DASPy: A Python Toolbox for DAS Seismology

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Abstract

Distributed acoustic sensing (DAS) has emerged as a novel technology in geophysics, owing to its high sensing density, cost-effectiveness, and adaptability to extreme environments. Nonetheless, DAS differs from traditional seismic acquisition technologies in many aspects: big data volume, equidistant sensing, measurement of axial strain (strain rate), and noise characteristics. These differences make DAS data processing challenging for new hands. To lower the bar of DAS data processing, we develop an open-source Python toolbox called DASPy, which encompasses classic seismic data processing techniques, including preprocessing, filter, spectrum analysis, and visualization, and specialized algorithms for DAS applications, including denoising, waveform decomposition, channel attribute analysis, and strain-velocity conversion. Using openly available DAS data as examples, this paper makes an overview and tutorial on the eight modules in DASPy to illustrate the algorithms and practical applications. We anticipate DASPy to provide convenience for researchers unfamiliar with DAS data and help facilitate the rapid growth of DAS seismology.

1 Introduction

Distributed acoustic sensing (DAS) is an emerging vibration monitoring technology increasingly utilized in geophysics. It converts fiber optic cables into an ultradense seismic array with meter-scale spacing and a frequency range of 0.01 Hz to 100 kHz. DAS recovers axial strain or strain rate along the fiber-optic cable by measuring the subtle optical phase shift of backscattered light within the fiber (Lindsey & Martin, 2021; Zhan, 2019). Over recent years, it has been demonstrated useful in many seismological applications such as earthquake monitoring (Z. Li et al., 2021; Z. Li & Zhan, 2018; Lindsey et al., 2017; Nayak et al., 2021; Zeng et al., 2022), source property estimate (Chen, 2023; J. Li, Kim, et al., 2023; J. Li, Zhu, et al., 2023), subsurface imaging (Ajo-Franklin et al., 2019; Cheng et al., 2021; Dou et al., 2017; Luo et al., 2021; Nayak & Ajo-Franklin, 2021; Yang, Atterholt, et al., 2022), fault zone detection (Atterholt, Zhan, & Yang, 2022; Jousset et al., 2018; Lindsey et al., 2019; Yang, Zhan, et al., 2022) and urban seismology (Lindsey, Yuan, et al., 2020; X. Wang et al., 2021; T. Zhu et al., 2021). It has also been applied broadly outside seismology, such as volcanology (Jousset et al., 2022; Nishimura et al., 2021), oceanography (Lin et al., 2024; Sladen et al., 2019; Williams et al., 2019, 2022; Xiao et al., 2022), glaciology (Hudson et al., 2021; Walter et al., 2020), marine biology (Bouffaut et al., 2022; Landrø et al., 2022; Rørstadbotnen et al., 2023; Wilcock et al., 2023), and meteorology (Hong et al., 2024; T. Zhu & Stensrud, 2019).

DAS produces data gathers with regular spacing, similar to exploration seismic data. Hence, one may process DAS data with software for exploration data, such as Seismic Unix (Cohen & Stockwell, 2008) and Madagascar (http://www.reproducibility.org). However, compared to conventional seismic arrays in earthquake seismology, DAS differs in several key aspects, especially the voluminous data and uniaxial measurement of strain or strain rate (Z. Li, 2021; Lindsey & Martin, 2021; Zhan, 2019). The noise composition of DAS tends to be more complex due to its different self-noise, common-mode noise, and traffic noise for often along-road fibers (Bakku, 2015; Costa et al., 2019; Lindsey, Rademacher, et al., 2020; Zhirnov et al., 2019). These differences often require different processing techniques from those for conventional seismometers, making it challenging for researchers newly using DAS data.

Inspired by the success of ObsPy for conventional seismic data processing (Beyreuther et al., 2010), we believe that a new Python processing package specifically designed for DAS data could facilitate the development of DAS seismology. We notice that an ongoing project, called DASCore, is developing a Python package for reading and writing, visualization, and basic processing of DAS data (Chambers et al., 2024). In this study, in addition to the functionalities offered by DASCore, we aim to provide a wider diversity of practical data processing tools dedicated for DAS applications. This new open-source Python package is named DASPy and comprises two primary components: a set of basic tools including modules for preprocessing, filtering, frequency attributes and visualization, and another set of advanced tools including modules for channel analysis, waveform decomposition, denoising and strain-velocity conversion (Fig. 1). As follows, we showcase the key functionalities using various publicly available datasets (Fig. 2) and ensure that the experiments can be easily replicated by readers.

2 Basic Tools

2.1 Classic processing techniques

Typical seismic data processing includes filtering, frequency attribute analysis and certain preprocessing methods. We wrap these techniques for 2-dimensional DAS data, eliminating the need for iterating over channels. For example, the Python code below bandpass filters the data from the RAPID dataset (Wilcock & Ocean Observatories Initiative., 2023; http://piweb.ooirsn.uw.edu/das/; Figure 2a) between 15 and 27 Hz and yields a spectrogram averaged over 100 channels and a frequency-wavenumber (FK) spectrum (Figure 3). This dataset was collected offshore central Oregon and recorded various signals including fin whale calls, northeast Pacific blue whale A and B calls, and ship noises (Wilcock et al., 2023).

```
>>> from daspy.basic_tools.filter import bandpass
>>> from daspy.basic_tools.freqattributes import spectrogram, fk_transform
>>>
>>> data_filtered = bandpass(data, fs, 15, 27, detrend=True, taper=0.04)
>>> spec, f1, t = spectrogram(data[4880-50:4880+50], fs=fs, nperseg=256, noverlap=246,
                              nfft=1024, detrend=True)
>>> fk, f2, k = fk_transform(data, dx, fs)
```

