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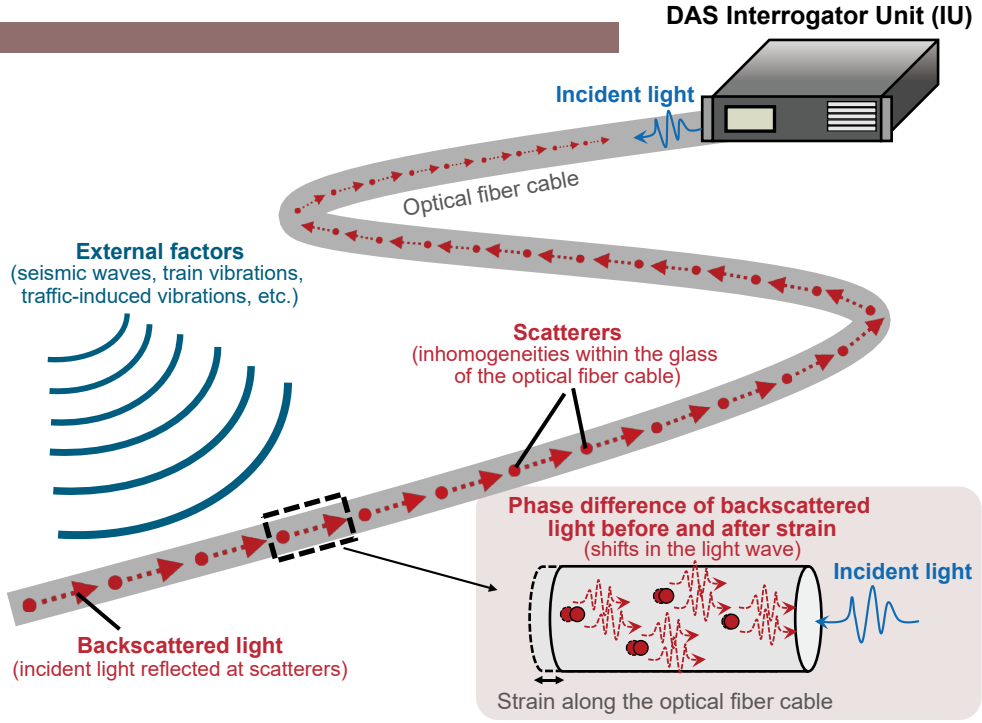



**Figure 1 Conceptual diagram of the DAS measurement principle**

# Construction of a Railway Seismic Observation Network Utilizing Optical Fiber Sensing Technology: Distributed Acoustic Sensing (DAS)

## Introduction

In recent years, the application of Distributed Acoustic Sensing (DAS)—a technology that uses optical fiber cables as sensors rather than solely as data communication media—has advanced rapidly. This technology analyzes changes in the optical phase (i.e., shifts in the light wave) of backscattered light generated at inhomogeneities (scatterers) within the glass of the optical fiber in response to incident light pulses emitted by an interrogator unit (IU*1) connected to one end of a single-core fiber, thereby enabling real-time, high-density measurement of strain along the optical fiber at intervals of a few meters (*Figure 1*)[1)2)].

*1 Interrogator Unit (IU)
The DAS observation device; a transceiver for optical signals. Connected to one end of an optical fiber cable, it emits light pulses into the optical fiber cable and receives the backscattered light reflected within the optical fiber cable, from which strain is calculated.

*2 STA/LTA
The STA/LTA (short-term average/long-term average) method detects the onset of wave-forms characterized by abrupt amplitude changes—such as P-wave arrivals—by compu-ting the ratio of the average amplitude within a short-term window to that within a long-term window. In the present study, the amplitude ratio was computed using a short-term window of 0.5 s and a long-term window of 10 s.

*3 hypomh
A method for determining hypocenter location by maximum likelihood estimation using P-wave arrival times obtained at multiple observation points. Maximum likelihood estimation is an approach in which the model parameters (here, the hypocenter) are estimated so as to maximize the probability (likelihood) of obtaining the observed data.

