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Monitoring of remote seismic events in metropolitan area fibers using distributed acoustic sensing (DAS) and spatio-temporal signal processing

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Abstract: Remote seismic activity is monitored with DAS using a pre-existent fiber installation in an urban area. Background noise, which greatly exceeds the amplitude of the monitored seismic signals, is eliminated via 2D (spatio-temporal) signal processing.

OCIS codes: (060.2370) Fiber optics sensors; (060.2430) Fibers, single-mode; (290.5870) Scattering, Rayleigh;

1. Motivation

Distributed acoustic sensing (DAS) is a powerful tool allowing to transform a conventional optical fiber cable into a dense array of strain seismometers, capable of measuring minute values of relative fiber deformation (in the order of 10^{-9}) along lengths of tens of kilometers, with meter-scale spatial resolutions. DAS has been found attractive in a large number of applications including pipeline protection [1], borehole monitoring [2] and train tracking [3], among others. In the context of seismology, DAS offers many possibilities that would not be available with the use of conventional point seismometers [4]. This potential is still basically unexplored, but inevitably relies on the possibility of using existing fiber installations for seismic wave detection.

A dedicated fiber installation, with high and homogenous mechanical coupling to the ground and no ambient interferences (other than the seismological signals to be measured) could be viewed as the ideal situation. However, such a perfect installation may not be practically feasible or even desirable in most cases. On one side, the requirement of a dedicated installation over tens of kilometres would pose a strong economic challenge, comparable to the deployment of a large array of broadband seismometers. This need would probably discourage widespread adoption of the technology in realistic cases. However, the ability to use pre-existent (and non-ideal) fiber installations would allow for a quick and massive deployment of DAS, particularly in urban areas, where such installations already exist and are widely available. On the other side, the possibility of providing seismological profiling in urban areas with high ambient interferences (such as human activity) would certainly increase the impact of DAS technology, since the potential for human losses and economic impact due to seismic events is greatly increased in these areas.

In this paper, we report the use of DAS to monitor remotely-triggered seismic activity using a pre-existing fiber installation in a densely populated urban area, where ambient noise interferences (such as traffic) greatly exceed the amplitude of the seismic signals to be monitored. Concretely, we use a fiber installation in the city of Pasadena, CA, to monitor seismic activity generated in the Fiji islands, approximately 9000 kilometers away. The dominant background noise (mostly related to traffic) is greatly eliminated via 2D image processing (using temporal and spatial information), as it presents entirely different features from the seismic signals. This is demonstrated even for interferences affecting the same frequency windows of the seismological signals, which would not be possible for point seismometers or individual processing of single channels in DAS.

2. Experiment

Fiber installation: We employ a fiber installation running across the city of Pasadena, CA. The fiber departs from the South Mudd building in Caltech and runs in three main sectors: first, from East to West, ≈2 km; then, from South to North along ≈6 km; and lastly, from West to East along ≈5 km. Additional fiber loops exist along the installation, leading to a higher fiber length than the geometrical distance of the installation. Between the second and third sector, a piece of ≈1km of aerial cable is present, contributing to introduce noise in the signals acquired. The cable is essentially composed of standard G-652 fiber.

DAS sensor [5]: Traditional DAS employs coherent detection of the backscattered optical signal in order to obtain a linear transduction of the strain reaching the fibre into measured optical phase. While this method is very sensitive, it suffers from the existence of fading points (i.e. positions with zero back-reflected intensity), which translates into the occurrence of blind spots randomly placed along the fibre. In order to avoid this problem, in this paper Chirped-pulse DAS [5] is used, for the first time in seismology applications. Chirped-pulse DAS (CP-DAS) has now become a reference technique for DAS sensing without the problem of fading sensitivity points, thus allowing for a true quantitative measurement of the strain applied to the fibre in every spatially resolved point of the fibre. In addition, this technique allows for the complete compensation of first-order laser phase noise, which is indispensable in order to achieve high sensitivities. While an extensive comparison with traditional DAS is out of the scope of this paper, the use of CP-DAS provides a true 2D image (strain along space and time) with no spatial blind spots and homogeneous sensitivity/noise along the fibre. This allows for the ideal starting scenario for 2D/3D signal processing algorithms to be applied.