2.2 Visualization

The function, `plot`, can be used to visualize 2-dimensional DAS data. It offers a number of optional parameters to accommodate the users' requirements for plotting a variety of data types, such as waveforms, spectra, spectrograms, and FK spectra. Below is the Python code for visualizing the data in the previous example: unfiltered and filtered data, the spectrogram and the FK spectrum (Figure 3). The bandpass filtered waveform reveals high-frequency fin whale calls, with amplitudes approximately four to five orders of magnitude lower than the ocean wave signals (Figure 3b). The spectrogram demonstrates the sequential production of high- and low-frequency calls by the fin whale (Figure 3c). The FK spectrum reveals an apparent velocity of this acoustic signal exceeding 1400 m/s along the axial direction of the optical cable (Figure 3d).

```
>>> from daspy.basic_tools.visualization import plot
>>>
>>> fig, ax = plt.subplots(4, 1, figsize=(7,8))
>>> plot(data, dx=dx, fs=fs, ax=ax[0], transpose=True, x0=xmin*dx, xlabel=False,
          colorbar_label='Strain')
>>> plot(data_filtered, dx=dx, fs=fs, ax=ax[1], transpose=True, x0=xmin*dx,
          xlabel=False, colorbar_label='Strain')
>>> plot(Zxx, fs=fs, obj='spectrogram', ax=ax[2], f=f1, t=t, vmin=2e-8, vmax=3e-6,
        ylim=[0, 40])
>>> plot(fk, obj='fk', ax=ax[3], f=f2, k=k, xlim=[-0.025, 0.025], ylim=[0, 40],
        vmin=0.05, vmax=0.2)
>>> plt.tight_layout(pad=0.5)
>>> plt.savefig('figure3.pdf', dpi=800)
```

3 Advanced Tools

3.1 Channel analysis

DAS channels have equidistant spacing but the location of each channel is often unknown and requires tap tests. Besides, the linearity and ground coupling of the fibers often need to be taken care of. We develop three functions for channel location and quality analysis: channel location interpolation, turning point detection, and low-quality channel checking.

Channel location interpolation for DAS is calculated using two types of inputs: points with known channel numbers, and optional fiber spatial track points without channel numbers. Points with known channel numbers are typically acquired through tap tests and are often sparse. The spatial fiber track points are used to constrain the array geometry. They are optional but dense track points are particularly useful for accurate location interpolation. Fig. 2a shows examples of the two DAS arrays of the RAPID dataset (Wilcock & Ocean Observatories Initiative., 2023). In DASPy, we implemented the interpolation method used by the RAPID team, in which interpolation is performed after the coordinates are projected to the Universal Transverse Mercator (UTM) coordinate system.

The turning point detection function determines the points where the fiber strike varies noticeably based on the given channel coordinates or based on waveform coherency across neighboring channels. The application of the coordinate-based detection function to Brady's geothermal field DAS array (University of Wisconsin, 2016a; https://gdr.openei.org/submissions/829; Fig. 2c) produces results consistent with those of Piana Agostinetti et al. (2022). As cross-channel waveform coherency is not only affected by the fiber strike angle, but also controlled by other factors including the quality of the backscattered light, coupling conditions and small-scale scatterers at different locations, its results could be less stable than those of coordinate-based computations assuming the coordinates are accurate. However, when the coordinates are unavailable or inaccurate, inference from cross-channel waveform coherency could be an alternative.

The channel quality checking function detects segments with obvious poor coupling (e.g., zip-tied loops of telecommunication cables) by identifying outliers of waveform energy along the fiber. It fits the waveform energy (the square of the amplitudes) variations with channels by a high-order polynomial and removes the fitted polynomial from the data. A threshold of four times of standard deviation below the median is set to identify the outliers. We assume that poor coupling tends to be spatially continuous. Hence, isolated normal values among a group of outliers would be identified as bad channels and vice versa. Using this function, we assess the channel quality of Ridgecrest DAS (Fig. 2d) with 15 seconds of traffic noise (Atterholt, 2021; https://data.caltech.edu/records/1955, Fig. 4). Our waveform-based detection results are generally consistent with the hand-picked results of Atterholt, Zhan, Shen, et al. (2022) (Fig. 4b-f), except for the initial segment which was identified from a priori knowledge during field installation. It is noteworthy that the spikes (Fig. 4a) do not significantly influence the low-quality channel detection because we use a robust fit for the waveform energy (abnormal points are excluded from fitting).

3.2 Data denoising

As aforementioned, DAS data are often mixed with complex types of noise. DASPy integrates functions for the removal of typical noise types, including spike noise (Bakku, 2015), common-mode noise (Lindsey, Rademacher, et al., 2020), stochastic noise (Costa et al., 2019), and coherent noise. DASPy constructs a denoising module that incorporates three methods that take advantage of different noise properties.

Spikes are unusually large amplitudes (Fig. 5a) and could be caused by laser frequency drift or laser noise (Zhirnov et al., 2019). The spike removal function first applies the across-channel median filter and then the across-time median filter to generate a median map from the absolute amplitudes. Points with amplitudes exceeding a predefined threshold of the median map are identified as spikes. All spikes are subsequently substituted with interpolated values from adjacent channels. The spike removal function is validated using an earthquake waveform recorded by the Stanford-1 DAS array (Fig. 2b and Fig. 5a-b; Biondi et al., 2017; Martin et al., 2017).

Common-mode noise, also known as in-phase noise is generated by vibrations of the optoelectronic system and arises on all channels simultaneously (Fig. 5d). DASPy employs spatial averaging of waveforms to obtain common mode noise. Subsequently, we compute the correlation coefficient with the channel record and the common-mode noise, multiply the common-mode noise by the coefficient, and subtract it from the channel record. We evaluate the common-mode noise removal algorithm using a segment of offshore channels of the RAPID dataset (Wilcock & Ocean Observatories Initiative, 2023; Fig. 2a). The processing effectively mitigates the common-mode noise (Fig. 5d-e).