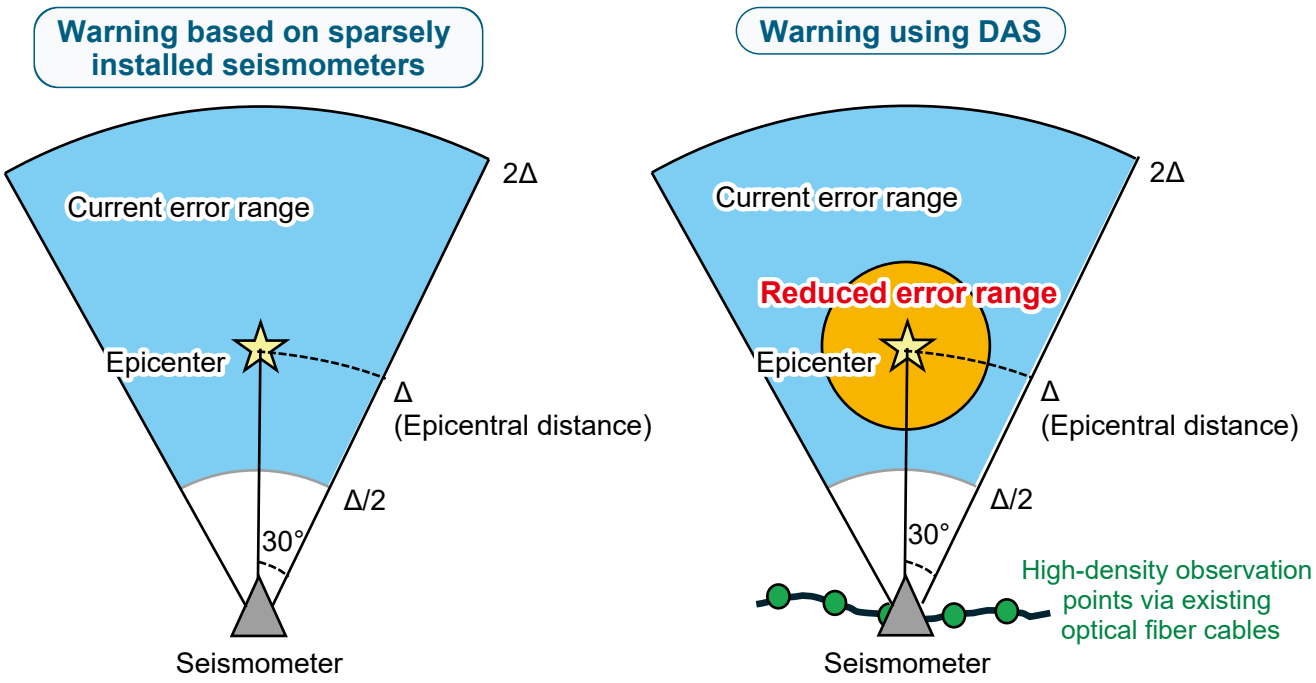



**Figure 2 Comparison of error ranges in earthquake early warning between the conventional method (seismometers) and DAS**

Optical fiber cables for telecommunications are commonly installed along railway lines, and by connecting an IU to such a single-core fiber, DAS-based measurements can be conducted along the railway line. Moreover, DAS-based seismic observation has been extensively tested at numerous sites on land and on the seafloor, demonstrating that a wide variety of seismic waveforms, including those from local earthquakes and teleseismic events can be recorded using optical fiber cables[3)4)].

