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Source models of great earthquakes from ultra low-frequency normal mode data

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A B S T R A C T

We present a new earthquake source inversion technique based on normal mode data for the simultaneous determination of the rupture duration, length and moment tensor of large earthquakes with unilateral rupture. We use ultra low-frequency (f <1 mHz) mode singlets and multiplets which are modelled using Higher Order Perturbation Theory (HOPT), taking into account the Earth's rotation, ellipticity and lateral heterogeneities. A Monte Carlo exploration of the model space is carried out, enabling the assessment of source parameter tradeoffs and uncertainties. We carry out synthetic tests to investigate errors in the source inversions due to: (i) unmodelled 3-D Earth structure; (ii) noise in the data; (iii) uncertainties in spatio-temporal earthquake location; and, (iv) neglecting the source finiteness in point source inversions. We find that unmodelled 3-D structure is the most serious source of errors for rupture duration and length determinations especially for the lowest magnitude events. The errors in moment magnitude and fault mechanism are generally small, with the rake angle showing systematically larger errors (up to 20°). We then investigate five real thrust earthquakes ($M_w \geqslant 8.5$): (i) Sumatra-Andaman (26th December 2004); (ii) Nias, Sumatra (28th March 2005); (iii) Bengkulu (12th September 2007); (iv) Tohoku, Japan (11th March 2011); (v) Maule, Chile (27th February 2010); and, (vi) the 24 May 2013 M_w 8.3 Okhotsk Sea, Russia, deep (607 km) event. While finite source inversions for rupture length, duration, magnitude and fault mechanism are possible for the Sumatra-Andaman and Tohoku events, for all the other events their lower magnitudes only allow stable point source inversions of mode multiplets. We obtain the first normal mode finite source model for the 2011 Tohoku earthquake, which yields a fault length of 461 km, a rupture duration of 151 s, and hence an average rupture velocity of 3.05 km/s, giving an independent confirmation of the compact nature of this event. For all the other earthquakes studied, our new source models agree well with previous studies. We do not find any unexplained systematic differences between our results and those in the literature, suggesting that for the wave frequencies considered, the moment magnitude and the fault mechanism of the earthquakes studied do not show a strong frequency dependence.

1. Introduction

Since the great 1960 Chile earthquake, the Earth's low-frequency normal modes have been observed and used to investigate deep Earth structure (e.g., Dziewonski and Anderson, 1981; Masters, 1982; Ritsema et al., 1999; Mégnin and Romanowicz, 2000), and to some extent, to study earthquake sources (e.g., Abe, 1970; Ben-Menahem et al., 1972; Gilbert, 1973; Kedar et al., 1994; Park et al., 2005; Lambotte et al., 2006; Lambotte et al., 2007). Normal mode data are useful to characterise the overall source kinematics of very large earthquakes ($M_w > 8.0$), notably to estimate their seismic moment. However, compared to other data types (e.g., body and surface waves), the Earth's free oscillations have been less used in source studies, because they typically require very long continuous high-quality recordings of several days, which restricts their use in fast and routine source studies.

Early source studies using normal mode data were limited to seismic moment determinations (e.g., Abe, 1970; Kedar et al., 1994) or to fault geometry and mechanism estimates

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(e.g., Ben-Menahem et al., 1972). Examples of events whose source parameters have been determined using normal mode data include the great 22 May 1960 M_w 9.5 Chile earthquake (e.g., Kanamori and Cipar, 1974; Kanamori and Anderson, 1975; Cifuentes and Silver, 1989), the 13 October 1963 M_w 8.5 Kuril earthquake (Abe, 1970), the 28 March 1964 M_w 9.2 Alaska earthquake (Abe, 1970; Ben-Menahem et al., 1972) and the 23 May 1989 M_w 8.0 Macquarie ridge earthquake (Kedar et al., 1994).

During the last decade various very large magnitude ($M_w \geqslant 8.5$) earthquakes have occurred in subduction zones worldwide, causing significant damage and deadly tsunamis, and being often characterised by complex rupture processes. Great earthquakes with very long source duration >250 s, like the 2004 Sumatra-Andaman event, can be difficult to study using routine techniques. For example, Park et al., 2005; Stein and Okal, 2005; Okal and Stein, 2009 used normal mode data to show that the magnitude of the 2004 Sumatra earthquake was much larger ($M_w \sim 9.3$) than initially inferred from mantle waves by the GCMT ($M_w \sim 9.0$). Lambotte et al., 2006; Lambotte et al., 2007 used the phase of normal mode singlets to determine the rupture duration and length of the 2004 Sumatra event and to investigate the rupture history of the 28 March 2005 M_w 8.6 Nias earthquake. They obtained the first estimates of rupture duration and length ever obtained from normal mode data. Moreover, normal mode data have been used to test source models of the 2005 Nias earthquake (Konca et al., 2007; Lentas, 2013) and of other recent large subduction events (Lentas, 2013). Nevertheless, and despite this recent progress, the potential of normal mode data for source studies has not been fully investigated yet.

