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A new database of source time functions (STFs) extracted from the SCARDEC method

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ABSTRACT

SCARDEC method (Vallée et al., 2011) offers a natural access to the earthquakes source time functions (STFs), together with the 1st order earthquake source parameters (seismic moment, depth and focal mechanism). This article first aims at presenting some new approaches and related implementations done in order to automatically provide broadband STFs with the SCARDEC method, both for moderate and very large earthquakes. The updated method has been applied to all earthquakes above magnitude 5.8 contained in the NEIC-PDE catalog since 1992, providing a new consistent catalog of source parameters associated with STFs. This represents today a large catalog (2782 events on 2014/12/31) that we plan to update on a regular basis. It is made available through a web interface whose functionalities are described here.

1. Introduction

Earthquake moment rate functions – often referred as source time functions (STFs) – offer an integrated view of the seismic source process. Their duration and their peak value are used to infer the global earthquake characteristics and in particular the stress or strain drop (Bilek and Lay, 1999; Houston, 2001; Tocheport et al., 2007; Vallée, 2013). Compared to corner frequency measurements (Brune, 1970; Boatwright, 1984; Allmann and Shearer, 2009), STF are richer as they contain the broad-band spectrum of the source process. As such, they can be used to calculate the radiated energy (Vassiliou and Kanamori, 1982), and to explore how the source spectrum behaves with respect to theoretical models (for example the omega-square model, Aki, 1967, 1972). Observations of STFs are therefore an efficient tool to quickly determine abnormal earthquakes such as the tsunami earthquakes, that are strongly depleted in high frequencies (Kanamori, 1972). From a practical point of view, their properties can also be studied to understand the influence of the seismic source on the strong ground motions generated by earthquakes (Margaris and Hatzidimitriou, 2002; Baltay et al., 2013; Cotton et al., 2013; Courboulex et al., 2016). Finally, STFs are more and more used in tomographic studies, as recent approaches aims at fitting the waveforms for periods close to the source duration (Sigloch and Nolet, 2006; Stähler and Sigloch, 2014; Garcia et al., 2013; Hosseini and Sigloch, 2015).

STFs are closely related to the seismic waves observed at teleseismic distances. In an infinite non-attenuating medium and for a point source representation, STFs are directly the P or S waveforms scaled by a factor depending on the radiation pattern, the distance and the elastic properties. The more realistic configuration of an extended source in a spherical Earth adds some complexities to the STF extraction, in particularly when the earthquake is shallow, which leads to wave interferences between direct waves (P or S) and surface reflected phases (pP, sP, sS…). In this case, STF has to be determined together with focal mechanism and earthquake depth. The source extent also has the consequence that each seismic station and wave type (P or S) theoretically provide a different estimate of the STF (called apparent source time function, or ASTF). However, when using P waves, this effect is modest, except for very long and fast-propagating earthquakes, and the ASTF extracted from a given station gives a good estimate of the STF.

Thanks to this close link with the observed seismograms, STFs are known to be one of the most robust characterizations of the source process, and have the potential to be provided routinely. However, a global catalog of STFs – similar to what GCMT provides for the 1st order source parameters (Ekström et al., 2012) – does not exist today, although several groups are building STF catalogs for specific applications (Stähler and Sigloch, 2014; Garcia et al., 2013; Hosseini and Sigloch, 2015). Up to now, only Tanioka and Ruff (1997) followed this direction of making available their derived STFs through the Michigan STF catalog. This catalog was containing a number of STFs for earthquakes of the 1990s and

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beginning of the 2000s but does not appear to have been updated since.

A recent approach, called SCARDEC (Vallée et al., 2011), is able to provide routinely the STF, together with the 1st order earthquake characteristics (seismic moment, focal mechanism and depth). This method has been validated on large earthquakes with independent techniques and wave types (Lentas et al., 2013) and first examples of exhaustive analyses of the SCARDEC STFs can be found in Vallée (2013) and Courboulex et al. (2016). Recent automatic solutions can be seen on the GEOSCOPE website (http://geoscope.ipgp.fr/index.php/en), where a near-real time solution is provided about 45 min after an earthquake of magnitude larger than 5.5–6.

In this article, we first provide the main steps that have been followed to extract the STFs, with an emphasis on the points which have not been explicitly described in the original SCARDEC article (Vallée et al., 2011). The characteristics of the STF catalog – which also offers independent estimates for magnitude, depth, focal mechanism for each earthquake – are then discussed, and we also underline some precautions that should be taken when using the STFs. Finally, we describe the functionalities of the web request tool providing public access to the whole catalog (in 2015, about 2800 STFs for earthquakes with occurrence posterior to 1992).

