

Measuring rock strain with distributed acoustic sensing (DAS) and cemented patch cables

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Accepted 2026 September 30. Received 2026 September 29; in original form 2026 March 26

SUMMARY

A rigid connection between the optical fiber and the rock allows to properly measure ‘rock strain’ with distributed acoustic sensing (DAS). We demonstrate this by running four interrogator units (IU) on a testbed with single-fiber patch cables being cemented into a groove in the concrete floor of Black Forest Observatory (BFO). The recorded signals are compared with the recordings of a calibrated Invar wire strainmeter array that has been continuously in operation for the last decades at a distance of about 350 m to the testbed. In this way, we compare the ‘fiber strain’ against ‘rock strain’ at frequencies below 0.2 Hz. We investigate this on the background of a previous study with DAS cables unreel on the floor and loaded down by sand and sandbags, where we found a significant loss of strain amplitude between rock and fiber. Waveform similarity for strong earthquake signals is high with typical values of the normalized correlation coefficient greater than 0.95. The strain amplitude measured by all four IUs is very consistent and by about 10 per cent larger than the strain measured by the strainmeters. We attribute this minor discrepancy to spatially varying strain–strain coupling caused by the local topography. At frequencies up to 14 Hz we make an intercomparison of IUs, showing no significant variation with frequency. The scatter of strain amplitude in between channels which are spatially near to each other in the same fiber route is about ± 10 per cent in most cases. The variation of median values in between different IUs and earthquakes is less than 5 per cent. By subtracting the common mode noise, which is coherent along the fiber route, we lower the background signal level to an rms amplitude of 100 pstrain at 0.1 Hz and 5 pstrain at 1 Hz in a bandwidth of 1/6 decade for the best cases. This allows the detection of the marine microseisms during times of moderate amplitude level.

Key words: Transient deformation; Distributed acoustic sensing; Seismic instruments.

1 INTRODUCTION

Distributed acoustic sensing (DAS) is one of many distributed fiber-optic sensing techniques by which the backscattered signal of a laser pulse sent down an optical fiber is used to measure the conditions (deformation and temperature) along the potentially many kilometres long fiber over intervals of a few metres or less. DAS, using coherent Rayleigh backscatter, as is common today, was developed in the early 1990s. Pioneering work was carried out by J.P. Dakin (1990), followed by H.F. Taylor & C.E. Lee (1993). A.H. Hartog (2017, his section 1.2.6) summarizes the progress made since the early days. Though the term most commonly found in literature is ‘DAS’, A.H. Hartog (2017) prefers the term distributed vibrational sensing as many applications focus on rapid variations in strain, commonly referred to as dynamic strain. For the same reason, in other contexts the term ‘distributed dynamic strain sensing’ is preferred (P. Jousset *et al.* 2025), which better expresses the quantity discussed in the current study. Fields of application (A.H. Hartog 2017, his chapter 9) include structural health monitoring and intruder detection, but also seismic applications. N.J. Lindsey & E.R. Martin (2021) and Y. Li *et al.* (2021) present an overview of fields of application in geosciences. M.F. Ghazali *et al.* (2024) address applications in civil engineering, but also fundamental considerations in setting up installations for meaningful measurements. Many different types of optical read-out techniques have been realized in the various types of DAS IUs (A.H. Hartog 2017, his section 6). M. Gonzalez-Herraez (2025) recently pointed out that more variants tailored to specific application areas would be conceivable but are unlikely to be developed for commercial purposes due to the limited size of the respective instrument markets.

The specific power of DAS lies in its ability to sample deformation signals along an optical fiber at hundreds or even thousands of locations over distances of many kilometres with a single interrogator unit (IU). In particular, if already deployed but unused telecommunication infrastructures (so-called dark fibers) can be used, this is very cost-efficient.

Although many applications rely only on the phase information in the recorded data, the IU also provides a quantitative measure of the deformation of the fiber, the ‘fiber strain’. The spatial derivative of displacement, namely strain, is very sensitive to structural heterogeneity (D. Emter & W. Zürn 1985), which, in combination with the unprecedented spatial density of the measurements, makes DAS a powerful tool for mapping subsurface structures such as fault zones at high resolution, as demonstrated, for example, by P. Jousset *et al.* (2018). DAS might also provide a spatially distributed measurement of volume strain, which leads to applications beyond the field of seismology. For example, with cables running in six appropriately chosen 3-D directions from a single location, the full strain tensor could be composed. From this, changes in mass density could be estimated to support the reduction of Newtonian noise (J. Harms 2015; J. Harms *et al.* 2022), an application being explored at the planned location of the proposed Einstein Telescope (ET Steering Committee 2020). However, the background noise in currently available DAS recordings might still be too strong for this specific application.

Such applications would hinge on the ‘fiber strain’ being equal to the actual rock deformation, the ‘rock strain’. T. Forbriger *et al.* (2025) recently showed in a comparison with an independent measurement of ‘rock strain’, that the ratio of ‘fiber strain’ to ‘rock strain’, the so-called ‘strain transfer rate’ is likely to be less than one. This presumably is due to elastic deformation within the fiber optic cable and because of imperfect coupling of the fiber to the cable jacket and of the cable jacket to the rock. This was also indicated by investigations of N.J. Lindsey *et al.* (2020) and P. Paitz *et al.* (2020) in comparison with seismometer data. T. Reinsch *et al.* (2017) made a quantitative estimation of ‘strain transfer rate’ based on the elastic properties of the different layers in the cable, based on the theoretical model by D. Li *et al.* (2006). Their results are summarized in more detail by T. Forbriger *et al.* (2025, their introduction).

T. Forbriger *et al.* (2025) used several fibers in a tunnel installation of two different types of cables, a standard telecommunication cable and a tight-buffered cable (dedicated by the manufacturer to DAS applications). Sections of these cables were loaded down by piled up sand and sandbags in order to improve the coupling to the rock. Although the waveform similarity of DAS signals compared with strainmeter signals was very high for large amplitude signals, the fibers did not pick up the full ‘rock strain’. The ‘strain transfer rate’ turned out to vary between 0.13 and 0.53, depending on the type of cable and installation, though no consistent effect of the sandbags could be identified.

C.C. Chien *et al.* (2025) calibrated the strain response of the onshore and offshore sections of dark fibers in a commercial telecommunication cable connecting two islands in Puget Sound, Washington, USA. They used a DAS interrogator (Sintela Onyx v1.0) on one of the fibers and an optical fiber strainmeter on another. Both turned out to provide highly consistent waveform data in terms of strain amplitude and phase. Waveform similarity with respect to strain simulated from a seismometer record is better for the onshore data (normalized correlation coefficient, NCC 0.88) than for the offshore data (NCC 0.48) (C.C. Chien *et al.* 2025, their fig. 7) for 0.01–0.1 Hz. However the ‘strain transfer rate’ turned out to be 0.23 only, a result which they attribute to imperfect coupling.

The current study investigates to which extent DAS (as a technology and with standard components) is able to record proper values of ‘rock strain’. For this purpose, we have cemented eight single fiber optic patch cables, composed by only the glass fiber (core and cladding), thin coating and tight buffer, in a 250 m long groove in the concrete floor of a tunnel in granite, so that the isolation of the fiber itself from the rock was minimal. Four different IUs were operated simultaneously on this testbed, to avoid interpretations based on a single, specific interrogator type. Data from nearby and calibrated Invar wire strainmeters are used to compare with what we consider to be ‘true’ ‘rock strain’. We measure waveform similarity, ‘strain transfer rate’, and the detection threshold (background noise level) in the frequency range from 20 mHz to 20 Hz.

2 DATA

2.1 Black Forest Observatory

The Black Forest Observatory (BFO) uses a former silver mine in the central Black Forest, Germany (D. Emter *et al.* 1994). Fig. 1 shows the part of the gallery and the installations used in the current study. The gallery is mostly horizontal and is excavated in granite (formation: ‘Triberger Granitmasse’), which is covered with Triassic sedimentary rocks (mainly ‘Red Sandstone’ and ‘Eck’s Conglomerate’). A cross-section is shown by D. Emter *et al.* (1994, their fig. 2). Overburden increases with distance to the tunnel entrance (the western end), is about 100 m at the ‘Anton Gang’ and reaches 170 m at the ‘strainmeter array’. The extent of the DAS testbed installation is marked by the ‘Splice Box West’ and the ‘Splice Box East’. We compare DAS data with recordings from the ‘strainmeter array’.

