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Distributed Acoustic Sensing (DAS) data for seismic monitoring: influence of cable geometry and installation context

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1. Introduction

Distributed Acoustic Sensing (DAS) system exploits laser interrogation of fiber optic cables (FOCs) to retrieve a very-dense virtual array of longitudinal strain/strain-rate sensors (Zhan, 2020). DAS uses optical interferometry to detect phase changes in the backscattered energy from natural fiber inhomogeneities. Raw optical measurements are integrated along a discrete cable portion, called "gauge length" and then related to local strain/strain-rate at each "DAS channel". DAS can record external inputs deforming FOCs in a broadband frequency range (Paitz et al., 2021), with a maximum interrogation range around 100 km (Landrø et al., 2021).

DAS is a promising research field for seismology. Indeed, it allows for unprecedented wavefield spatial sampling (up to < 1 m) and potential ubiquitous monitoring, especially when pre-existing telecommunication optical fibers are interrogated (Lindsey & Martin, 2021). As a matter of fact, it can map subsurface heterogeneities (Jousset et al., 2018; Lindsey et al., 2020; Lior et al., 2022, Yuan et al., 2020), monitor natural (Lindsey et al., 2017; Biondi et al., 2017; Ugalde et al., 2022) or induced seismicity (Karrenbach et al., 2019) , especially in geothermal fields (Lellouch et al., 2020; Obermann et al., 2018), implement fast response to study aftershock sequences (Li et al., 2021), characterize natural seismicity induced by glacier movements (Walter et al., 2020) and urban noise (Biondi et al., 2022; Shen and Zhu, 2021). However, DAS data is usually affected by lower signal-to-noise ratio (SNR) compared to standard seismic sensors (Li & Zhan, 2018; Walter et al., 2020). Moreover, signal incoherencies are common, due to site effects and poor ground-fiber coupling (Van den Ende & Ampuero, 2021).

This work focuses on the potential of DAS for seismological monitoring, detection and epicentral location of seismic events. Standard seismic arrays are usually evaluated based on (a) their geometry and (b) the SNR of the recorded events. The potential of DAS arrays instead, is conditioned by the following factors: a) the signal directivity, i.e. the strain/strain-rate are measured only for their longitudinal components along the fiber direction; b) the differences in FOC coupling with the ground, and c) the higher susceptibility to local rock elasticity variations (Ajo-Franklin et al., 2019; Van den Ende & Ampuero, 2021). Indeed, all these factors affect the spatial signal coherency and therefore influence the uncertainty of the estimated locations.

FOCs are the backbone of the global telecommunication network and show a worldwide distribution (e.g., urban, ocean seafloor environments). Despite various successful case-studies (Fichtner et al., 2022; Jousset et al., 2018; Klaasen et al., 2021; Lellouch et al., 2020; Lindsey et al., 2017; Nishimura et al., 2021; Van den Ende & Ampuero, 2021; Walter et al., 2020; Zhu & Stensrud, 2019), a more general exploration on the influence of geometry and installation environment on the monitoring potential is still lacking. Therefore, in this work, DAS is tested for a seismic monitoring task, investigating the influence of different sources of noise in DAS recordings and exploiting an unprecedently various database, including different kind of seismic events (earthquakes, ice-quakes, volcanic earthquakes) recorded by different typologies of FOCs.

2. Data and methods

Diversified DAS datasets have been collected from online open access databases and from direct agreements with researchers responsible for the specific acquisitions. Both telecommunication cables, repurposed for DAS monitoring tasks, and suited installations, are included in the study (**Figure 1**). Each DAS dataset is provided with the recording of at least a local seismic event (< 100 km from the array barycenter). A reference event is then selected for the study and an independent location is provided, from the analysis of seismological catalogs or "expert" analysis of local seismic arrays/selected DAS channels. A basic pre-processing is adopted to increase the SNRs of the recorded events, including linear de-trending, cosine tapering and bandpass filtering. Moreover, spatial subsampling is embraced when the DAS gauge length is larger than channel spacing. This procedure can help increasing the SNRs (Piana Agostinetti et al., 2022), especially in badly coupled FOCs portions. A coherent automatic picking procedure (Baer & Kradolfer, 1987) is adopted to pick the first onsets at the DAS channels of each pre-processed event. Then, a Markov Chain Monte Carlo (MCMC) approach is used for estimating hypocentral parameters (Riva and Piana Agostinetti, 2022).

Beside the estimated locations, based on observed arrival times, four synthetic tests are implemented to simulate different sources of noise in DAS recordings, which derive from geometry and installations context, and to measure how such noise sources affect the detection and location capabilities. (1) The first test (SYNTH-01) consists of the inversion of synthetic traveltimes computed on the DAS channels, assuming the independent location as the "true" one and adding white Gaussian noise. This exercise offers a view on the geometrical effects which influence the epicentral location precision. Then, 2) three different assumptions are considered on such traveltimes, to simulate common observations in DAS recordings, that is: i) traveltime picking uncertainty increases with the distance from channel to the event (SYNTH-02), ii) S-wave is mis-labelled as P-wave at some DAS channels (SYNTH-03) and iii) fiber coupling is inhomogeneous (SYNTH-04). Eventually, those synthetic traveltimes are inverted to evaluate the impact of these assumptions on the final product of the monitoring exercise, the event location.

