

Electronic supplement to *Measuring rock strain with distributed acoustic sensing (DAS) and cemented patch cables*

Thomas Forbriger, Felix Münch, Laura Hillmann, Verónica Rodríguez Tribaldos,
Rudolf Widmer-Schmidrig, Han Xiao, Andreas Rietbrock, Angelo Strollo, Philippe Jousset

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S1 Introduction

This supplement adds some technical details regarding the location and time accuracy as well as signal amplitude scaling. Results for all the analyses discussed in the main manuscript are displayed here for each of the

interrogator units (IUs) separately. Though we do not intend to rank the IUs in any way. Please consider the respective comment in section S5 ‘Interrogators’.

S2 Channel locations

Individual sensors, such as seismometers, have a known location that is selected and georeferenced during installation. In contrast, an optical fiber is a spatially extended sensor that, in our case, was folded multiple times over a distance of more than 1 km in a narrow tunnel. Specific DAS channels located in the ‘Vorstollen’, for example, are identified by their distance to the IU. Establishing this connection between linear distance and specific location in the case of a fiber with multiple folds is a challenge in itself.

The most reliable basis for this are so-called tap-tests. Vibrations are excited at well defined locations in the tunnel by tapping on the ground (we stamped a foot on the concrete floor next to the mark). In order to improve the location accuracy as much as possible, tap tests were recorded using a short GL and small channel interval (both typically 1 m or 2 m) on 2024-02-16, prior to the actual experiment which had a larger GL and channel interval. The tap test signals were identified in the data and the linear distance to the IU was determined. Despite the small GL and channel interval during the tap test, there remains a significant inaccuracy for at least three reasons: 1) the vibrations propagate as elastic waves and are present on several channels, 2) optical fading modulates the signal amplitudes between channels, such that the channel of largest amplitude might not be the closest to the tap, and 3) signal to noise ratio at small GL typically is reduced and some of the tap signals might be missed. For this reason, we have cross-checked the consistency of the tap-test results against distance marks printed on the fiber

and against OTDR measurements, which allowed us to identify some (not all) of the fusion splices in the splice boxes. The marks printed on the fibers alone cannot solve the problem, because the concatenation of several fibers accumulates the inaccuracy of pigtail lengths and because the Febus A1-R adds an internal lead-in of approximately 25 m to the total fiber route (where this is not precisely specified in the manual).

We at least know that the section from SPP2 to SPP7 (see Fig. 4 in the main text) is sampled eight times. By taking the distance to SPP7 and averaging over the eight fiber sections, we increase the precision of the optical distances between the marks. The relative distances vary by less than 1 m between the eight sections in most cases. Their inaccuracy increases with distance to SPP7 and can become almost 5 m near SPP2 in some cases. We find the distance between SPP7 in front and behind the splice box east to be (66.7 ± 0.7) m very consistently for all four pairs. This way, we compose Table S1 for the linear distances between the IUs and the marked locations in the mine. The GL of 50 m in the actual experiment is so large that practically every channel along the groove, even those near the splice box east, picks up rock strain signals during earthquakes. By comparison of signal levels along the fiber route, we convince ourselves that the splice box section, as expected from the values in Table S1, becomes apparent by reduced coupling.

The Table S1 is complemented by Table S2 which specifies the absolute coordinates of marked points as derived from geodetic surveying.

Table S1: Distances at which marked locations along the fiber routes are found in the DAS data (see Fig. 4 in the main text). Fiber routes ec1 and ec2 start in the electronics vault and routes lab3 and lab4 start in the Laboratory building. On 2024-03-19 the routes were swapped pairwise in order to rule out that specific properties of data and noise levels are due to one of the cables. The Febus A1-R adds an internal lead-in of approximately 25 m to the total fiber route.

mark	Febus A1-R		ASN OptoDAS		OptaSense QuantX	Terral5 Treble+
	before 2024-03-19 route ec1	after 2024-03-19 route ec2	before 2024-03-19 route ec2	after 2024-03-19 route ec1	before 2024-03-19 after 2024-03-19 route lab3	before 2024-03-19 after 2024-03-19 route lab4
SPP1	442.7 m	459.6 m	434.6 m	417.7 m	926.7 m	930.5 m
SPP2	495.1 m	512.0 m	487.0 m	470.1 m	979.1 m	982.9 m
SPP3	519.5 m	536.4 m	511.4 m	494.5 m	1003.5 m	1007.3 m
SPP4	551.6 m	568.5 m	543.5 m	526.6 m	1035.6 m	1039.4 m
SPP5	577.3 m	594.2 m	569.2 m	552.3 m	1061.3 m	1065.1 m
SPP6	591.9 m	608.8 m	583.8 m	566.9 m	1075.9 m	1079.7 m
SPP7	640.2 m	657.1 m	632.1 m	615.2 m	1124.2 m	1128.0 m
SPP7	706.9 m	723.8 m	698.8 m	681.9 m	1190.9 m	1194.7 m
SPP6	755.2 m	772.1 m	747.1 m	730.2 m	1239.2 m	1243.0 m
SPP5	769.8 m	786.7 m	761.7 m	744.8 m	1253.8 m	1257.6 m
SPP4	795.5 m	812.4 m	787.4 m	770.5 m	1279.5 m	1283.3 m
SPP3	827.6 m	844.5 m	819.5 m	802.6 m	1311.6 m	1315.4 m
SPP2	852.0 m	868.9 m	843.9 m	827.0 m	1336.0 m	1339.8 m
SPP1	904.4 m	921.3 m	896.3 m	879.4 m	1388.4 m	1392.2 m
Start coil	947.1 m	954.0 m	929.0 m	922.1 m	1426.1 m	1419.9 m
End coil	1740.1 m	1188.0 m	1163.0 m	1715.1 m	1636.1 m	1625.9 m

S3 Timing accuracy

As discussed in the main text, timing was provided to the QuantX and the Treble+ through GPS antennas. The A1-R also used a GPS signal provided through an optical link (Meinberg GOAL: GPS Optical Antenna Link). For the OptoDAS, GPS reception from the optical link was unsuccessful and time was synchronized to a 1 PPS signal and the 10 MHz signal from the GOAL.

We checked the timing accuracy by cross-correlating signals of co-located channels of different IUs for the short period signals of the earthquakes near Albstadt and Italy (see Table 2 in the main text). We find timing offsets between 6 ms and 40 ms, which are not exactly stable over a longer period of several days. While the origin of these offsets is not known, they do not affect the results for the low-frequency investigations (marine microseism background and the Hualien City earthquake).

For the short period earthquakes, the time offsets still are smaller than the shortest investigated signal period band of 55 ms to 333 ms for the Albstadt earthquake. To reduce their potential impact, we have time shifted the signals during analysis by the offset measured with cross-correlation in order to align the compared signals with each other.

The finite speed of wave propagation along the fiber can add additional signal delays, in particular for surface waves incoming from the east. For the Albstadt earthquake (BAZ approximately to the east), we find an average delay of 2.5 ms over the 10 m channel spacing. This is consistent with a phase velocity of 2.5 km s^{-1} , which is in the expected order or magnitude for surface waves in the local crustal structure.

S4 Optical fibers sensing strain

DAS interrogators in first place measure a change of the phase of the light pulse returned from the fiber with respect to some reference. The phase of light responds to deformation of the fiber mostly due to three mechanisms as illustrated by Miah and Potter (2017, their figure 5): a change of distance the light pulse travelled due to axial strain, a change in core diameter, and a change of refractive index. The full theory is discussed by Budiansky et al. (1979), Giallorenzi et al. (1982), and Kuvshinov (2016), who approach the problem from slightly different perspectives. Non-isotropic strain of the fiber can cause the dielectric tensor of the fiber to become non-isotropic, so that the light pulse experiences birefringence. This is likely to become relevant where the bending radius of the fiber becomes small. We do not consider consequences of this effect.

S4.1 Sensitivity to axial strain

Like it is common in DAS applications, we consider that phase changes of the light pulse are a measure for axial strain in first place. Due to the boundary conditions of a free fiber, the axial extension will also result in a radial compression, controlled by the fibers Poisson's ratio. This must be accounted for in the scaling relation, which we discuss in more detail below. Our setup differs from the commonly assumed in that the fiber is cemented into the concrete floor, which changes the radial boundary conditions and may affect the effective Poisson's ratio. The degree to which this changes the scaling relation is controlled, among other parameters, by the elastic moduli of the tight buffer and coating.

Table S2: UTM32N coordinates of marks in the gallery (see Fig. 4 in the main text).

	easting	northing
SPP1	449858.53	5353094.29
SPP2	449907.03	5353113.53
SPP3	449931.23	5353119.73
SPP4	449951.44	5353144.35
SPP5	449972.55	5353157.78
SPP6	449988.29	5353160.32
SPP7	450037.14	5353159.88
SPP8	450067.41	5353160.58

S4.2 Spurious sensitivity to transverse strain

The fiber embedded in the cement can also experience radial forces. Plane strain within the rock in a direction perpendicular to the fiber, which does not result in an axial strain of the fiber, can in this way cause a signal in IU as well, as changes in core diameter and dielectric tensor result in a phase change of the light pulse as well. We take this as a possible parasitic sensitivity of the fiber, similar to the sensitivity of the strainmeters to vertical displacement at high frequencies. The level of this sensitivity is unknown, because of the elastic moduli of tight buffer and coating are unknown for the specific fibers in use. They are definitely smaller than the moduli of concrete (Kuvshinov, 2016, his eq. 6 and his section ‘3.1 Interaction of fibre with cable’). Nevertheless, strain components in the Rayleigh-wave other than strain in axial direction of the fiber, can contribute an additional, spurious signal in the analyzed examples.