2. Exhaustive extraction of STFs from the SCARDEC method

We describe here the main steps which have been followed to extract the STFs of the present catalog. Most of the specifics have been described in the article of Vallée et al. (2011), where the SCARDEC method has been introduced. SCARDEC deconvolutive method uses the teleseismic body waves (P and SH, but also PP, PcP, and ScSH) recorded at the global stations of the Federation of Digital Seismograph Networks (FDSN) to determine the earthquake source parameters (double couple focal mechanism, moment magnitude, depth and STF). Teleseismic phases are modeled with an approach combining the reciprocity theorem and the reflectivity method (Bouchon, 1976; Müller, 1985), in the IASP91 Earth model (Kennett and Engdahl, 1991). Mantle attenuation is taken into account through a frequency dependent t^* operator. This is motivated by the fact that constant t^* values of the order of 1 s (as the one deduced from PREM; Dziewonski and Anderson, 1981) lead to an underestimation of the P-wave high frequency content (e.g. Der, 1998). This frequency dependency is here modeled by $t^*(f) = 0.39 \cdot f^{-0.25}$ (for a discussion on the frequency dependent t^*, see Choy and Cormier, 1986; Anderson and Minster, 1979), which implies for example $t^*(0.01) = 1.24$ s, $t^*(0.1) = 0.7$ s and $t^*(3) = 0.3$ s. Fig. 1 shows how the SCARDEC method has been extended here in order to (1) analyze earthquakes over the broad magnitude range M = [5.8–9] and (2) automatically extract optimal and average STFs from the ASTFs.

In order to guarantee the stability of the SCARDEC method, an important point is a first-order knowledge of the source duration (named T_d in Fig. 1). When the earthquake is large, typically larger than magnitude 7, this information can be obtained from the P waves records filtered around 1 Hz (e.g. Ni et al., 2005; Vallée et al., 2011). Such an approach is not suitable for smaller earthquakes as the signal to noise ratio is lower and more importantly because the high-frequency signal duration is dominated by the P-wave coda rather than by the source duration. In this case, T_d is defined as a function of magnitude (Fig. 1). This empirical value is efficient to extract the focal mechanism and depth of the earthquake, but may lead to an underestimation of the STF duration (and therefore an underestimation of the moment magnitude), in case of earthquakes longer than expected with respect to their magnitude. That is why at the end of the first step of Fig. 1, we consider a longer time, named T_s, to estimate the moment magnitude. The same time T_s is then used to retrieve the broadband ASTFs (step 2). In the final step, each ASTF is cut to a value T_R ($<T_s$) based on the information provided by the ASTFs stack: the stacking procedure is efficient to reduce the amplitudes of the ASTFs features which are inconsistent between stations and thus to determine the average duration after which the moment release becomes not significant. The ASTF-dependent T_R value is the time at which the ASTF takes very low values in the vicinity of the average duration.

The flowchart of Fig. 1 has been applied to all the events recognized as earthquakes with moment magnitude larger than 5.8 in the NEIC-PDE catalog (http://earthquake.usgs.gov/data/pde.php) since 1992 ($\sim$5500 earthquakes between 1992 and 2015). STFs are not available for all these events, for the following reasons, listed from the most common cases to the less ones. (1) Events with not enough stations having a good signal-to-noise ratio, which complicates the determination of their focal mechanism and depth (step 1 in the flowchart). This is often the case for "old" earthquakes in the period 1992–1994 because of the small number of available digital stations; a common case is also the occurrence of a large earthquake in the hours preceding the event to be analyzed. (2) Earthquakes without a sufficient number of good P-wave broadband signals, which does not allow to reliably extract ASTFs (step 2 in the flowchart). This is often the case for strike-slip earthquakes with moderate magnitudes, because of their low radiation coefficients. (3) Complex earthquakes or earthquakes occurring in a complex structure. Complex earthquakes can be events including a significant mechanism change or a large vertical extent. This can affect the step 1, in which case the first-order source parameters cannot be reliably determined, or more commonly the step 2. In this case also, strike-slip earthquakes are more likely to be rejected, because even a small mechanism change has a large effect on the radiation. Complex structure (in particular related to a deep water layer) results in P-wave broadband signals that cannot be reliably deconvolved from the point-source synthetics (step 2). (4) Rare cases related to the duration of the earthquake. The a priori choice of the maximum duration for earthquakes in the magnitude range [5.8–7] (step 1) can lead to rejection of some if they are anomalously long (or composed of several subevents). Large earthquakes (M > 7) should not suffer from this issue, because the duration is empirically determined from the high-frequency P waves (see also Ni et al., 2005). However, extreme events with a duration longer than 200 s cannot be analyzed with the SCARDEC method because of interferences between the main body wave phases: we cannot select in this case a time window where a given body wave is not mixed with another one (when *P*-wave is mixed with *PP*-wave, *PP*-wave is mixed with *PPP*-wave, *PPP*-wave *with S*-wave...). In the period 1992–2015, the only event excluded for this reason is the 2004/12/26 Sumatra earthquake. As a result of these limitations, the STF SCARDEC catalog contains 2782 events between 1992 and 2014/12/31.

The focal mechanism and depth of these earthquakes are shown in the map of Fig. 2. A consistency indicator of the SCARDEC method can be provided by comparing these 1st order source parameters with the ones provided by the Global CMT method (Ekström et al., 2012). Fig. 3a and b shows the comparison for the moment magnitude and depth, respectively, while Fig. 3c shows the comparison for the 6 independent components of the moment tensor. In terms of average differences, observed biases are small. A noticeable one concerns the moment magnitude which is in average 0.02 larger for SCARDEC than for Global CMT. Fig. 3a shows that this difference comes from moderate earthquakes (up to Mw $\sim$ 7). We can attribute it to the complex STF shapes allowed by the SCARDEC method which can lead to larger moment than the simple shapes (boxcars or triangles) imposed by Global CMT.