3. Results

The epicentral locations estimated from the automatic traveltime picking procedure are characterized by different degree of uncertainty. The DAS arrays with a greater azimuthal coverage show more consistent locations (**Fig 2a**), which is an expected behavior, also in light of the longitudinal polarization of strain/strain-rate measurements. This behavior is confirmed by SYNTH-01 (**Fig 2b**). Moreover, assuming the independent location as the" true" one, the epicentral uncertainty shows a dependency on the azimuthal gap parameter. However, exceptions to this behavior are common, which confirms that the geometrical factor is not the only factor controlling the uncertainties in source location with DAS. Such "biases" between observed and reference locations are indeed partially explained by traveltime uncertainties due to phase mis-picks and fiber coupling issues (SYNTH-03, SYNTH-04). As an example, **Figures 2c-d** show how the observed location uncertainty can be reproduced, to a certain degree, from synthetic simulations that considers noise coming from the FOCs coupling inhomogeneities (SYNTH-04).

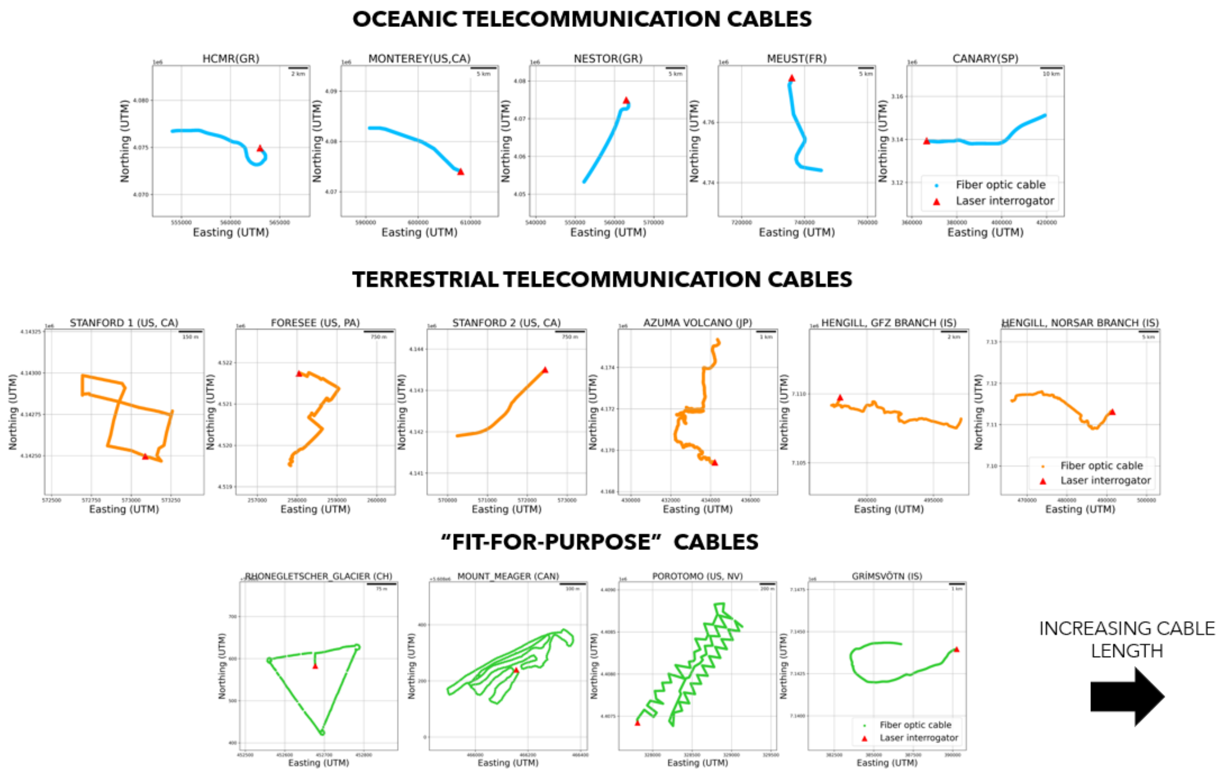

Figure 1. DAS array geometries. Three categories are identified: 1) oceanic telecommunication cables, which represent FOCs installed in continental shelf or continental shelf-oceanic floor transition environments (names: HCMR, MONTEREY, NESTOR, MEUST, CANARY); 2) terrestrial telecommunication cables, which represent FOCs installed in sub-aerial environments (names: STANFORD-1, AZUMA-VOLCANO, FORESEE, STANFORD-2, HENGILL-GFZ, HENGILL-NORSAR) and 3) "fit-for-purpose" cables, which represent FOCs installed for scientific studies (names: MOUNT-MEAGER, RHONEGLETSCHER-GLACIER, POROTOMO, GRÍMSVÖTN).

