Earthquake Monitoring Using Fibre-Optic Distributed Acoustic Sensing

Marcelo A. Soto(1), Jaime A. Ramírez(2)

(1) Department of Electronic Engineering, Universidad Técnica Federico Santa María, 2390123 Valparaíso, Chile, marcelo.sotoh@usm.cl
(2) Novelcode SpA, 2580216 Viña del Mar, Chile

Abstract *We review the use of distributed acoustic sensing (DAS) for monitoring earthquakes and other seismic waves using telecom optical cables, as well as novel signal processing approaches that exploit the spatiotemporal information contained in DAS seismic measurements.* *©2023 The Author(s)*

Introduction

In the past few decades, distributed optical fibre sensing [1] has attracted the attention of different academic and industrial sectors due to their unique capability of providing spatially resolved information of environmental quantities. Among different technologies, the high sensitivity of the Rayleigh scattering optical phase to mechanical perturbations allows for the distributed monitoring of vibrations. This is achieved by *distributed acoustic sensors* (DAS) [1,2], which can convert an optical fibre into an array of vibration sensors.

Among a wide range of applications, DAS has emerged in the last decade as a novel technology with great potential in the field of seismology [3-8]. In this case, DAS offers unique monitoring features, providing spatial information that cannot be obtained with traditional seismic sensors, like geophones, seismographs, or accelerometers.

Most of existing demonstrations of earthquake detection have used dark optical fibres; however, the possibility of using existing telecom optical cables is encouraging the further deployment of DAS technology. DAS actually represents a cost-effective solution to implement of a dense seismic monitoring network in harsh and remote areas, offering the possibility of monitoring thousands of points in a synchronised way along an optical fibre. Existing telecom cables are installed all over the globe, even in the middle of oceans and near tectonic faults, which can trigger massive earthquakes and where the use of large arrays of traditional broadband seismometers is unviable.

This paper reviews the capabilities of DAS to monitor earthquakes and other seismic waves. Possibilities of novel two-dimensional (2D) signal processing approaches are also discussed to exploit the spatiotemporal information of seismic activity provided by DAS measurements.

DAS working principle

DAS exploits the interference resulting from the coherent superposition of Rayleigh scattering signals generated by multiple scattering points along an optical fibre. Mechanical perturbations on the fibre induce linear changes of the fibre refractive index, leading to a linear modulation of the Rayleigh scattering optical phase. Due to this, most of distributed acoustic sensors are based on demodulating the Rayleigh optical phase [1,2].

A common long-range interrogation technique is based on *phase-sensitive optical time-domain reflectometry* (ϕOTDR) [1]. The method launches a short coherent optical pulse into the sensing optical fibre and, normally, measures the phase of the coherent Rayleigh backscattering using an optical coherent receiver or an interferometric detection. Another approach uses chirped optical pulses and direct detection [9].

The distributed acoustic profile is obtained with a typical spatial resolution of a few metres, which is defined by the optical pulse width, the detection bandwidth, and some processing parameters that determine the so-called gauge length. Each fibre position (sometimes referred to as *acoustic channel*) is sampled with consecutive pulses at a frequency determined by the fibre length, which defines the acoustic bandwidth of the sensor. Trace averaging is sometimes also used to enhance the measurement signal-to-noise ratio (SNR), at the cost of reducing the effective acoustic bandwidth of the DAS sensor.

Earthquake monitoring using a telecom cable

Here we report the use of a telecom submarine optical cable connecting Valparaiso, Chile, with Los Angeles, USA, for DAS-based microseism and earthquake monitoring. The cable is installed at the ocean floor, reaching a depth of 2.5 km below sea level at ~33.2 km from the beach manhole in Las Torpederas beach, in Valparaiso. Details on the DAS and cable deployment can be found in [10]. A DAS interrogator from Aragon Photonics is used to monitor the first 45 km of the fibre from the cable landing station, where the interrogator is placed. Measurements are carried out using a 10 m spatial resolution, and an acoustic bandwidth of 125 Hz (after averaging).

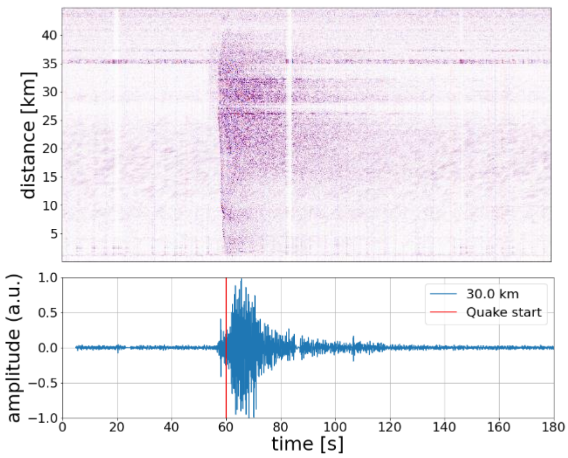

Fig. 1: DAS measurement of a M2.7 earthquake occurred offshore Valparaiso, at 18 km from the submarine cable. Image extracted from Ref. [10].

