3rd URSI AT-AP-RASC, Gran Canaria, 29 May – 3 June 2022

Earthquake Epicenter Localization Using Fiber Optic Distributed Acoustic Sensing

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Abstract

This paper summarizes the results of our earthquake localization research, using distributed acoustic sensing (DAS) technology, with two 25 km long dark communication fiber optic cables close to North Anatolian Fault in the Sea of Marmara. In a previous study, we provided detection statistics for over 250 earthquakes, with analysis metrics such as distance to fiber and magnitude. In this paper, we extend these results to include P and S wave lag time-based epicenter distance estimation and localization based on trilateration and provide results on its accuracy, and comparison with data provided by Kandilli Observatory and Earthquake Research Institute – Regional Earthquake-Tsunami Monitoring Center (KOERI). Considering the advantages of the DAS-based seismic monitoring, such as abundant dark fibers that are already available for seismic monitoring, synchronous and distributed data capture capabilities and cost effectiveness, with no need for power supply in the field, DAS based seismic monitoring systems are promising new tools for both detection and epicenter estimation of earthquakes.

1. Introduction

In order to detect physical influence on a fiber optic cable (FOC), techniques that are based on optical time domain reflectometry (OTDR) can be utilized. By analyzing reflected signal that propagates along the fiber till the end, one or many types of backscattered signals, namely, Rayleigh, Brillouin and Raman, can be captured and analyzed [1]. One of the most popular techniques used in fiber optic distributed acoustic sensing (DAS) is OTDR systems that captures Rayleigh type backscatters.

Successful applications and implementations of DAS systems can be found in many fields. Although DAS is mainly used for intrusion detection [2, 3], perimeter security [4] and mining [5, 6] applications and research activities, it is gaining popularity in seismic monitoring applications [7 – 12]. Although three axis seismometers are the main players in seismic monitoring and research activities, fiber optic DAS based seismic monitoring systems are on the rise lately. Fiber optic DAS based systems are utilized to monitor and detect various seismic events by many scholars. More and more scholars who are interested in seismology are becoming more familiar with the potential in DAS opportunities.

Fiber based communication infrastructures require laborious work in order to lay fiber optic cable underground. In deployment of fiber-based communication network, digging of trenches is generally the most costly and laborious work to be done. So, once the trenches have been dug, more than required amount of fiber cables are installed for a negligible amount of cost to cope with future cabling demands. Abundant amount of fiber cables are left unused in this scenario, which are named as dark fibers. Dark fibers are already laid out and require no additional charge to use, which lowers deployment cost of DAS based sensing schemes. DAS systems offer synchronous sensing of many virtual sensing nodes whose number is determined by spatial resolution and FOC length. In DAS, power and data communication is requires only one end of the FOC where the interrogator is placed, not in every sensing node. On the contrary, seismometers need power source, proper data transmission medium (wireless radio, telephone line etc.), ownership of the land on which seismometer will be deployed for every station [13]. Although DAS based seismic monitoring schemes provide lower dynamic range and sensitivity compared to seismometers, it can evolve almost any dark fiber into fruitful seismic sensing array while mandating fraction of the cost of conventional seismic network with similar properties.

This paper organized as follows. In Section 2, proposed methods are presented in detail. In Section 3, earthquake localization results originating from our DAS data and methods, with fiber cables located close to North Anatolian Fault in the Sea of Marmara are provided.

2. Methods

In this section we have presented DAS architecture in detail and seismic wave types and trilateration method used in this work to localize earthquake epicenter in the next three subsections respectively.

2.1. DAS Architecture and Sensing FOC

In order to capture seismic events, we have used a DAS system that was initially used for intrusion detection purposes [3], and has been modified to monitor and capture seismic events [7]. DAS system is configured to capture DAS data continuously, and these data is used for extracting particular seismic events occurred inside the border of Turkey exclusively. Captured events are labeled and stored as raw recordings. Block diagram of the utilized DAS system is presented in Fig. 1.

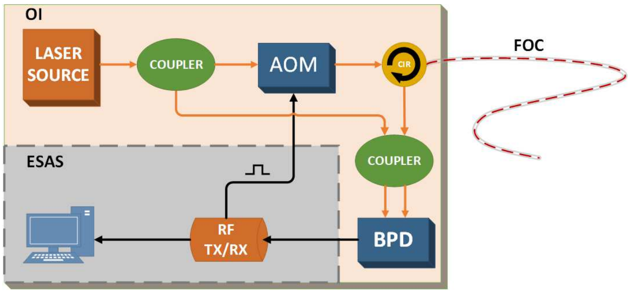

Figure 1. Block diagram of utilized DAS system [7]. DAS system is composed of three main components, namely, FOC, optical interrogator (OI) and electrical signal analysis and storage system (ESAS). Optical interrogator configured to work as a phase sensitive OTDR (Φ-OTDR) with coherent detection.

