Techniques to compare and cross-calibrate DAS and seismometer data

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Abstract

DAS provides high-resolution imaging, but amplitude information is typically lacking or uncalibrated, so earthquake magnitudes cannot be accurately calculated from DAS alone. DAS sensitivity to ground motion is not constant, but varies with several factors including frequency, directions of wave propagation and polarization, and coupling factor of the fiber to the ground. Also different units of strain, strain rate, or optical phase for DAS, versus velocity or acceleration for conventional sensors make it difficult to compare specifications and model the expected performance.

This study describes how DAS strain data can be converted to equivalent seismic velocity as measured by seismometers, and presents a model of expected noise for DAS. We define key locations for deployment of seismometers on and around a DAS line, in order to cross-calibrate DAS signal amplitudes, complement the measurement of wave modes where DAS sensitivity is minimal, and optimize earthquake source location and magnitude accuracy.

Seismic signals as measured by DAS vs. Seismometers

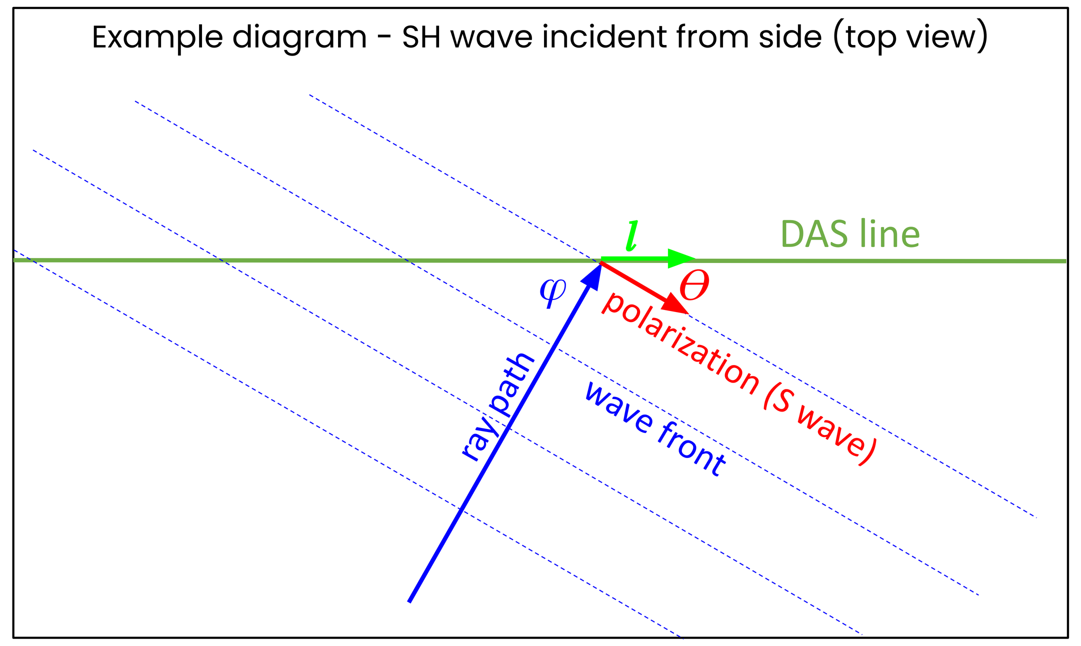
A seismometer directly measures particle velocity $\boldsymbol{v} = \boldsymbol{A}e^{i(kr-\omega t)}$ (1)