During the measurement campaign of several days, many earthquakes have been measured. Fig. 1(a) shows the spatiotemporal measurement of a M2.7 earthquake that occurred offshore Valparaiso, ~18 km from the optical cable in its closest point. The earthquake can be seen after 60 s and in almost the entire measured section of the cable, being especially stronger from 15 km to 40 km distance. Fig. 1(b) show the earthquake waveform measured at 30 km distance. Interestingly, the DAS system seems to have measured the event slightly before the estimated time (red line) according to the official seismic records. This demonstrates the big advantage of earthquake DAS monitoring using submarine cables, which are normally closely located to faults where strong seismic activity regularly takes place, and where traditional seismometers are scarce or simply are not present. This relevant feature gives valuable seconds of action before strong earthquakes could arrive to populated cities, making DAS a key tool for the development of future earthquake and tsunami early-warning systems.

Calculating the power spectral density (PSD) through fast Fourier Transform (FFT) of DAS measurements at each fibre position provides interesting and unique information regarding the different kinds of vibrations affecting the fibre. This is shown in Fig. 2(a), where it is possible to see the presence of ocean waves in relatively shallow waters (< 300 m depth) with frequencies of 0.072 Hz and 0.15 Hz (primary microseism) until ~18 km distance. Scholte waves (secondary microseism) are seen in deeper waters (500 m to 1500 m depths) around 15 km to 27 km distance, showing a broader spectral range with a peak component at 0.3 Hz. These results agree with the behaviour reported previously for microseism observations using DAS [5]. In addition, the earthquake can be observed in the 1-10 Hz range

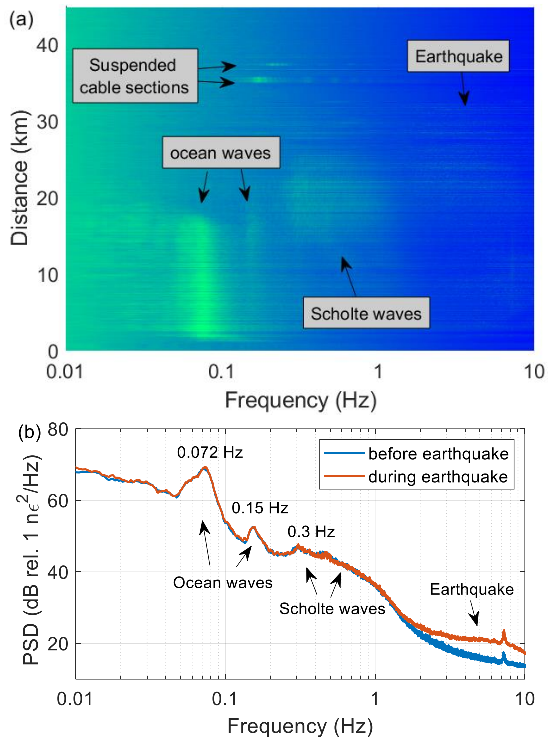

Fig. 2: (a) 1D FFT as a function of the sensing fibre position, (b) PSD of acoustic measurements averaged between 10-20 km distance, identifying several seismic waves.

along the entire cable, but mostly after 15 km. For better visualisation, the spectra between 20 km and 30 km are averaged and the resulting PSD is shown in Fig. 2(b). This shows all the mentioned seismic waves, before (blue curve) and during (red curve) the earthquake takes place.

Note that the Fourier analysis in Fig. 2(a) also points out the existence of two 200 m-long fibre sections suspended in deep waters at 35 km and 37 km, oscillating at ~0.17 Hz. A spectrogram analysis reveals that this frequency varies over time between 0.05 Hz and 0.28 Hz, with a pattern that repeats almost every 12 hours, depending on seafloor ocean currents [10]. This proves the potential of DAS to monitor deep ocean currents.

2D signal processing for DAS seismology

The 2D spatiotemporal domain of DAS data enables the possibly to apply advanced 2D signal processing methods to improve signal quality and extract novel information that cannot be retrieved with time-series measured by local and sparsely distributed traditional sensors. By calculating the 2D FFT, the spectral content in the frequency-wavenumber (f-k) domain can be analysed [5]. This 2D FFT approach permits the identification of the phase velocity of the different acoustic waves measured along the fibre, allowing the evaluation of dispersion in seismic propagation.