In this work, we have used two different FOCs to capture seismic events. First one is 25 km long buried regular communication FOC which has submarine portion and passes from Gebze to Yalova under Gulf of Izmit approximately 40 km southeast of Istanbul. It crosses over Marmara Fault Line, which is expected to create an earthquake with a magnitude of 7.0 or more. Second cable has the same length and same specs as first one. But it lies between Gebze and Maltepe, follows a route of nearby highway. Both FOCs have many splices, connections and slack loops along their paths. These factors reduce signal quality by increasing unwanted noise and introducing attenuation in every splice and connection. Also, both fibers pass through urban areas and are exposed to manmade noise which is another negative factor on signal quality.

2.2. Estimation of Earthquake Epicenter Distance

Seismic waves travel through layers of the Earth, and they carry energy originating from a seismic event. Seismic waves are divided into two main groups, namely, body and surface waves. Body waves are composed of primary (P) and secondary (S) waves. P wave is the fastest among other seismic wave types followed by S waves. In the event of seismic activity, P waves arrive first and S waves arrive later on.

S and P wave arrival times, S-P lag time in particular, is commonly used for determining earthquake epicenter distance. Stored DAS recordings are processed to detect and pick P and S waves of captured earthquake events. In order to increase subsequent analysis accuracy, currently this picking is done by hand, but could be done by various methods found in literature. Clear representation of picked P and S waves from a DAS recording is given in Fig. 2.

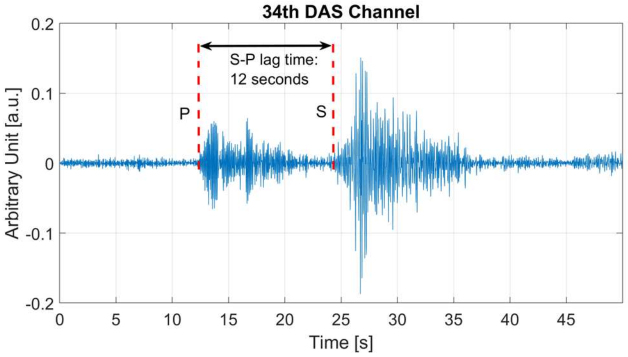

Figure 2. P and S wave representation of an earthquake that occurred offshore of Marmara Sea which has magnitude of M=3.7. Selected DAS channel filtered using band pass filter. (DAS configuration: spatial resolution = 25 m, PRF = 500 Hz, oversampled by 10, 34th channel is 850 m far from the DAS interrogator)

Using picked P and S waves from the DAS recordings we can calculate P-S lag time and calculate epicenter distance to observer. To estimate distance between observing fiber section and earthquake epicenter, S-P lag time can be multiplied by a constant velocity of 8 km/s for local and most crustal events. For farther events, P and S wave arrival time chart can be used [14].

2.3. Trilateration

Trilateration is a method for determining the intersections of three sphere surfaces or circles when their center position and radius information is provided. GPS systems employ trilateration to calculate precise position based on signals received from a satellite and the time it takes for the signal to travel from the satellite to the receiver. This method also find place in the field of seismology in order to determine earthquake epicenter [14]. Utilized method is shown in Fig. 3.

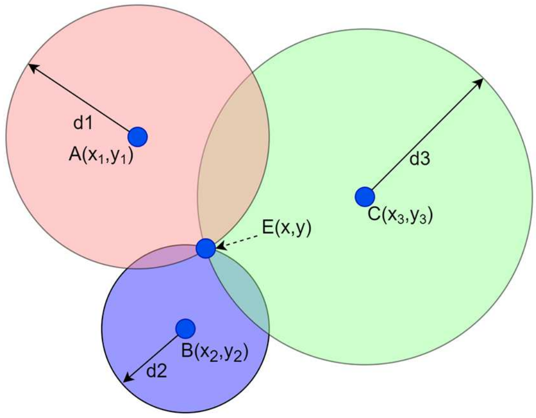

Figure 3. Simplified 2D trilateration method utilized in this work (A, B and C points are the locations of the sensing nodes). Radius values presented as d1, d2 and d3 are calculated epicenter distances to corresponding observation points. E is the estimated location of the event.