2D Strain processing: The idea of the use of 2D image processing has been introduced in distributed sensing in the context of improving the SNR of temperature/static measurements in systems limited by white noise, mostly derived from instrument/fundamental thermal noises [6]. In this paper, 2D image processing (using temporal and spatial information) is used to remove the interference caused by complex (non-white) acoustic signals generated by unknown activity occurring along the fiber in a metropolitan area. An initial concept demonstration is provided, with the use of window filters applied to the 2D FFT of the recovered signal (strain along fiber position and time).

3. Results

DAS systems detect any perturbation affecting the refractive index of the fiber under test (e.g., strain or temperature variations) [5]. As such, it is expected that the sensor measures not only seismic waves affecting the sensing fiber, but also vehicles circulating close to it as well as other events affecting the environmental conditions around the fiber. The information recorded by our DAS due to those incidents can be considered as noise and therefore should desirably be removed. Acoustic signals recorded at given positions in DAS may be treated as the output of individual seismometers or as a spatial array of such seismometers, exploiting the redundancy between neighbouring channels. This redundancy can be made evident by plotting the individual DAS traces in a waterfall plot, as visualized in Fig.1. Fig 1(a) represents measured raw strain along the fiber in the last 5 km of fiber (which run in direction W-E) during the occurrence of the Fiji M8.2 earthquake in Aug 19 2018, between 00:13 and 01:03 UTC. It is obviously visible that ambient noise is significantly stronger than the seismic signals, which have nevertheless very distinctive features (very long-wavelengths and frequencies up to a few Hz, i.e. the quasi-vertical lines appearing along the image). Moving perturbations along the fiber produce a linear trail whose slope is proportional to its velocity. Hence, it is possible to recognize in the waterfall vehicles passing close to the fiber, which appear as straight lines with different orientations. Seismic waves appears as quasi-vertical lines, as their velocity is extremely fast (in the order of km/s) compared to normal vehicles. Additional sources of noise are also evident in the trace, including the effect of loose fiber sections.

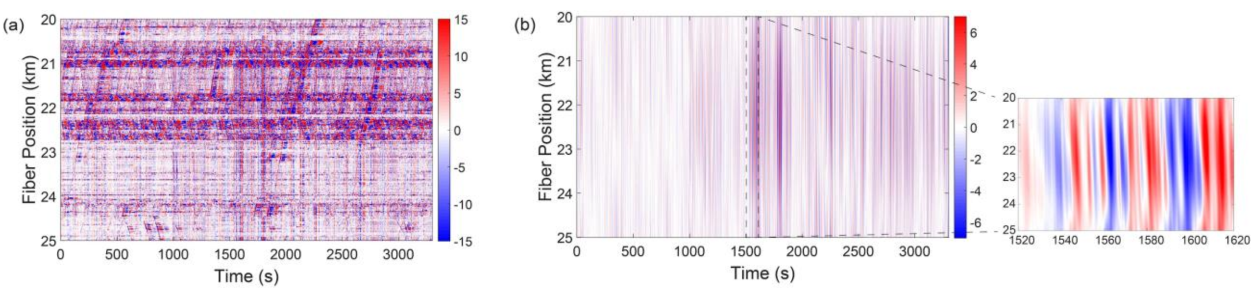

Fig. 1. Trace waterfall obtained during the Fiji earthquake from a HDAS located in Pasadena, CA: (a) Measured data; (b) Data after linear 2D signal processing.