The inherent stochastic noise in DAS data is primarily caused by instrumental deficiencies such as sampling error and phase noise (Costa et al., 2019). The fast discrete curvelet transform (FDCT) (E. Candès et al., 2006; E. J. Candès & Donoho, 2004) is used to obtain an effective non-adaptive sparse representation of the regular-spaced DAS seismic data and remove stochastic noise (Atterholt, Zhan, Shen, et al., 2022). The basis functions of curvelet transform are defined as polar wedges in the FK domain and represent the object position, scale, and angle. The curvelet denoising function uses a silent DAS recording to estimate stochastic noise. After FDCT, the amplitude of the curvelet coefficients is used as an empirical threshold. By default, DASPy employs a soft threshold to remove stochastic noise in the curvelet domain. We apply curvelet denoising to the spike-removed waveform of Stanford-1 DAS (Biondi et al., 2017; Martin et al., 2017; Fig. 2b and Fig. 5b), resulting in a notable reduction in stochastic noise before the arrival of P waves (Fig. 5c).

Coherent noise can be defined as any coherent signal that are not of interest. For example, for studies on an earthquake, a traffic signal is coherent noise; for studies on traffic footprints, an earthquake signal is coherent noise. Coherent noise can be removed by applying velocity screening in either the curvelet transform or the FK transform. In this case, coherent noise removal is treated as wavefield decomposition based on apparent velocity, which will be elaborated upon in the subsequent section.

3.3 Wavefield decomposition

Image processing techniques, such as the 2D Fast Fourier Transform (e.g., FK transform in DAS data processing) and FDCT, have been widely used in the decomposition of 2D DAS wavefields, such as the separation of seismic signals and traffic noise and the separation of direct seismic waves and locally scattered seismic waves (Atterholt, Zhan, Shen, et al., 2022; Williams et al., 2022). DASPy integrates the FK filtering and curvelet windowing techniques in the decomposition module.

Each point within the FK domain corresponds to a specific apparent velocity. In wavefield decomposition, the FK filter method employs a velocity threshold for separation, followed by an inverse transform to produce low-speed and high-speed waveforms. Analogously, the curvelet basis utilized by the curvelet transform are wedges on the FK domain, with specific velocity ranges. The curvelet window technique separates the curvelet coefficients of the curvelet basis with different velocities. Therefore, the effects of these two techniques are nearly identical, which can be clearly determined in the FK domain of the separated waveforms. Both wavefield decomposition techniques are evaluated on stripping traffic noise from seismic waveform from the Ridgecrest DAS array (Z. Li et al., 2021; Fig. 2d). The results show that both techniques effectively enhance the signal-to-noise ratio without significant difference (Fig. 6).

3.4 Conversion to ground motions

DAS measures strain or strain rate, in contrast to ground-motion velocity and displacement used in typical seismology studies. Strain and strain rate can be converted to particle velocity and acceleration by multiplying apparent phase velocity. The difficulty of such conversion lies in the accurate estimation of apparent phase velocity of every wiggle. DASPy integrates three methodologies for converting strain/strain rate into ground-motion velocity: FK rescaling (Lindsey, Rademacher, et al., 2020), curvelet transform (Yang, Atterholt, et al., 2022), and time-domain slowness determination (Lior et al., 2021). The FK rescaling method is implemented by multiplying each point in the FK domain by its corresponding apparent velocity (slop in the FK domain). Similarly, the basis functions of the curvelet transform, which are defined in the FK domain, also correspond to varying velocity ranges. The curvelet transform conversion method multiplies each curvelet coefficient by the median velocity of its basis function. The coefficients of the largest scale basis functions, which represents waves with all velocity ($-\infty$ to $+\infty$), is set to zero. The time-domain slowness determination method obtains the apparent velocity at each time step by searching for the maximal semblance.

These three methods are tested using an M_L 4.3 earthquake recorded by a co-located DAS and seismometer array in the Brady Hot Springs (University of Wisconsin, 2016b; University of Wisconsin, 2016c; https://gdr.openei.org/submissions/848; https://gdr.openei.org/submissions/846; Fig. 3c), following H. F. Wang et al. (2018). We define a nodal geophone and a DAS channel whose distance is less than 5 m as a geophone-channel pair. Among 238 geophones and 8,621 DAS channels, we match a total of 344 geophone-channel pairs. For each geophone-channel pair, we find the corresponding linear DAS segment (Fig. 2c) and rotate the three-component geophone recording to the axial fiber direction. The original DAS strain rate recordings are integrated to strain in the time domain, and converted to velocity using FK rescaling, curvelet transform and time-domain slowness determination methods respectively (Fig. 7). We correct the DAS data timing (-1.048 s) using the GPS timing of nodal seismometers, and cross-correlate the waveforms of each geophone-channel pair with time shift less than ±0.01 seconds. All waveforms are bandpass filtered to 1-5 Hz.

We evaluate the cross-correlation coefficient between the converted DAS velocity and the rotated geophone velocity. For all 344 geophone-channel pairs, 104, 71 and 0 pairs obtain cross-correlation coefficients greater than 0.7 after FK rescaling, curvelet transformation and time-domain slowness determination, respectively. For this particular case, the curvelet transform and the time-domain slowness determination have limitations. Most linear segments consist of about 100 channels, which is not quite enough for curvelet transform at larger scales. The largest scale curvelet coefficients, which are set to zero, miss more details, resulting in smaller amplitudes of the converted waveforms (Fig. 7). As for time-domain slowness determination methods, the assumption of monochromatic wavefields makes it difficult to recover the complex shallow surface scattered waves and earthquake coda waves.

4 Discussion and Conclusions

DASPy aims to offer a user-friendly, integrated Python toolkit that facilitates the analysis and processing of DAS data. Overall, the toolkit includes "basic tools" of preprocessing, filtering, spectrum analysis, and visualization techniques and "advanced tools" of channel attribute analysis, noise removal, wavefield decomposition, and strain-velocity conversion.

