SUBMARINE SEISMIC TOMOGRAPHY USING OPTICAL FIBRES

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The repurpose of the available telecommunication fibre optical network as a seismic monitoring tool has been recently tested with very promising prospects. Optical fibre networks possess all the ingredients to become the next generation seismic monitoring system, offering high performance at minimum deployment and maintenance cost, especially at hardly accessible regions such as the oceans' bottom.

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Seismic tomography is a technique employed for imaging the subsurface of the Earth. It is based on the acquisition of surface seismic waves, which can be produced by the movement of tectonic plates, earthquakes, volcanic eruptions, or any ground trembling event. The acquired data is employed in an inverse engineering process, creating three-dimensional images of wave propagation anomalies that can be interpreted as structural or compositional variations. Seismology studies have additionally fostered the emergence of applications that boost social and economical sectors, such as resource exploration, ground motion prediction, development of effective early warning systems, and more.

Nowadays, seismic data recording almost uniquely depends on seismograph networks deployed around the world. Seismograph networks are arrays of precisely synchronised point seismographs. They are capable of providing spatio-temporal information susceptible to be smartly analysed via special digital signal processing to reveal information beyond earthquake monitoring. However, the density of this kind of stations worldwide is still low (with sensors separation of several km), as the cost of deployment and maintenance of larger and denser networks results unsustainable. In general, the vast majority of the seismic arrays are distributed onshore, close to populated areas. Yet, oceans cover 71% of the Earth's surface. The implementation of seismographs and seismic arrays offshore remains a challenge from both technical and economical points of view. Hence, the low density of stations together with the poor coverage across oceanic regions result in a biased and poorly sampled analysis of the seismic activity. In addition, the lack of significant seismic instrumentation offshore makes it more complicated to explore the mechanisms that launch disastrous oceanic events such as tsunamis.

In the last few years, the idea of leveraging the existing telecommunication optical fibre networks for distributed seismic monitoring has proliferated across the research community. Conventional telecom optical fibre cable can be readily used as distributed acoustic sensors (DAS), allowing for the fully distributed monitoring of acoustic vibrations. The final goal is to develop a novel conception for ubiquitous seismic monitoring systems with high capacities and minimal investment.

Why distributed optical fibre sensors?

Optical fibres have proven to be outstanding vibration or strain distributed sensors, mainly for applications where large surfaces need to be monitored. As a sensor, an optical fibre provides high sensitivity, robustness, long lifespan and cost-effectiveness [1]. The whole length of the fibre (currently reaching operation ranges up to 100 km) acts as an array of intrinsically synchronised point sensors separated by the spatial resolution (~10 m), providing up to three orders of magnitude better resolution than the one achieved by traditional seismograph networks, and only requiring a single interrogation unit. Another important advantage of optical fibre sensors is their capacity to perform remote sensing, allowing the interrogation unit to keep a safe placement away from harsh locations and providing minimal intrusiveness in their deployment. This is particularly interesting for subsea ground motion monitoring. Nowadays, there exists a vast network of fibre-optic cable deployed all over the planet, often running over vast unmanned areas, and sometimes even in very remote and hardly accessible areas like very deep underwater regions in the middle of the oceans. This situation assures a fairly good spatial resolution and surface coverage for seismology analyses with minimal deployment cost. An optical fibre used as a DAS exploits the Rayleigh backscattering occurred in the fibre in combination with optical time domain reflectometry (OTDR) technique [1], [2].

DAS for underwater seismic monitoring

Numerous DAS-based seismological research works have been developed within the last four to five years, using either dedicated fibre installed for a particular study or pre-installed telecommunication dark (unemployed) fibres. The excellent sampling provided by DAS has provided unaliased sampling of seismic wavefields along cables, revealing high-resolution imaging of seismic structures such as fault zones or basin edges, as well as information not provided by conventional seismometers, such as the direction of the seismic energy [3], [4]. Besides, the use of advanced processing techniques including template matching or machine learning have allowed to detect order of magnitude more seismic events than traditional seismic networks [5]. It was not until the end of last year when a few works were published almost simultaneously on the use of DAS in oceanic environments [6]–[8], presenting accurate observation of different ocean phenomena. In spite of their short lifetime, the achievements reached to date prove a great potential handling the three major areas of local and regional seismology: seismicity monitoring, structure imaging, and hazard assessment. Further improvement in the technology is still required to target global seismology, although the prospections are very favourable.