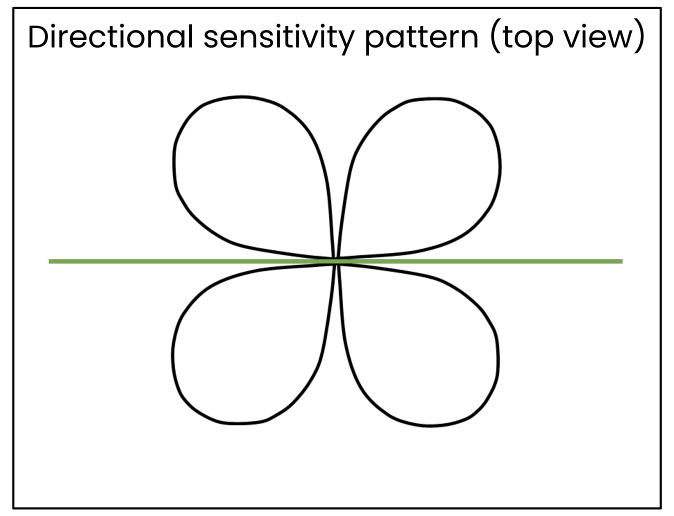
The associated ground strain rate is $\dot{\boldsymbol{\varepsilon}} = \frac{d\boldsymbol{v}}{dr} = ik\boldsymbol{v} = \frac{i\omega}{V}\boldsymbol{v}$ (2)

which produces strain rate of a DAS line $\dot{\varepsilon}_{DAS} = C\frac{d(\boldsymbol{v}\cdot\boldsymbol{l})}{dl} = C\frac{i\omega}{V}A\cos\theta\cos\varphi$ (3)

where $\boldsymbol{l}$ is the local line direction vector,
C is the ground coupling factor (ranging from 0 to 1),
V is the wave velocity,
θ is the angle of wave polarization with respect to the line, and
φ is the angle of wave propagation with respect to the line.

(Note some DAS instruments output strain, whereas others output strain rate.)





DAS amplitude is highly variable, depending on:

- Ground coupling factor, which varies widely depending on installation method - low for cable on surface or in conduit, moderate for direct burial in sediment, high when cemented into rock
- Wave velocity, specifically phase velocity along the line $V/\cos\varphi$
- Wave polarization with respect to the line
- Frequency, for a strain rate signal. However, strain is proportional to particle velocity.

This variability makes magnitude estimation problematic, and some wave modes may not be measurable (at least on some sections of the DAS line), depending on the source-to-line geometry.

DAS signal can be compared with nearby seismometers to calibrate amplitudes and fill in all wave modes.

DAS noise from SEAFOM test

SEAFOM Fiber Optic Monitoring Group

"SEAFOM™ is an international Joint Industry Forum aimed at promoting the growth of fiber optic monitoring system installations in the upstream oil and gas industry."
- SEAFOM website https://seafom.com/

SEAFOM has defined a standard test procedure MSP-02 for DAS equipment. Results for specific instruments are available from manufacturers.

Below is a copy of Figure 3 from MSP-02 V2.0 showing a representative example of a DAS noise test (figure is cropped to show only strain noise not optical phase).

Note that noise on a 50 km fiber (plot b) is much higher (20 to 70 dB more) than noise on a 5 km fiber (plot a). Furthermore, noise at the 5 km position on the 50 km fiber is higher than at the end of the 5 km fiber, meaning overall fiber length matters, as well as distance from the interrogator.

This is a per-channel (gauge length) noise result.
If N channels are averaged together in processing, noise is reduced by $\sqrt{N}$.