As the trilateration method suggests, with the help of at least three epicenter distance estimations that are calculated from different nodes, one can locate the epicenter of captured earthquake. Using S-P lag times gathered from three different sensing nodes and trilateration method, we can locate the epicenter of the source by finding the intersection of three circles. Although we preferred to use three observation points for location epicenter of earthquakes, using more than three observation points may enhance the location accuracy. Ideally, three observations intersect at a single point. But in reality, due to the error in either or both of observation position and distance to the event source, there is not one single intersection, but an area of possible locations. In these cases, area bounded by the smallest intersection triangle is used for estimating event location by calculating centroid of it.

3. Results

We are able locate many earthquakes solely using DAS based seismic data, which are mostly considered as local earthquakes. Located earthquakes have magnitude ranges from 2.8 to 4.0 and distance to FOC ranges from 22 km to 114 km. To locate earthquake epicenter location, first, three different DAS channels (virtual sensing node) are selected and used for picking of P and S phases. Second, sensing nodes and estimated epicenter distances are plugged in trilateration algorithm, thus we estimate the epicenter location of the investigated earthquake. Epicenter estimation of an earthquake that occurred offshore of Marmara Sea which has magnitude of M=3.7, and distance to FOC sensing nodes of about 114 km is given in Fig. 4.

Figure 4. Trilateration result of offshore Marmara earthquake. Locations labeled as 1, 2 and 3 are selected sensing nodes in FOC, E is estimated earthquake epicenter location and K is the earthquake epicenter location provided by KOERI.

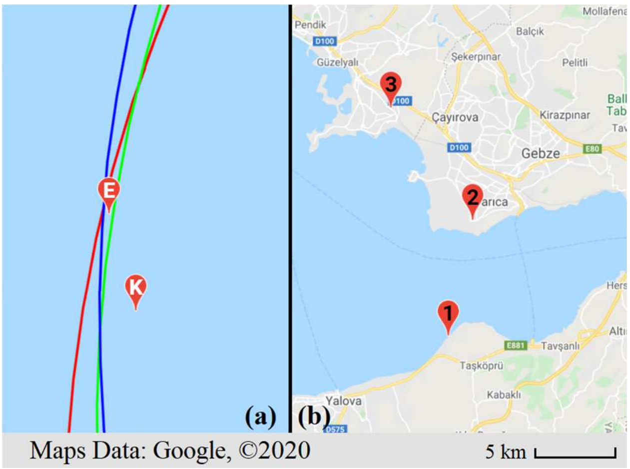

Figure 5. (a) Comparison of estimated earthquake epicenter and earthquake epicenter location provided by KOERI, (b) Locations of selected FOC sensing nodes. Both images are magnified and cropped from Fig. 4.

Located earthquakes including the one presented in Fig. 4 and 5 are given in Table 1 in detail.

Table 1. Comparison table of estimated epicenter locations of given earthquakes and epicenter locations provided by KOERI

Event	Event Epicenter	Estimated Epicenter	Error (km)	Error (%)
Yalova M=2.8	N 40.7653° E 29.084°	N 40.76156° E 29.05339°	2.62	8.8
Yalova M=3.2	N 40.5906° E 28.9832°	N 40.59°, E 28.96109°	1.87	4.2
Marmara M=3.7	N 40.8353° E 28.2995°	N 40.89272° E 28.27812°	6.63	6.98
Yalova M=3.3	N 40.5878° E 28.9843°	N 40.59675° E 28.93922°	3.94	8.56
Sultanbeyli M=4.0	N 40.9487° E 29.2052°	N 40.95776° E 29.17601°	2.66	7.77

As seen in the Table 1, total of five earthquake events are investigated in this paper. Presented earthquake epicenter estimations have error ranges from 1.87 km to 6.63 km, error percentage ranges from 4.2% to 8.8%. Localization errors could be due to one or many of the following factors; noise introduced by RF acquisition and optical components, splices and connector induced attenuation along the FOC, coarsely calibrated FOC sensing node positions. In this work, seismic wave velocities are assumed to be constant which is another possible source of error for epicenter estimation due to the heterogeneous nature of the earth. This work provides initial proof of maturity of the DAS based systems for seismic event localization purposes for the active and important North Anatolian Fault in the Sea of Marmara. We believe that DAS based seismic monitoring systems can be used in conjunction with conventional seismic monitoring systems. As future work, we plan to increase the number of earthquakes utilized in the analysis, consider farther, and higher magnitude events to establish the effects of these parameters on localization accuracy.