DASPy can read and write a variety of DAS file formats, including .h5, .segy/.sgy, .tdms and .pkl (used for storing `daspy.Section` instances). These formats are often required by other open-source software. For example, PhaseNet-DAS (W. Zhu et al., 2023) take input in .h5 or .segy format. DASPy also supports reading DAS-RCN format as a `daspy.Section` instance which inherits the attributes from source DAS-RCN files (Lai et al., 2024). One may note that DASCore supports more reading formats than DASPy. Also, ObsPy provides IO support for almost all traditional seismological formats, such as SAC and MiniSEED. Therefore, we provide methods (`Section.to_obspy_stream`, `Section.to_dascore_patch`, `Section.from_obspy_stream`, and `Section.from_dascore_patch`) for mutual transformation between `daspy.Section` instances and ObsPy's `Stream` instances (Beyreuther et al., 2010) and DASCore's `Patch` instances (Chambers et al., 2024). These conversion functions allow smooth data flow between ObsPy, DASCore and DASPy.

DASPy operates in the form of functions, which are designed to accommodate as many optional parameters as possible, and with sensible default values. All functions within DASPy are implemented as methods of the `daspy.Section` class. This approach is advantageous in that data attributes are stored within the class and avoid the need for manual entry. Calling functions and using methods of `daspy.Section` class are functionally equivalent, providing flexibility to suit users' needs.

Moreover, DASPy is currently programmed in pure Python for ease of use and modification but in some cases computational efficiency is compromised. Consequently, processing continuous data with a large number of channels and/or a high sampling rate could take a long time. As an example, downsampling a 30-second waveform recorded at 1000 Hz by a 10,000-channel DAS array takes 12.08 seconds. Therefore, we suggest that users consider implementing CPU parallelization when undertaking large tasks. Future development of DASPy could include exploring the potential of shared libraries to replace computationally intensive functions.

With aforementioned designs, DASPy can be easily incorporated into the data up- and down-stream tasks. The following is an example code snippet that combines DASPy and ObsPy (Beyreuther et al., 2010), for a typical task phase picking in earthquake monitoring:

```
>>> from daspy import read
>>> from obspy.signal.trigger import classic_sta_lta, trigger_onset
>>>
>>> sec = (
>>>     read('raw_data.h5')
>>>     .spike_removal()
>>>     .downsampling(xint=10, tint=10)
>>>     .fk_filter(fmin=1, fmax=15, vmin=2000)
>>> )
>>> sec.plot()
>>> sec.save('preprocessed_data.h5')
>>> onsets = []
>>> for d in sec.data:
>>>     cft = classic_sta_lta(d, nsta=int(0.5*sec.fs), nlta=int(5*sec.fs))
>>>     onsets.append(trigger_onset(cft, thres1=5, thres2=4))
```

The code reads in DAS data into an instance of `daspy.Section`, removes spike noise, performs a tenfold downsampling in both distance dimension (stacking every 10 channels into one) and time dimension (after an automatic lowpass filter), separates signal with frequency of 1-15Hz and apparent velocity less than 2000 m/s using FK filter. Subsequently, the preprocessed data is visualized, saved and fed into ObsPy to compute the short-term average/long-term average (STA/LTA; Allen & Rex, 1982) and to generate triggered picks.

As shown in the previous example, we envision that users can take advantage of DASPy to develop advanced packages developing new functions and/or modules (such as earthquake monitoring, ambient noise imaging, and traffic detection algorithms). We welcome users to contribute to the improvement and expansion of the DASPy project. Also, to foster a community of compatible packages, we add instructions for potential developers about how to contribute to the DASPy platform (https://github.com/HMZ-03/DASPy/blob/main/CONTRIBUTING.md). Developers are recommended to fork the DASPy repository on Github (https://github.com/HMZ-03/DASPy/) and submit their modifications and additions through pull requests.

Data and Resources

The RAPID dataset is openly available at http://piweb.ooirsn.uw.edu/das/. The traffic signals recorded by the Ridgecrest DAS can be downloaded from https://data.caltech.edu/records/31emd-wmv98. The Stanford DAS-1 dataset from PubDAS is accessible via the link https://app.globus.org/file-manager?origin_id=706e304c-5def-11ec-9b5c-f9dfb1abb183&origin_path=%2F. The earthquake waveforms recorded by Brady's Geothermal Field DAS and seismometer array are available at https://gdr.openei.org/submissions/848 and https://gdr.openei.org/submissions/846. The DASPy python package is open source and available at https://github.com/HMZ-03/DASPy/. We include tutorials in both English and Chinese (https://daspy-tutorial.readthedocs.io/en/latest/, https://daspy-tutorial-cn.readthedocs.io/zh-cn/latest/) and a Jupyter notebook for quick use (https://github.com/HMZ-03/DASPy/blob/main/document/example.ipynb). All websites were last accessed in June 2024.

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Declaration of Competing Interests

The authors acknowledge there are no conflicts of interest recorded.

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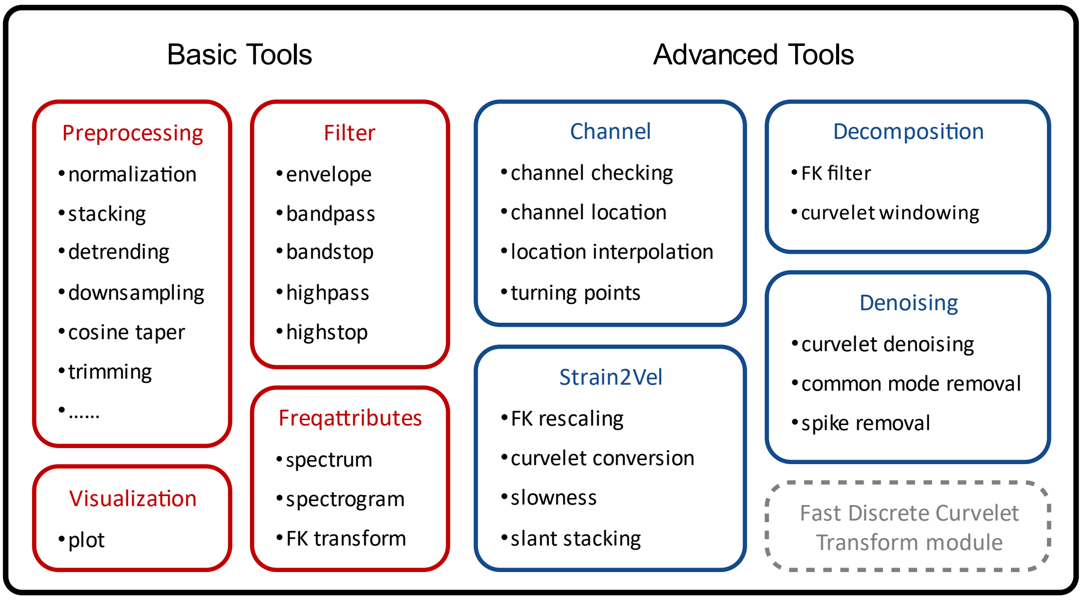