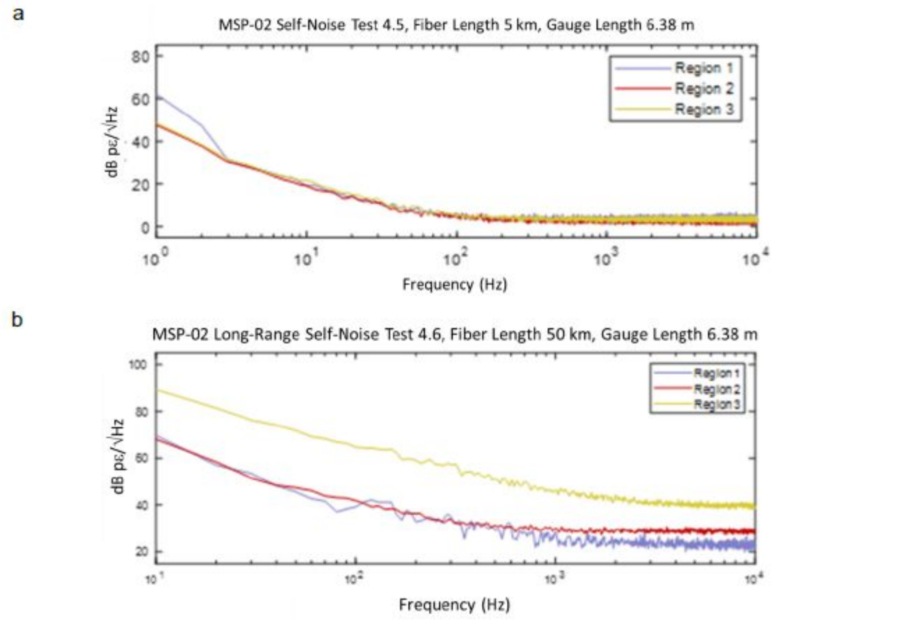


Figure 3: Typical DAS amplitude spectral density curves (simulated SEAFOM Self-Noise tests 4.5 and 4.6) expressed in ~~both decibel radians and~~ decibel pico-strain (pε) per root-Hertz. a: 5 km fiber; regions 1-3 = 0-1, 2-3, 4-5 km. b: 50 km fiber; regions 1-3 = 0-5, 22.5-27.5, 45-50 km. Gauge length 6.38 m in each case

Converting DAS strain noise to equivalent acceleration

DAS noise in picostrain/√Hz can be converted to equivalent acceleration noise in units of m/s^2/√Hz, based on equation (3) with channel averaging

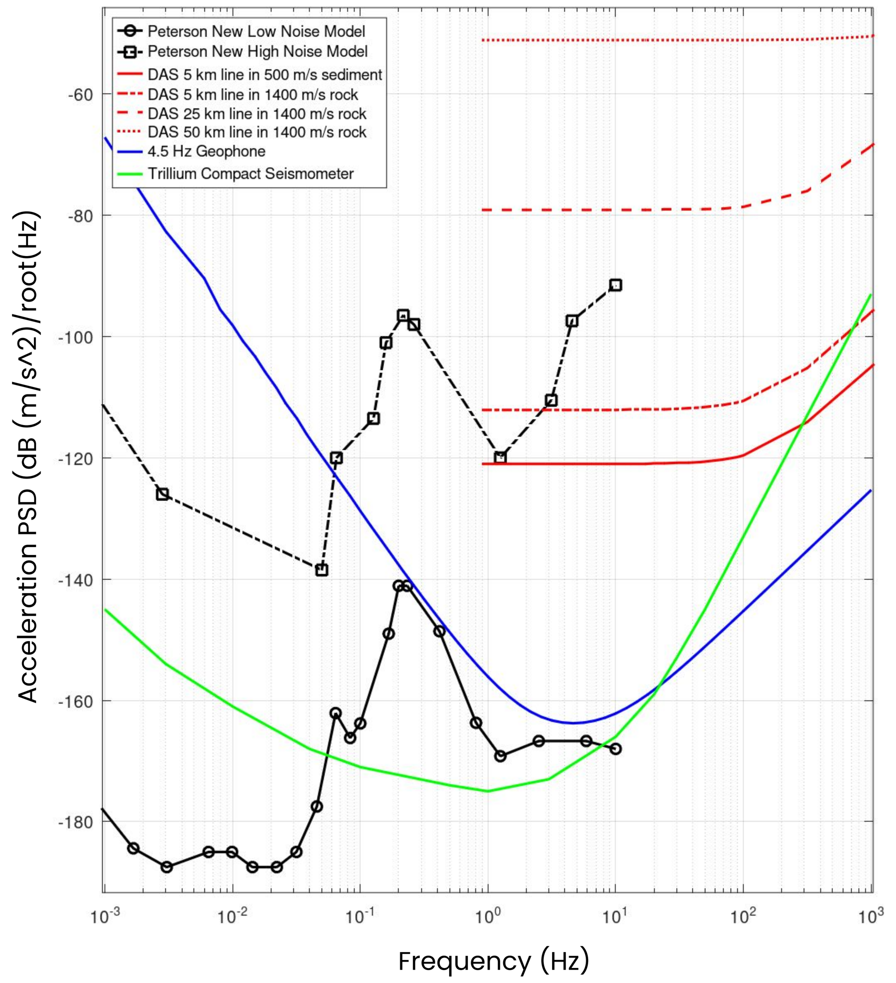
$$a_n = \frac{i\omega V}{\sqrt{N}\cdot C\cos\theta\cos\varphi}\cdot\varepsilon_n \quad (4)$$