2.2 The testbed

For the testbed, a 10 mm wide and about 10–20 mm deep groove was cut into the concrete floor of the front part of the mine (see Fig. 2, left) over a distance of approximately 235 m. There we installed 0.9 mm thick patch cables, consisting of core, cladding, coating and

BFO (Black Forest Observatory)

Huddle-Test 2024

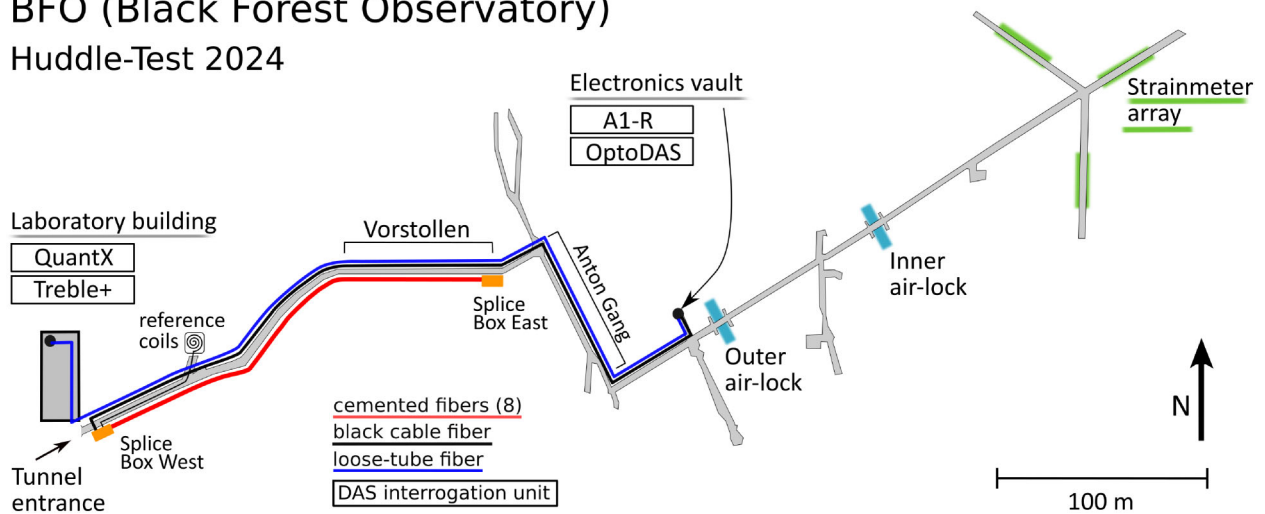
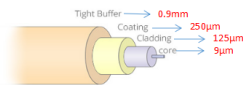


Figure 1. Floor map of the BFO. The part of the gallery used for the current experiment is shown. The entrance is at the western end of the tunnel. The overburden increases to the east and is about 170 m at the strainmeter array, which is used as a reference instrument in the current study. The eastern part hosts the majority of observatory instruments and is additionally protected by two air locks. They are discussed by B. Richter *et al.* (1995) and W. Zürn & E. Wielandt (2007), but have been substantially improved since then to act as a low-pass with a corner period of about 2 d. The DAS installation and the testbed with the cemented fibers in particular is located in the western part of the gallery. Details are shown in Fig. 4.



Figure 2. A 10 mm wide and 10–20 mm deep groove has been cut into the concrete floor of the front part of the gallery (see Fig. 1). Eight single-fiber patch cables, each of them being 0.9 mm thick (see Fig. 3), run in parallel in the groove. The groove has been filled with non-shrinking cement. The rightmost picture shows a cross-section of a preliminary test installation of 10 cables.

9 μm	Core
125 μm	Cladding
250 μm	Coating
900 μm	Tight buffer



print on reel:
 Fiber Patch Cable, 1000m
 Simplex 9/125 Single Mode 0.9 mm OFNR Cable
 P/N: FSSM PCW20231010070038-01
 www.fs.com

Figure 3. The structure of the single-fiber cable cemented into the groove. The cables are 0.9 mm thick. Eight of them run in parallel in the cemented groove as shown in Fig. 2. The tight buffer provides some protection against mechanical and chemical damage in the groove while still providing a tight strain coupling to the rock.

tight buffer only (see Fig. 3). In the following we refer to them as ‘fibers’, because they are not surrounded by a jacket with a strength member which would let them become ‘cables’. Eight of them were placed in the groove, which was then filled with non-swelling cement (‘PCI Repaflow[®]’ grout of shrinkage class ‘SKVM 1’ and ‘Modulus of elasticity’ specified as ≥ 40 GPa, sold by ‘PCI Augsburg GmbH’). To avoid curling of the fibers during installation they were manually tensioned with a force between 2 and 5 N. A cross-section of a test installation is shown in the rightmost panel of Fig. 2. The ends of these fibers are collected in two wall cabinets, which we call ‘Splice Box West’ and ‘Splice Box East’ (see Figs 1 and 4). The fibers are simply looped back in the ‘Splice Box East’ such that they are

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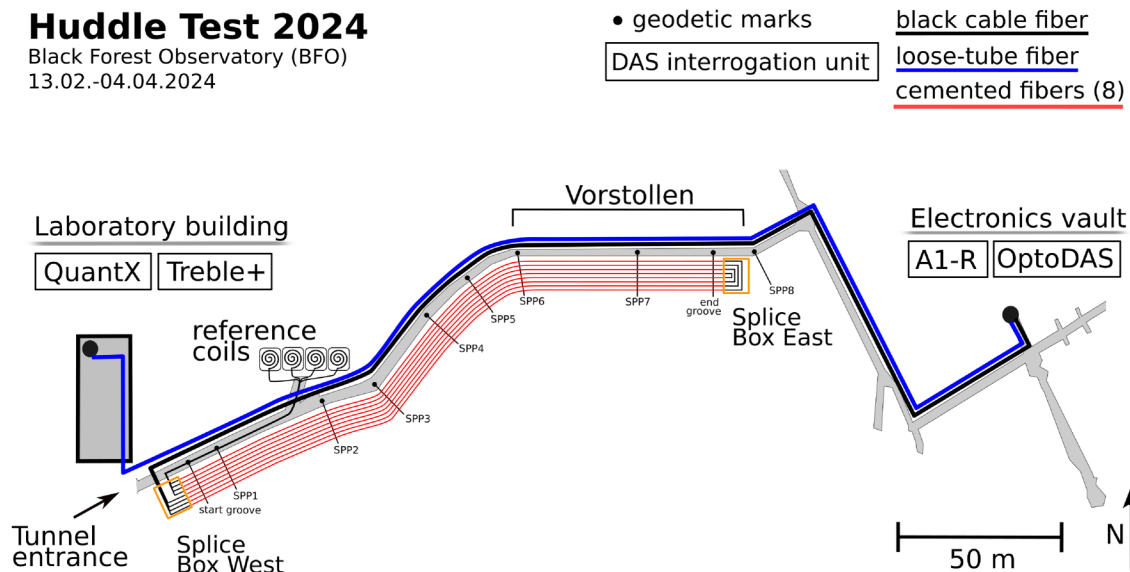


Figure 4. Detail of the floor map (Fig. 1) focusing on the DAS testbed. The eight lines along the section between ‘Splice Box West’ and ‘Splice Box East’ schematically indicate the path of the cemented fibers (see Fig. 2). SPP1–SPP8 are marked points within the gallery, to which the channel offsets are aligned in tap tests. The reference coils are decoupled from the rock, are located in a niche and protected against dripping water, but are not additionally shielded. Due to space constraints only two IUs (A1-R and OptoDAS) could be installed in the electronics vault. The other two units (QuantX and Treble+) were installed in the laboratory building. We analyse signals recorded in the straight section of the ‘Vorstollen’.

combined to four pairs. In the ‘Splice Box West’, each of the four IUs is connected to one of these pairs, where the opposite end of the pair is connected to one of four ‘reference coils’, which are placed in a niche along the gallery (see Fig. 4). Excess fiber ranging from 200 to 800 m in length (see table in the Supplementary Material) is wound onto standard cable drums with diameters between 10 and 15 cm. The longer these fiber sections the better, as this allows to take the average or median of more channels to capture the common mode noise signal. Fibers on the drums are sufficiently decoupled from the rock so that they do not pick up earthquake signals as is demonstrated by T. Forbriger *et al.* (2025, their figs S26 and S27). This is also confirmed by the NCC [see eq. (5) below] being in between 0 and 0.1 when comparing signals (after removing the common mode noise) in a channel on the reference coil with a channel in the groove (‘Vorstollen’) during the passage of an earthquake signal. At the very end of each fiber route, the fiber is wound tightly around a pen (actually a used felt-tip pen) of about 8 mm diameter for proper termination. Due to this small radius, the light penetrates the cladding and coating and decays away within a few centimetres such that no reflection from the end of the fiber takes place.

As the signals from reference coils are subtracted from the channel data (see the discussion of pre-processing below), it is essential to protect the coils from disturbances (e.g. dripping water), which otherwise would contaminate the analysed data. One might even consider to provide extra thermal insulation to these coils, which has not been done in the current experiment. We analyse DAS data which are predominantly recorded in a straight section, called ‘Vorstollen’ (Figs 1 and 4). This section is about 70 m long and runs along the azimuth N90°E.

The entire fiber route beginning at the IU and ending at the end of the reference coil appears to the IU as a long linear sensor. Channels are typically identified by their optical distance from the IU along the fiber route. The actual fiber is folded several times in the gallery such that the same point in the ‘Vorstollen’ is interrogated with two channels of each fiber route. In order to identify these channels, we excited signals at marked locations (SPP 1–SPP 7 in Fig. 4) by tapping on the floor (so-called ‘tap tests’) and then identifying these signals in the recorded data. The procedure and obtained accuracy is discussed in more detail in the Supplementary Material.

2.3 The interrogators

Four different IUs, listed in Table 1 were operated in parallel. Two of them, the ASN OptoDAS and the Febus A1-R, were installed in the electronics vault (see Fig. 4). Due to limited space, the other two units, the OptaSense QuantX and the Terra 15 Treble+, had to be installed in the laboratory building (see Fig. 4). The laser pulses of the latter two are transmitted through two fibers in a standard telecommunication cable (called ‘loose-tube fiber’ in Figs 1 and 4) to the electronics vault. Four fibers in a cable running from there (called ‘black cable fiber’ in Figs 1 and 4) transmit the pulses to the ‘Splice Box West’ where the pulses are fed into the testbed fibers.