S4.3 Scaling to linear axial strain

Here we summarize the factors controlling the conversion of phase change $\Delta\Phi$ to axial fiber strain ε , which caused the phase change in a typical DAS setup. They are the optical wavelength λ in vacuum of the laser, the refractive index n of the fiber, the opto elastic factor ξ of the fiber, and the gauge length G . The opto elastic factor ξ accounts for the change of refractive index and core diameter, if the fiber gets strained in axial direction, as described by Hartog (2017, his eq. 6.6 in his chapter 6.2). For IUs which convert the phase change $\Delta\Phi$ directly to fiber strain

$$\varepsilon = \frac{\lambda \Delta\Phi}{4\pi n G \xi} \quad (S1)$$

the respective equation is given in the document by SEAFOM (2024, their EQ 10).

λ is an instrument property of the IU and G is set by the configuration for the experiment. n and ξ , however, are properties of the fiber being in use. Their exact values are not available to the IU and some of the IUs use standard values for fused silica without allowing to adjust them in the configuration. In fact, the fiber manufacturers commonly do not specify the exact values for their fibers.

During the fabrication process of the fiber n is adjusted by dopants (Sillard and Molin, 2017, their section 2.2.3 Fiber Fabrication). This at least is needed to separate the cladding from the core to provide total reflection but does not change n by more than 1 %. In graded fibers n varies continuously with the radius (Horiguchi et al., 1980, their Figure 9). Further, the index of refraction is dispersive (Lee et al., 2016). At $\lambda = 1550\text{nm}$,

the wavelength used by the IUs in the current experiment, the value for the fiber typically falls in the range of $n = 1.46$ to 1.47 . In the absence of more accurate values a choice of $n = 1.47$ appears reasonable.

Abe et al. (1995) have explored the range for the reciprocal of ξ at large strain for various specimens of fibers and find values of $\xi^{-1} = 1.26$ to 1.30 for the smaller strain values and $\lambda = 1550\text{nm}$. This range corresponds to $\xi = 0.77$ to 0.794 . $\xi = 0.78$, a value consistent with the elastic parameters of silica (Giallorenzi et al., 1982, their eq. 1), appears to be a reasonable choice if no information regarding the actual properties of the fiber are available.

The opto elastic factor might differ from the value of $\xi = 0.78$ in the current setup, because the fibers are cemented into the groove, which changes the boundary conditions with consequences for the transverse contraction. The unknown elasticity of the coating and tight buffer would control how strong this effect might be. The radial boundary conditions applied to the cemented fiber would rather reduce the amplitude of radial strain and hence would likely decrease the change in optical path length and hence phase change $\Delta\Phi$, as well as ξ . We base this conclusion on the theory presented by Kuvshinov (2016, his eqs. 6 and 8).

Kuvshinov (2016, his eq. 6) expresses the relative change in optical path length

$$\frac{\Delta L_0}{L_0} = 0.7 e_{zz}^{(f)} - 0.2 e_{\perp}^{(f)} \quad (S2)$$

in terms of the longitudinal (axial) strain $e_{zz}^{(f)}$ inside the fiber and the transverse strain $e_{\perp}^{(f)}$. According to his eq. 8 the transverse strain is

$$e_{\perp}^{(f)} = -2\nu_f e_{zz}^{(f)} \quad (S3)$$

for a free fiber with Poisson’s ration ν_f . If $\nu_f = 0.2$, like suggested by Kuvshinov (2016), then

$$\frac{\Delta L_0}{L_0} = 0.7 e_{zz}^{(f)} + 0.2 \times 2 \times 0.2 e_{zz}^{(f)} \quad (S4)$$

$$= 0.7 e_{zz}^{(f)} + 0.08 e_{zz}^{(f)} \quad (S5)$$

$$= 0.78 e_{zz}^{(f)}, \quad (S6)$$

which matches the standard value for the opto elastic factor $\xi = 0.78$ in a free fiber. The cemented fiber, however, experiences boundary conditions, which potentially reduce the amount of transverse contraction $e_{\perp}^{(f)}$. Hence the second term in Eq. (S2) would become smaller in magnitude and the total factor scaling $e_{zz}^{(f)}$ to $\Delta L_0/L_0$ would become closer to 0.7 (rather than closer to 1) in Eq. (S6). Hence the amplitude of apparent strain ε derived from the DAS data by Eq. (S2) would be smaller than the actual fiber strain (not larger), if a

value of $\xi = 0.78$ (which would be too large then for the cemented fiber) is used for the opto elastic factor in the conversion.

S5 Interrogators

In the following section we list selected recording parameters for each of the IUs (interrogator units). We supplement the figures from the main manuscript with diagrams for each of the IUs. Before doing so, we repeat a statement from the main manuscript, regarding 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 analyzed frequency bands for the four IUs have been chosen as similar as possible, which in turn means, that these parameter might not be optimal for each of the IUs. In the data we find details, which we still do not fully understand like the modulation of signal amplitude with frequency in Fig. S24, narrow-band elevated signal levels in Figs. S31 and S32, or single channels of elevated noise level like in Fig. S15. 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.

S5.1 Waveform diagrams

The effect of subtracting the average of signals recorded on the reference coils is demonstrated by showing strain seismograms for the Taiwan earthquake with (top of Figs. S1, S9, S17, and S25) and without (bottom of the same figures) this procedure being applied, which potentially reduces coherent noise from the recordings. This measure of noise reduction is applied to the fiber-strain seismograms for the Albstadt and the Italy earthquake, respectively, of the A1-R (Figs. S3 and S5), QuantX (Figs. S11 and S13), and OptoDAS (Figs. S19

S4.4 Sensitivity to temperature

The temperature sensitivity of the refractive index lies in the order of magnitude of 10^{-5} K^{-1} and is large enough to cause an apparent strain signal due to temperature variation. It is however negligible with respect to its consequences for signal amplitude scaling.

and S21), but not for the Treble+ (Figs. S27 and S29). For background levels of rms-amplitude both versions are shown before swapping the fiber routes (Figs. S7, S15, S23, and S31) and after swapping the routes (Figs. S8, S16, S24, and S32). See the figure captions for details.

S5.2 Waveform residuals

The waveform similarity in most cases is so high that a visual comparison of traces, be it between DAS signals and strainmeter signals or be it in an intercomparison of DAS signals, shows almost no obvious differences. For this reason we also compute numerical signal differences and show diagrams of these. Please note that the vertical scale and the offset between traces is adjusted to the signal amplitude. Values on the vertical scale must be read to compare signal amplitudes in the diagrams of the residual waveforms quantitatively.

S5.2.1 Differences between DAS and strainmeters

For the Taiwan earthquake a reasonable comparison with the strainmeters is possible and we show difference waveform with respect to the strainmeter signal. Where no noise reduction is applied to the signals of A1-R (Fig. S2 bottom) and QuantX (Fig. S10 bottom) only the stationary coherent background noise dominates the residual. For the Treble+ incoherent stationary noise dominates in both cases, with and without the reference coil signal being subtracted (Fig. S26 bottom). Only for the OptoDAS a faint signature of the earthquake wavegroups seems to become apparent in the residual even if no noise reduction is applied (Fig. S18 bottom). When the noise reduction is applied the A1-R (Fig. S2 top), QuantX (Fig. S10 top), and OptoDAS (Fig. S18 top) show clear signatures of the SS-phase and Rayleigh wavegroups in the residual, though at only a fraction of the amplitude of the full signal. Having a careful look at the full signal waveforms for the A1-R (Fig. S1 top), QuantX (Fig. S9 top), and OptoDAS (Fig. S17 top) we notice that the amplitudes of the Rayleigh wave train match between strainmeters and DAS traces, while the SS-phase amplitude (at 500 s on the time scale and different to other body waves) on the strainmeter is clearly

smaller than the signal on the DAS traces. This corresponds with the SS-phase residual being of an amplitude similar to the Rayleigh-wave residual (top diagrams in Figs. S2, S10, and S18).

We postulate that this is a result of strain-strain coupling as a consequence of local surface topography. All wavegroups and the non-plane Rayleigh waves in particular are dominant in different components of the strain tensor. Strain-strain coupling due to topography, as discussed in detail by Berger and Beaumont (1976) and Harrison (1976), couples the various strain components into the measured horizontal linear strain in N90°E azimuth, where the coupling coefficients depend on strain component, as well as on location with respect to topographic features and thus differ for the location of the strainmeters and the ‘Vorstollen’. Considerations of strain-strain coupling have been applied to normal mode strain observations by Zürn et al. (2015). Although we postulate a consequence of strain-strain coupling, as estimated numerically for the linear strain along the ‘Vorstollen’ by Emter and Zürn (1985) which we discuss in section 3.2 ‘Linear strain from the strainmeter array as a reference’ in the manuscript, we cannot rule out contributions by parasitic sensitivities of the instruments. The parasitic response to vertical ground motion in the strainmeters becomes significant only at frequencies above the resonance (expected around 5 Hz) of the mass-spring system of the pickup. Nevertheless, this might be in effect at a smaller level at smaller frequencies (2nd-order high-pass roll-off) as well. At the same time the DAS fibers cemented into the floor might experience radial forces and thus a transverse strain (a sensitivity obvious due to the response to pressure in a fluid, Godin, 2026), which in our setup cannot be distinguished from the response of refractive index to axial

strain.

S5.2.2 Differences in between DAS channels

For the Italy and the Albstadt earthquake we cannot reasonably compare with the strainmeter data due to the higher frequencies at which the parasitic response of the strainmeters to vertical ground motion becomes significant. We therefore compute differences with respect to the nearest channel in the ‘Vorstollen’ along the fiber route, i. e. an intercomparison of DAS data.

