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Insights into earthquake ruptures from analysis of DAS data

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Summary. — The possibility to exploit fibre optic cables through Distributed Acoustic Sensing (DAS) systems is a powerful tool for seismologists, providing spatially continuous recordings of earthquakes. This technology is suitable for the analysis of seismic ruptures, continuously mapping the source properties as observed along the sensed cable. In this study we describe how far-field strain radiation from a circular rupture can be modelled to evaluate the earthquake size and released stress drop during fault slippage. We then fit earthquake signals recorded along a 150 km long dark fibre cable deployed offshore the coast of Central Chile sensed by DAS, to evaluate the rupture properties of small to moderate subduction events. We show that stress drop increases for moderate magnitude events, indicating a complexity in the slip pattern and the presence of small scale asperities also at this scale.

1. – Introduction

Distributed Acoustic Sensing (DAS) systems are establishing as a cutting-edge tool in seismology, transforming fibre optic cables in spatially dense deployments of seismic sensors. These systems compose of an Interrogator Unit (IU) connected to an ending point of a fibre, sensing the cable by repeatedly sending laser pulses. Part of the light is backscattered due to impurities in the fibre core and returns to the IU that monitors the phase of the backscattered pulse. Whenever the cable is deformed, the phase variation with time is related to the longitudinal strain rate along the direction of the cable [1]. The measure is distributed along the cable, whose points are mapped through the arrival time of the backscattered light.

As main advantages, DAS systems produce almost continuous recordings of seismic waves both in time and space. Furthermore, the IU can be connected to already deployed fibres, opening the opportunity to exploit unlit cables managed by telecommunications companies. The use of standard seismometers is often too expensive or unfeasible in harsh environments. As a consequence, DAS systems have been used to record earthquakes in remote areas [2].

Thus, this technology is appealing to test and validate seismological techniques. For arrival times, polarity and signal correlation, the portability of existing tools have been shown to be effective for DAS [3]. On the other hand, use of DAS amplitudes requires further development, due to differences in the recorded quantity and azimuthal sensitivity. For earthquake source characterization, application of displacement based models requires conversion to kinematic quantities, increasing the uncertainty of in the measurements [4]. An alternative approach is the analysis of spectral ratios between colocated events, leading to relative estimations of seismic moment and corner frequency [5]. For these reasons, a new model based on far-field strain field radiated from a seismic source has been developed [6], allowing to model strain rate DAS amplitudes. Here we illustrate how this new model can be used for characterizing ruptures of small earthquakes and then applied to a dataset of Chilean seismic events.

2. – Earthquake rupture characterization

Seismic rupture characterization is a fundamental task to understand the mechanics of faults. For small events, simplified macroscopic models have been proposed that rely on few source parameters [7], in which the observed displacement u in the angular frequency domain ω is related to the Source Time Function (STF) S,

$$u(\omega) = S(\omega)G(\omega)F(\omega), \tag{1}$$

where $G(\omega)$ is the Green's propagator and $F(\omega)$ accounts for site effects. In the following, we neglect the contribution of the site ($F(\omega) = 1$). For a circular rupture the STF can be described in the frequency domain by the generalized Brune's model [8],

$$\tilde{S}(\omega; \omega_c, M_0, \gamma) = \frac{M_0}{1 + (\frac{\omega}{\omega_c})^\gamma}. \tag{2}$$

According to eq. (2), the displacement amplitude spectrum is flat at low frequencies, and the plateau level measures the seismic moment M_0. The spectrum decreases at high-frequency because of the interference of short-wavelength waves. The corner frequency $f_c = \omega_c/2\pi$ represents the frequency at which this change in the spectral behavior is observed and is related to the source duration, while the γ exponent accounts for the velocity of the spectral decay.

The Green's function depends on the selected seismic phase. For a body wave c (c is P or S) [9], it writes

$$\tilde{G}_c(\omega; Q) = \frac{R^c_{\theta,\phi}}{4\pi r c_H^{5/2} c_R^{1/2}} e^{-\frac{\omega T}{2Q}}, \tag{3}$$

where T is the source-observer travel-time, Q is the anelastic attenuation quality factor, $R^c_{\theta,\phi}$ represents the radiation pattern, r is the hypocentral distance and c is the seismic wave velocity at the hypocenter (c_H) and at the receiver (c_R).

