Assessing tomographic capabilities of distributed acoustic sensing data near the Mendocino Triple Junction

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Abstract

In recent years, distributed acoustic sensing (DAS) has emerged as an effective tool for seismological applications, with its use rapidly expanding. The global growth of fiber infrastructure provides an ideal framework for enhancing continuous seismic monitoring by integrating DAS into existing seismic networks. Despite the challenges posed by the vast data volumes generated by DAS (terabytes per day), modern computational architectures, such as general-purpose graphics processing units, and novel methodologies like machine-learning algorithms, allow for efficient processing and analysis of these datasets. DAS has already proven useful for earthquake monitoring, rupture imaging, and subsurface characterization.

Building on this, we test the resolution achievable using the United States Geological Survey (USGS) DAS array deployed within the Mendocino Triple Junction (MTJ) in 2022 by applying an adjoint-state Eikonal tomography method. This approach combines traveltime picks from body waves, obtained using the PhaseNet-DAS algorithm, and surface-wave traveltimes derived from noise cross-correlation. The MTJ region, a complex tectonic setting where the Gorda, North American, and Pacific plates converge, is currently monitored by the USGS DAS array, which provides high spatial density data for seismic analysis. By leveraging these DAS data and integrating them with existing seismic catalog information, we aim to generate high-resolution subsurface images and improve earthquake location accuracy in this region. The high-resolution tomographic images from this DAS array could enhance our understanding of the subsurface structures in the MTJ and further demonstrate the potential of DAS arrays for detailed seismic imaging and earthquake monitoring.

The Mendocino Triple Junction

The Mendocino Triple Junction (MTJ) is a highly complex fault system beneath Cape Mendocino, where the Gorda, North American, and Pacific plates converge, connecting the Cascadia subduction zone with the San Andreas transform fault system (Figure 1). Over the past 50 years, the MTJ has accounted for more than 25% of the total seismic energy released by earthquakes in and around California. Recently, a Mw 6.4 earthquake in 2022 and a Mw 7.0 earthquake in 2024 triggered significant aftershock sequences, revealing potential interactions between intra-slab earthquakes and the slip on the subduction megathrust. In this study, we employ a distributed acoustic sensing (DAS) OptaSense Plexus unit that was deployed by USGS in this area since 2022.