For this calculation, since the raw strain data was not available, the strain noise curves in Figure 3 were fitted based on a 1/f + white noise model.

Also, since the conversion from strain to acceleration depends on factors external to the instrument (wave velocity, direction, etc.), the acceleration noise level is not a constant for the instrument in the same way as for an inertial sensor, and we must pick appropriate values for these external parameters.

The plot below shows examples of DAS noise from Figure 3 converted to equivalent acceleration, for the following parameter values:

- N = 10 gauge lengths averaged
- C = 50% coupling
- $\theta = \varphi$ = 45 degrees
- V = 500 m/s for near-surface sediment (solid red line) or 1400 m/s for sedimentary rock (other red lines)



Conclusions

Based on the SEAFOM test results, DAS noise varies dramatically with cable length:

- The highest noise was measured at 50 km (dotted red line).
- Noise at 25 km on a 50 km cable (dashed red line) was still well above the Peterson high noise model.
- Noise on a 5 km cable was lower, more comparable to background signal levels but still well above a geophone (blue) or seismometer (green).

Noise varies depending on other parameters such as the velocity of the medium. For a 5 km line on 500 m/s sediment (solid red line), equivalent acceleration noise is 10 dB lower than the same line on 1400 m/s rock (dash-dot red line). Note this refers to instrument self-noise not background signal, which would likely be higher in sediment.

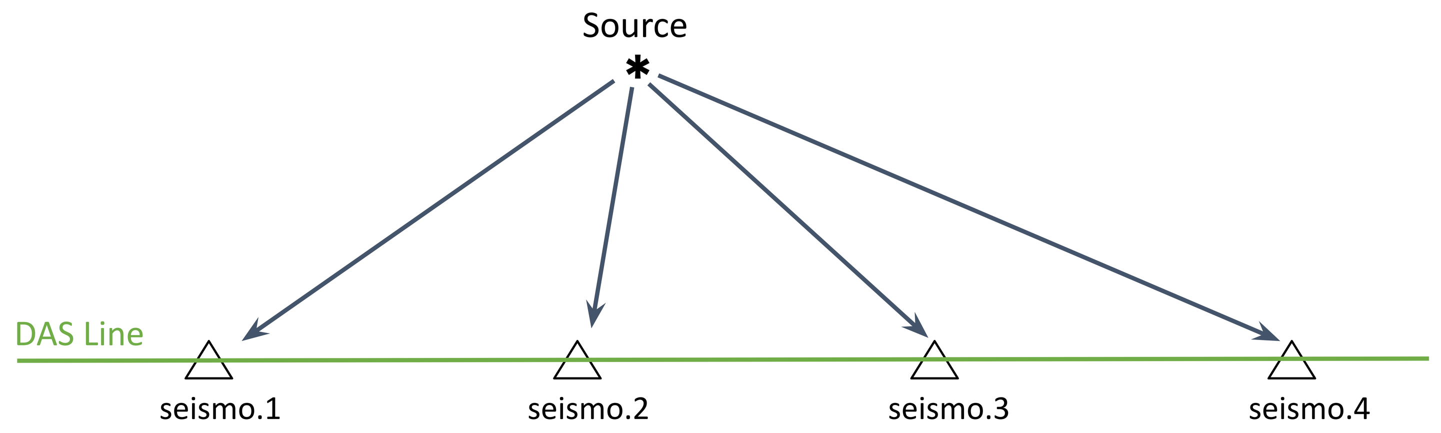
Noise will also vary with values of other external parameters (not shown), increasing for lower C or higher θ or φ.