The four IUs base their measurements on the analysis of changes in the phase of Rayleigh backscattered light, although they implement this in different ways and with different reference. Details on the interrogation principles of each IU are given in the subsections below. It is important to note that the Treble+ uses an interrogation concept that differs substantially from the other IUs, with a focus on improving noise levels and sensitivity at high sampling rates. Consequently, in the current study, the Treble+ is operated

Table 1. IUs and recording parameters which were chosen according to manufacturers recommendations. They were set to be as close as possible to a gauge length of 50 m, a sampling rate of 200 Hz and a channel spacing of 10 m. Parameter values are rounded to 3 digits.

Interrogator, manufacturer	Recorded quantity	Gauge length (m)	Sampling rate (Hz)	Pulse rate (kHz)	Channel spacing (m)
A1-R, Febus	Strain rate	50.0	200	10	9.6
OptoDAS C01-S, ASN	Strain rate	40.9	250	50	10.2
QuantX, OptaSense	Strain	51.0	200	10	10.2
Treble+, Terra 15	Velocity	49.8	1959	25.5	9.8

outside its preferred frequency range, which should be taken into account when evaluating our observations. Despite this difference, we use these data in our evaluations as well, because they are consistent with the data from the other IUs in that they confirm the ‘strain transfer rate’ near unity obtained with the cemented fibers.

Recording parameters were set to be as similar as possible for all IUs. The essential recording parameters for each unit are given in Table 1 (more detailed parameters are listed in the Supplementary Material). At a given level of phase noise, the strain noise level decreases with increasing gauge length. For this reason, we selected a rather large gauge length, as close to 50 m as possible for the respective IU. With a channel interval of approximately 10 m, this allowed us to use more than one channel in the ‘Vorstollen’.

Timing was provided to the QuantX and the Treble+ through GPS antennas. The A1-R also used a GPS signal, which was provided through an optical link (Meinberg GOAL: GPS Optical Antenna Link) and re-radiated near the IU in the mine. For the OptoDAS reception of the re-radiated GPS signal was unsuccessful and time was synchronized to a 1 PPS signal and the 10 MHz signal from the GOAL. In the Supplementary Material, we discuss observed time deviations on the order of milliseconds.

On 2024 March 19, the fiber routes were swapped in order to verify that there were no obvious quality issues with the one or the other route. The swap took place pairwise. The route of the A1-R was swapped with that of the OptoDAS and likewise between the QuantX and the Treble+.

2.3.1 Febus A1-R

The Febus A1-R is a Φ -OTDR device providing quantitative acoustic (vibrational) measurements through optical phase extraction. The system uses a single-pulse heterodyne approach for phase detection, as described by Z. Pan *et al.* (2011). A fraction of the light produced by the laser in the IU is used as the ‘local oscillator’ reference signal. The light backscattered in the optical fiber interferes with this reference signal, converting phase information into intensity. The differential phase over a gauge length provides the strain measurement, which can also be converted to strain rate through time differentiation. The system allows independent and customizable gauge lengths to be acquired simultaneously in real time.

2.3.2 OptaSense QuantX

The OptaSense QuantX IU also uses the principle of coherent phase-sensitive optical time-domain reflectometry (phase-OTDR) with the pulsed interrogation technique, in which short, coherent pulses of light are launched into the fiber and coherent methods are used to record the phase changes of the backscattered signal. The unit offers both single- and two-carrier interrogation modes, to be chosen by the operator based on the application and desired output. The single-carrier measurement is recommended when large, high-frequency signals are expected, in a configuration in which losses along the fiber are low and high spatial resolution is important. In two-carrier mode, two independent pulses are launched to interrogate the fiber. This provides two overlapping, semi-independent backscatter patterns that result in two independent phase measurements which are combined to reduce fading. This mode is recommended for large measurement range and long gauge lengths, and handles challenging losses more effectively, but has the drawback that there might be a small amount of crosstalk between different locations on the fiber (OptaSense, private communication, 2025). The current study uses the two-carrier setup, as that was the configuration available in the IU for a 50 m gauge length. The QuantX records optical phase change between the end points of the gauge length at a given time, which is proportional to strain over the gauge length, and not strain rate. As a result, measurements are expected to be more stable at low frequencies. This IU uses ultrastable, very coherent lasers ensuring stability of the laser over the entire time the light travels through the fiber and back to the IU, minimizing laser-related drift over time (OptaSense, private communication).

2.3.3 ASN OptoDAS

The ASN OptoDAS IU uses the frequency swept interrogation technique for measuring the DAS signal reflected from the fiber. In this measurement principle, a linear frequency modulated (LFM) optical signal is launched into the fiber during a relatively long period of time (longer than for pulsed interrogation techniques), and chirped compression techniques are used on the detected backscattered light to compress the LFM signal into a short pulse, as described by O.H. Waagaard *et al.* (2021). This approach enables launching high optical energy per interrogation period, at limited power. This way, the maximum energy is not limited by optical nonlinearities

that appear if power exceeds the limit. However, this measurement technique requires a low-noise laser. The interrogator measures the time-differentiated optical phase between consecutive sweeps over the gauge length, which can be converted to longitudinal strain rate along this section. Each sample then records the average strain(rate) modulation over the gauge length.

2.3.4 Terra15 treble+

The Terra15 Treble+ interrogator is another type of pulsed interrogating system operating on the phase-sensitive OTDR measurement principle. Unlike the other IUs, the Treble+ measures phase difference between two consecutive pulses backscattered from the same location in the fiber, and not across a ‘gauge length’. The change in phase difference over time provides the change of fiber length up to the backscattering point. Its time derivative is taken as the ‘fiber velocity’ at the interrogated point. For a fiber perfectly coupled with the ground along its length, this measurement of velocity should be equivalent to the vector component of ground particle velocity along the fiber axis. Strain rate can be derived by post-processing, either on the interrogator or, as it was done in the current study, by the data analyst, by defining a gauge length of separation between two interrogation points. The difference in velocity between these points divided by the gauge length equals strain rate.

Another significant difference between the Terra15 Treble+ and the other interrogators is the laser used to launch light into the fiber. The Treble+ is purposely designed to obtain high sensitivity and low noise levels at high frequencies (> 50 Hz). To achieve that, a broad-band laser is used, which results in more accuracy at high frequencies, less signal fading at certain frequencies and improved location precision, but is prone to higher noise levels at lower frequencies (Terra15, private communication, 2025). As stated above, in the current study the Treble+ was operated at frequencies outside its domain of optimal performance, which shall be kept in mind.

2.4 Vibration isolating platform

In order to decouple the IUs from floor vibrations as much as possible, the A1-R, QuantX and Treble+ were placed on ‘Minus K Technology 100BM-8 Vibration Isolating Platforms’. These platforms are completely passive. They use negative-stiffness mechanisms and an arrangement of springs in order to isolate six degrees of freedom.

The horizontal natural frequency of these tables is between 1.5 and 2.5 Hz (depending on the payload). The vertical natural frequency is 0.5 Hz (independent of the weight). At higher frequencies, the platform does not follow the ground motion due to the inertia of its payload.

The OptoDAS was shipped in a rugged field rack too heavy for the vibration isolation table, and the interrogator was not dismantled to be placed on such a table. Instead, the OptoDAS was kept in its rugged case throughout the tests. For the A1-R, the weight had to be increased by placing brass cylinders on top of the casing, to provide sufficient inertia. Despite this arrangement, the platform could not be properly adjusted and tended to drift against its stops. For both the OptoDAS and the A1-R, the vibration isolation was less essential than for the other two IUs, as the floor in the mine provides a more stable and less vibrating support than the wooden floor of the laboratory.

2.5 The strainmeter array

We compare the DAS recorded strain with data from the BFO strainmeter array, which is understood to represent ‘rock strain’. The array (see Fig. 1) consists of three 10 m long, horizontal, Invar-wire strainmeters, which are well calibrated for the purpose of tidal research. The SEED codes for the instruments are IL.BFO.00.BSA, IL.BFO.00.BSB and IL.BFO.00.BSC. Data are available through the (Scripps Institution of Oceanography 1986) via the EarthScope Data Center (IRISDMC).¹ The design of these instruments is based on the instruments by G. King & R. Bilham (1976) and are discussed in more detail by W. Zürn *et al.* (2015). Depending on the method used, the calibration accuracy can be better than 2 per cent or 5 per cent for calibration with respect to ‘Crapaudines’ or synthetic tides, respectively. Details of the calibration mechanism are discussed by T. Forbriger *et al.* (2025, their section S2.4).

Signals recorded by these instruments are used only up to frequencies below 1 Hz. At higher frequency, they show a linear parasitic sensitivity to vertical ground acceleration, while at the same time, the sensitivity to strain would be reduced, both due to the inertia of the pick-up system. The signal waveform in consequence differs from the strain waveform and has a larger amplitude at higher frequencies. Apart from this effect we have no indication for a frequency dependent scaling of the strainmeters.

Other studies use seismometer data to compare with DAS signals. By using ‘rock strain’ directly measured with strainmeters we can avoid this. The use of seismometer data hinges on a plane-wave assumption, which in heterogeneous settings and with crustal wave propagation is likely to be incorrect. T. Forbriger *et al.* (2025, their sections ‘Comparison with seismometer data’ and S4) discuss this and point out further complications due to local strain–strain coupling in their supplementary section S2.5.

¹<https://www.earthscope.org/data/>

Table 2. Earthquake signals used for the analysis. We estimate the SNR by comparing amplitude spectra of the earthquake signal recorded with the A1-R to spectra of a sequence of the same length preceding the earthquake.