In addition, 2D image processing methods can be used to denoise the spatiotemporal data. If no coherent acoustic interferences exist, like in the ocean floor, the redundancy of information in 2D DAS data facilitates the efficient use of image denoisers. However, if the measurements are contaminated with in-band coherent acoustic interference, like in urban environments, this noise cannot be easily removed by classical image denoisers. In addition, machine learning techniques, like self-supervised deep learning [11], can be used to eliminate in-band incoherent noise without the need of a noise-free ground truth, improving also the signal coherence.

To detect earthquakes in noisy DAS data, machine learning approaches can also be used. Convolutional neural networks (CNNs) are commonly used to perform classification tasks using images, and hence can be applied to the spatiotemporal measurements provided by DAS. However, the lack of standardised large DAS databases for training machine learning models has led researchers to apply different techniques using for instance synthetic data generated by generative adversarial networks (GANs) [12] or geophysical model-based DAS simulations [13].

The approach we have proposed [14] is based on training neural networks with earthquake waveforms measured by classical seismometers, thus taking advantage of large existing seismic databases. This approach provides reliable pre-trained models, leading to an F-score metric of around 90%-96% when evaluating the models using DAS data [14], as shown in Fig. 3 (dashed lines). This reduced inference rate using seismic DAS data is due to the lower SNR of DAS signals when compared to classical measurements. To improve the earthquake detection performance using DAS data, a hybrid database including DAS data and traditional seismic recordings is used [15]. Continuous lines in Fig. 3 show the F-score achieved by the three trained neural networks, showing improvements in F-score up to 99.0%, 97.7%, and 97.5% for a fully connected neural network (FC-ANN), a CNN and a CNN+LSTM (long short-term memory), respectively.

Another very interesting possibility that DAS measurements enable is the use of array signal processing methods to implement beamforming-based spatial filters and to localise the epicentre of earthquakes and other acoustic sources. Most of existing approaches use far-field methods to detect the direction of arrival of seismic waves [16], whilst the epicentre can be obtained only by triangulation using several DAS arrays or a single long array with specific fibre orientations.

However, the use of classical beamformers is not straightforward with DAS measurements due to the typical uneven response of DAS sensors along the fibre, which is due to: *i)* the directional response of DAS, which responds only to axial

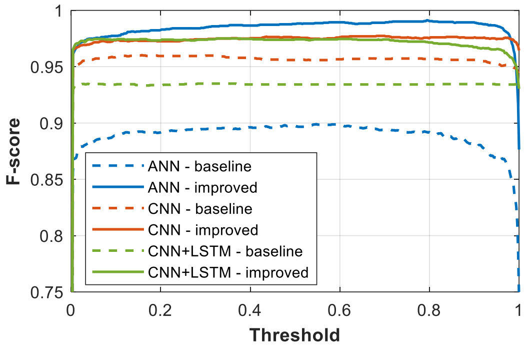

Fig. 3: Earthquake detection based on deep learning and DAS measurements. F-score metric vs threshold, using a hybrid earthquake database. Image extracted from Ref. [15].

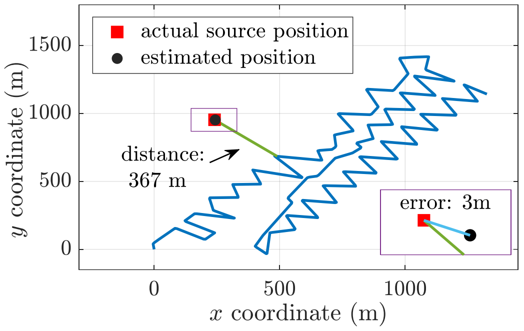

Fig. 4: Localisation of artificial seismic wave source based on a blind beamforming approach and good-quality DAS channels, and using an optical fibre (blue curve) installed with good angular diversity. Image modified from Ref. [17].

strain, *ii)* the nonuniform strain coupling between the fibre and ground, and *iii)* the presence of Rayleigh intensity fading that leads to blind fibre positions. Acoustic channels with poor strain response worsen the beamformer output, and hence, using a blind method for selecting good-quality channels and a near-field approach [17] we could enhance the precision of array signal processing to localise acoustic sources, provided that there is a good angular diversity of the optical fibre orientation [17]. Fig. 4 shows the source localisation of artificially generated seismic waves, verifying that our blind near-field approach can reach very low relative errors (~0.83%).

Conclusion

DAS technology is currently revolutionising the field of seismology, due to the possibility of using the extensive network of telecom cables and the additional spatial information offered by DAS data. The 2D spatiotemporal data enables novel and more powerful signal processing and deep learning approaches to enhance the DAS capabilities in earthquake detection and to study several areas of interest in seismology. The increased spatial density and possibility of measuring closer to submarine faults, especially in deep oceans, make DAS a relevant tool for earthquake and tsunami early warning systems.

Funding: ANID (Fondecyt 1200299, Basal FB0008).

