# Optical fibers in detection of seismic events

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***Abstract*—Using traditional methods to detect earthquake can often prove to be problematic in certain ways - it can be costly and difficult to cover a large area. Thankfully, by using optical fibers we can succesfully mitigate the disadvantages, while keeping the quality level high, on-par with that of traditional seismic sensors. Through examining the phase shift of a backscattered signal, transmitted through a fiber, it is possible to determine the waves affecting an optical fiber. Both terrestrial and submarine fibers can be used. In this paper we tackle the topic of earthquake detection through optical fiber. We focus on using the DAS technology, present examples of this technique being used to detect actual earthquakes happening and go into detail of the technical side of this solution.**

***Keywords*—Rayleigh back-scattering, DAS, phase shift, dark fiber, interrogator, gauge length, seismic events, seismic sensors, submarine optical fiber cables***

## I. Introduction

There exists an ever-increasing need among the entire human race to attempt to fully understand Earth and its internal behavior. One particular topic would be earthquakes, a sudden release of energy which creates seismic waves. These waves can be intercepted by special sensors, so as to detect tremors as soon as possible, both in order to prepare the evacuation of people endangered by this natural disaster and to gather more knowledge about the nature of these incidents. The analysis of seismic events is one of the key tools for the study of the internal dynamics of the Earth and is currently based on a network of seismic stations spread around the world. These stations utilise seismic sensors, which work using the principle of inertia – inside them, there lies a mass on a spring or between two magnets, and by analysing its harmonic oscillation one is able to calculate the power and direction of seismic waves affecting said sensors [8][9]. Although such methods are refined and their dominance in the sector cannot be denied, a rise of another solution can be seen over the last few years – using optical fibers. They are advantageous compared to traditional sensors in many ways – they are much cheaper, have a higher signal to noise ratio, and possess an enormously wider sensor pattern, being a very long line instead of a single point [6]. Although using optical fibers to detect earthquakes on land has plenty of benefits, where it truly excels is submarine measurements. When it comes to examining the breaking lithosphere on the ocean floor, using traditional sensors becomes difficult, owing to hard conditions and high costs needed to overcome them. Since 70% of the surface of our planet is covered by water, underwater seismic stations are scarce when compared to those on land. *"[...] a permanent array of wired OBSs large enough to cover Earth's waters would be extremely expensive to install."*[2] Ocean bottom sesimometers' construction causes them to be prone to wind driven tides, impairing their capabilities by reducing their signal to noise ratio. Several alternative solutions have been proposed, but none of them has proven to be as effective yet affordable as using already existing optical fibers. The total length of submarine fiber cables is over 1 million kilometers, and that number is growing exponentially [2]. Society's desire for fast internet connection is growing, and so is the amount of optical fibers installed.

The detection of seismic waves happens thanks to DAS technology, which stands for distributed acoustic sensing. This technique was developed by the gas and oil industy to monitor pipelines. By using Rayleigh back-scattering and observing phase shift of the backscattered signal we can determine the magnitude of the earthquake, as well as where it happened. We go into details of this technique in next paragraphs.

## II. Dark Fiber

A dark fiber is simply an optical fiber that is inactive – whilst no information is being sent over it, there is no light inside – hence *dark*. There exists an abundance of them in certain countries, such as The United States, The Netherlands or Germany. There are two main causes to this phenomenon – money, and underestimate of how rapid the technology development would be. The latter can be explained quite easily, as it happened frequently in human history. People investing in optical fibers assumed that many fibers would be necessary in order to achieve the highest transmission speed, and had it not been for the rise of wave division multiplexing, they might have been correct. WDM increased the capacity of a single fiber dramatically, which made it more affordable to use, since utilising more fibers equaled installing more and more expensive equipment on each end of every cable. As to why it was profitable to install more fibers than required – the cost of the fiber itself was not as significant when compared to that of labour. Therefore, more cables were installed than actually needed in that particular moment, should they become useful later on. These dark fibers, put in the ground mostly around 1990s and 2000s, during the boom of telecommuncation, may now be used for the purpose of diagnosis of earthquakes and possibly other types of events, such as landslides [10][11].

