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# Using centroid time-delays to characterize source durations and identify earthquakes with unique characteristics

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ABSTRACT

The relationship between $M_0$ and the rupture duration is often difficult to establish. This is particularly true for large earthquakes for which the moment rate functions (MRF) generally have complicated shapes, and the estimated durations can vary considerably depending on the methodology used to evaluate the MRF. In this work, we show that the centroid time-delay ($\tau_c$) provides an alternative estimate of the source duration. Inverted MRFs often end gradually, making the end of coseismic rupture difficult to detect. In such cases, when the rupture duration is not well defined, the time-delay $\tau_c$ is a useful quantity to represent the first-order temporal characteristics of the rupture process. Variations in stress parameter $\Delta\sigma$ can be investigated by assuming a standard scaling relationship between the seismic moment $M_0$ and $\tau_c$. This simple scaling relationship can also be used to identify unusual earthquakes, with unique source properties, such as events involving complicated rupture processes or earthquakes characterized by unusual rupture velocities, stress drops or aspect ratios.



## 1. Introduction

Scaling relations are often used in seismology to understand basic and common properties of the seismic source (Kanamori and Anderson, 1975). One of the most commonly used relationships is that between seismic moment ($M_0$) and rupture dimension (e.g., Aki, 1972; Romanowicz, 1992; Scholz, 1982), which can in turn be used to estimate common source properties (e.g., the stress drop). However, source dimensions are usually only indirectly estimated which can cause considerable uncertainties in the estimated source properties. Several studies have also focused on the link between $M_0$ and the corner frequency ($f_c$) of small earthquakes (e.g., Aki, 1967; Shearer et al., 2006). In such analyses, it is common practice to use seismic moment and corner frequency ($f_c$) measurements to estimate an average stress drop ($\Delta\sigma$). This estimate usually requires a number of assumptions about the source, such as the shape of the faulting area or the average rupture velocity (e.g., Brune, 1970). The resulting stress drop estimates usually vary over several orders of magnitude (Allmann and Shearer, 2009) and we may ask if this scatter is real or is a consequence of incorrect assumptions about the source model and of uncertainties in $f_c$ estimates. Despite this variability in stress drop measurements, corner frequency observations are of primary importance as they contribute to various ongoing debates about earthquake self-similarity and regional variations of source properties. These analyses are, however, more difficult to conduct for large earthquakes (i.e., $M_w \geq 6.5$), partly because source complexity is more apparent as magnitude increases.

Long-period seismology is a robust tool to characterize elastic structure (Dziewonski and Anderson, 1981) and quantify source parameters of earthquakes (Dziewonski et al., 1981; Kanamori and Given, 1981). With the advent of broad-band instrumentation (Wielandt and Steim, 1986; Wielandt and Streckeisen, 1982) and the expansion of global seismological networks, long-period observations today provide some of the most robust information on the characteristics of large earthquakes. In particular, we can now determine the relationship between $M_0$ and the source duration objectively and directly from seismograms. In this short note, we show that the centroid time-delay ($\tau_c$) estimated from long-period source inversion provides a very straightforward and reliable estimate of the rupture duration. A scaling relation between the seismic moment $M_0$ and the centroid time-delay $\tau_c$ is discussed on the basis of an extensive set of earthquake data, including all events of $M_w \geq 6.5$ between 1990 and 2012. This scaling relation is used to study the relative variation of source properties and identify events with unique source characteristics.

## 2. Centroid time-delay measurements

Source inversion approaches such as the Global CMT (GCMT) or the W-phase source inversion algorithm (WCMT) use a very simple parameterization of the source with a small number of parameters

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to be determined (Dziewonski et al., 1981; Kanamori and Rivera, 2008). The source is assumed to be a point source in space, with an isosceles-triangular moment rate function (MRF). The source parameters to be determined are then the elements of the seismic moment tensor, the point-source space–time coordinates (latitude, longitude, depth, time at the center of the MRF) and the rupture half-duration (i.e., half-width of the triangular MRF).

We use two catalogs that provide the point-source parameters of worldwide earthquakes of $M_w$≥6.5 between 1990 and 2012. The first catalog contains the WCMT solutions provided by Duputel et al. (2012) for 1990–2010 earthquakes (available at the url http://wphase.unistra.fr). We extended this catalog to 2011–2012 events using the same procedure. The second catalog is built with the GCMT solutions between 1990 and 2012 (Ekström et al., 2012; also available at the url: http://www.globalcmt.org). To focus on well-constrained point-source parameters, we rejected events whose signals are contaminated by large amplitude waveforms of a preceding event. These earthquakes, defined as “disturbed events” in Duputel et al. (2012), are listed in the Online Supplementary Information. Fig. 1a compares the moment magnitude estimates from the GCMT and WCMT catalogs for all events between 1990 and 2012. The reliability of such catalogs is well illustrated here with an absolute magnitude deviation smaller than 0.2 for 99% of the events.