> **"Fibre-optic cables deployed over the planet form a huge sensor network"**

State-of-the-art research at the University of Alcalá

In 2016, the Photonics Engineering research team at the University of Alcalá (UAH) pioneered the development of a DAS system based on the use of interrogation pulses with a linear frequency modulation along their width, also termed as linearly chirped pulses [9]. This system has a similar performance than a conventional DAS (using unmodulated optical pulses) but with several important benefits. First, the use of linearly chirped pulses provides robust shot-to-shot linear measurements of acoustic vibrations using intensity-only detection (without the need of optical phase recovery like conventional DAS). Hence, the required number of photodetectors is reduced in fourfold, along with the complexity associated to their synchronisation and unevenness. Besides, circumventing the phase demodulation process solves an important shortcoming of traditional DAS, which is the high sensitivity to intensity fading

▼ FIG. 1: Prototype of the chirped-pulse DAS developed by the UAH.

points related to the interferometric nature of its operation. Additionally, the combination of linearly chirped pulses with a mechanically isolated reference fibre allows correcting the vast majority of the laser phase noise issues, permitting a drastic reduction of the laser coherence requirements. Those advantages imply a substantial cost saving in terms of number and quality of components required in the system without a major compromise in the performance. This architecture has attracted the interest of two manufacturers in the sensing domain (Omnisens [https://www.omnisens.com/] and Aragon Photonics [https://aragonphotonics.com/hdas-distributed-acoustic-sensing/]), who have licensed this technology.

One of the pioneering submarine seismic monitoring studies using DAS was precisely based on the use of chirped-pulse (CP-)DAS [7] (Fig. 1). This work was developed by the UAH in collaboration with the Spanish National Research Council (CSIC) and the Seismological Research Lab in Caltech. **In this work, a complete analysis of ocean dynamics is performed, including observations of microseismicity due to ocean waves, local surface gravity waves and even an earthquake occurred more than 16,000 km away from the fibre location** (Fig. 2). All this is achieved from 1 hour recording of strain data from a telecommunication preinstalled shallow fibre (< 40 m deep), where the background strain noise due to ocean waves is extremely high. Further analyses are currently being performed by the UAH group and different collaborators around the world, attempting long time recordings (along several weeks/months) at different ocean depths. The goal is to test the performance of the CP-DAS in different submarine environments and explore long-term oceanic phenomena detected by the fibre, reaping all the benefits of this novel and promising strategy for seismic tomography studies. ■

About the authors

María R. Fernández-Ruiz, **Sonia Martín-Lopez** and **Miguel Gonzalez-Herraez** are with the Photonics Engineering Group at the UAH, as postdoctoral researcher, associate professor and full professor respectively and **Hugo F. Martins** is with Instituto de Optica of CSIC as postdoctoral researcher. The group initially gained visibility with an ERC grant for distributed temperature sensing and since then has extended its core-research into DAS. The group's state-of-the-art research and results in DAS have been internationally recognized by several conference awards as well as international scientific and industrial projects/works of relevance.

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▾ FIG. 2: (a) Distribution of the telecommunication optical fibre employed as a distributed seismic sensor. The fibre connects the city of Zeebrugge (Belgium) with a wind farm located 40 km away from the shore. (b) The raw strain variations recoded by the fibre are processed using 2D linear filtering, as signals from different origins (*e.g.* ocean waves, microseisms or teleseisms waves) are clearly isolated in a frequency-wavenumber (f-k) representation of the recordings. (c) An earthquake produced in the Fiji Islands (> 16,000 km away from the fibre under test) was also recorded, and the signal detected by the DAS was compared with the signal recorded from a nearby seismometer (BOST), showing an excellent matching.