## III. Distributed Acoustic Sensing

The main purpose of Distributed Acoustic Sensing is to detect the seismic events without the need of reinstalling the already existing infrastructure. To fulfill that requirement, a laser interrogator unit was implemented. It is a set of electronic and optical components which is placed at the end of the fiber. It sends short pulses into the fiber and due to the Rayleigh scattering the signal is reflected back to the source. This allows the interrogator to perform the measurements of the signal, that travelled the entire length of the optical fiber – that signal is obviously deformed by the vibrations from the surrounding environment. The main point of the measurement is calculating the phase shift – this is the parameter that is proportional to the change in strain. Therefore, optical fiber can serve as a sensor being able to detect any seismic event [7].

Figure 1. shows signal recorded by the interrogator – the higher the colour temperature, the higher the magnitude of the acoustic signal on the specific length of the fiber cable. This acoustic signal can be a wide range of various events – it might be a passing car, but the interrogator is sensitive enough to detect even as little as a human's footsteps - anything that makes a temporary change in the fiber's geometry. Therefore, there must be a way to distinguish whether the detected seismic event is an earthquake or not.

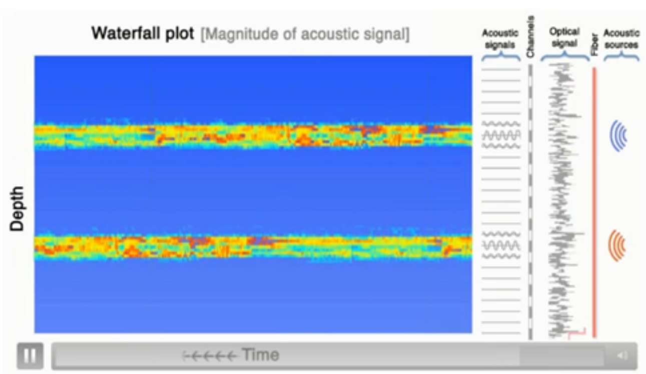


Fig. 1. [6] Signal recorded by the interrogator – high colour temperature on the magnitude plot corresponds to the significant phase shift, which means that seismic event has been detected.

The solution is, as often in digital signal processing, discrete Fourier transform. Converting the signal into a function of frequency and then implementing passband filter allows to separate impulses that consist of specific frequency components. Those components that are included in the earthquake's signal frequency are within the range 0.1 Hz to 20 Hz. Impulses with other components are discarded, and thus the ones that are left almost certainly originate from an earthquake [6].

The sensitivity of Distributed Acoustic Sensing depends upon three main factors – types of fiber, cable and the interrogator. The properties of the materials that the core consists of are the ones connected to the type of fiber, while the other ones are the geometry of the cable and the interrogators built-in laser and electronic hardware systems. Higher sensitivity means higher signal-to-noise ratio and farther monitoring distances [6].

Assuming the fiber is a long straight line, it is possible to precisely determine the distributed sensor location at particular locations along the fiber by looking at the time it takes for a light pulse to reach a certain distance along the fiber. If a waveform impinges on the fiber's structure (e.g. such as one coming from an earthquake) the fiber will sense the change of the strain in its surroundings and will pick it up - not just at one point, but over a certain distance. It will record an optical phase shift of the light in the fiber between two sensors [6]. Every sensor has its gauge length, and those sensors are distributed over the entire cable. Gauge length is a fiber segment where we measure the strain of the fiber [4]. If the fiber were not moving at all, the phase change would be non-existent. If the fiber is compressed and elongated within that gauge, an optical phase shift takes place. The gauge length specifies how we measure the seismic waves, and it is the fundamental difference between the point sensors, as they can detect them only in one particular location [6]. DAS actually has thousands of sensors, densely distributed along the entire length of the optical fiber. Those sensors are placed in otherwise inaccessible locations, are insensitive to electrical noise and the cost per sensor is very low. Additionally, the whole system is incredibly durable - the fiber can be working properly as much as even for decades. Several examples confirm the reliability of that system in practice and that is what we cover in another paragraph.

## IV. Usage

There are several cases of DAS technology being successfully used in order to detect earthquakes. On 24 August 2016, an earthquake of moment magnitude of 6.0 in central Italy, followed by two more events on 26 and 30 October, was detected at the National Physical Laboratory (NPL) in Teddington, United Kingdom, during frequency metrology experiments on an optical fiber link that wasn't originally meant to be a seismic sensor. The link in question connects NPL in Teddington with the town of Reading and is located in geographical distance of 1400 km from the epicenter of the earthquake. Figure 2. presents the phase fluctuations on the laser light propagating in the fiber link induced by the seismic event on 30 October compared with data from a seismic station in Swindon [2].