With the Italy earthquake the A1-R residuals (Fig. S6) show only a faint signature of remainders of the earthquake signal in the stationary noise. For the QuantX (Fig. S14) a clear remainder of the earthquake signal is apparent with small differences in between different channels. The relative amplitude of earthquake remainders in the residuals for the OptoDAS (Fig. S22) range in between the previous two. For the Treble+ (Fig. S30) the stationary noise dominates any possible remainder of the earthquake signal.

Remainders of the Earthquake signal show a slightly more systematic behavior for the highest frequencies, which are present in the signals from the Albstadt earthquake. For the QuantX (Fig. S12) and the OptoDAS (Fig. S20) the maximum amplitude of the residual is the larger, the larger the spatial distance (see Table S1) to the reference channel with respect to which the differences are computed. This might indicate that waveform residuals here are predominantly due to phase delays due to the propagation delay of the seismic waves along the fiber. For the Treble+ (Fig. S28) we see a similar tendency, while this is not the case for the A1-R (Fig. S4), even though the maximum amplitudes significantly vary in between channels.

S5.3 Febus A1-R

Table S3: Parameters used by the Febus A1-R interrogator when processing the data in the unit.

Manufacturer:	Febus
Model:	A1-R
Firmware version:	version 2.2.2
Optical wavelength:	1550 nm
Refractive index of the fiber:	1.5 (changed to 1.47 in the preprocessing)
Opto-elastic correction factor:	1 (changed to 0.78 in the preprocessing)
Fiber length:	1200 m
Pulse width:	20 m
Pulse rate frequency:	10 kHz
Block rate:	1 Hz
Amplifier power:	20 dBm
Sampling resolution:	80 cm
Gauge length (GL):	50 m
Derivation time (DT):	20 ms
Spatial sampling interval:	9.6 m
Temporal sampling interval:	5 ms
Downsampling:	with decimation filter
Primarily recorded quantity:	strain-rate

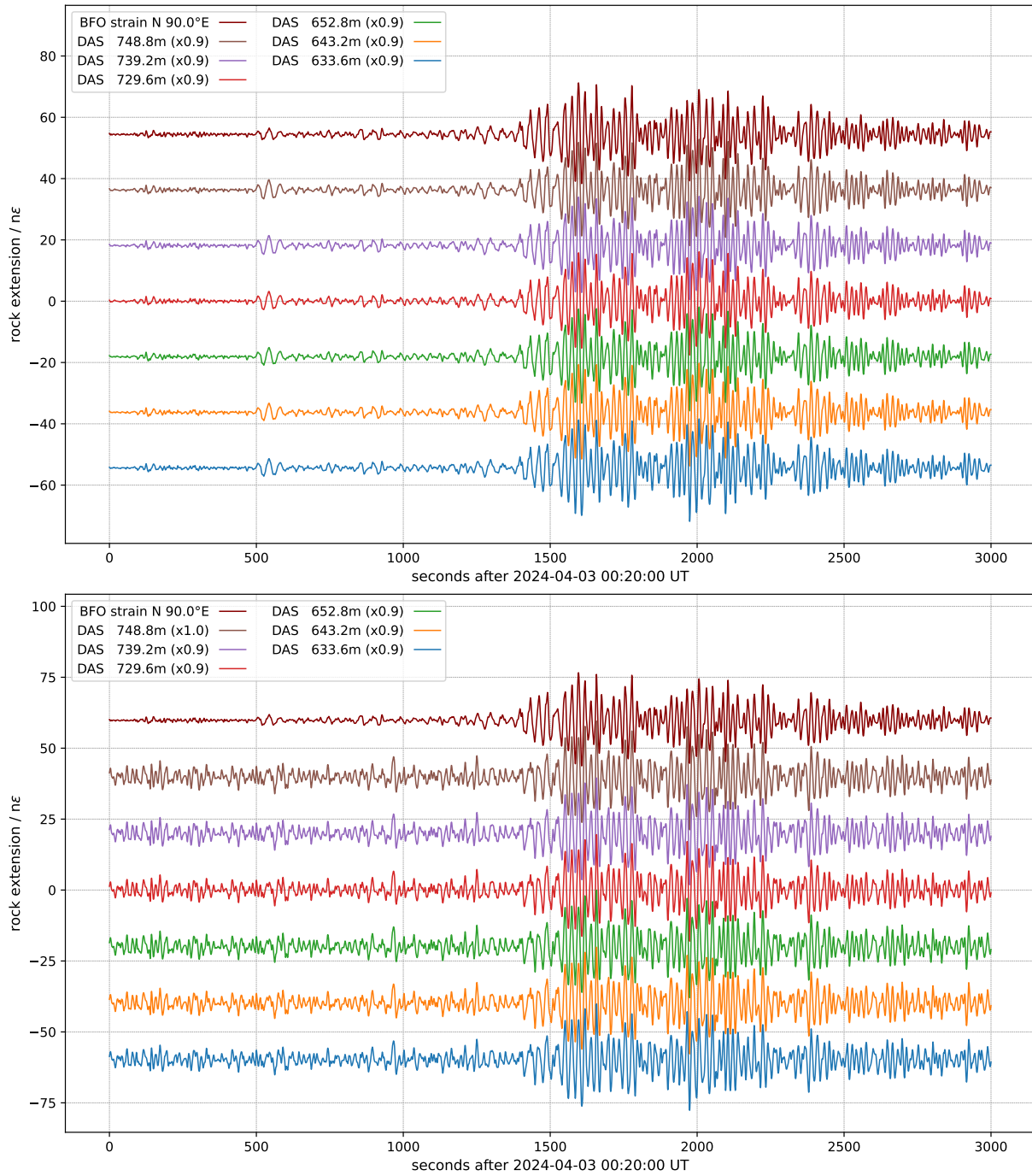


Figure S1: Waveform comparison for the Taiwan earthquake (see Table 2) recorded with the A1-R. The traces are vertically shifted for better visibility of details. The S-phase arrives at about 2024-04-03 00:21 UTC. The P-phase (not shown) does not exceed the noise level. Rayleigh waves arrive after 1300 s on the time scale. All signals are band-passed to frequencies from 20 mHz to 200 mHz. The top trace is the signal from the BFO strainmeters in N90°E azimuth. The other six traces are recorded by the A1-R in the ‘Vorstollen’. Optical channel offset and amplitude scaling factors are given in the legend, where the scaling factors are the reciprocal regression coefficients with respect to the strainmeter (RCS). Upper diagram: The average signal recorded on the reference coils is subtracted. Lower diagram: No noise reduction (based on the reference coils) is applied.

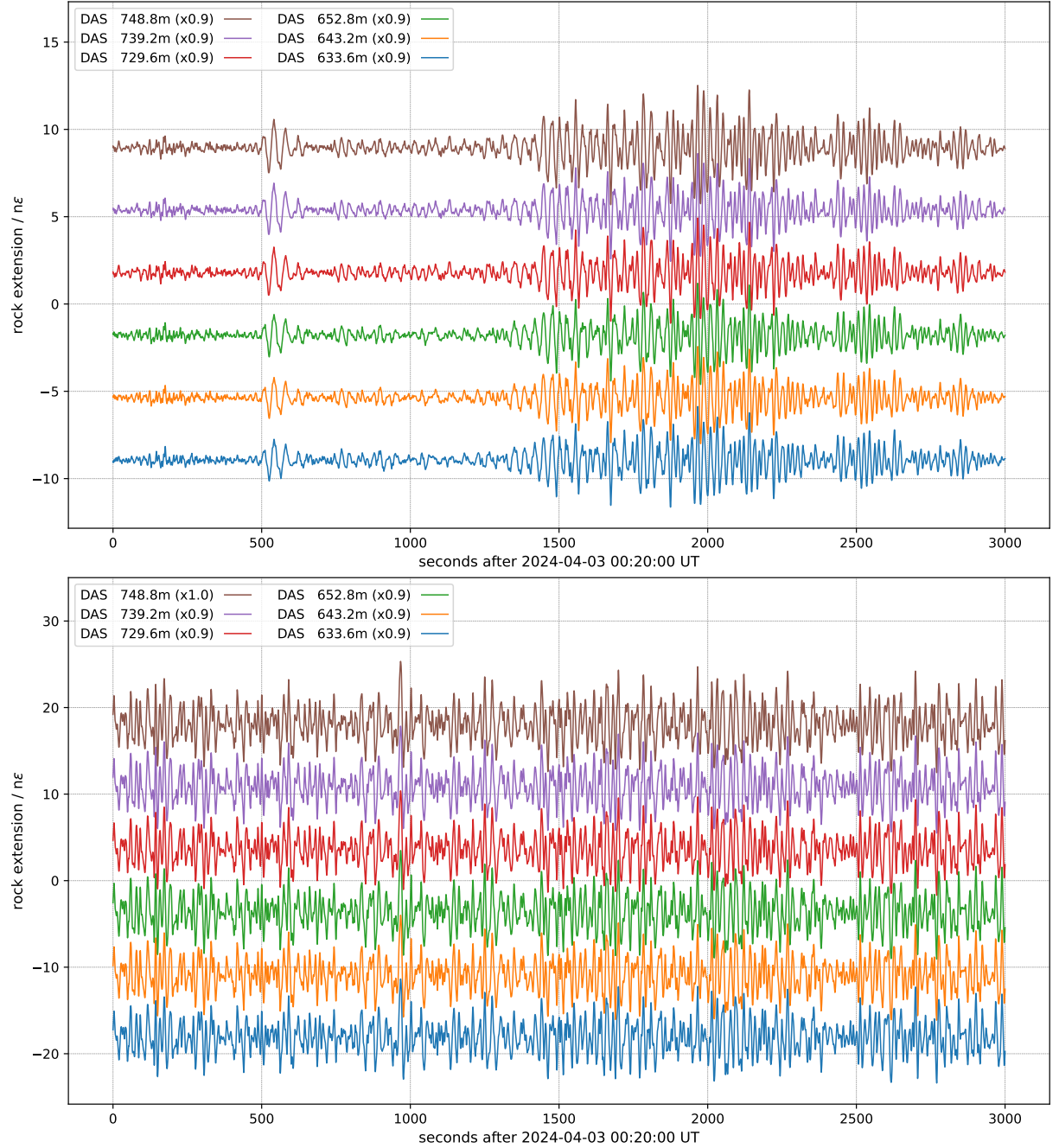


Figure S2: Residuals of waveforms recorded with the A1-R with respect to the BFO strainmeters. The upper and lower diagram correspond to those in Fig. S1. Please note that the amplitude scale in each of the diagrams is adjusted to the signal amplitude.

