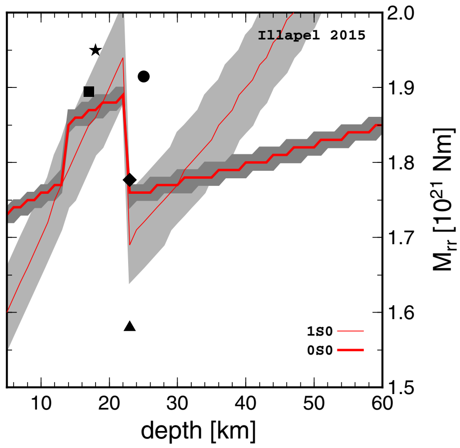

Figure 5
Dependence of the M_{rr} component of the centroid moment tensor on the centroid depth obtained from the inversion of the radial modes ${}_0S_0$ (*thick lines*) from the records of 325-h length and ${}_1S_0$ (*thin lines*) from the records of 170-h length. The *gray* areas correspond to the errors of the quality factors (Table 1). The several published solutions are denoted by the symbols explained in Fig. 3

published solutions that were here used for comparison with our results. They were obtained from data in higher frequency domain but they are sufficiently close to our results. On one hand, this demonstrates the robustness of the ultralong-period normal-mode inversion, but on the other hand, there is probably no additional energy in the spheroidal and radial modes below 1 mHz, i.e., a slow source mechanism ("postseismic slip") is either negligible or its content is characterized by extremely low frequencies.

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