To exploit the redundancy between neighbouring DAS channels and de-noise our seismic data, it is possible to apply any kind of image processing methods to the resulting trace waterfall. Those might include linear or nonlinear filtering, and its choice is typically determined by the nature of the signal to be denoised and behavior of the data (in terms of noise, dynamic range, presence of artifacts, etc.). In general, the application of a linear low-pass filter is recommended for the processing of images with high levels of noise. Besides, our previous knowledge of seismic events allows us to predict certain features of ground-motion events, such as their typical spectral content and their speed. In particular, seismic waves usually have periods above 1 s, i.e., spectral contents below 1 Hz, and spatial periods above 1 km. These spectral components can be easily isolated from the rest of information provided by the distributed sensor by means of a linear band pass filter. In this case, we have employed a 2D rectangular band-pass filter that maintains the temporal frequencies ranging from 0.02 Hz and 1 Hz, and the spatial frequencies ranging from 0 to $2{\cdot}10^{-4}$ m^{-1}. The filter only includes passbands in the quadrants 2 and 3 of the cartesian plane, corresponding to moving targets going in the W-E direction.

The trace waterfall resulting from the application of the 2D rectangular filter is shown in Fig. 1 (b). As observed, only the lines corresponding to the movement of seismic waves are kept, while the vehicles and other noise sources have been filtered out.

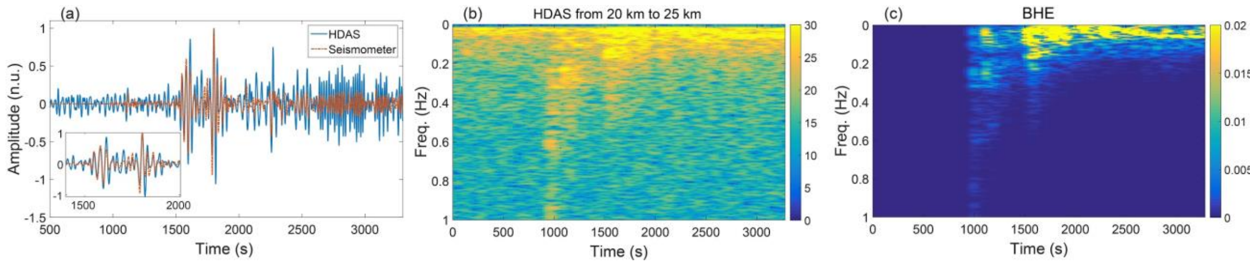

Fig. 2. (a) Stacked traces after 2D filtering from the last 5 km of fiber (solid blue line) and BHE trace from conventional seismometer (dashed-dotted orange line). Inset shows a zoomed region of the traces. (b) Stacked spectrogram of the DAS recording from the last 5 km of fiber; (c) Spectrogram of the BHE trace of the seismometer.

Figure 2 (a) compares the results obtained from the CP-DAS (in solid blue line) with the trace obtained from a conventional seismometer (in dashed-dotted orange line). The CP-DAS trace has been obtained by stacking traces of the last 5 km of fiber after the filtering process. As it can be observed from the figure, the trace from the CP-DAS contains higher levels of noise before the earthquake (starting at about 1500 s) than the seismometer trace, but a very good matching between the two curves can be well appreciated. Figure 2 (b) presents the spectrogram obtained from the CP-DAS traces after the 2D filter, in which the last 5 km of fiber have been considered. The spectrogram shows a high energy peak around 0.05 Hz along the recorded time starting from 1500 s, consistent with the spectrogram of the BHE (east-west) recording of a broadband seismometer (Fig 2(c)). Besides, around the instant 1000 s, a broadband peak with high frequency spectral component appears also in the spectrogram of the CP-DAS data, correctly matching the behaviour obtained from the BHE trace in the seismometer. These results validate the proper operation of the proposed methodology.

4. Conclusion

In conclusion, we have shown that metropolitan area fibers can also be used to track remote seismic events happening as far as 9000 km away. While the amount of measured ambient noise is huge in these fibers, it is clear that adequate signal processing methodologies can eliminate the vast majority of the ambient noise and provide clean signals with low-frequency signatures matching those recorded in broadband seismometers. Further investigation into more advanced signal processing methodologies should be developed, in order to approach the performance of more conventional point technology.

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