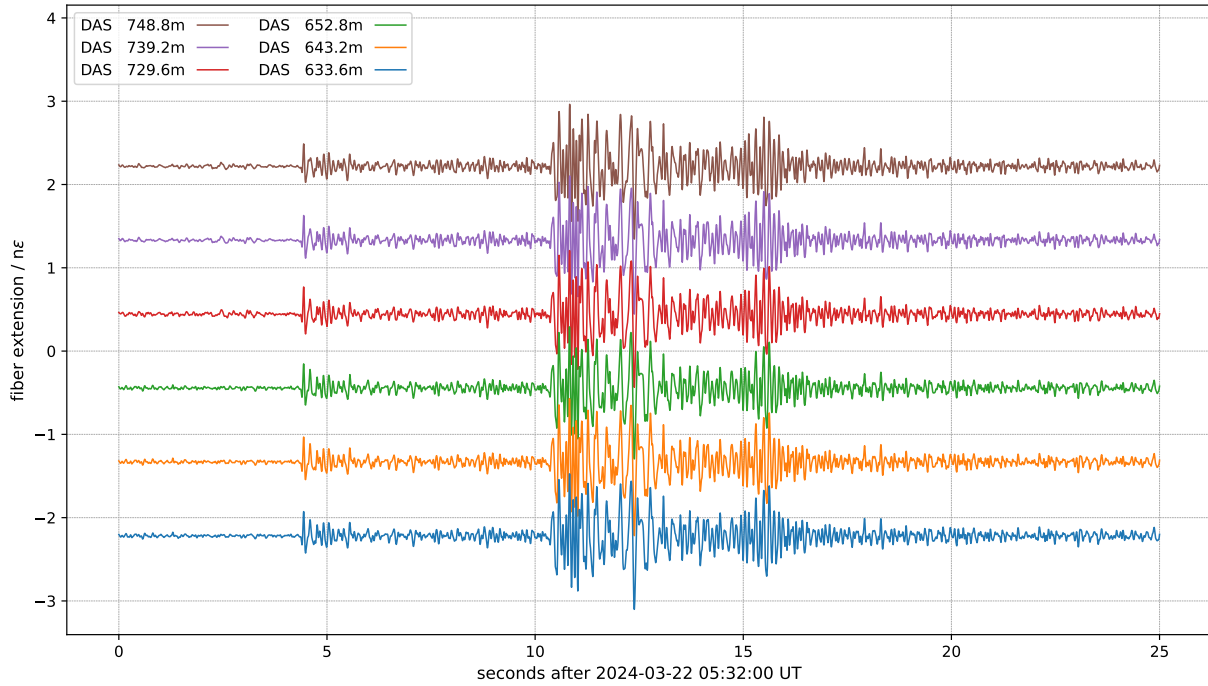


Figure S3: Waveform comparison for the Albstadt earthquake (see Table 2) recorded with the A1-R. All signals are band-passed to frequencies from 3 Hz to 18 Hz. Optical channel offsets (all traces located in the ‘Vorstollen’) are given in the legend. Extension represents ‘fiber strain’. The average signal recorded on the reference coils is subtracted.

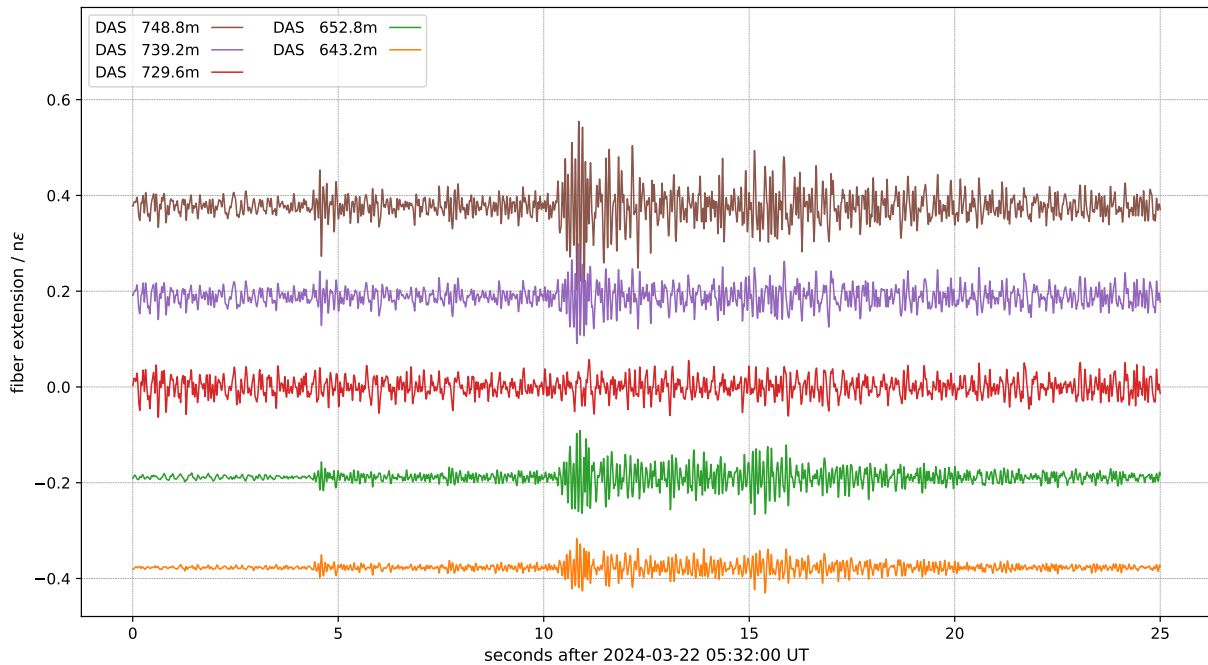


Figure S4: Residuals of waveforms recorded for the Albstadt earthquake (see Table 2) with the A1-R. Residuals are computed with respect to the channel of smallest offset in Fig. S3. Please note that the amplitude scale in each of the diagrams is adjusted to the signal amplitude.

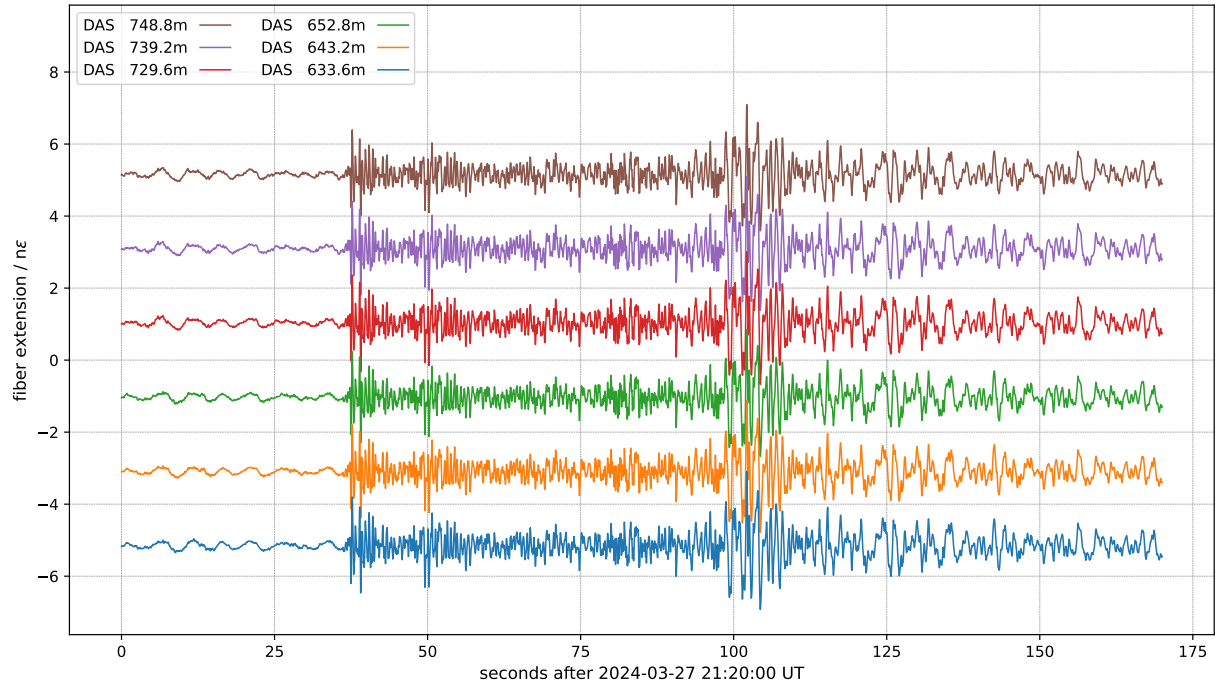


Figure S5: Waveform comparison for the Italy earthquake (see Table 2) recorded with the A1-R. All signals are band-passed to frequencies from 0.2 Hz to 8 Hz. Optical channel offsets (all traces located in the ‘Vorstollen’) are given in the legend. Extension represents ‘fiber strain’. The average signal recorded on the reference coils is subtracted.