The current algorithm for seismic parameter estimation used in earthquake early warning (EEW) for Shinkansen lines estimates parameters such as epicentral distance (C- Δ method) and epicentral azimuth (principal component analysis) from single-station data. While this approach enables warnings to be issued more rapidly than methods based on multi-station data (with a minimum lead time of 1 s), the estimated epicentral distances are subject to uncertainties up to a factor of 2, and the estimated epicentral azimuth to uncertainties of ± 30 ° (*Figure 2*). In contrast, because DAS can acquire data at intervals of a few meters, it is possible to detect seismic waves at multiple points almost simultaneously (e.g., within 0.5 s), thereby enabling the application of high-precision hypocenter determination methods that utilize data from multiple observation points (*Figure 2*). In addition, post-earthquake operations—such as train withdrawal and the delineation of areas requiring inspection—currently rely on representative indices of seismic intensity (e.g., acceleration) recorded by sparsely distributed seismometers at intervals of approximately 10-40 km along the railway line. High-density acquisition of such indices through DAS is thus expected to enable more precise delineation of inspection zones and optimization of related operations (*Figure 3*). Furthermore, the use of DAS has the potential to facilitate more rapid and rational post-earthquake inspection activities and decisions to resume train operation. An additional major advantage is that a high-density seismic disaster prevention system along railway lines can be constructed at reduced cost by leveraging existing telecommunication optical fiber cables. Against this background, this article presents the results of seismic observations conducted by connecting DAS interrogator units to existing optical fiber cables installed along railway lines.

## DAS-based seismic observation along the Kyushu Shinkansen line

DAS-based seismic observations were conducted twice over approximately one-month periods each, utilizing existing telecommunication optical fiber cables

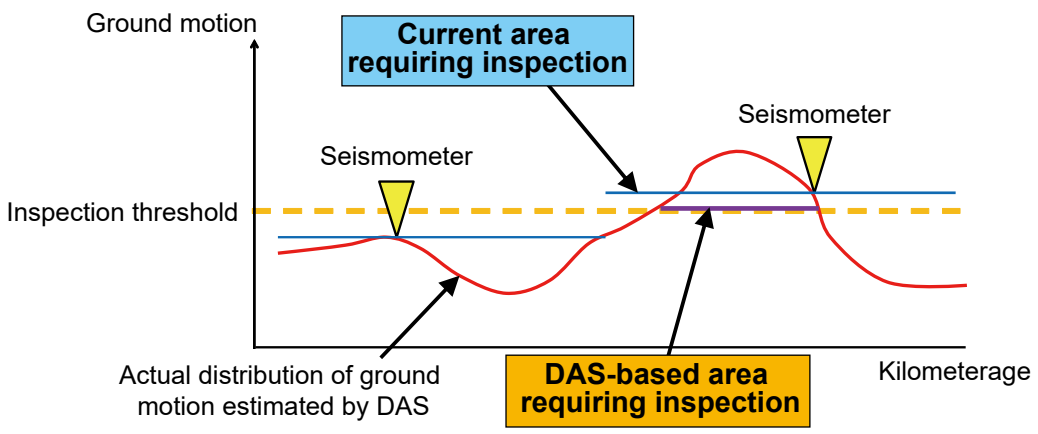



**Figure 3 Optimization of areas requiring inspection based on DAS-derived spatial distributions of ground motion along the railway line**

**Table 1 DAS observation parameters**

| | FY2022 | FY2023 |
|---|---|---|
| Observation distance | Approx. 75 km | Approx. 100 km |
| Observation period | Early January–Early February | Early February–Early March |
| Observation section | Shin-Yatsushiro–Shin-Omuta stations | Shin-Yatsushiro–Kurume stations |
| Sampling rate | 500 Hz | 1,000 Hz |
| Gauge length | 10 m | 5 m |
| Spatial sampling interval | 5 m | 5 m |
| Total number of channels (observation points) | 15,082 channels | 20,762 channels |

installed along the Kyushu Shinkansen line[5]. The observation parameters are summarized in *Table 1*. Here, gauge length refers to the length of the optical fiber segment over which strain is calculated; for example, a gauge length of 10 m means that the elongation and contraction of the cable over a 10 m section can be measured. The spatial sampling interval was set to 5 m. The observation sections were approximately 75 km and 100 km long, corresponding to 15,082 and 20,762 channels (observation points), respectively. The observation sections encompass a variety of railway structures, including rigid-frame viaducts (Rahmen viaducts), bridges, tunnels, and embankments. In general, the optical fiber cables are routed inside cable ducts installed beside the tracks on these structures. Within tunnels, however, the cables are fixed to the tunnel walls at regular intervals and suspended from the walls.