The half-duration $\tau_h$ is generally poorly constrained in CMT inversions because of the long-period character of the waveforms used in these methods (i.e. periods of 40–350 s for GCMT, 100–1000 s for WCMT). In fact, in GCMT inversions, an empirical scaling between half-duration and seismic moment $M_0$ is assumed to set $\tau_h$ (Dziewonski and Woodhouse, 1983; Ekström, 1989; Ekström and Engdahl, 1989). The centroid time, on the other hand, is generally well constrained. In this study, we use the centroid time-delay $\tau_c$ as a proxy for the half-duration $\tau_h$ of the event. This assumption is explicitly used in the WCMT algorithm in which we assume $\tau_h = \tau_c$ after estimating $\tau_c$. The time-delay, $\tau_c$, is the difference between the MRF center time and the rupture nucleation time (i.e. the origin time). As we will see in the next section, the assumption $\tau_c = \tau_h$ is reasonable as long as the origin time, which is generally determined from body-wave travel-times, is accurate. The raw $\tau_c$ values in GCMT and WCMT solutions are generally given with respect to preliminary estimates of the origin time, which can be affected by large errors. To improve our measurements, we thus updated the time-delays $\tau_c$ using the origin times from the final USGS PDE catalog. Fig. 1b compares the resulting estimates from GCMT and WCMT catalogs for all events between 1990 and 2012. The total set of $\tau_c$ measurements is given in Table S2 of the Online supplementary information. Time-delays are compared with rupture duration estimates in the next section.

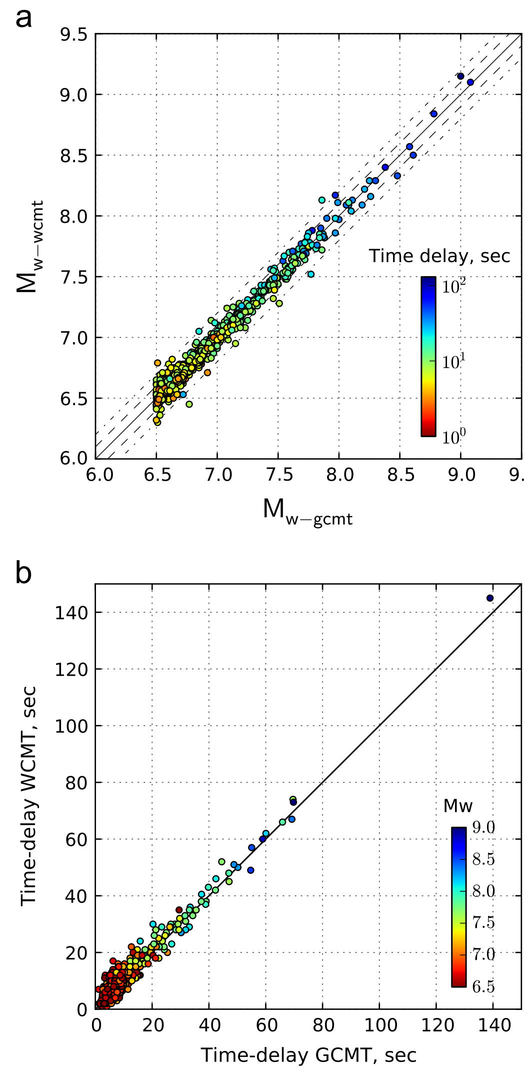


**Fig. 1.** An illustration of the consistency between GCMT and WCMT catalogs. (a) Comparison of moment magnitude estimates from the WCMT ($M_{w\text{-}wcmt}$) and GCMT ($M_{w\text{-}gcmt}$) catalogs. Symbols are colored according to the GCMT centroid time-delay. Dashed lines indicate $\pm 0.1$ and dot-dashed lines $\pm 0.2$ magnitude units. (b) Comparison of centroid time-delay estimates from WCMT and GCMT catalogs. Symbols are colored according to the GCMT moment magnitude. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

## 3. Comparison between centroid time-delay and rupture duration

The source duration, $\tau_d$, is given by $\tau_d = t_e - t_0$ where $t_0$ is the time when the rupture on the fault begins (i.e. the origin time) and $t_e$ is when the co-seismic slip motion ends. For the widely used Haskell model, $t_e = t_0 + L/V + \tau$ where $L$ is the unilateral rupture length, $V$ is the rupture speed, and $\tau$ is the rise-time of local slip function. The moment rate function (MRF) for this source is given by a trapezoid with a rise and fall time of $\tau$, and a top flat portion of duration $L/V - \tau$. The rupture duration, $\tau_d$, is usually determined from the MRF, $m(t)$, determined as part of the slip inversion using seismic waves.

On the other hand, the centroid time-delay is given by $\tau_c = \int (t - t_0)\, m(t)\, dt / \int m(t)\, dt$, where the time integrals are taken over the entire MRF. In GCMT and WCMT analyses, $m(t)$ is assumed to be an isosceles triangle and the time at the center of the triangle (i.e., the centroid time $t_c$) is determined by inversion. The origin time, $t_0$, is determined from high-frequency P-wave arrival times. If the centroid time-delay ($\tau_c = t_c - t_0$) is accurately determined, the source duration ($\tau_d$) can be estimated by $\tau_d = 2\tau_c$. This assumption is reasonable since, for most earthquakes, $m(t)$ is well approximated by a symmetrical triangle, trapezoid, or a single sinusoid (e.g., 2010 Maule earthquake; 2011 Tohoku-oki earthquake; Lay and Kanamori, 2011).

Fig. 2a shows a comparison between GCMT and WCMT centroid time-delays and rupture duration measurements provided in the literature. We see that there is an overall consistency between duration and time-delay measurements. The centroid time-delay ($\tau_c$) is a very straightforward observable and there is good agreement between $\tau_c$ measurements estimated from the GCMT and from the WCMT catalogs. This indicates a small uncertainty for $\tau_c$, as expected for long-period robust CMT inversion techniques. In general, as long as the time-smoothed $m(t)$ is relatively simple and symmetric around the center, then $\tau_d = 2\tau_c$ is a good