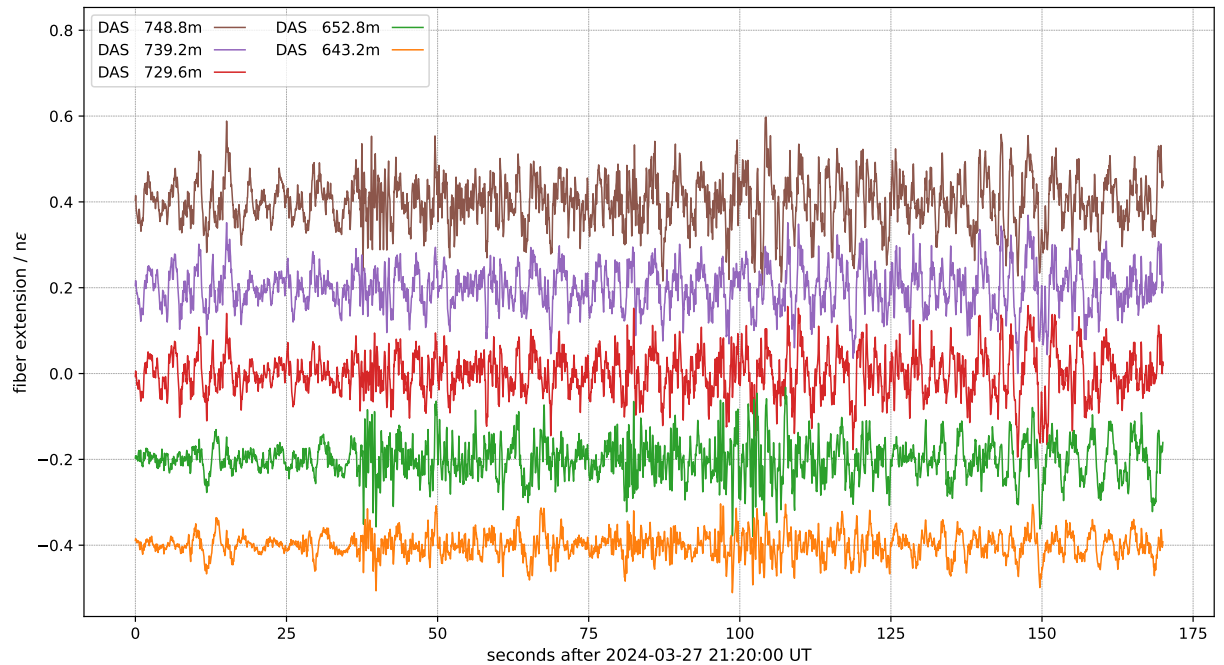


Figure S6: Residuals of waveforms recorded for the Italy earthquake (see Table 2) with the A1-R. Residuals are computed with respect to the channel of smallest offset in Fig. S5. Please note that the amplitude scale in each of the diagrams is adjusted to the signal amplitude.

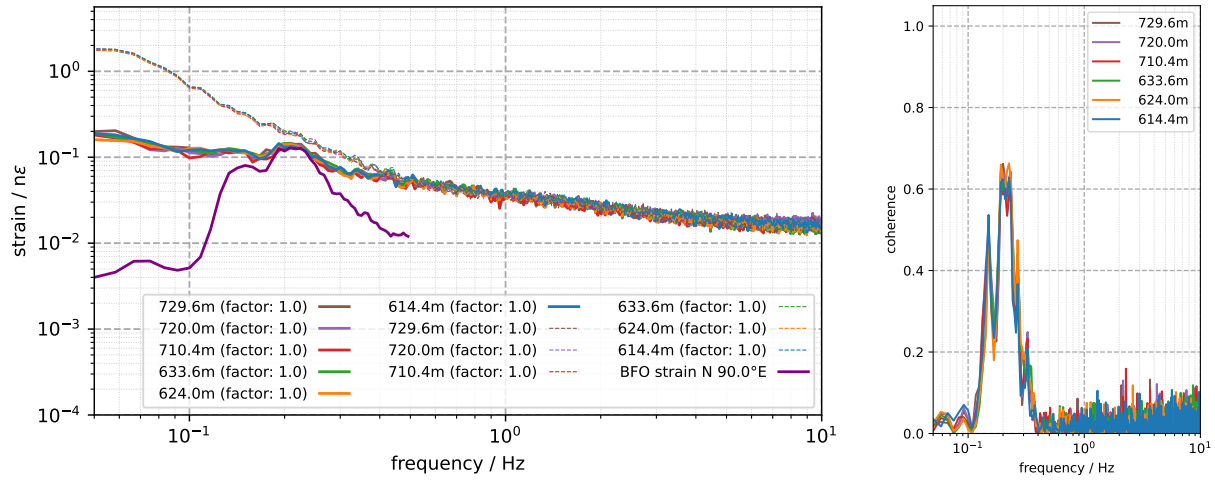


Figure S7: Analysis of the background signal on 2024-03-08 1 UTC to 2 UTC for recordings of the Febus A1-R: rms amplitude in 1/6 decade (left, see section 4.1 by Forbriger, 2023) and magnitude-squared coherence (Carter et al., 1973, their eq. 2) with respect to the BFO strainmeter data (right). The corners 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. Signal amplitudes are not further scaled to correct for ‘strain transfer rate’ (factor: 1.0).

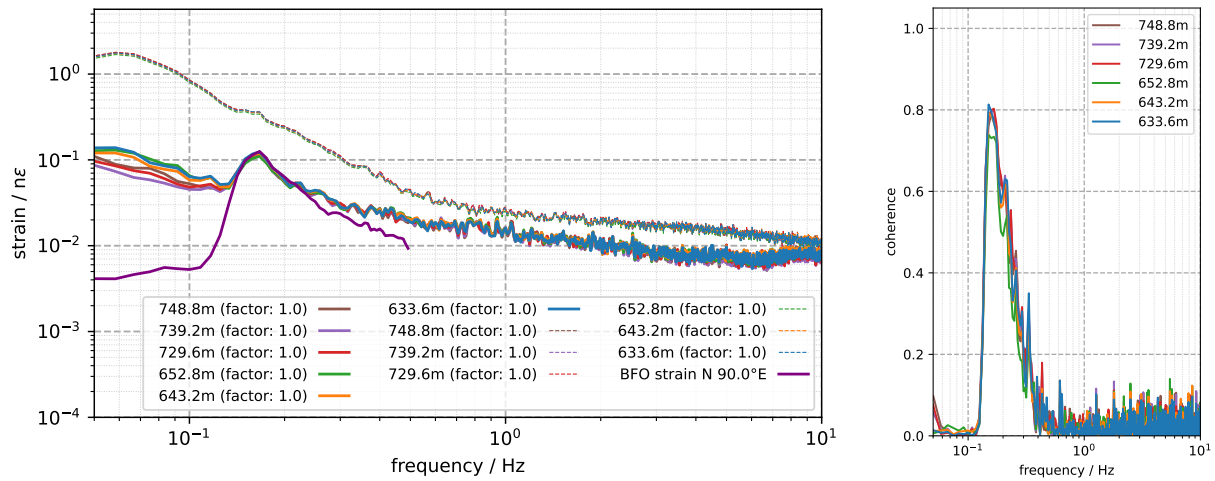


Figure S8: Analysis of the background signal on 2024-03-26 1 UTC to 2 UTC for recordings of the Febus A1-R: rms amplitude in 1/6 decade (left, see section 4.1 by Forbriger, 2023) and magnitude-squared coherence (Carter et al., 1973, their eq. 2) with respect to the BFO strainmeter data (right). The corners 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. Signal amplitudes are not further scaled to correct for ‘strain transfer rate’ (factor: 1.0).

S5.4 OptaSense QuantX

Table S4: Parameters used by the OptaSense QuantX interrogator when processing the data in the unit. Where the data file headers specify more digits, the values have been rounded to three digits.

Manufacturer:	LUNA OptaSense
Model:	QuantX
Firmware Version:	Light Acquisition 5.11.0
Data type:	Diversity Processed Phase XY Dual Pulse Balanced OCP 100
Optical wavelength:	1550 nm
Refractive index of the fiber:	1.47
Opto-elastic correction factor:	0.78
Pulse width:	250 ns
Pulse rate:	10 kHz
Gauge length (GL):	51.0 m
Spatial sampling interval:	10.2 m
Temporal sampling interval:	5 ms
Primarily recorded quantity:	strain