The same formulation of eq. (1) applies to the integral of the strain $\xi(\omega) = S(\omega)\tilde{G}_c^{strain}$, where

$$\tilde{G}_c^{strain}(\omega; Q) = \frac{R^{c,fibre}_{\theta,\phi}}{8\pi r c_H^{5/2} c_R^{3/2}} e^{-\frac{\omega T}{2Q}}. \tag{4}$$

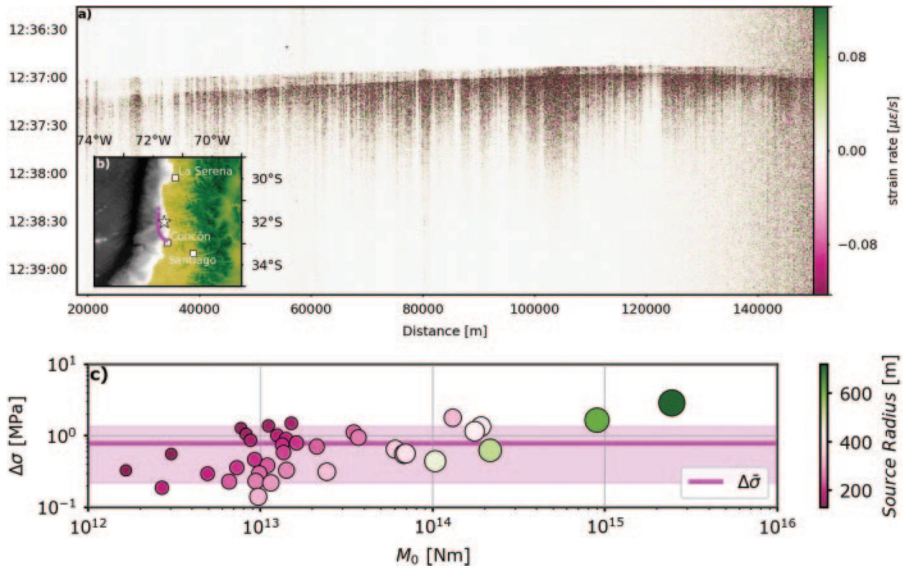

Fig. 1. – Example of a $M_L3.0$ earthquake recorded by the DAS (a). The event location is marked by the star in inset (b). (c) Stress drop as a function of the seismic moment. The size and colour of the circles is scaled based on estimates of the source radius. The solid horizontal line marks the average stress drop, with the shaded area representing the standard deviation of $\Delta\sigma$ across the events.

The main difference between the formulations in displacement and strain are in an enhanced sensitivity to the velocity beneath the fiber, which appears to an exponent of 3/2, while in classical kinematic approach the associated exponent is 1/2, and in the average radiation pattern for the P- and S-waves ($\langle R_{\theta\phi}^{P,fibre}\rangle = 0.259$ and $\langle R_{\theta\phi}^{S,fibre}\rangle = 0.252$ [6]) which accounts for DAS azimuthal sensitivity.

This approach can be directly applied to strain rate data, and the parameters can be determined by inverting DAS recordings. After double integration in time and computation of the amplitude spectrum, this latter can be fit using eqs. (2), (4) to perform an estimation of the source parameters.

From source parameters we can compute the source radius [10]

$$r = \frac{\kappa_c c_s}{f_c}, \tag{5}$$

where the geometrical factor κ_c is $\kappa_P = 0.38$ and $\kappa_S = 0.26$. Moreover the stress drop released during the rupture process writes as [11]

$$\Delta\sigma = \frac{7}{16}\frac{M_0}{r^3}. \tag{6}$$

3. – Source radius and stress drop estimates from DAS records

We computed the stress drop, the seismic moment and the rupture size for earthquakes occurred in central Chile. DAS data were recorded on a 150 km long telecommunication cable lying on the ocean floor offshore the Chilean coast. The dataset is composed of small to moderate events, ranging from $M_L2.5$ to $M_L4.3$.

The rupture characteristics are extracted from the analysis of spectral amplitudes associated to the S wave. The data were fit in the frequency bandwidth where the signal can be clearly discerned from the background noise (we set a threshold of SNR > 3.5). Using the model from eq. (4) the misfit between theory and observation was minimized to estimate M_0 and f_c.

An example of an earthquake recorded along the cable is shown in fig. 1(a). After computation of seismic moment and corner frequency, we focused on the estimation of the stress drop and rupture size, and their variability with seismic moment (fig. 1(c)). We observe that higher magnitude events feature larger radius but also larger stress drop, indicating that these ruptures occur over relatively smaller patches than what expected in a scale invariant model. For low magnitude events (small radius) the stress drops are within one standard deviation (shaded area) from the average value (solid horizontal curve).

4. – Conclusions

Within this work we illustrated how earthquake rupture parameters can be obtained from DAS data and used to characterize the spatial size and released stress drop of small events. We used native strain rate recordings obtained from a DAS survey in Central Chile.

Results exhibit peculiar scaling when analysing the stress drop as a function of the seismic moment, showing almost scale invariant stress drops for low magnitude events, while earthquakes with large seismic moment seem to accumulate stress on relatively small patches, resulting in higher stress drops.

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