Earthquake origin time	Location	BAZ	Magnitude	Distance	Bandwidth with SNR ≥ 10 (Hz)
2024-04-02 23:58:09 UTC	Hualien City, Taiwan	N57 °E	M 7.4	86.6°	0.02–0.2
2024-03-27 21:19:37 UTC	Tolmezzo, Italy	N121 °E	M 4.5	3.7°	0.2–8.0
2024-03-22 05:31:50 UTC	Albstadt, Germany	N105 °E	M 2.8	59 km	3.0–18.0

Note. BAZ: backazimuth.

2.6 Analysed time windows

The recording of the experiment covers the period from 2024 March 05 to April 04. During this one month, we find three earthquakes which provide a signal-to-noise ratio (SNR) of about 10 for at least three of the IUs. These signals cover a frequency range of about 20 mHz to 20 Hz and are listed in Table 2. Due to their different magnitude and epicentral distance, each of the earthquakes covers a different frequency band in the following analyses.

Additionally, we use time windows free of earthquakes to estimate the background signal level. Here, we focus on a time window with moderate to low marine microseism amplitude.

3 ANALYSES

We would like to begin with a statement of our intentions. We use four IUs in order to corroborate the properties of the testbed and the ‘strain transfer rate’ in particular, by validation with IUs which implement different techniques. We do not intend to rank the IUs in any way. The recording parameters and analysed frequency bands for the four IUs have been chosen as similar as possible, which in turn means that these parameters might not be optimal for each of the IUs. In most of the data we find details, which we still do not fully understand (we mention examples in the Supplementary Material). Some of them might be due to the recording conditions and be caused by water occasionally dripping from the mine ceiling onto the fibers, by temperature fluctuations, or by the different installation conditions for the IUs themselves. These details need not represent a property of the respective IU. Where disturbances are obvious, we have not used the affected time windows. In the following, we discuss the gross features of the DAS data, in particular with respect to the coupling of the fiber to the rock and the potential of this technology to record rock strain. We will mention similarities and differences between data from different IUs, but like to remind the reader that these might be specific to the particular setup. Only selected data examples are shown, because we do not intend a 1:1 comparison. Diagrams for signals for all IUs are provided in the Supplementary Material.

3.1 Pre-processing of DAS data

Raw data recorded by the different IUs differ in size per file and duration of file from 1.1 MB for 10 s of OptoDAS data to 2 GB for 50 min of Treble+ data. In the first step, we select the time period to be analysed from the raw data, concatenate the files and downsample (an eighth-order Chebyshev type I anti-alias filter is applied) to 20 or 200 Hz depending on the frequency band of interest. The polarity is consistently set to make rock extension positive. For the A1-R and Treble+, where the IUs use other values than $n = 1.47$ and $\xi = 0.78$ for the refractive index and the opto elastic factor for fused silica, respectively, we adjust the scaling accordingly to make data consistent (see the respective discussion in the Supplementary Material). The application of identical parameter values ensures that signals for all IUs are scaled consistently. The value of $\xi = 0.78$ might be chosen too large in closer examination of the boundary conditions by which the cemented fiber deformation is constrained. The resulting strain amplitude might be too small in consequence. At the same time, the fibers might pick up spurious signals of axial strain which actually are due to radial strain. Both considerations are discussed in the Supplementary Material (Section ‘S4 Optical fibers sensing strain’).

Samples are scaled to strain rate in nstrain s^{-1} , or in the case of the QuantX to strain in nstrain , and then are written to intermediate files in a common format. Upon reading these data for the subsequent analysis, time-series in strain rate are converted to strain by integration (cumulative sum in the time domain multiplied by sampling interval). Prior to the integration we cast the data to double precision, where IUs do not provide them as 64-bit floats. This is necessary to avoid significant loss of numerical precision in cases of strong strain drift.

Common mode noise, which is coherently present on all channels, is a typical issue of DAS systems and partly can be due to effects in the laser in the IU (N.J. Lindsey *et al.* 2020, their section 2.6, Optical Noise). This type of noise can be due to a combination of laser frequency drift, mechanical vibrations of the interrogator box caused by seismic or acoustic waves, or temperature changes around the IU and other similar effects. In our experiment, noise of this character typically dominates at lower frequencies in the investigated band. In order to remove this noise, we employ the reference coils mentioned above. These reference coils (see Fig. 4) are decoupled from the rock. Thus, signals extracted from channels on these coils are expected to contain only system-generated noise. By subtracting the

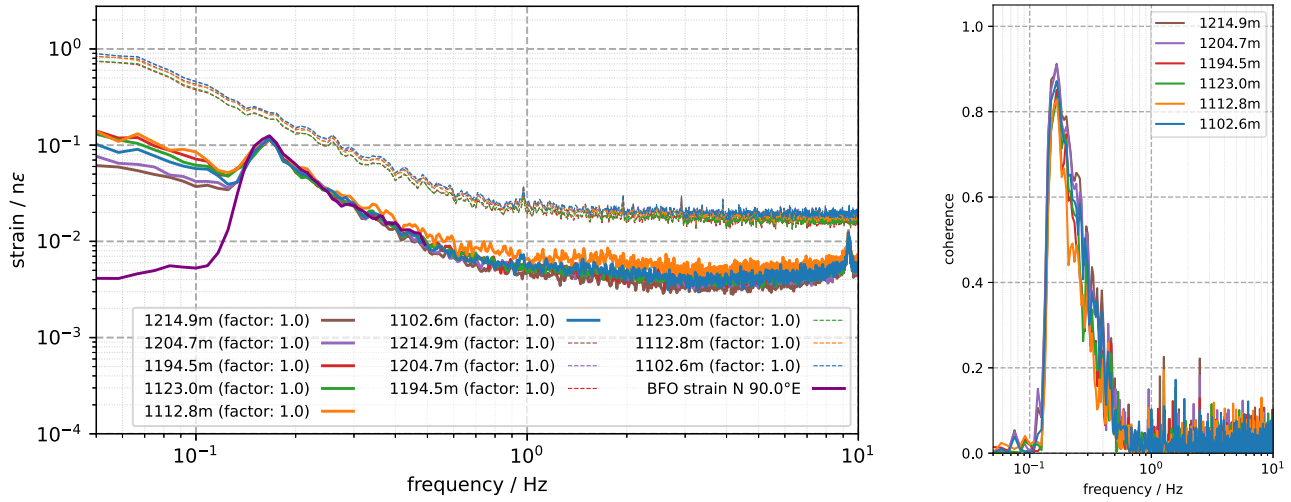


Figure 5. Analysis of the background signal on 2024 March 26 1 to 2 UTC for recordings of the QuantX: rms amplitude in 1/6 decade (left, see section 4.1 by T. Forbriger 2023) and magnitude-squared coherence (G. Carter *et al.* 1973, their eq. 2) with respect to the BFO strainmeter data (right). The corners of the applied bandpass are at 20 mHz and 15 Hz and thus lie outside the displayed range. We compare signals from six channels (indicated by their offsets) to the ‘rock strain’ in N90°E as obtained from the BFO strainmeter array (purple curve). The curve for the latter is truncated at 0.5 Hz, because of the parasitic sensitivity to vertical ground motion at higher frequencies. The dashed lines in the left diagram show the signal level of the raw DAS data. The solid lines are the levels after subtracting the average of the signal on the reference coil in the time domain. Amplitudes are given as ‘fiber strain’. They follow the curvature of the purple line (‘rock strain’) at 0.14–0.5 Hz. The signal amplitude of the marine microseisms is at a rather low level of 0.1 nstrain in this example. Nevertheless the signal is detected by the DAS, which is also confirmed by the coherence being raised to 0.8 in the microseism frequency band.

average time-series of the channels on the reference coil from the signal obtained from a channel in the groove, coherent noise can be reduced. This can improve the SNR by up to 20 dB at 0.1 Hz. At the same time, this makes the reference coils a critical component. Any additional noise (dripping water, temperature fluctuations, etc.) in the reference channels potentially deteriorates the signals under investigation. S. Diaz-Meza *et al.* (2023) discuss stacking of signals recorded in colocated fibers in order to improve the SNR. We have not applied this in order to be able to analyse signals from colocated fibers separately.

An example of improved SNR is shown in Fig. 5 and is discussed in Section 3.3. Only for the Treble+, which is operated outside its preferred frequency range, incoherent noise dominates all channels such that this measure does not improve the signal quality and we do not apply this procedure to Treble+ data. Time-domain examples of the procedure are discussed by T. Forbriger *et al.* (2025, their section S2.3 and figs S26 and S27) and are shown in the Supplementary Material of the current contribution.

Finite phase shifts between waveforms become discernible for frequencies of about 10 Hz, which are present in the data from the Albstadt earthquake (Table 2). All IUs are synchronized to UTC time by GNSS reception. Nonetheless, we observe consistent time-shifts of 6–40 ms between different units. Additionally, we see the faint signature of propagation delay, which can be 2.5 ms over the channel distance of 10 m for a surface wave at 2.5 km s⁻¹ wave speed and incidence from the East (Albstadt) along the ‘Vorstollen’ (Fig. 4). Phase shifts would systematically reduce the measures we use [‘NCC’ and ‘regression coefficient’ (RC), see below]. For this reason, we determine the time-shifts by cross-correlating the waveforms and then correct for the time-shift, by accordingly resampling the waveform with respect to the reference signal in the respective analysis (at least for the signals of the Albstadt earthquake).