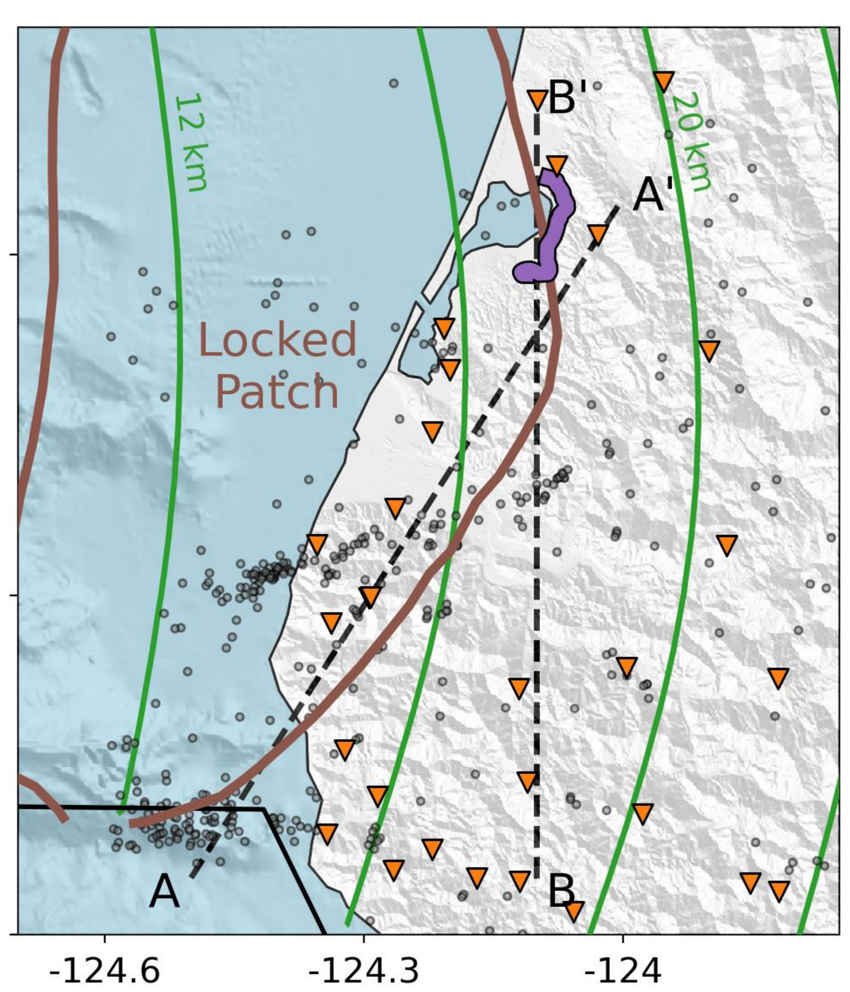


Figure 1: Study area and events from the DAS array. Map of the study area in which the DAS channels (purple line), seismic stations (orange triangles), and the earthquakes (gray dots) are indicated. The green lines indicate the depth of the subducting plate. The black dashed lines delineate the cross-sections shown in Figure 2.

Eikonal surface- and body-wave tomography

The inversion of traveltime picks from the DAS array and seismic stations is performed using an Eikonal-equation-based matrix-free iterative algorithm that can invert surface- and body-wave arrival times. The objective function is posed as follows:

$$\phi(\boldsymbol{v}) = \frac{1}{2}\left\| \begin{matrix} \lambda_B[\boldsymbol{f}_B(\boldsymbol{v}) - \boldsymbol{\tau}^B_{obs}] \\ \lambda_S[\boldsymbol{f}_S(\boldsymbol{v}) - \boldsymbol{\tau}^S_{obs}] \end{matrix} \right\|_2^2$$

where λ_B and λ_S are the relative weights of the body- and surface-wave traveltime errors, respectively, $\boldsymbol{\tau}^{\cdot}_{obs}$ are the observed traveltimes, $\boldsymbol{f}_{*}$ are the Eikonal operators, and $\boldsymbol{v}$ the velocity vector.

Body-wave resolution tests

Figure 2 shows the results of applying the Eikonal body-wave tomography within a checkerboard resolution test using 384 selected events to assess the resolution that can be achieved using the available data from the DAS and the seismic network.