Another event captured by two optical fiber links in two different countries occurred on 12 November 2017 on the Iran-Iraq border. One of these links was installed between Turin (the region of Piedmont, Italy) and Medicina near the town of Bologna (Emilia-Romagna region) by the Instituto Nazionale di Ricerce Metrologica (INRiM) in Turin and the other one was located in southeast England [2]. However, both cases mentioned above refer to terrestrial optical fiber links, whereas submarine links can perform even better concerning earthquake detection. That stems from the fact that at the bottom of an ocean the environmentally induced noise level is significantly lower. In 2017, a group of scientists from Italy,

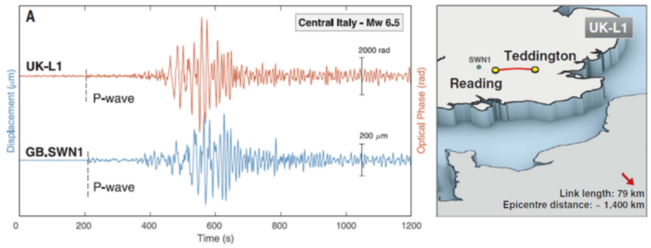


Fig. 2. [2] Earthquake in central Italy, 30 October 2016
Optical phase changes detected on Teddington-Reading link (UK-L1) and signal from seismometer in Swindon (GB.SWN1)

Malta and UK showed that the phase noise per unit length of submarine fibers is over two orders of magnitude lower than for fibers in ground. That allows the detection of small earthquakes [1]. In September 2017, during the measurement campaign on the 96.4 km long submarine cable between Malta and Sicily, an earthquake of Mw 3.4 was successfully observed, with its epicenter in the Malta Sea, situated 89 km away [2].

On 19 August 2018, the DAS system enabled to observe Fiji deep earthquake of moment magni-tude 8.2. As a couple of cases above, this event was also detected by two different links within huge distance from each other. This time, one of them was submarine and the other one was ter-restrial. The Belgium DAS Array (installed by the University of Alcalá, Spain) occupied a submarine cable in the Southern Bight of the North Sea offshore Zeebrugge and was installed to monitor a power cable for the Belwind Offshore Wind Farm. This link is located in the distance of 16300 km from the epicenter [4]. The second optical fiber link which detected Fiji deep earthquake lies under ground in Pasadena, California, USA. The seismic activity was recorded in the California Institute of Technology in Pasadena. This city is located about 9000 km from the earthquake epicenter. Link in question was dedicated to telecommunication in a metropolitan area. Therefore DAS can provide reliable teleseismic detection even near a city – noisy environment - and at a great distance from the earthquake epicenter [5].

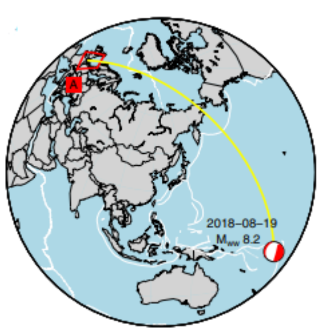


Fig. 3. [4] World map showing the location of the DAS array (red box) and the curved path (yellow) between the array and the Fiji earthquake epicenter (red and white circle)

Groups of experts around the world are still trying to master usage of DAS technology for earthquake detection. In the summer of 2020 the research team from the Institut de Ciències del Mar (ICM-CSIC) de Barcelona and the Instituto de Óptica (IO-CSIC) which are both part of the Spanish National Research Council (CSIC) along with the Universidad Alcalá (UAH) de Madrid and Spanish academic network RedIRIS converted submarine optical fiber links that rest on the seabed between Canary Islands to ultrasensitive seismic sensors array. These cables connect Tenerife and Gran Canaria. Area of Canary Islands is seismically active and most of traditional seismometers in this zone are situated on the ground. Therefore this experiment can significantly improve earthquake monitoring of the area [3].

## V. Conclusion

Although detecting earthquakes through studying optical fibers has been used now for well over the past few years, it is still a relatively young branch of both seismic and optical studies, with much room for development. We firmly believe that it is a path we should take, and move in this direction as far as seismology is concerned. Among various options the DAS technology seems to be the best choice, but we ought not to overlook potential other solutions.

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