For the purpose of waveform comparison, we apply a bandpass by separate Butterworth high- and low-pass filters. Both are fourth-order filters. Below, we will specify only the filter frequencies for the respective case. For regression and correlation analysis all involved time-series are resampled to the highest sampling rate involved by Lanczos interpolation as implemented in ObsPy (L. Krischer *et al.* 2015).

3.2 Linear strain from the strainmeter array as a reference

We compare DAS recordings with recordings of the three strainmeters (eastern end of the tunnel in Fig. 1). Linear strain in the azimuth $\psi = \text{N}90^\circ\text{E}$ of the ‘Vorstollen’ (Figs 1 and 4) is obtained by a linear combination of the three strain values ϵ_A , ϵ_B and ϵ_C from the three array instruments with azimuths of N2°E, N60°E and N300°E, respectively. They correspond to the SEED channel names BSA, BSB and BSC.

From the components $\epsilon_{\theta\theta}$, $\epsilon_{\phi\phi}$ and $\epsilon_{\theta\phi}$ of the strain tensor in the horizontal plane, linear horizontal strain in an arbitrary azimuth ψ is

$$\epsilon(\psi) = \epsilon_{\theta\theta} \cos^2(\psi) + \epsilon_{\phi\phi} \sin^2(\psi) - \epsilon_{\theta\phi} \sin(2\psi) \quad (1)$$

as given by W. Zürn *et al.* (2015, their eq. 2). Based on the strainmeter recordings, this is

$$\epsilon(\psi) = \begin{pmatrix} \cos^2(\psi) \\ \sin^2(\psi) \\ -\sin(2\psi) \end{pmatrix} \mathbf{M}^{-1} \begin{pmatrix} \epsilon_A \\ \epsilon_B \\ \epsilon_C \end{pmatrix}, \quad (2)$$

where the rotation matrix

$$\mathbf{M}^{-1} = \begin{pmatrix} 1.002 & -0.041 & 0.040 \\ -0.334 & 0.680 & 0.653 \\ 0.000 & -0.577 & 0.577 \end{pmatrix} \quad (3)$$

is the inverse of

$$\mathbf{M} = \begin{pmatrix} \cos^2(2^\circ) & \sin^2(2^\circ) & -\sin(2 \times 2^\circ) \\ \cos^2(60^\circ) & \sin^2(60^\circ) & -\sin(2 \times 60^\circ) \\ \cos^2(300^\circ) & \sin^2(300^\circ) & -\sin(2 \times 300^\circ) \end{pmatrix}. \quad (4)$$

The strainmeters are at a distance of about 350 m from the ‘Vorstollen’ (Fig. 1). At frequencies below 0.2 Hz, where the strainmeter data are used, wavelength is much larger than this distance even for the surface waves which propagate at about 3 km s⁻¹. For this reason, we expect the strain waveform at both locations to be practically the same. The strain amplitude, however, is altered due to the local surface topography at BFO (strain–strain coupling resulting from stress-free surfaces). W. Zürn *et al.* (2015) report an amplitude reduction to 58 per cent for the N60°E strainmeter, which appears more or less consistent with the reduction to 67 per cent in N90°E as computed by 2-D finite-element analysis as reported by D. Emter & W. Zürn (1985). While this effect generally applies to the location of the strainmeter array as well as the ‘Vorstollen’, we expect the N90°E strain amplitudes to be slightly (5 to 10 per cent) larger at the ‘Vorstollen’, based on the results by D. Emter & W. Zürn (1985, their fig. 5). Strain–strain coupling not just results in scaling of linear strain components, it potentially couples all components of the strain tensor into the component of interest. Under topography this coupling becomes location dependent and can result in waveform differences, which are due to spurious strain signals. Further details are discussed in the Supplementary Material and by T. Forbriger *et al.* (2025, their section S2.5).

3.3 Background signal

Fig. 5 shows the analysis of the background signal on a day with low marine microseism amplitude. The dashed lines show the raw signal levels of six channels in the ‘Vorstollen’ for the QuantX. By subtracting the average of the signals on the reference coil in the time domain, the signal level is lowered to the solid lines, which demonstrates the effectiveness of this procedure to remove coherent noise. This measure is similarly effective for the OptoDAS and A1-R data, though they arrive at slightly different signal levels (see the additional diagrams in the Supplementary Material). These three IUs detect the marine microseism signal at about 0.14–0.3 Hz, which is also indicated by the increased level of coherence (Fig. 5, right-hand panel). The signal level in Fig. 5 (left) is consistent with the level of ‘rock strain’ measured with the BFO strainmeter array for 0.14–0.5 Hz. The raw Treble+ data are at the level of the raw data of the other three, but are dominated by incoherent noise. The subtraction of the reference coil signal hence does not lower the background level. We should remind ourselves that the Treble+ is operated outside its optimal use case, which would be at frequencies larger than investigated here.

We have run this type of analysis as shown in Fig. 5 for all IUs at times of moderate signal level of the marine microseisms before and after the swapping of fiber routes on 2024 March 19. Analysis results for the 2024 March 08 and the 26 are shown in the Supplementary Material. By this, we have convinced ourselves that the results regarding background level are largely independent of the fiber route used.

3.4 Waveform similarity

For transient signals, we measure the waveform similarity by the NCC

$$c = \frac{\sum_k x_k y_k}{\sqrt{\sum_k x_k^2} \sqrt{\sum_k y_k^2}}, \quad (5)$$

where x_k and y_k are the samples of the one and the other time-series, respectively. A waveform example with signals recorded after the M_w 7.4 Taiwan earthquake (see Table 2) with the OptoDAS IU is shown in Fig. 6. Waveform differences are hardly noticeable in this display as the NCC for the displayed traces is 0.98 and larger (see Table 3). We show waveforms for the other IUs and earthquakes as well as waveforms of signal differences in the Supplementary Material (Section ‘S5 Interrogators’). There we also discuss a small systematic effect, which is also apparent in Fig. 6. While the majority of the signals (body waves and Rayleigh wave train) appear

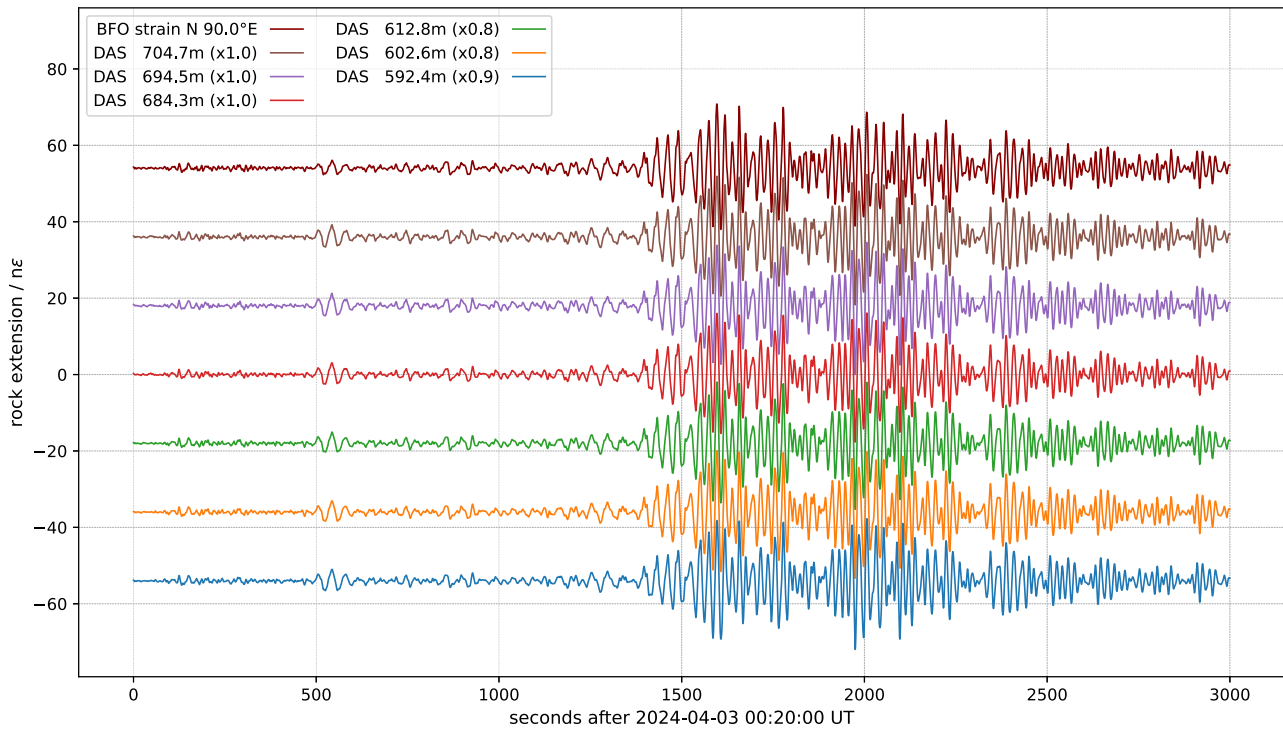


Figure 6. Waveform comparison for the Taiwan earthquake (see Table 2) recorded with the OptoDAS. The traces are vertically shifted for better visibility of details. The *S*-phase arrives at about 2024 April 03 00:21 UTC. The *P* phase (not shown) does not exceed the noise level. Rayleigh waves arrive after 1300 s on the timescale. All signals are bandpassed to frequencies from 20 to 200 mHz. The top trace is the signal derived from the BFO strainmeters in N90°E azimuth. The other six traces are recorded by the OptoDAS in the ‘Vorstollen’. Optical channel offset and amplitude scaling factors are given in the legend, where the scaling factors are the reciprocal RCS (see Table 3).