## Seismic and train vibration waveforms recorded by DAS

During the observation period, numerous waveforms were recorded, including seismic waveforms associated with earthquakes occurring in and around the observation area, and train vibrations from Shinkansen trains in service. Representative examples of DAS-recorded strain rate data are shown below:

- Seismic waveform of an earthquake (Mj 3.3) that occurred in Kumamoto Prefecture on January 19, 2022 (*Figure 4a*)
- Non-seismic waveforms including train vibrations and tunnel compression waves (*Figure 4b*)

During the observation period, numerous earthquakes occurred in Kumamoto Prefecture and the surrounding subduction zone. *Figure 4a* shows the DAS strain-rate waveforms recorded for a Mj 3.3 earthquake that occurred within a few

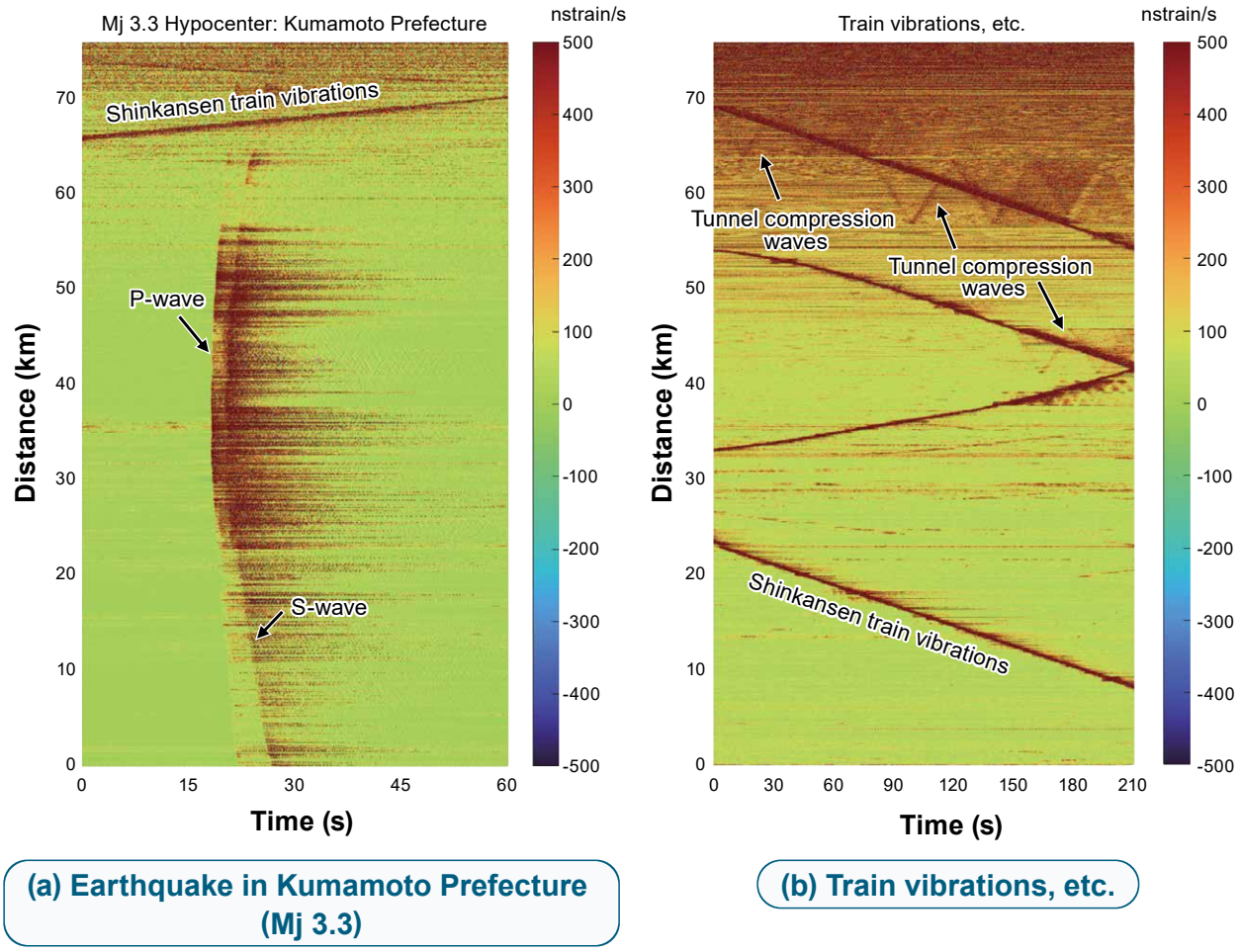



**Figure 4 Various strain rate waveforms recorded by DAS**

tens of kilometers of the railway line. Data from each channel were bandpass filtered between 1 and 10 Hz, with color intensity representing strain rate amplitude. Clear P-wave and S-wave arrivals are identifiable in most channels. However, at approximately 55-64 km and 66-70 km along the line, waveform amplitudes appear relatively small. This is attributed to reduced coupling between the optical fiber cable and the surrounding ground in tunnel sections, where the cable is partially suspended from the tunnel walls, resulting in lowering sensitivity to ground motion. At the section closest to the hypocenter (approximately 35 km along the line), the maximum strain rate was recorded, and the propagation of seismic waves in both directions away from that point is clearly visible.

In addition to seismic waveforms, passages of several hundred Shinkansen trains were also recorded during the observation period. *Figure 4b* shows the strain rate waveforms acquired by DAS after bandpass filtering between 10 and 40 Hz. Vibrations associated with downbound train passages are identifiable at approximately 8-23 km, 42-54 km, and 55-69 km, while those from upbound trains are visible at approximately 33-41 km. In certain tunnel sections (particularly 42-47 km and 58-63 km), tunnel compression waves generated as trains enter and exit the tunnels are observed; these reflect air pressure waves propagating within the tunnel interior. These results demonstrate that DAS can simultaneously acquire not only the spatial distribution of seismic ground motion along the railway line, but also a diverse range of signals including train vibrations, train positions, and tunnel compression waves.