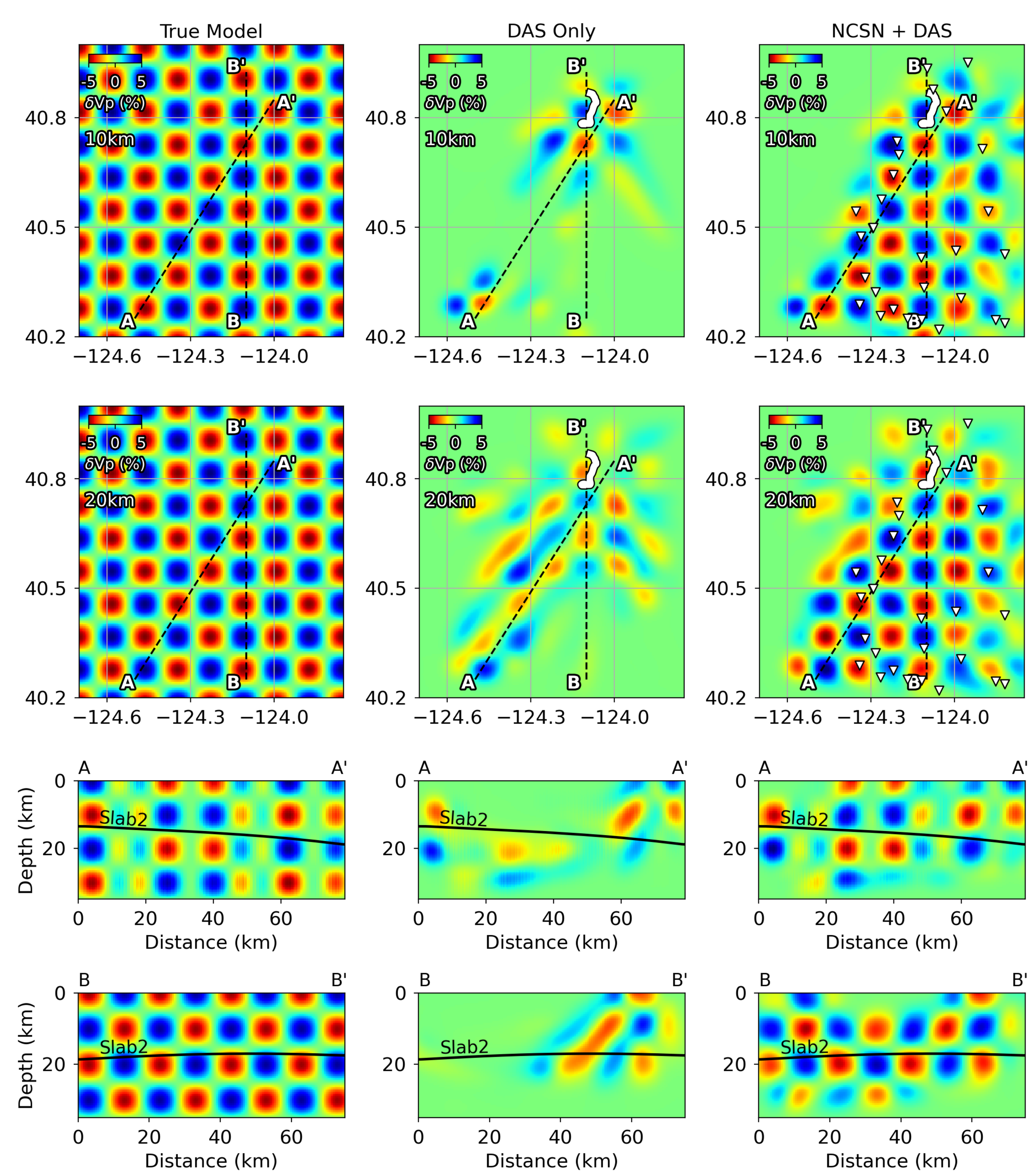


Figure 2: Checkerboard test for Eikonal body-wave tomography. (Left column) true checkerboard anomaly at 10 and 20 km depths, along with the two cross sections indicated in Fig. 1. (Central column) Resolved checkerboard using DAS only. (Right column) Resolved checkerboard using DAS and seismic network stations. The size of the anomalies is approximately 10 km.

Body-wave traveltime picking

To obtain the traveltime picks, we employ a machine-learning method called PhaseNet-DAS (Zhu et al., 2023). Figure 3 shows how this method can enable the accurate picking of body wave arrivals on this array.

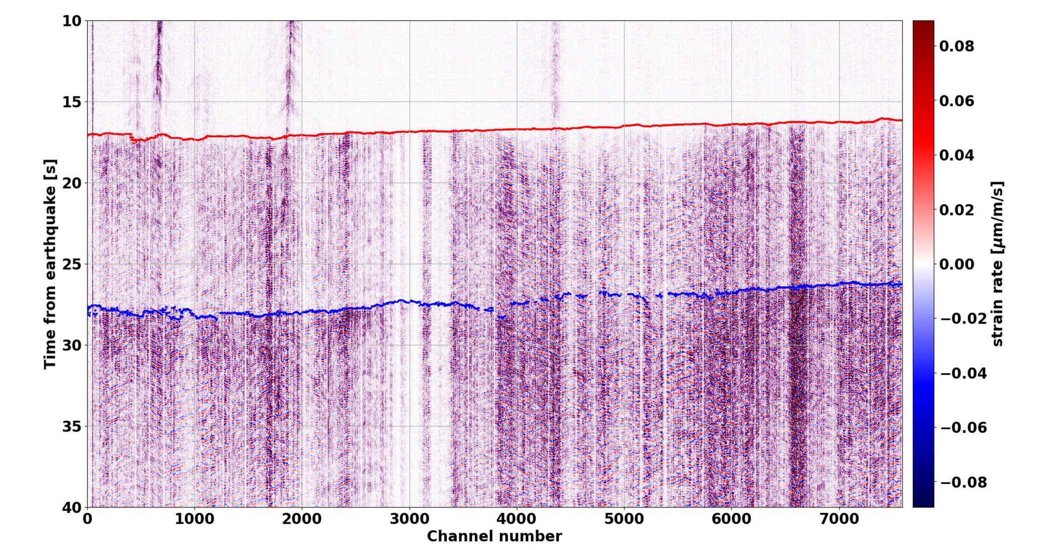


Figure 3: PhaseNet-DAS applied to DAS earthquakes. Representative event showing the performance of PhaseNet-DAS to pick body-wave traveltime arrivals. The red and blue dots represent the P- and S-wave arrivals, respectively

Surface-wave cross-correlation

In addition to body-wave arrival times, we plan to enhance the near-surface resolution by inverting arrival times for surface waves obtained using noise cross-correlations. Figure 4 shows an example of how vertical broadband components can give rise to meaningful seismic gathers when correlated with DAS recordings.