Table 3. NCC and RCS for the data example in Fig. 6.

Channel	592.4 m	602.6 m	612.8 m	684.3 m	694.5 m	704.7 m
NCC	0.98	0.99	0.99	0.98	0.98	0.98
RCS	1.17	1.21	1.19	0.96	1.02	1.03

consistent in the strainmeter and the DAS recording, the *SS*-phase (500 s on the timescale) has a smaller amplitude in the strainmeter recording. This is also obvious from the waveform differences shown in the Supplementary Material, where earthquake wave groups are present in the residuals. We propose that this is due to strain–strain coupling, which potentially couples any strain component at a small but finite level into the linear strain in direction of the ‘Vorstollen’, as discussed in Section 3.2. Spurious signal components due to the fibers sensitivity to radial strain may contribute to this as well, as discussed in Section 3.1. We also cannot rule out that the parasitic sensitivity of the strainmeters to vertical ground displacement might contribute, although we consider this rather unlikely due to the high-pass characteristic of this effect.

We have run the same analysis for the other IUs. The values for the NCC with respect to the strainmeter signal are displayed in Fig. 7 (left). They are 0.98 and larger, except for the Treble+, for which they still are 0.7 and larger. The Treble+ signals do not benefit from the reference coils and thus their SNR is lower. For the A1-R, QuantX, and OptoDAS the waveforms in the investigated time window and frequency band are practically identical to the strainmeter signals.

At higher frequencies, a comparison with the strainmeter signal cannot be done reasonably, because the strainmeter shows a parasitic sensitivity to vertical ground motion above 1 Hz. Thus, for the analysis of the waveforms recorded after the Italy and Albstadt earthquakes (see Table 2), we choose the A1-R as a reference. The values for the NCC are displayed in Fig. 7 (right) and most are close to 1. The effect of the lower SNR for the Treble+ is obvious. The SNR for the Albstadt and the Italy earthquake is generally smaller, which is indicated by a slightly stronger scatter and reduced values of the NCC, in particular for the Albstadt earthquake, though the median values for the QuantX and the OptoDAS are still close to 1. The Treble+ shows a higher NCC for the Albstadt earthquake than for the other two earthquakes. This might indicate the better waveform quality, which could be obtained in its preferred domain of operation at even higher frequency.

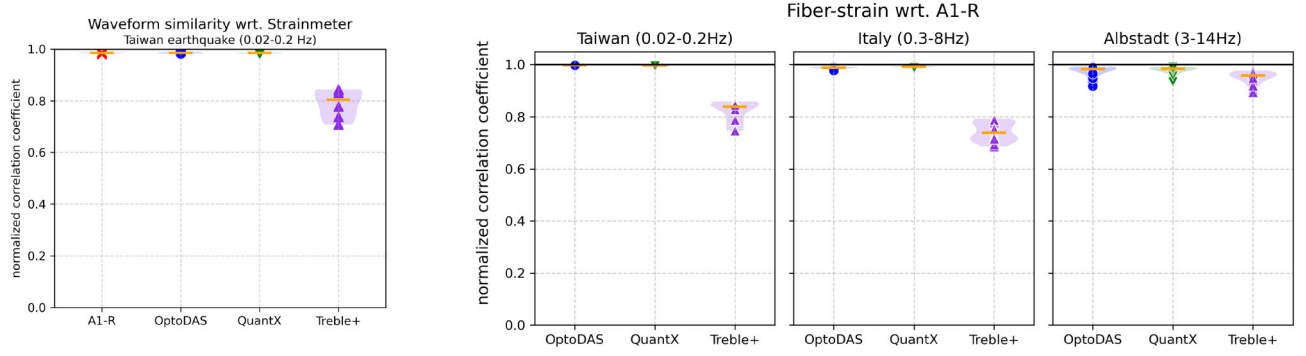


Figure 7. Compilation of values for the NCC with respect to the BFO strainmeters (left) and with respect to the A1-R (right). For the frequency band of 0.02–0.2 Hz, the DAS data can be compared with the BFO strainmeter data. For each of the IUs six channels along the ‘Vorstellen’ are selected. The intercomparison of DAS signals (right) is also meaningful for frequencies larger than 0.2 Hz. To account for variations in the A1-R signals between channels, we compute the NCC with respect to each of the six A1-R channels, which results in 36 data points in the diagrams on the right (six A1-R channels times six channels for the IU under investigation). The scatter is so small that most of these 36 points are not distinguishable. The duration of the analysed waveforms are 2820, 150 and 25 s for the Taiwan, Italy and Albstadt earthquakes (Table 2), respectively. In each case, the window covers the *P*-wave arrival as well as the surface wave train. The horizontal bars mark the median values. The shaded background (so-called ‘violin plots’, which display kernel density estimates) is added to illustrate the spread in the distribution of values.

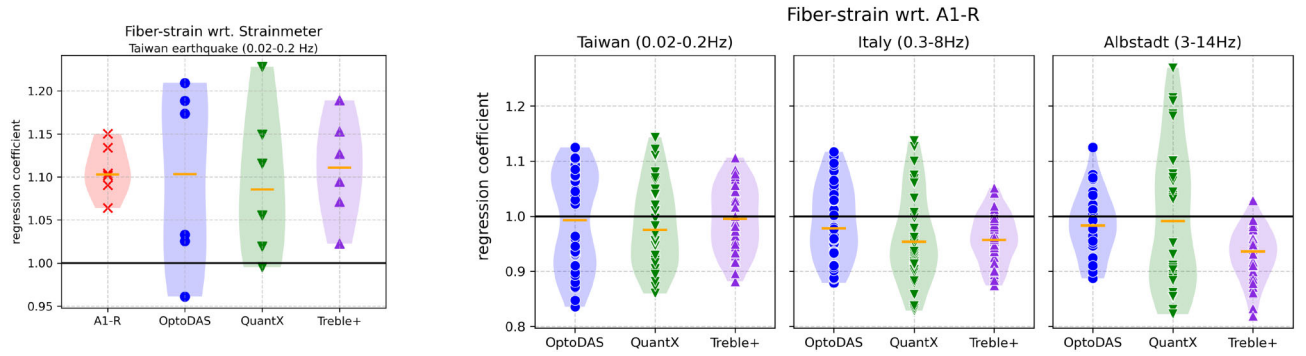


Figure 8. Compilation of values for RCS (left) and RC with respect to the A1-R (right). See Fig. 7 for parameters. Because the RCS for the A1-R varies between the channels, we compute the RC with respect to each of the six A1-R channels, which results in 36 data points in the diagrams on the right (six A1-R channels times six channels for the IU under investigation). The horizontal bars mark the median values (to emphasize the comparably small variation of the ‘centroid’ of the six channels for each frequency band). The shaded background (so-called ‘violin plots’, which display kernel density estimates) is added to illustrate the spread in the distribution of values.

3.5 Strain transfer rate

The high waveform similarity allows to measure amplitude ratios between time-series x_k and y_k in a phase-sensitive way (rejecting noise in x_k) by the RC

$$r = \frac{\sum_k x_k y_k}{\sum_k y_k^2}. \quad (6)$$

The concept of using this to derive ‘strain transfer rate’ is introduced by T. Forbriger *et al.* (2025, their eq. 5). There x_k is the DAS time-series of ‘fiber strain’ and y_k is the strainmeter time-series understood to be ‘rock strain’. Strictly spoken y_k must represent ‘rock strain’ exactly at the location of the DAS fiber to make r equal ‘strain transfer rate’. We use eq. (6) to compare DAS recorded ‘fiber strain’ with the strainmeter recording as well as for an intercomparison of DAS recordings in terms of the RC.

We compute the regression coefficient with respect to the strainmeters (RCS) for signals recorded after the M_w 7.4 Taiwan earthquake (see Table 2) in the frequency band from 20 to 200 mHz. The resulting values are displayed in Fig. 8 (left). The values for the waveform example in Fig. 6 are given in Table 3. Like T. Forbriger *et al.* (2025, their fig. 2), we find a substantial scatter between channels. Additionally, the values for the RCS for different IUs vary about an average value of 1.1 where the median values for all IUs consistently are close to 1.1 and thus about 10 per cent larger than 1. This apparent amplification of the strain amplitude with respect to the strainmeter signals presumably is due to the strain field being altered by about 5–10 per cent in between strainmeters and the ‘Vorstellen’ as discussed above. We cannot rule out a contribution to this effect by the limited accuracy of the strainmeter calibration (expected to be better than 5 per cent as discussed in Section 3.2) or a change in the opto elastic factor due to the boundary conditions

for the fiber in the cemented groove as mentioned in Section 3.1. The latter, however, would rather have the opposite effect (scaled ‘fiber strain’ being too small). Spurious signals due to the fibers sensitivity to radial strain, strain–strain coupling of other tensor components into the linear strain in direction of the ‘Vorstollen’, and due to the parasitic response of the strainmeters to vertical displacement are considered unlikely to be the cause, because the linear regression would reject non-matching waveform components. Additionally spurious signals in the strainmeter signal would rather reduce the RCS in eq. (6). Taking the topography effect as the main cause for the enlarged RCS, the IUs practically measure ‘rock strain’ amplitude at the location of the ‘Vorstollen’, which implies a ‘strain transfer rate’ of practically 1 for the cemented fibers, as might have been expected.