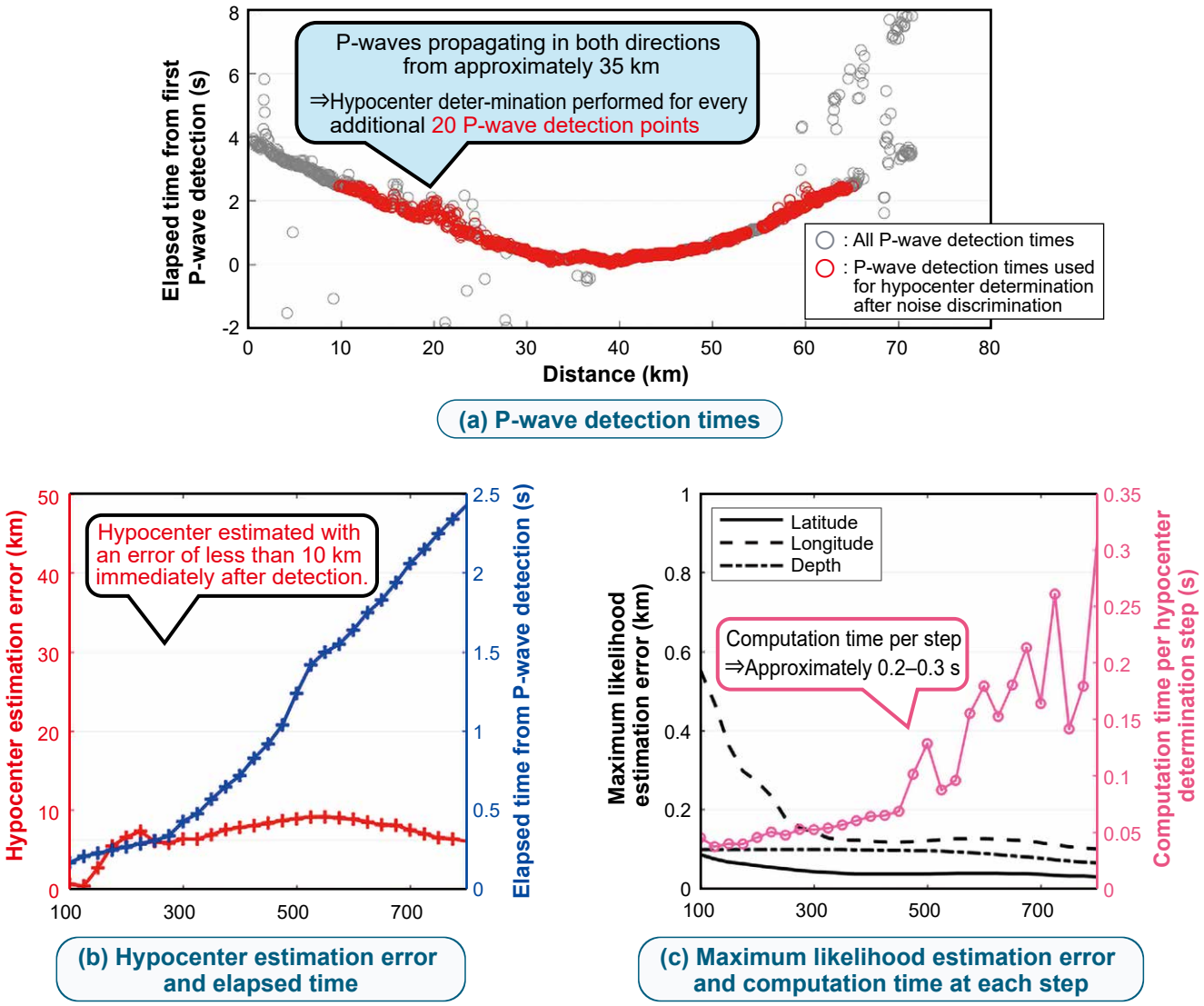



**Figure 5 Results of applying the immediate hypocenter determination method using DAS**

## Development of immediate hypocenter determination method using DAS

Using DAS seismic observation data acquired via existing optical fiber cables, a method was developed to rapidly estimate the hypocenter by integrating information from multiple observation points following seismic wave detection[6]. The processing workflow is outlined as follows:

(a) The STA/LTA[*2,7] is computed continuously at 10-channel intervals.

(b) When the cumulative number of channels in which P-waves have been detected by the STA/LTA method reaches 100, the initial hypocenter determination is performed using hypomh[*3,8].

(c) The hypocenter location obtained in step (b) is saved as the initial estimate.

(d) Each time the number of P-wave detection channels increases by an additional 20, the hypocenter is re-estimated using hypomh.

(e) Steps (c) through (d) are repeated sequentially until the total number of P-wave detection channels reaches 800.

Applying this method to the Mj 3.3 earthquake in Kumamoto Prefecture (*Figure 4a*), clear P-wave detections were obtained at

multiple observation points (*Figure 5a*). Even when only P-wave arrival times obtained within approximately 1 s of the first P-wave detection were used, the hypocenter was estimated with an error of approximately 5 km (*Figure 5b*). Although the estimation error slightly increased thereafter, the hypocenter was again determined to within approximately 5 km accuracy approximately 2.5 s after the initial detection. As the number of P-wave detection points increases, the computational load also grows; however, the computation time at each step was generally less than 0.3 s, confirming that real-time processing is fully feasible (*Figure 5c*). The temporary increase in hypocenter estimation error (observed at approximately 500 P-wave detection points) is attributed to the predominantly north-south orientation of the optical fiber, which renders east-west positional determination unstable. The developed method demonstrates that, compared with conventional single-station hypocenter estimation methods (C- Δ method and principal component analysis), it achieves far superior hypocenter determination accuracy while maintaining equivalent immediacy. In addition, it was confirmed that earthquake magnitude can be estimated with an error of approximately ± 0.5 units within 1-2 s after P-wave detection, thus demonstrating the applicability of this method to earthquake early warning systems.