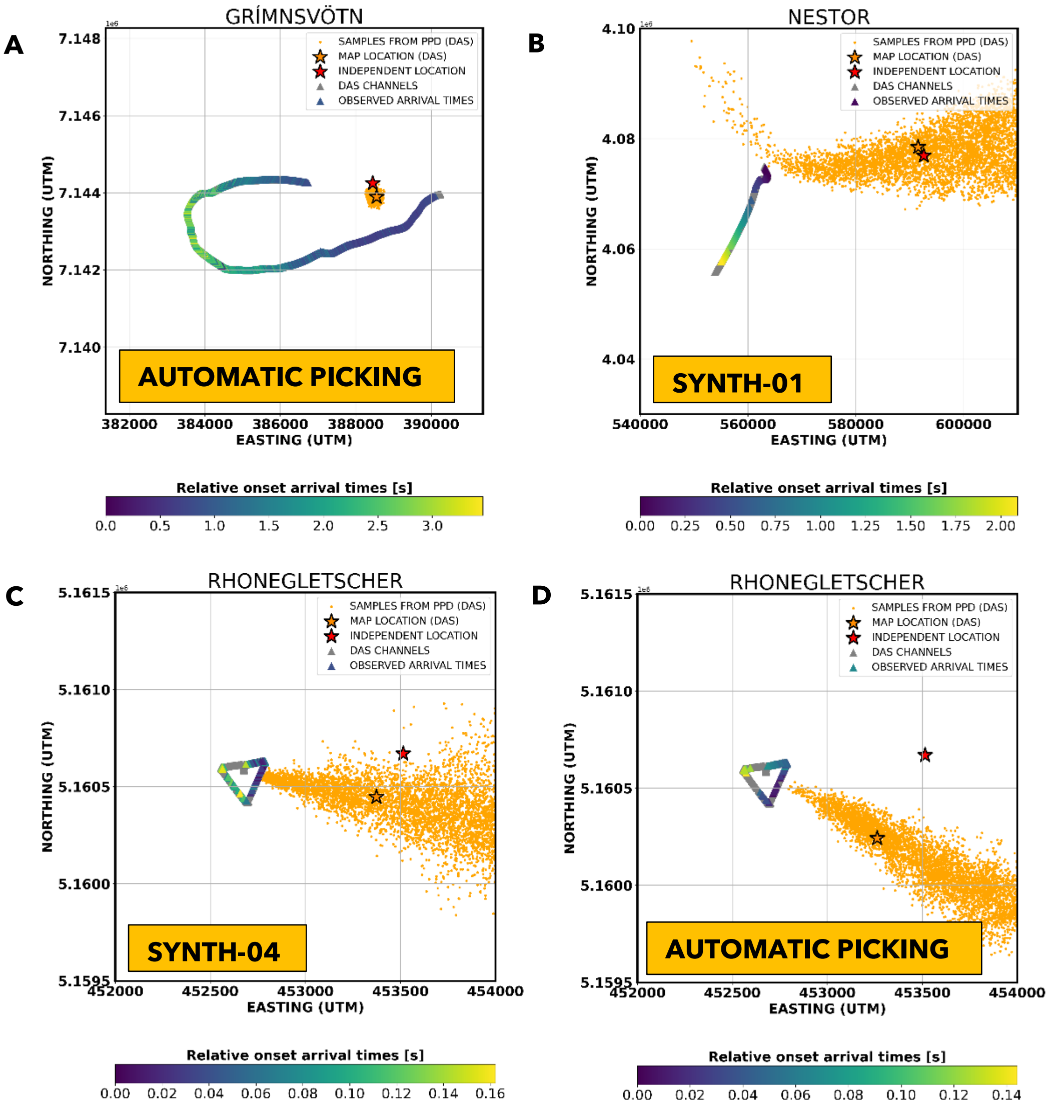

Figure 2. DAS epicentral locations and their uncertainties compared with independent locations. Orange dots are used to plot the samples from the posterior probability density (PPDs) functions, while orange stars represent the mean solutions and red stars the independent locations. A) The event location obtained from automatic arrival time picking reproduces satisfactorily the reference one, for the event recorded by GRÍMSVÖTN, given the low epicentral gap. B) SYNTH-01 test for NESTOR DAS array shows a high longitudinal uncertainty, given the quasi-linear north-south geometry. C) SYNTH-04 test for RHONEGLETSCHER array shows that, if coupling effects on traveltimes are considered, the synthetic location can partially reconstruct the D) calculated location.

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