At higher frequencies, the regression with respect to the strainmeter data is meaningless because of its parasitic response to vertical ground motion. For the Albstadt and the Italy earthquakes (see Table 2), we run an intercomparison by computing the RC, r , where we choose the A1-R data for y_k in eq. (6). We select the A1-R as a reference, because the scatter of its RCS is least in Fig. 8 (left). To account for variations in the A1-R signals between channels, we compute the RC with respect to each of the six A1-R channels, which results in 36 data points. The resulting values for all three earthquakes are shown in Fig. 8 (right). The median values are all close to 1 and variations between IUs and between the earthquakes are clearly smaller than the scatter. For this reason, we are not looking for subtle systematic effects in these data. All four IUs provide consistent amplitudes at frequencies of 0.02–14 Hz.

3.6 Coherent background signals

A substantial amount of coherent background signal in the DAS data is removed by subtraction of the signals recorded on the reference coils as is demonstrated in Fig. 5 (left). These signals obviously are system generated noise, because they are uniformly present in the ‘Vorstollen’ as well as on the reference coils. The remaining background may as well contain signals which are coherent between DAS channels. Where DAS recorded signals are coherent with the strainmeter signals, we take them as large-scale strain, as is the case in Fig. 5 (right) for frequencies at which ‘fiber strain’ represents the Rayleigh waves of the marine microseism. Outside this frequency band, the level of coherence with the strainmeters drops below 0.1, except for larger amplitude earthquake signals with values of NCC close to 1.

Nevertheless, we observe coherent signal components in between different channels in the ‘Vorstollen’ of the same IU. Where these channels are on different fibers in the groove, the coherence suggests that both fibers pick up a signal from the same physical source outside the fiber. This might be local fluctuations of the ‘rock strain’ or fluctuations of temperature affecting the refractive index of both fibers in the same way, for example. Where this coherence between channels on adjacent fibers does not exist, we expect that adjacent channels on the same fiber should show a significant level of coherence, because at a gauge length of 50 m and a channel interval of 10 m neighbouring channels essentially sample the same 40 m of the fiber. The coherence in this case would be expected to decrease with increasing channel distance and decreasing overlap.

We show examples for the A1-R recordings of the M_w 7.4 Taiwan earthquake (see Table 2). We apply narrow bandpass filters to a 45 min long recording and compute the NCC for the respective frequency band, which is a very strong test for coherent signals in the recording. As expected, the NCC is practically 1 in the frequency bands up to 0.2 Hz, where the earthquake signal dominates ‘fiber strain’.

In Fig. 9, we compare adjacent channels (A with B, as well as C with D) on the same fiber and channels on adjacent fibers (A with C and D, as well as B with C and D). Fig. 9 (bottom) shows the corresponding NCC values. At frequencies higher than 0.2 Hz, there is little energy from the earthquake in the recording. Consequently, NCC values for channels of adjacent fibers drop with increasing frequency, indicating that no common ‘rock strain’ signal dominates. This is not the case for signals recorded on the same fiber (A versus B and C versus D), which means that there are similarities in ‘fiber strain’, though it does not represent a common ‘rock strain’ signal. We see similar behaviour for signals recorded with the OptoDAS and the QuantX, however not as clear as with the A1-R.

Fig. 10 shows how the NCC decreases with decreasing overlap for channel pairs on the same fiber. However, even for no overlap there remains some coherent signal component. At the same time the NCC slightly drops with decreasing overlap in the frequency band of high earthquake signal SNR up to 0.2 Hz, as one of the channels in the pair leaves the straight stretch of the ‘Vorstollen’ and apparently measures a slightly different component of the strain tensor. For the QuantX and the OptoDAS, the drop of NCC with increasing frequency is even stronger for most channel combinations, meaning that less coherent signal remains even with a finite overlap.

We find the expected coherent component in the background signal of channels with overlapping gauge, where coherence becomes smaller the shorter the common section of the fiber is. The NCC value drops to 0.2 where there is no overlap (Fig. 10). This is different to Fig. 9, where the NCC value for signals from channels at the same location with non-overlapping gauge (because they are on adjacent fibers) is around 0.5. We checked for remainders of the common mode noise by computing the NCC between the raw signal of a channel on the reference coil and a channel in the ‘Vorstollen’ (after removing the common mode noise from the latter) for the same time interval, and find values of NCC all being smaller than 0.3. In consequence, these signals in Fig. 9 could indicate a common signal component being picked up by the fibers in terms of strain or temperature fluctuations, while the NCC values of 0.2 in Fig. 10 are likely due to remainders of the common mode noise signal.

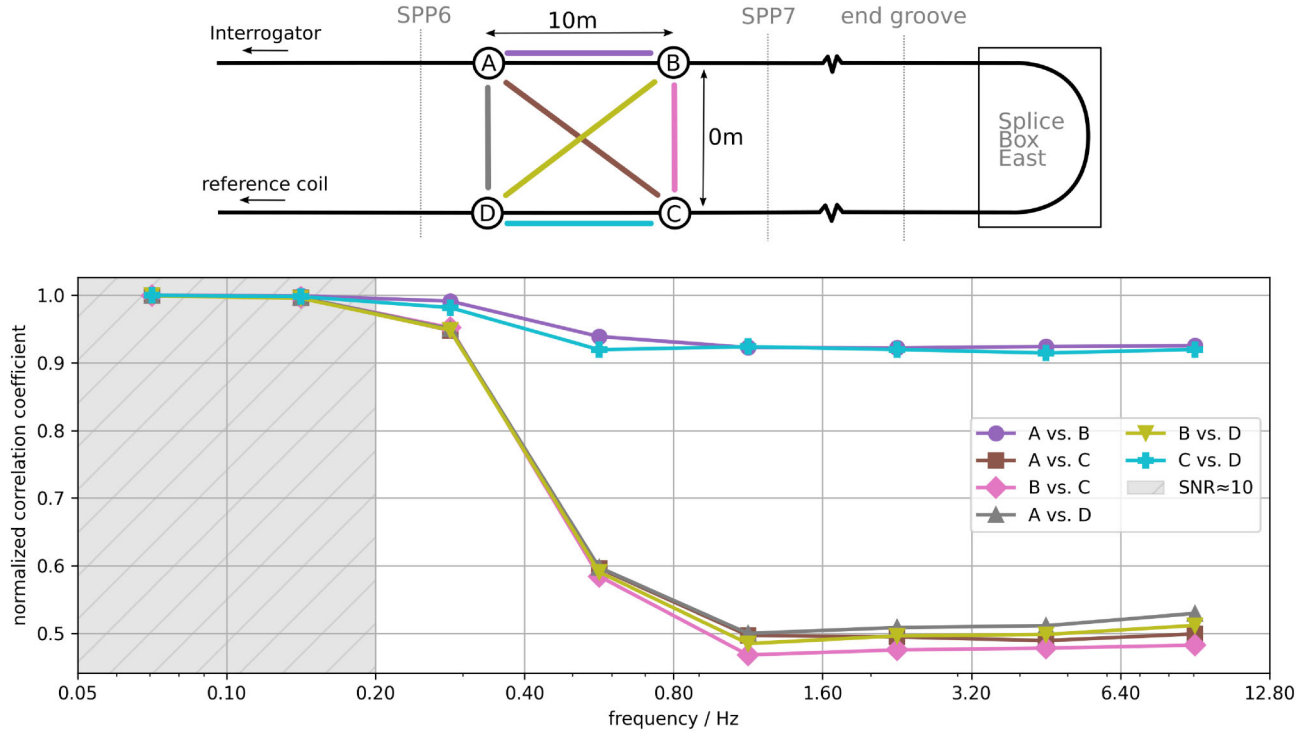


Figure 9. Signal similarity between adjacent channels. Top: schematic layout of the analysed channels (not to scale). Bottom: signal similarity for pairs of adjacent channels recorded by the A1-R. Four channels are used to compose six pairs in the lower diagram. The upper diagram sketches their locations. Two of them (A and B) are in front of the turnaround of the fiber in the ‘Splice Box East’ and the other two (C and D) are behind, i.e. they are on two different fibers in the groove but on the same folded route. Although the two sections of the fiber are right next to each other in the groove (0 m distance), A and D as well as B and C need not be exactly adjacent to each other due to the constant read-out interval (channel spacing of 10 m) of DAS channels along the folded route. While A and B as well as C and D are at a distance of the read-out interval, A and D as well as B and C are considered to be closer than the read-out interval. Because the read-out interval is about 10 m and the gauge length is chosen close to 50 m (Table 1) the pair A and B samples a common section of the fiber, just like the pair C and D does on the opposite fiber. In contrast, the pairs A and D as well as B and C sample a common section of the rock on different fibers. The analysed signals were recorded during 45 min after 2024 April 03 00:40 UTC (the time window of the wave train from the the M_w 7.4 Taiwan earthquake, see Table 2). They are compared in different frequency bands (tick marks on the abscissa give the upper and lower limit). The value of the NCC for channel pairs sketched in the upper diagram is displayed in the respective frequency interval in the lower diagram. For frequencies below 0.2 Hz, the earthquake signal dominates the recordings and the NCC is large for all of the pairs. The SNR for the earthquake drops with increasing frequency. Pairs on a common section of the fiber then produce a larger value of NCC.