References

[1] A. H. Hartog, *An Introduction to Distributed Optical Fibre Sensors,* CRC Press: Boca Raton, FL, USA, 2017. DOI: 10.1201/9781315119014

[2] Z. He and Q. Liu, "Optical Fiber Distributed Acoustic Sensors: A Review," *J. Lightw. Technol.*, vol. 39, no. 12, pp. 3671-3686, 2021, DOI: 10.1109/JLT.2021.3059771

[3] Z. Zhan, "Distributed Acoustic Sensing Turns Fiber-Optic Cables into Sensitive Seismic Antennas," *Seismol. Res. Lett*., vol. 91, no.1, pp. 1–15, 2020. DOI: 10.1785/0220190112

[4] S. Dou, N. Lindsey, A. M. Wagner, *et al.* "Distributed Acoustic Sensing for Seismic Monitoring of The Near Surface: A Traffic-Noise Interferometry Case Study," *Sci. Rep.,* vol. 7, p 11620, 2017. DOI: 10.1038/s41598-017-11986-4

[5] E. F. Williams, M. R. Fernández-Ruiz, R. Magalhaes, R. Vantillho, Z. Zhan, M. González-Herráez and H. F. Martins, "Distributed sensing of microseisms and teleseisms with submarine dark fibers," *Nat. Commun.*, vol. 10, p 5778, 2019. DOI 10.1038/s41467-019-13262-7

[6] D. M. Flores, A. Sladen, J.-P. Ampuero, et al, "Monitoring Deep Sea Currents with Seafloor Distributed Acoustic Sensing," *Authorea*. October 28, 2022, 10.1002/essoar.10512729.1

[7] M. R. Fernández-Ruiz, M. A. Soto, E. F. Williams, S. Martin-Lopez, Z. Zhan, M. Gonzalez-Herraez, and H. F. Martins, "Distributed acoustic sensing for seismic activity monitoring," *APL Photonics*, vol. 5, pp. 030901, 2020, DOI: 10.1063/1.5139602

[8] M. R. Fernández-Ruiz *et al*., "Seismic Monitoring With Distributed Acoustic Sensing From the Near-Surface to the Deep Oceans," *J. Lightw. Technol.* vol. 40, no. 5, pp. 1453-1463, DOI: 10.1109/JLT.2021.3128138.

[9] M. R. Fernández-Ruiz, L. Costa, H. F. Martins, "Distributed Acoustic Sensing Using Chirped-Pulse Phase-Sensitive OTDR Technology," *Sensors,* vol. 19, no. 20, p. 4368, 2019, DOI: 10.3390/s19204368

[10] M. A. Soto, J. A. Ramírez, E. Saravia, Z. Zhan, Valey Kamalov, "Capabilities of Curie cable for distributed acoustic sensing," in *Suboptic 2023*, Bangkok, Thailand, 13-16 March 2023.

[11] M. van den Ende, I. Lior, J. -P. Ampuero, A. Sladen, A. Ferrari and C. Richard, "A Self-Supervised Deep Learning Approach for Blind Denoising and Waveform Coherence Enhancement in Distributed Acoustic Sensing Data," in press, *IEEE Trans Neural Netw Learn Syst.* DOI 10.1109/TNNLS.2021.3132832 .

[12] L. Shiloh, A. Eyal and R. Giryes, "Efficient processing of distributed acoustic sensing data using a deep learning approach," *J. Lightw. Technol.*, vol. 37, no 18, pp. 4755-4762, 2019, DOI: 10.1109/JLT.2019.2919713

[13] L. Shiloh, A. Lellouch, R. Giryes, A. Eyal, "Fiber-optic distributed seismic sensing data generator and its application for training classification nets," *Opt. Lett.* vol. 45, pp. 1834-1837, 2020, DOI: 10.1364/OL.386352

[14] P. D. Hernández, J. A. Ramírez, and M. A. Soto, "Deep-Learning-Based Earthquake Detection for Fiber-Optic Distributed Acoustic Sensing", *J. Lightw. Technol.*, vol.40, no.8, pp. 2639-2650, 2022 DOI: 10.1109/JLT.2021.3138724

[15] P. D. Hernández, J. A. Ramírez, and M. A. Soto, "Improving Earthquake Detection in Fibre-Optic Distributed Acoustic Sensors Using Deep-Learning and Hybrid Datasets", *2022 European Conference on Optical Communication (ECOC)*, Basel, Switzerland, 2022.

[16] M. P. A. van den Ende, J.-P. Ampuero, "Evaluating seismic beamforming capabilities of distributed acoustic sensing arrays," *Solid Earth*, vol. 12, no. 4, pp. 915-934, 2021. DOI: 10.5194/se-12-915-2021

[17] F. Muñoz, M. A. Soto, "Enhancing fibre-optic distributed acoustic sensing capabilities with blind near-field array signal processing," *Nat Commun,* vol. 13, p. 4019. 2022, DOI: 10.1038/s41467-022-31681-x