Recommendations for cross-calibration and array infill

DAS sensitivity and signal-to-noise ratio vary with external variables, as discussed. To mitigate this, seismometers can be

1. co-located at points on the DAS line to calibrate sensitivity (as in Boullenger, 2025) and
2. stationed at points off the DAS line to fill in the wave field and avoid "blind spots" (as in Nayak, 2023)

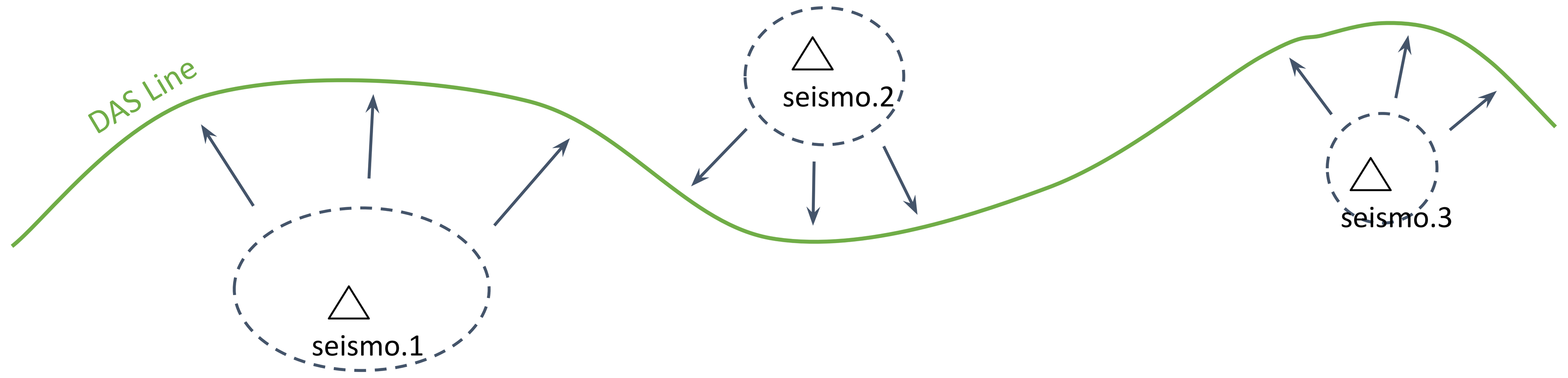
Ideally seismometers would be stationed along the DAS line at intervals similar to the expected distance of signal sources from the line, as shown below. This way when the propagation angle φ and polarization angle θ change significantly with distance along the line, amplitudes can be re-calibrated against the next seismometer station.



When equipment is limited, there is a benefit in deploying even a single seismometer on a DAS line to calibrate the DAS at one point. Then for a signal source at a known location, the expected relative amplitudes at other points on the line can be calculated based on geometrical factors. Variation in coupling factor along the line can be corrected (at least approximately) based on the difference between this expected amplitude and the actual amplitudes measured.

Another effect unique to DAS is low sensitivity to signal in certain directions, particularly to waves propagating perpendicular to the line. When the wavefront is parallel to the line, the gradient of displacement goes to zero so there is no strain signal. This corresponds to the cosφ term in equation (3) going to zero when φ = 90°.

For a straight DAS line as shown above, the source would not be detected at the closest point on the line, but would be detected at other points where the propagation angle is more favorable. However a curved line can have low sensitivity at many points for signal originating in areas near the center of curvature, as shown below. These "blind spots" can be filled in with a seismometer to provide a better magnitude of completeness.



Note also, waves from a distant source propagating near-vertically upwards will not be detected by a horizontal DAS line. Seismometers located anywhere near the DAS line can be used to capture this signal.

References

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