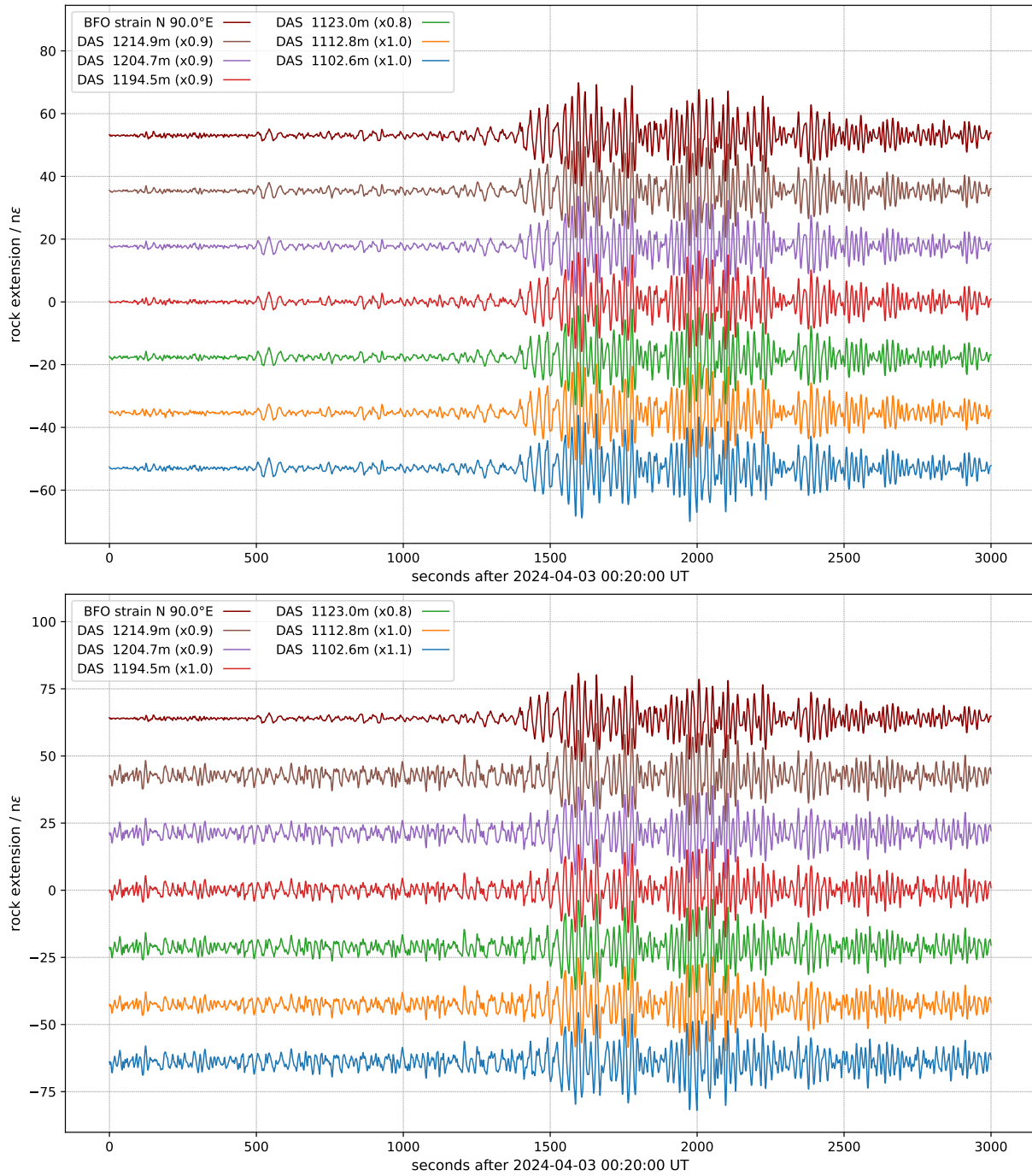


Figure S9: Waveform comparison for the Taiwan earthquake (see Table 2) recorded with the QuantX. The traces are vertically shifted for better visibility of details. The S-phase arrives at about 2024-04-03 00:21 UTC. The P-phase (not shown) does not exceed the noise level. Rayleigh waves arrive after 1300 s on the time scale. All signals are band-passed to frequencies from 20 mHz to 200 mHz. The top trace is the signal from the BFO strainmeters in N90°E azimuth. The other six traces are recorded by the QuantX in the ‘Vorstollen’. Optical channel offset and amplitude scaling factors are given in the legend, where the scaling factors are the reciprocal regression coefficients with respect to the strainmeter (RCS). Upper diagram: The average signal recorded on the reference coils is subtracted. Lower diagram: No noise reduction (based on the reference coils) is applied.

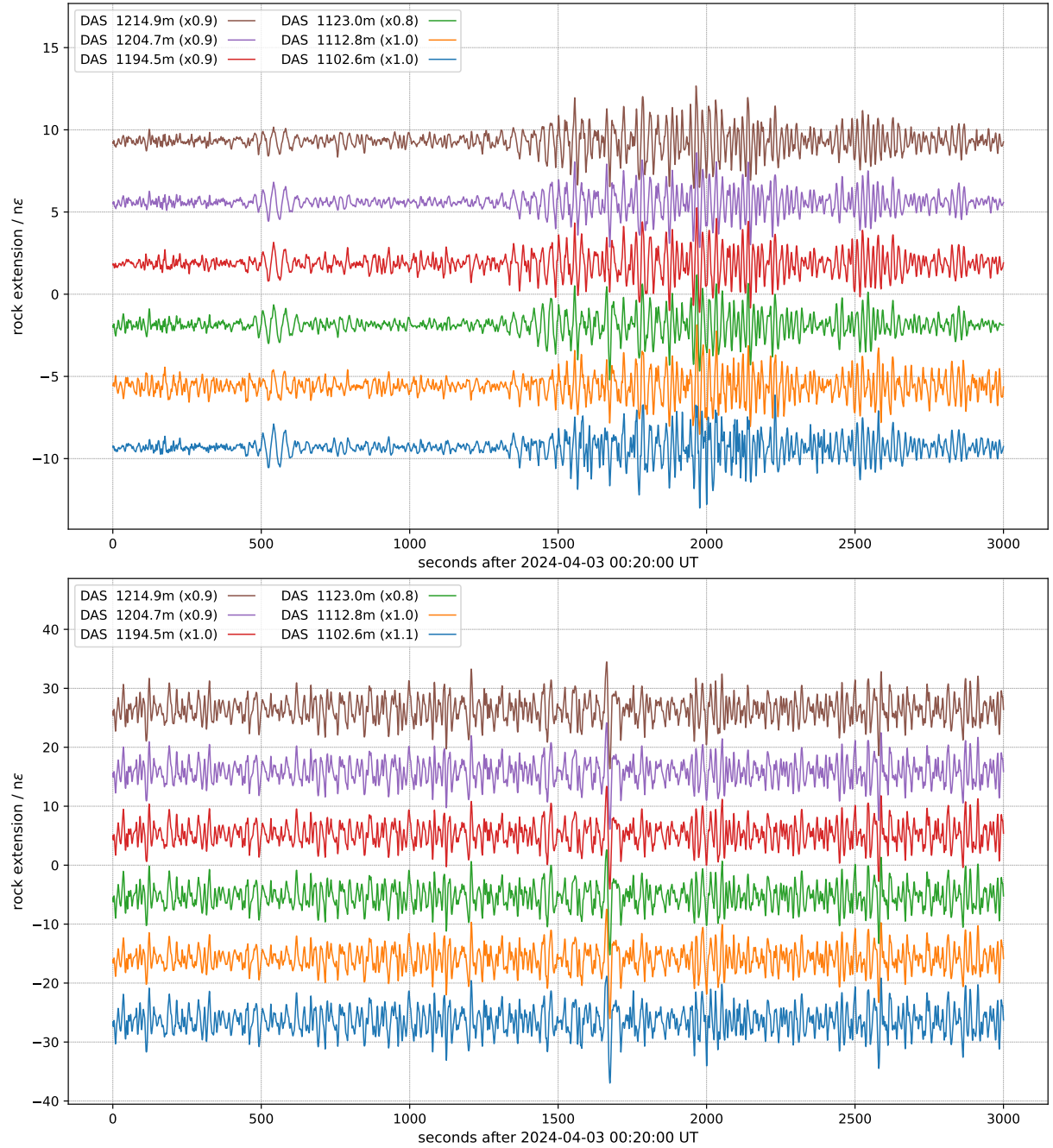


Figure S10: Residuals of waveforms recorded with the QuantX with respect to the BFO strainmeters. The upper and lower diagram correspond to those in Fig. S9. Please note that the amplitude scale in each of the diagrams is adjusted to the signal amplitude.

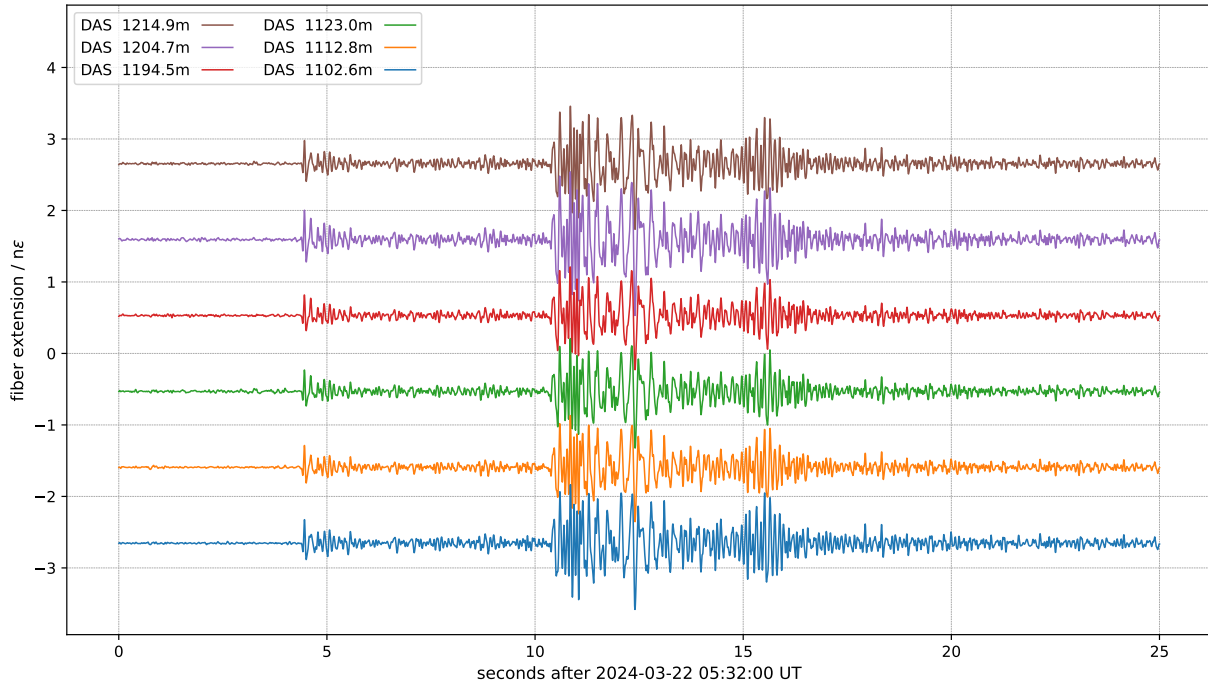


Figure S11: Waveform comparison for the Albstadt earthquake (see Table 2) recorded with the QuantX. All signals are band-passed to frequencies from 3 Hz to 18 Hz. Optical channel offsets (all traces located in the ‘Vorstollen’) are given in the legend. Extension represents ‘fiber strain’. The average signal recorded on the reference coils is subtracted.