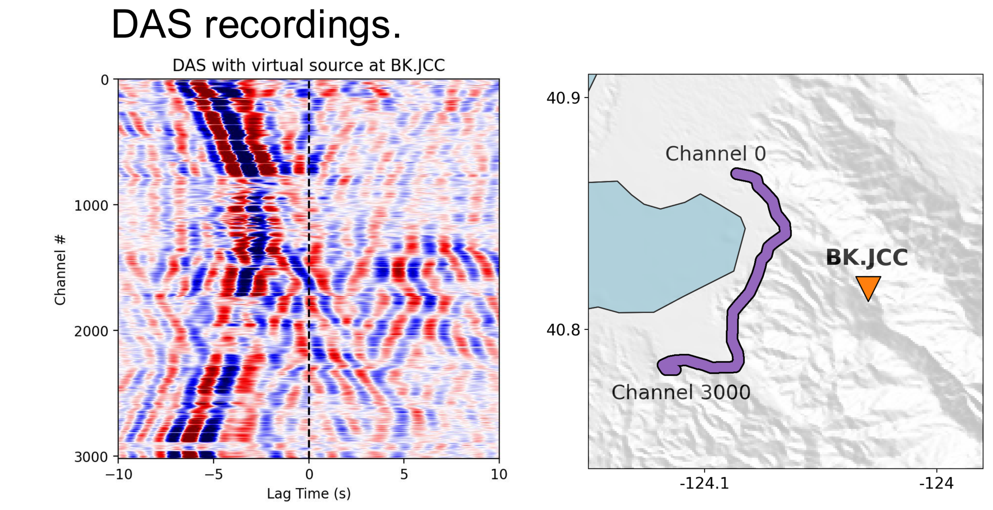
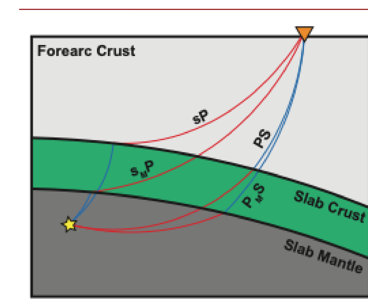


Figure 4: Cross-correlation between seismic station and DAS. Representative cross-correlation obtained by correlating a broadband station in the proximity of the DAS array.

Secondary phases



We are currently exploring the possibility of leveraging secondary phases to perform high-resolution tomography to enhance the sensitivity area below the DAS array and the seismic stations.

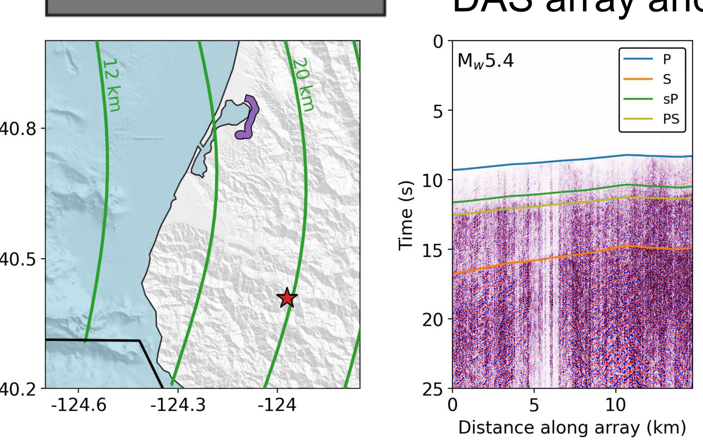


Figure 5: Secondary phases recorded by the DAS array. Schematic and observed secondary phases recorded on the DAS array for a Mw 5.4 event. The slab interfaces present high contrasts that result in potentially detectable secondary phases.

Conclusions

We are currently evaluating how DAS, combined with the seismic stations located in the MTJ area, could improve the definition of subsurface structures within and above the subducting slab. Preliminary analyses using an Eikonal traveltime inversion suggest that this combined dataset can resolve structural features. These initial results also allow us to delineate areas of high resolution versus regions where coverage remains limited.

References

Zhu, W., Biondi, E., Li, J., Yin, J., Ross, Z.E. and Zhan, Z., 2023. Seismic arrival-time picking on distributed acoustic sensing data using semi-supervised learning. Nature Communications, 14(1), p.8192.

Acknowledgements

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