This study presents a source inversion technique for the simultaneous determination of fault mechanism, moment magnitude and the length and duration of unilateral rupture earthquakes using normal mode data. We start by assessing the robustness of the technique by carrying out realistic synthetic tests to quantify errors in the source parameters due to noise in the data, incomplete knowledge of the earthquake's spatio-temporal location and unmodelled 3-D Earth structure. We use a direct search inversion scheme to explore the parameter space and investigate tradeoffs and uncertainties in the source parameters. In addition, issues such as the choice of misfit function used in the inversions and the effect of neglecting the source's finiteness in normal mode multiplet point source inversions are also addressed. We then apply our new technique to real global $M_w \geqslant 8.5$, shallow subduction earthquakes that occurred during the last decade: (i) 26 December 2004 M_w 9.3 Sumatra-Andaman; (ii) 28 March 2005 M_w 8.6 Nias; (iii) 12 September 2007 M_w 8.5 Bengkulu; (iv) 27 February 2010 M_w 8.8 Maule, Chile; (v) 11 March 2011 M_w 9.1 Tohoku, Japan. We discard the 11 April 2012 M_w 8.6 Sumatra strike-slip earthquake as it was followed by a M_w 8.2 event within two hours. Since our analysis requires tens of hours of continuous recordings there is significant mixing of the free oscillations excited by the two earthquakes; hence, it would be difficult for our technique to resolve the two seismic sources separately. Finally, we also study the recent 24 May 2013 M_w 8.3 Okhotsk Sea, Russia, deep earthquake in our analysis.

Fig. 1 shows illustrative examples of normal mode data of the earthquakes studied, highlighting the high quality of the data, notably for the largest magnitude events (M_w 9.3 Sumatra-Andaman, M_w 8.8 Maule, Chile and M_w 9.1 Tohoku, Japan). Since the M_w 9.3 Sumatra-Andaman event has been extensively studied using a wide range of techniques and data types, the comparison of our results with those from previous studies is a useful means to test our new source inversion method. We then present the first source model for the M_w 9.1 Tohoku event based solely on normal mode data, as well as new models for all the other earthquakes studied. We compare our results with previous studies and discuss the advantages and limitations of our technique.

2. Methodology

2.1. Theoretical background

Normal mode multiplets are characterised by spectral peaks of degenerate eigenfrequencies in a spherically symmetric, non-rotating perfectly elastic and isotropic (SNREI) Earth model. The Earth's rotation, ellipticity and heterogeneity remove this degeneracy and split the multiplets into $2l+1$ singlets each characterised by an azimuthal order m, where l is the angular order. When studying very large magnitude earthquakes with rupture lengths exceeding hundreds of kilometres, the finite character of the source cannot be neglected when modelling low-frequency Earth's free oscillations. Thus, a finiteness term F_m must be taken into account in order to represent correctly the amplitudes and phases of the normal mode singlets. The Fourier transform of the finite source acceleration response α_m^{fs} of an isolated singlet with azimuthal order m can be expressed as (Ben-Menahem and Singh, 1980):

$$\alpha_m^{fs}(x,\omega) = \alpha_m^{ps}(x,\omega)F_m, \tag{1}$$

where F_m is the source finiteness term and $\alpha_m^{ps}(x,\omega)$ is the point source acceleration response:

$$\alpha_m^{ps}(x,\omega) = \sum_{i=1}^{6}\psi_i^m(x,\omega)M_i. \tag{2}$$

M_i are the six elements of the seismic moment tensor and $\psi_i^k(x,\omega)$ are the excitation kernels, i.e., the partial derivatives of the synthetic spectra of a point source with respect to the moment tensor elements:

$$\psi_i^m = \frac{\partial\alpha_m^{ps}}{\partial M_i}. \tag{3}$$

Assuming a simple unilateral rupture with constant dislocation and step time dependence, the source finiteness term can be represented as a function of the so-called initial phase X_m of a singlet with azimuthal order $\pm m$ (Ben-Menahem and Singh, 1980):

$$F_m = \frac{\sin(X_m)}{X_m}e^{-iX_m} \tag{4}$$

with the initial phase being linearly related to the rupture duration (T_r) and length (L):

$$X_m = \frac{\pi T_r}{T_m} + \frac{Lm\sin(\phi)}{2r_o\sin(\theta)} \tag{5}$$

where r_o is the Earth's radius, T_m is the singlet's period, ϕ is the fault's azimuth and θ is the epicentral colatitude.

Eq. (5) is an approximate description of the phase of normal mode singlets (Dziewonski and Romanowicz, 1977; Ben-Menahem and Singh, 1980). It is exact only when the second term is close to zero, thus only for singlets with $m = 0$ and radial modes, or for E–W oriented faults lying on the equator (e.g., Lambotte et al., 2006). In Section 1 and Table S1 of the supplementary material we present numerical results of experiments that verify the domain of validity of Eq. (5).

2.2. Forward modelling

In order to obtain realistic theoretical low-frequency ($f < 1$ mHz) normal mode seismograms and point source excitation kernels $\psi_i^k(x,\omega)$ (see Eqs. (2) and (3)), we use the Higher Order Perturbation Theory (HOPT) approach developed by Lognonné (1990), Lognonné (1991) and Lognonné and Clévédé (2002). The equation of motion is solved in the frequency domain starting from a spherical, elastic or anelastic Earth using the 1-D PREM model (Dziewonski and Anderson, 1981). Perturbations are then added to the Coriolis and elasto-dynamic operators taking into account the Earth's rotation