Figure 1. Main structure of DASPy toolbox. Each block indicates a module composed of multiple user-facing functions. The modules for basic tools are shown in red boxes, and modules for advanced tools are shown in blue boxes. The module within the gray dotted box is specifically built for discrete fast curvelet transforms.

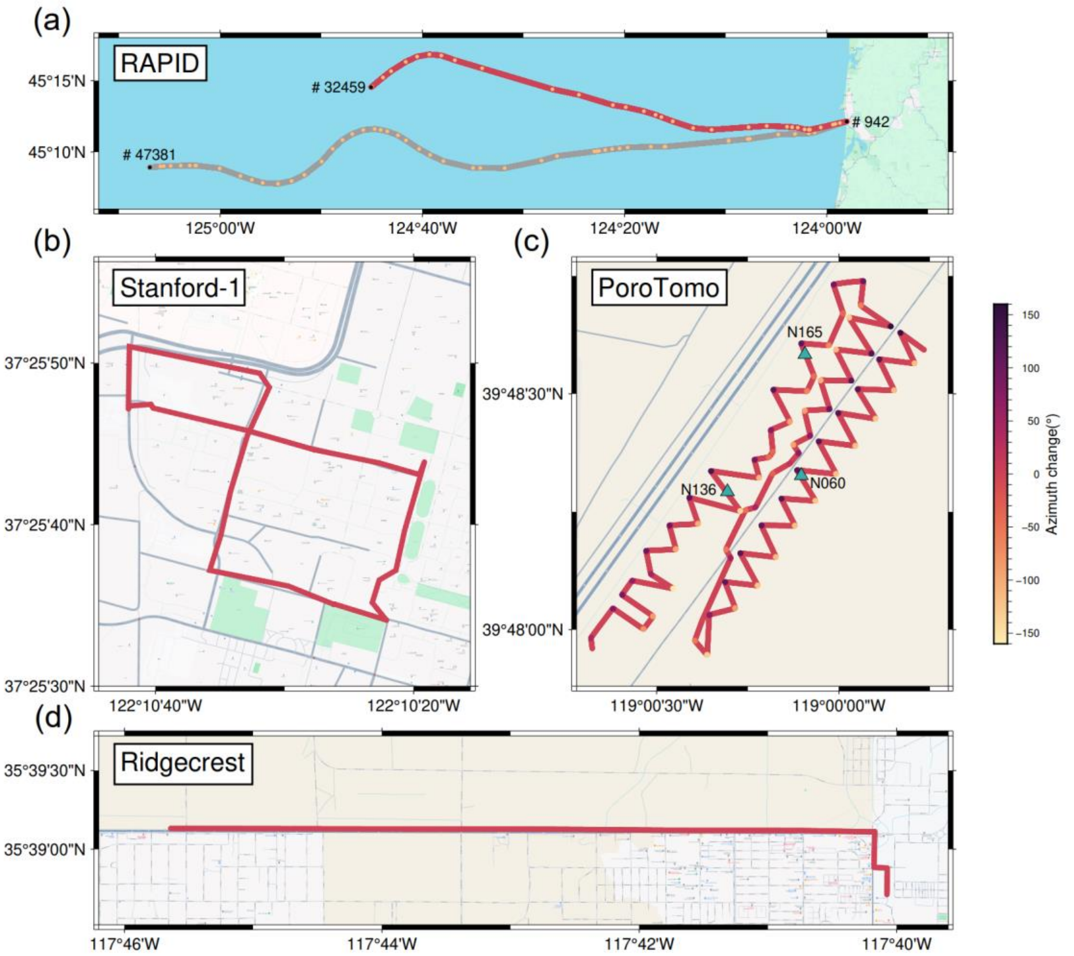

Figure 2. Geometry of DAS arrays whose data we used for testing. (a) RAPID DAS arrays that land at Pacific City, Oregon (Wilcock & Ocean Observatories Initiative., 2023). The red line indicates the array that we utilized for our test (referring to the north cable here), which is the same for (b) and (d). The grey line indicates the south cable, whose data are not used. The black dots represent three points along the cable with known coordinates and channel numbers, while the orange dots represent the those with known coordinates but unknown channel number. (b) Stanford campus array in California (Biondi et al., 2017; Martin et al., 2017). (c) Brady's geothermal field DAS array (University of Wisconsin, 2016b) and three co-located geophone stations

(University of Wisconsin, 2016c) in Nevada. The color of the DAS cable indicates the azimuth change of the cable before and after the corresponding channel. (d) DAS arrays started after the 2019 M_w7.1 Ridgecrest earthquake, California (Atterholt, Zhan, Shen, et al., 2022; Z. Li et al., 2021).