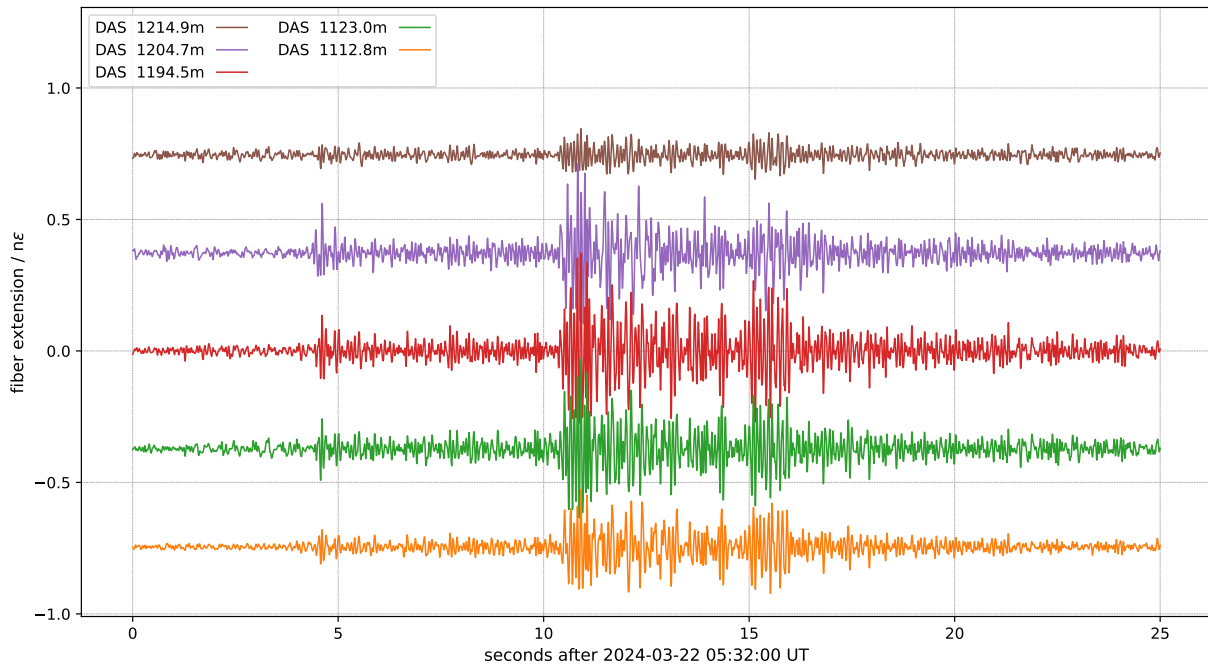


Figure S12: Residuals of waveforms recorded for the Albstadt earthquake (see Table 2) with the QuantX. Residuals are computed with respect to the channel of smallest offset in Fig. S11. Please note that the amplitude scale in each of the diagrams is adjusted to the signal amplitude.

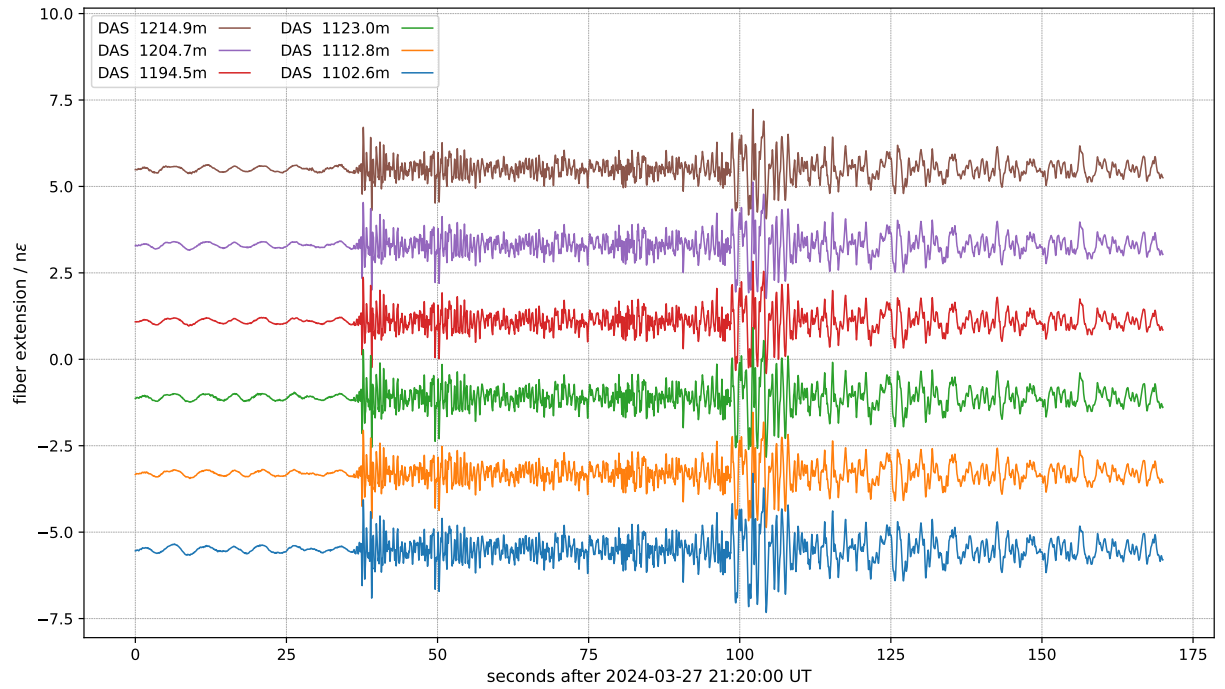


Figure S13: Waveform comparison for the Italy earthquake (see Table 2) recorded with the QuantX. All signals are band-passed to frequencies from 0.2 Hz to 8 Hz. Optical channel offsets (all traces located in the ‘Vorstollen’) are given in the legend. Extension represents ‘fiber strain’. The average signal recorded on the reference coils is subtracted.

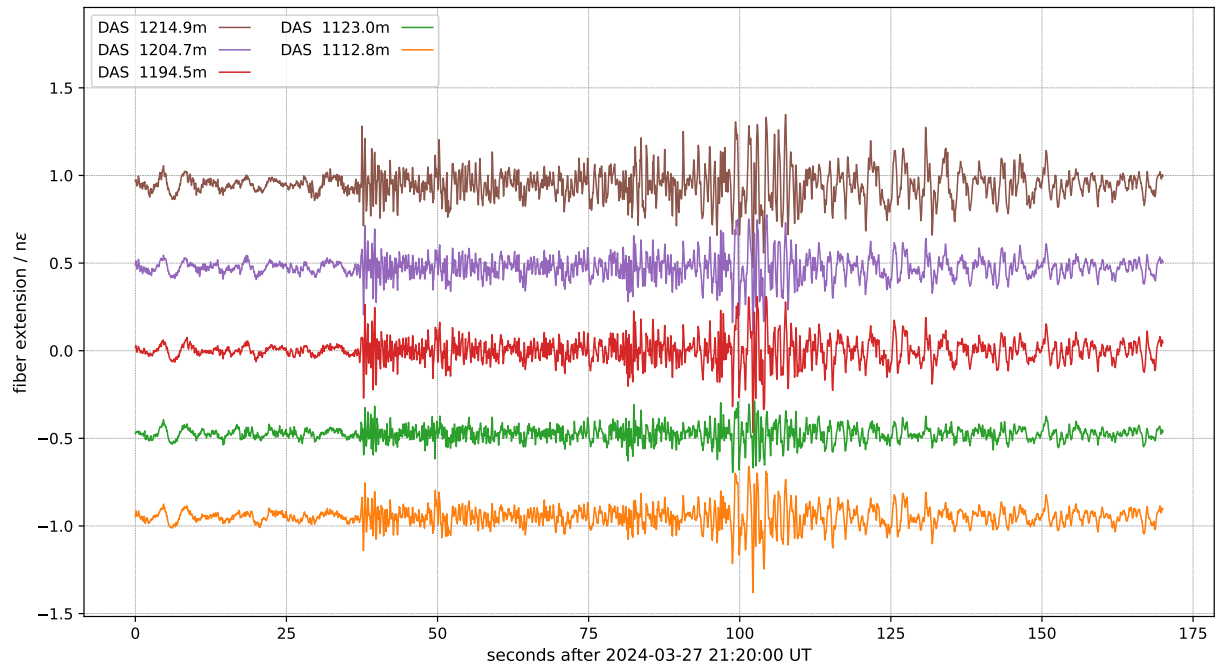


Figure S14: Residuals of waveforms recorded for the Italy earthquake (see Table 2) with the QuantX. Residuals are computed with respect to the channel of smallest offset in Fig. S13. Please note that the amplitude scale in each of the diagrams is adjusted to the signal amplitude.