4 CONCLUSIONS

On a testbed with optical fibers cemented into the concrete floor of BFO, we confirm that the amplitude loss, as indicated by a ‘strain transfer rate’ less than one in previous tests by T. Forbriger *et al.* (2025), can be overcome by tighter coupling. As a reference we take waveforms from the array of calibrated strainmeters at BFO in the frequency band 0.02–0.2 Hz. Taking the slight spatial distortion of the strain field due to surface topography into account, we find a ‘strain transfer rate’ of practically 1 for the cemented fibers. This result is corroborated by the data from four different IUs. At higher frequency (0.02–14 Hz), an intercomparison of data from different IUs confirms that up to 14 Hz no IU-specific frequency dependence of ‘strain transfer rate’ can be seen in consideration of scatter between different channels.

For this analysis, we use earthquake signals with high waveform similarity (the normalized correlation typically being ≥ 0.95 , see Fig. 7) between recordings of DAS IUs and strainmeters or between IUs. The ‘strain transfer rate’ for this reason can be measured in a phase-sensitive way by the RC. Between channels recorded by a single IU, we observe a scatter of about ± 10 per cent in most cases (Fig. 8), where the high waveform similarity would suggest a smaller variation in amplitude. This scatter might be due to the variation of effective ‘gauge length’ caused by the randomness of spatial distribution of backscatterers. The variation of the median values in between earthquakes and IUs, however, typically is less than 5 per cent.

The A1-R, OptoDAS and the QuantX, see a background signal which is coherent between all channels along the fiber route, so-called common mode noise (N.J. Lindsey *et al.* 2020, their section 2.6, Optical Noise). We improve the SNR by up to 20 dB by subtracting the average signal recorded on ‘reference coils’. In that way, we reduce the background noise level in the best cases to 100 pstrain at 0.1 Hz and 5 pstrain at 1 Hz in a bandwidth of 1/6 decade (see Fig. 5). The above-mentioned three IUs detect the marine microseisms at times of moderate amplitude. The remaining background signal is largely incoherent for channels on colocated fibers. The coherence of the background between neighbouring channels increases with increasing overlap of their gauge length.

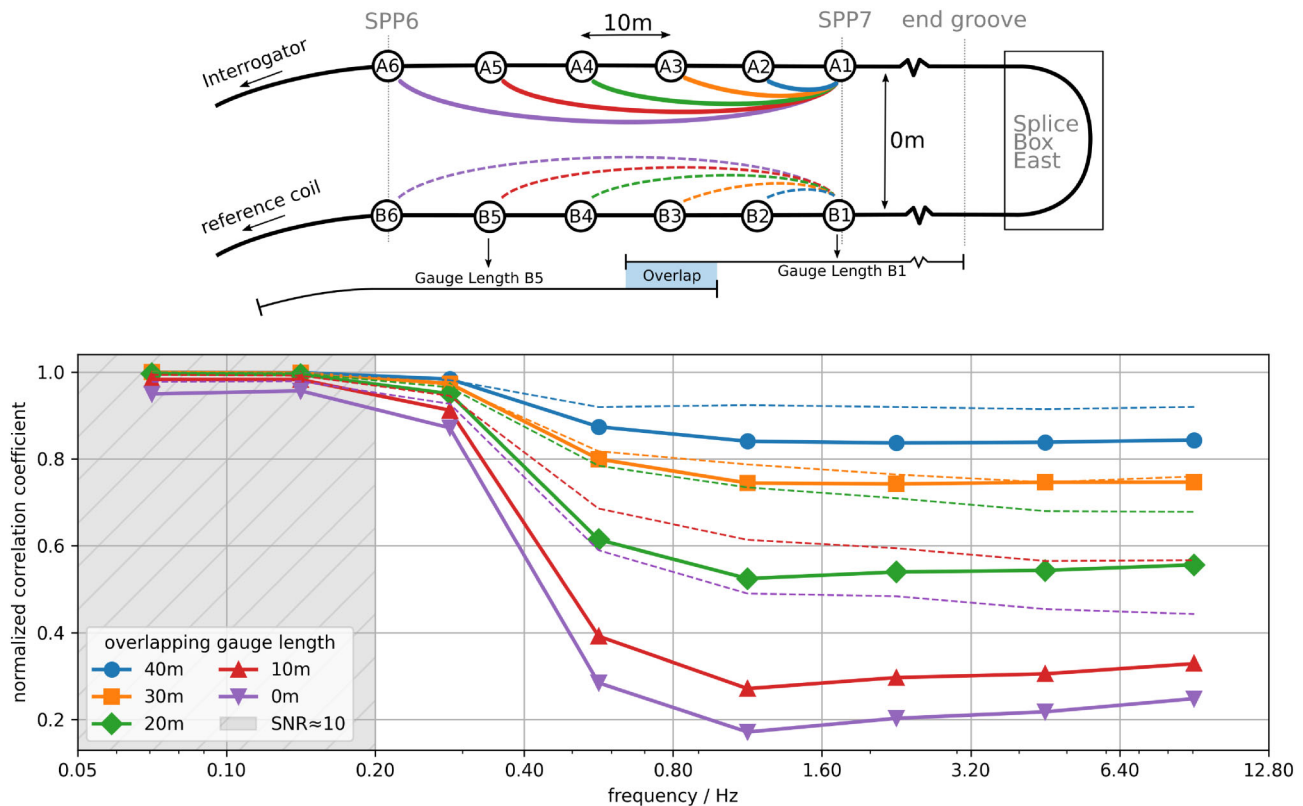


Figure 10. Signal similarity between overlapping channels. Channels do not represent point measurements but the signals of 50 m wide gauges. Depending on the channel distance these gauges overlap to a different fraction. Top: schematic layout of the analysed channels (not to scale). Bottom: signal similarity for pairs of overlapping channels recorded by the A1-R. Channels A1 and B1 are on the same fiber at opposite sides of the turnaround in the ‘Splice Box East’ and are selected to be at a spatial distance smaller than the read-out interval (channel spacing). The two sections of the fiber are right next to each other in the groove. Data from each of them are compared to signals of channels which are at a distance increasing stepwise with the read-out interval from A2 to A6 and B2 to B6, respectively. Because the read-out interval is about 10 m and the gauge length is chosen close to 50 m (Table 1), these pairs have different overlap on the common fiber. The time window and the frequency bands are the same as in Fig. 9.

The background level in the analyses is most likely controlled by various factors of the installation, like thermal effects on the reference coils or vibration isolation being different for the different IUs. The background signal level hence not necessarily represents a property of the respective IU alone.

The procedure of noise reduction makes the reference coils a critical component, which shall be protected from local disturbances like dripping water or strong temperature fluctuations. The remaining background signal is so low, that it might be due to temperature fluctuations of the fiber (possibly on the reference coil) at a level of a few μK , given that the temperature coefficient of the fiber refractive index is on the order of 10^{-5} K^{-1} .

ACKNOWLEDGMENTS

We thank Peter Duffner for taking care of the BFO strainmeters and their calibration devices. We are grateful to Walter Zürn for many fruitful discussions and his continuing support of the operation of the Invar-wire strainmeters. Peter Duffner, Felix Bögelspacher, Jérôme Azzola and Nino Krämer helped with the installation of the testbed. Rob Mellors and an anonymous reviewer provided thoughtful comments and helpful recommendations to improve the submitted manuscript. Many thanks for that. We are grateful to the teams of Alcatel Submarine Networks (ASN), Terra15, LUNA OptaSense, and Febus for helpful discussions of our observations.

AUTHOR CONTRIBUTIONS

According to the CRediT Taxonomy: Conceptualization: all authors; Data curation: TF, LH; Formal analysis: TF, FM, LH, HX; Investigation: TF, LH, RWS, AR, HX; Methodology: TF; Project administration: TF, RWS, LH; Resources: RWS, AR, TF, LH, VRT, HX, AS; Software: TF, LH; Visualization: TF, FM; Writing—original draft: TF, VRT, LH, FM; Writing—review & editing: all authors

SUPPLEMENTARY MATERIAL

Supplementary data are available at [GJIRAS](https://www.gjiras.com) online.

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Supplementary material is provided in a PDF file, which shows time-series examples for all IUs and all earthquakes listed in Table 2. We discuss these signals, their similarity and differences. This is complemented by a discussion of scaling factors potentially affecting the strain amplitude presented by the IUs. For all IUs, a spectral analysis of the background signal in a time window before and after swapping the fiber routes is presented, as well as a waveform example with and without subtraction of the reference coil signal. IU configuration parameters are given in tables. The supplementary text further discusses timing accuracy, the means used to locate the individual channels in the mine, and the accuracy by which this can be done. For the marks SPP1–SPP7 in Fig. 4 their location is given in terms of offset to the IU along the fiber route as well as their UTM coordinates.

DATA AVAILABILITY AND RESOURCES

All data were recorded locally at Black Forest Observatory [BFO] (1971, <https://dx.doi.org/10.5880/BFO>). Strainmeter and seismometer data are available through data centers at the Scripps Institution of Oceanography (1986, <https://dx.doi.org/10.7914/SN/II>) and the Federal Institute for Geosciences and Natural Resources, BGR (1976, <https://dx.doi.org/10.25928/MBX6-HR74>), respectively. Data and software used in this paper are provided for download by T. Forbriger *et al.* (2026, <https://dx.doi.org/10.35097/gj4yg6478gtesxdw>). Data analysis was carried out with ObsPy (The ObsPy Development Team 2022, <https://dx.doi.org/10.5281/zenodo.6327346>).

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