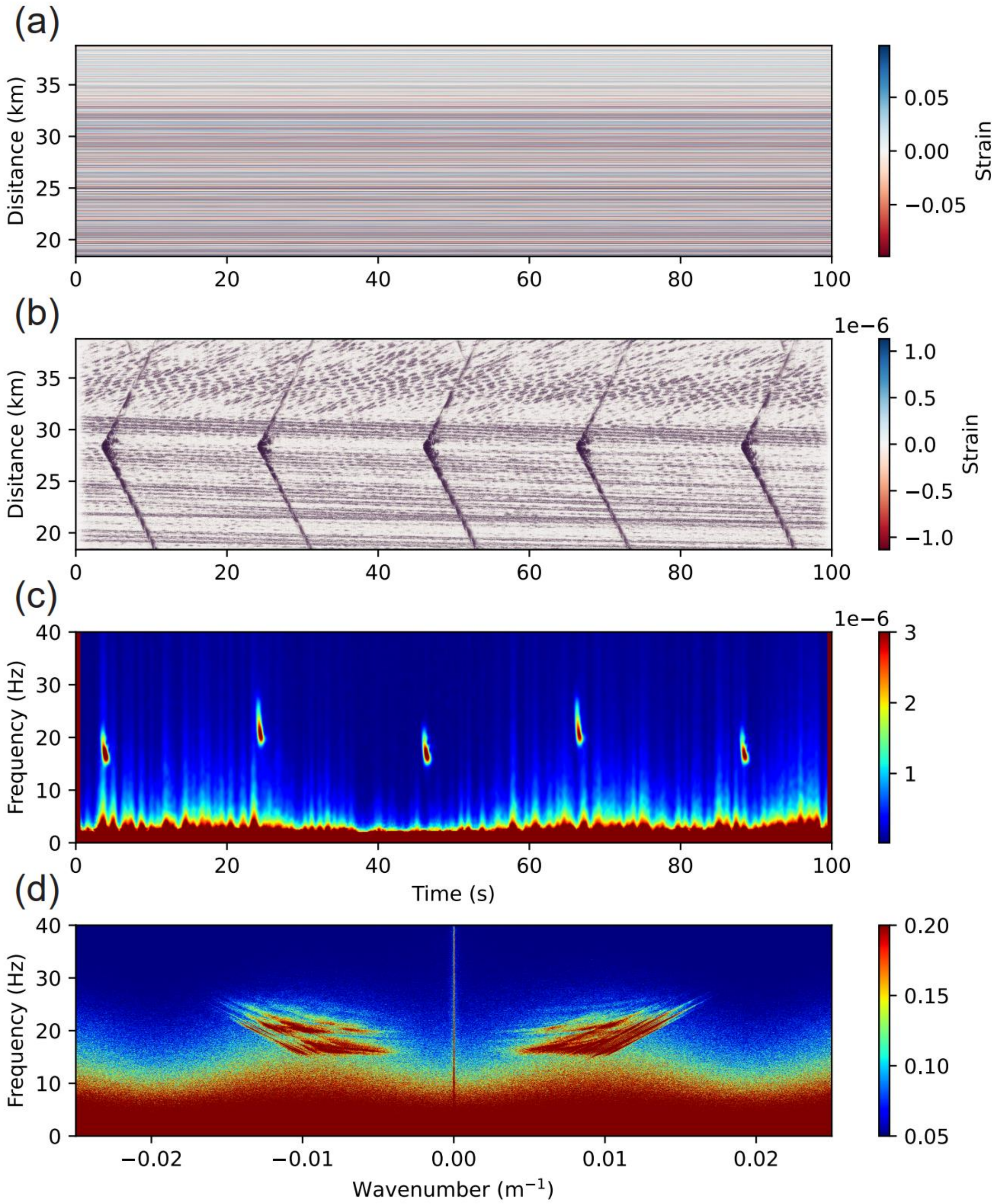

Figure 3. Demonstration of signal processing and visualization. (a) Original strain recording for 100 seconds beginning on November 4, 2021, 01:59:02 UT, recorded by the Optasense interrogator channel 9000-19000 on north ocean-bottom cable from RAPID dataset (Wilcock & Ocean Observatories Initiative., 2023). (b) Filter to 15-27 Hz, following Wilcock et al. (2023). (c) Spectrogram averaged over 100 channels. (d) FK spectrum calculated from 2D fast Fourier transform.