## Conclusion and future perspectives

Seismic observations were conducted using existing telecommunication optical fiber cables installed along the Kyushu Shinkansen line, with the aim of applying DAS technology to the railway sector. By leveraging the high temporal and spatial resolution of real-time DAS observation, it is possible to enhance the accuracy and immediacy of earthquake early warning and to obtain instantaneous spatial distributions of ground motion along the railway line immediately following an earthquake. This is expected to support the efficient delineation of areas requiring inspection and to provide information assisting train operation control decisions (e.g., train withdrawal), thereby further improving the seismic disaster prevention capability of railways. Moreover, DAS is considered applicable not only to earthquake ground motion but also to the detection of other disaster-related phenomena such as sediment inflow, rockfalls, avalanches, and fallen trees. Future development of a comprehensive multi-hazard monitoring system capable of simultaneously detecting and assessing these phenomena is therefore anticipated.

## References


1) Hartog, A., “An Introduction to Distributed Optical Fibre Sensors,” Boca Raton, FL: CRC Press. 2017.
2) Ide, S., Araki, E., and Matsumoto, H., “Very Broadband Strain-Rate Measurements along a Submarine Fiber-Optic Cable off Cape Muroto, Nankai Subduction Zone, Japan,” Earth, Planets and Space, 73(1), 63. https://doi.org/10.1186/s40623-021-01385-5. 2021.
3) Ajo-Franklin, B. J., Dou, S., Lindsey, J. N., Monga, I., Tracy, C., Robertson, M., Tribaldos, R. V., Ulrich, C., Freifeld, B., Daley T., and Li, X., “Distributed Acoustic Sensing Using Dark Fiber for Near-Surface Characterization and Broadband Seis-mic Event Detection,” Scientific Reports, 9(1), 1328. https://doi:10.1038/s41598-018-36675-8. 2019.
4) Naito, S., Fujiwara, H., Nakamura, H., Suzuki, H., Sakurai, K., Konishi, C., Ogawa, N., and Takebe, M., “Comparison of Ground Motion Monitoring Performance by DAS Test Observation Using Multiple Types of Optical Fibers and Interrogators,” Journal of Japan Association for Earthquake Engineering, 25(4), 4_206–4_219, 2025.
5) Katakami, S., Noda, S., Korenaga, M., Araki, E., Takahashi, N., and Iwata, N., “Potential of Earthquake Strong Motion Observation Utilizing a Linear Estimation Method for Phase Cycle Skipping in Distributed Acoustic Sensing,” J. Geophys. Res.: Solid Earth 129, e2023JB027327. https://doi:10.1029/2023JB027327. 2024.
6) Katakami, S., Korenaga, M., Iwata, N., Araki, E., Takahashi, N., and Noda, S., “Immediate and High-Precision Hypocentral Determination for Earthquake Early Warning Applications Using Distributed Acoustic Sensing,” Bulletin of the Seismological Society of America; 115 (1): 174–190. https://doi.org/10.1785/0120240184. 2025.
7) Allen, R. V., “Automatic Earthquake Recognition and Timing from Single Traces,” Bull. Seismol. Soc. Am. 68, 1521–1532. 1978.
8) Hirata, N., and Matsu’ura, M., “Maximum-Likelihood Estimation of Hypocenter with Origin Time Eliminated Using Nonlinear Inversion Technique,” Phys. Earth Planet. Inter. 47(1), 50–61. https://doi.org/10.1016/0031-9201(87)90066-5. 1987.