References

[1] A. H. Hartog, An Introduction to Distributed Optical Fibre Sensors, CRC Press, 2017.

[2] J. C. Juarez and H. F. Taylor, “Field test of a distributed fiber-optic intrusion sensor system for long perimeters”, Appl. Opt., 46, 11, 2007, pp. 1968–1971.

[3] E. Ozkan, T. Erkorkmaz, B. Cesur, H. Yetik, U. Uludag and I. Olcer, "FOTAS (Fiber Optic Based Acoustic Sensing System): requirements, design, implementation, tests and results", Proc. SPIE, SPIE Future Sensing Technologies, 115250B, 2020.

[4] J. Tejedor, J. Macias-Guarasa, H. F. Martins, S. Martin- Lopez, and M. Gonzalez-Herraez, “A Gaussian Mixture Model-Hidden Markov Model (GMM-HMM)-based fiber optic surveillance system for pipeline integrity threat detection”, 26th International Conference on Optical Fiber Sensors, Lausanne, Switzerland, 2018.

[5] P. Jousset, T. Reinsch, T. Ryberg, H. Blanck, A. Clarke, R. Aghayev, G. P. Hersir, J. Henninges, M. Weber, and C. M. Krawczyk, “Dynamic strain determination using fibre-optic cables allows imaging of seismological and structural features”, Nat. Commun., 9, 2509, 2018.

[6] S. Dou, N. Lindsey, A. M. Wagner, T. M. Daley, B. Freifeld, M. Robertson, J. Peterson, C. Ulrich, E. R. Martin, and J. B. Ajo-Franklin, “Distributed acoustic sensing for seismic monitoring of the near surface: a traffic-noise interferometry case study”, Sci. Rep., 7, 11620, 2017.

[7] H. Yetik, M. Kavakli, U. Uludag, A. Eksim and S. Paker, “Earthquake Detection Using Fiber Optic Distributed Acoustic Sensing," 2021 13th International Conference on Electrical and Electronics Engineering (ELECO), Bursa, Turkey, 2021.

[8] J. B. Ajo-Franklin, S. Dou, N. J. Lindsey, I. Monga, C. Tracy, M. Robertson, V. R. Tribaldos, C. Ulrich, B. Freifeld, T. Daley, X. Li, “Distributed Acoustic Sensing Using Dark Fiber for Near-Surface Characterization and Broadband Seismic Event Detection.” Sci. Rep., 9, 1328, 2019.

[9] G. Marra, C. Clivati, R. Luckett, A. Tampellini, J. Kronjäger, L. Wright, A. Mura, F. Levi, S. Robinson, A. Xuereb, B. Baptie, D. Calonico, “Ultrastable laser interferometry for earthquake detection with terrestrial and submarine cables”, Science, 361, 6401, 2018, pp. 486-490.

[10] C. Clivati, A. Tampellini, A. Mura, F. Levi, G. Marra, P. Galea, A. Xuereb, and D. Calonico, “Optical frequency transfer over submarine fiber links”, Optica, 5, 8, 2018, pp. 893-901.

[11] H. F. Wang, X. Zeng, D. E. Miller, D. Fratta, K. L. Feigl, C. H. Thurber, R. J. Mellors, “Ground Motion Response to an ML 4.3 Earthquake Using Co-Located Distributed Acoustic Sensing and Seismometer Arrays”, Geophysical Journal International, 213, 3, 2018, pp. 2020–2036.

[12] K. Tuinstra, F. Lanza, F. Grigoli, A. P. Rinaldi, A. Fichtner, and S. Wiemer, “Towards automatic microseismic cluster localization with DAS”, 2021

[13] A. Trnkoczy, P. Bormann, W. Hanka, L. G. Holcomb, R. L. Nigbor, M. Shinohara, H. Shiobara and K. Suyehiro. (2012): Site Selection, Preparation and Installation of Seismic Stations. - In: Bormann, P. (Ed.), New Manual of Seismological Observatory Practice 2 (NMSOP-2), Potsdam: Deutsches GeoForschungsZentrum GFZ, pp. 1-139.

[14] T. Lay, T. C. Wallace, Modern Global Seismology, London Academic Press, 1995.