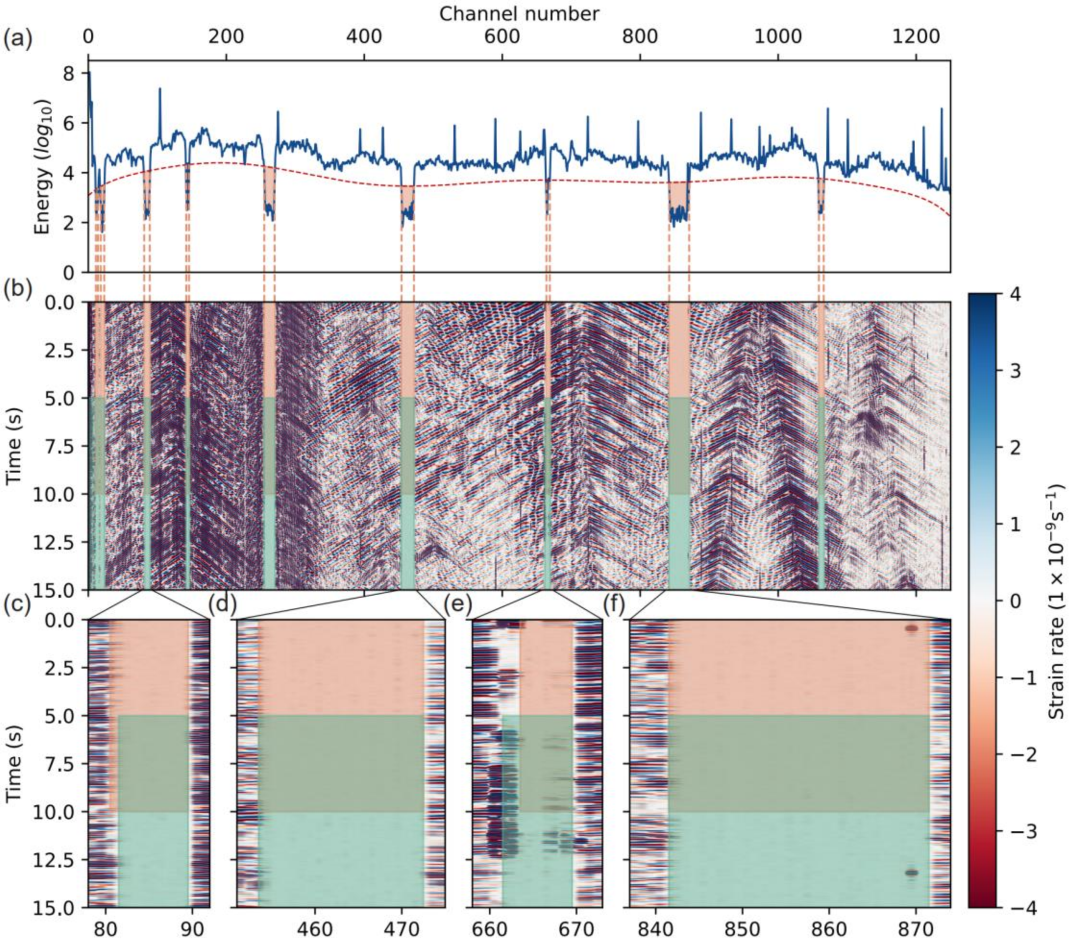

Figure 4. Bad channel detection of the DAS array near Ridgecrest, CA. (a) Energy curve (blue line) and thresholds (red dotted line) for bad channel detection. (b) DAS recording of 15-second traffic noise (Atterholt, 2021) used for bad channel detection. Orange areas indicate bad channels detected by our function, while green areas are bad channels picked by Atterholt, Zhan, Shen, et al. (2022). (c)-(f) Zoom-in plot of four parts of the DAS recording. Channel 81 (c) and channels 662&663 (e) are identified differently by our function and Atterholt, Zhan, Shen, et al. (2022).

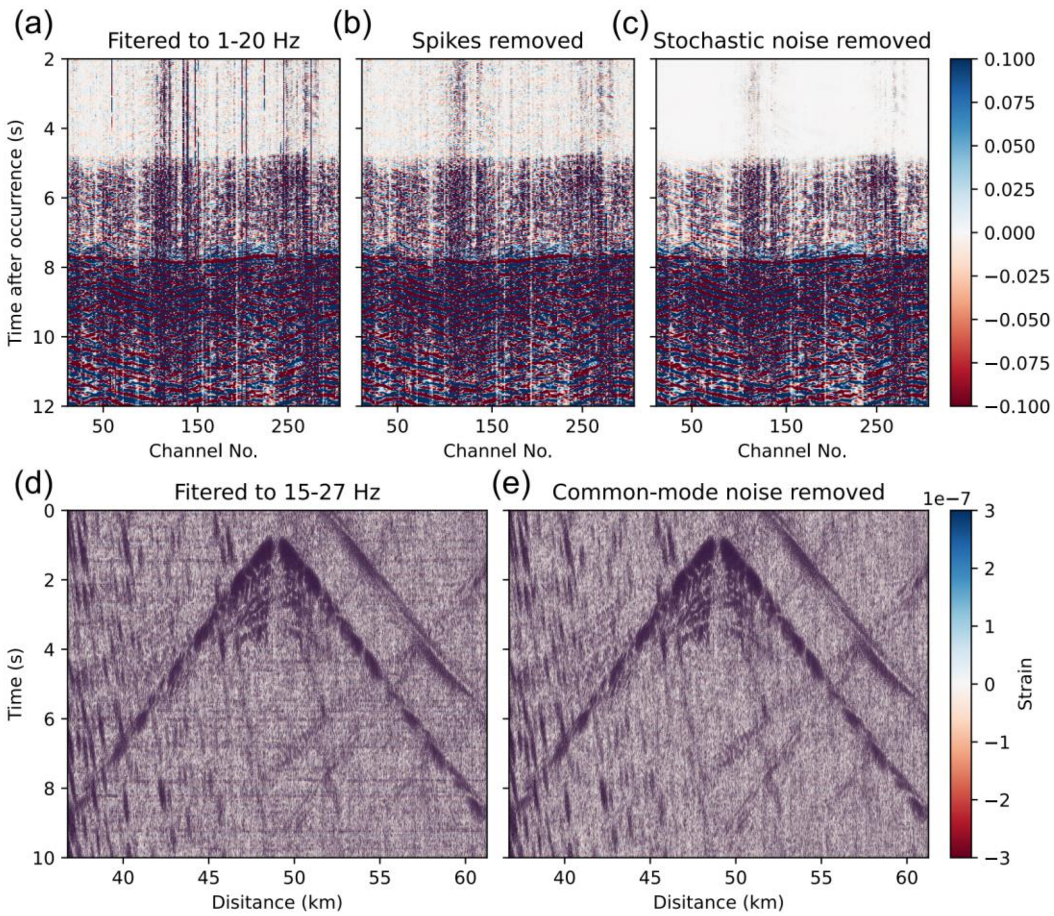

Figure 5. Cases of wavefield denoising. (a) Waveforms of an M_D 2.8 earthquake (https://earthquake.usgs.gov/earthquakes/eventpage/nc73940346/executive) recorded by Stanford-1 DAS array (Biondi et al., 2017; Martin et al., 2017). Bad channels are removed and bandpass filter to 1-20 Hz. (b) Waveforms with spikes removed based on (a). (c) Waveforms with stochastic noise removed by curvelet transform based on (b). (d) Strain recording filtered to 15 to 27 Hz for 10 seconds beginning on November 4, 2021, 01:59:22 UT, recorded by the Optasense interrogator on north ocean-bottom cable from RAPID dataset (Wilcock & Ocean Observatories Initiative., 2023). (e) Waveforms with common-mode noise removed based on (d).

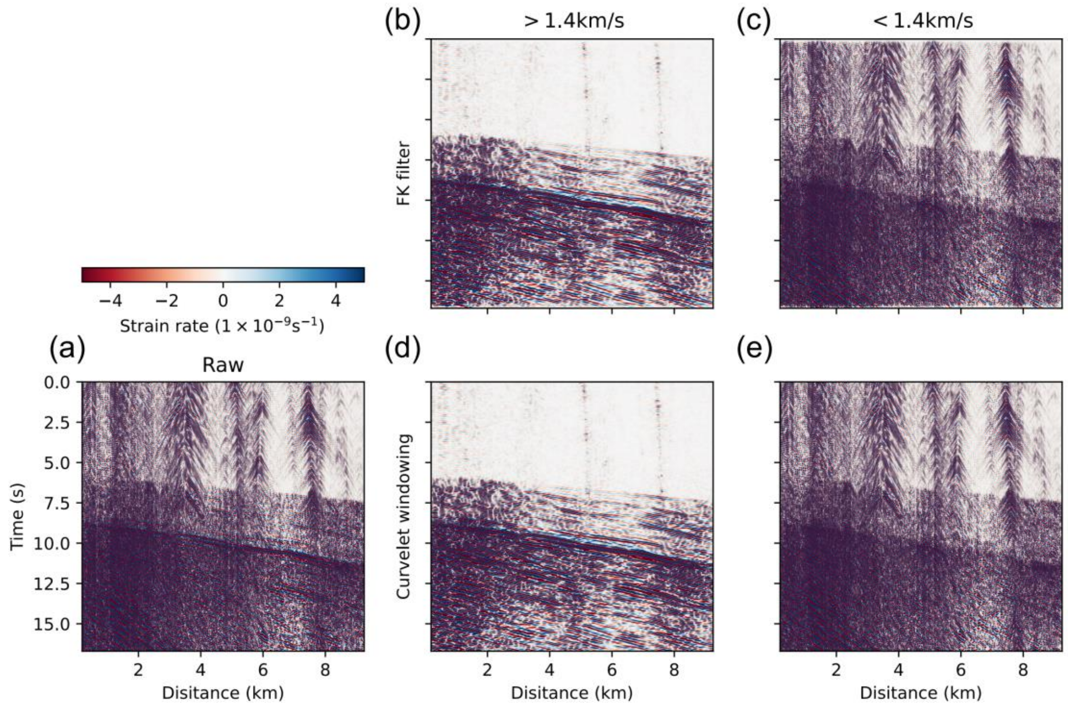

Figure 6. An example of wavefield decomposition. (a) Waveforms of an M_L 2.6 earthquake (https://earthquake.usgs.gov/earthquakes/eventpage/ci38972328/executive) recorded by Ridgecrest DAS array (Z. Li et al., 2021), with spikes removed. (b) Waveforms with an FK filter to retain energy with an apparent velocity >1.4 km/s (cosine tapered from 1.2–1.6 km/s). (c) Waveforms with an FK filter to retain energy with an apparent velocity <1.4 km/s (cosine tapered from 1.2–1.6 km/s). (d) Waveforms with curvelet windowing to retain energy with an apparent velocity >1.4 km/s. (e) Waveforms with curvelet windowing to retain energy with an apparent velocity <1.4 km/s.

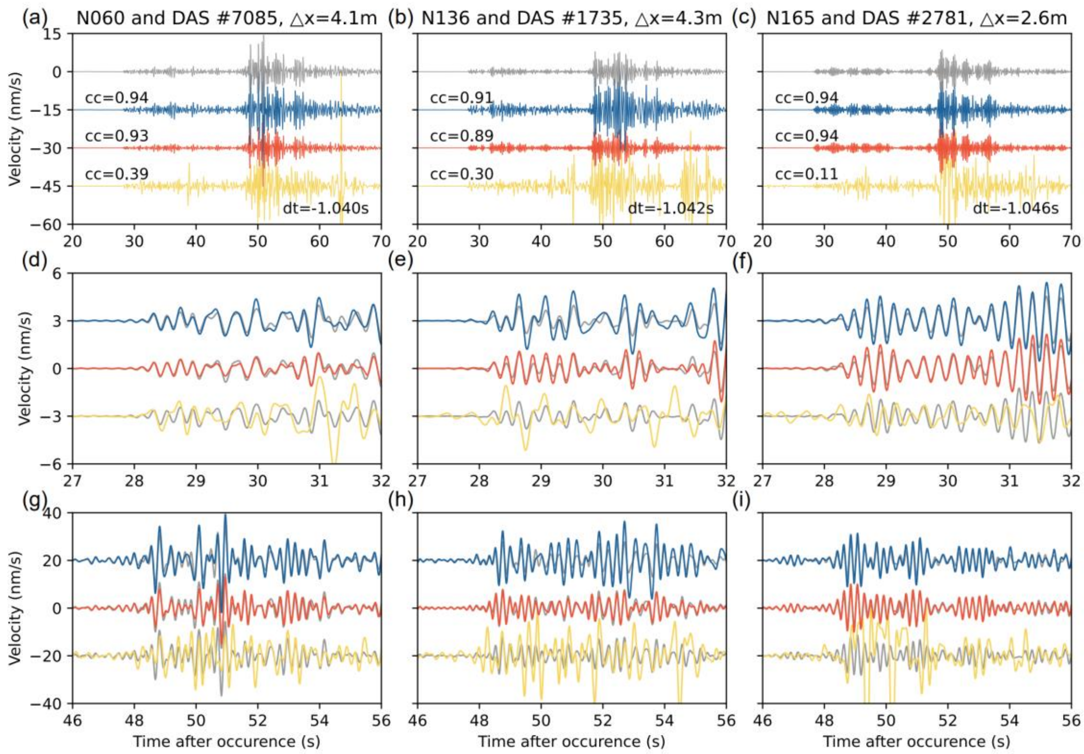

Figure 7. Conversion from strain to velocity by three methods of M_L 4.3 Hawthorne earthquake (https://earthquake.usgs.gov/earthquakes/eventpage/nn00536374) recorded by Brady's geothermal field DAS array. (a)-(c) Rotated geophone velocity (grey), and velocity converted from integrated DAS strain by FK-rescaling (blue), curvelet transform (red) and time-domain slowness determination (yellow), same as below. All waveforms are bandpass filtered to 1-5 Hz. (d)-(f) Zoom-in window for P arrival of (a)-(c). (g)-(i) Zoom-in window for S arrival of (a)-(c).