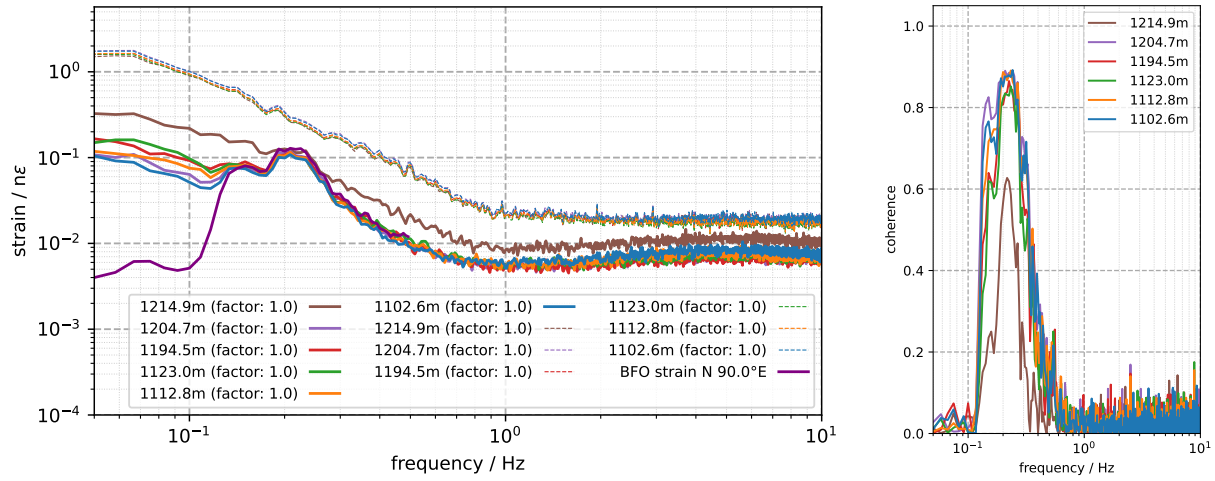


Figure S15: Analysis of the background signal on 2024-03-08 1 UTC to 2 UTC for recordings of the OptaSense QuantX: rms amplitude in 1/6 decade (left, see section 4.1 by Forbriger, 2023) and magnitude-squared coherence (Carter et al., 1973, their eq. 2) with respect to the BFO strainmeter data (right). 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. Signal amplitudes are not further scaled to correct for ‘strain transfer rate’ (factor: 1.0).

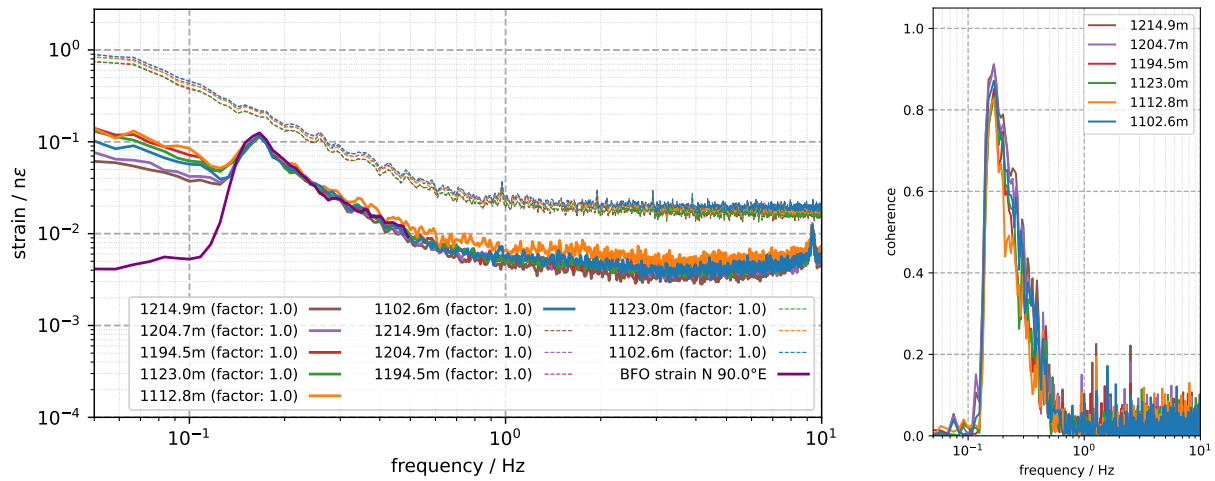


Figure S16: Analysis of the background signal on 2024-03-26 1 UTC to 2 UTC for recordings of the OptaSense QuantX: rms amplitude in 1/6 decade (left, see section 4.1 by Forbriger, 2023) and magnitude-squared coherence (Carter et al., 1973, their eq. 2) with respect to the BFO strainmeter data (right). 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. Signal amplitudes are not further scaled to correct for ‘strain transfer rate’ (factor: 1.0).

S5.5 ASN OptoDAS

Table S5: Parameters used by the ASN OptoDAS interrogator when processing the data in the unit. Where the data file headers specify more digits, the values have been rounded to three digits.

Manufacturer:	Alcatel Submarine Networks (ASN)
Model:	OptoDAS C01-S
Firmware Version:	DasControl Version: 2403011412
Optical wavelength:	1537 nm
Refractive index of the fiber:	1.47
Opto-elastic correction factor:	0.78
Sweep bandwidth:	80 MHz
Length of compressed chirp pulse:	≈ 12.5 ns
Pulse rate:	50 kHz
Gauge length (GL):	40.9 m
Spatial sampling interval:	10.2 m
Temporal sampling interval:	4 ms
Primarily recorded quantity:	strain-rate

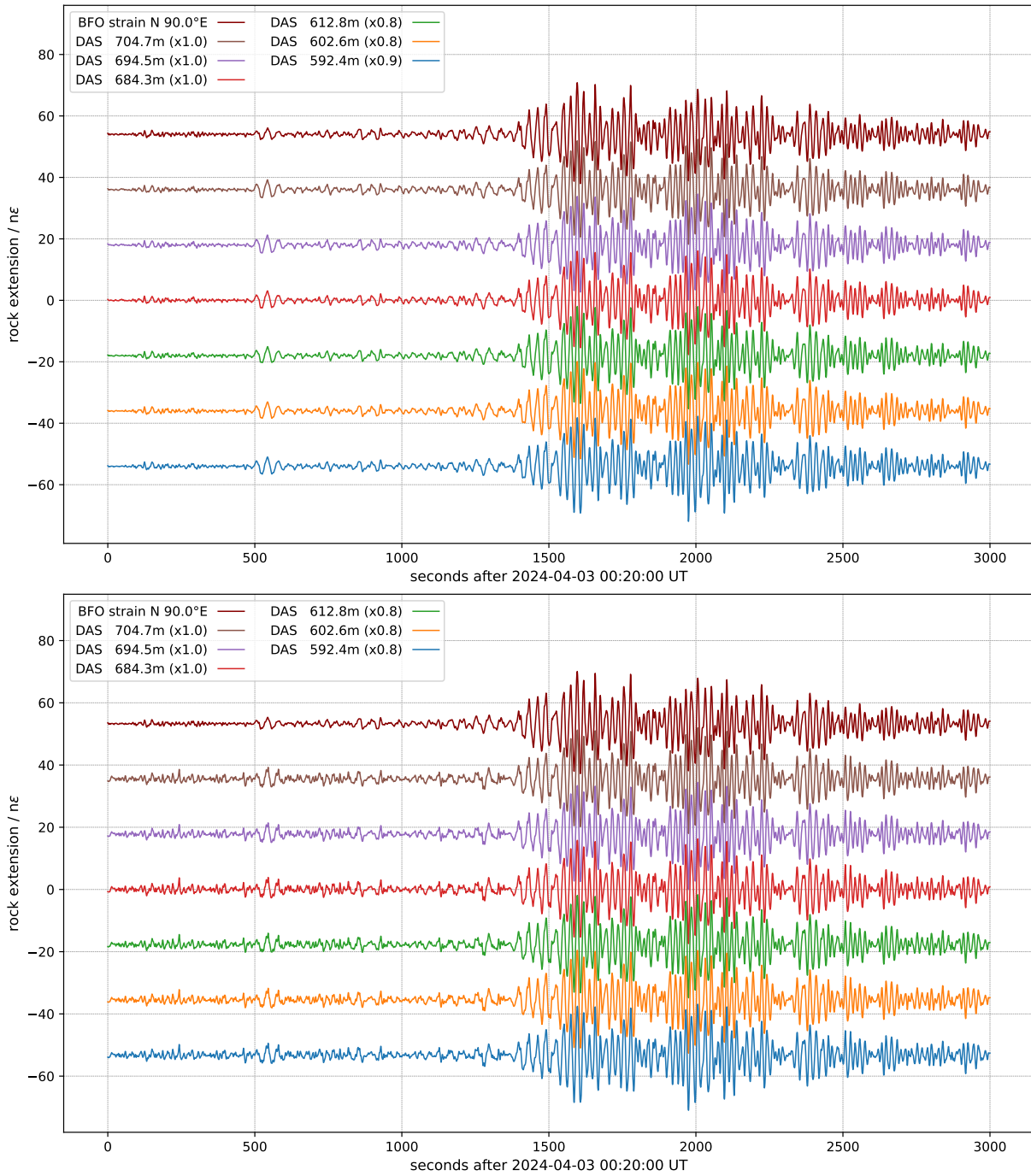


Figure S17: Waveform comparison for the Taiwan earthquake (see Table 2) recorded with the OptoDAS. The traces are vertically shifted for better visibility of details. The S-phase arrives at about 2024-04-03 00:21 UTC. The P-phase (not shown) does not exceed the noise level. Rayleigh waves arrive after 1300 s on the time scale. All signals are band-passed to frequencies from 20 mHz to 200 mHz. The top trace is the signal 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 regression coefficients with respect to the strainmeter (RCS). Upper diagram: The average signal recorded on the reference coils is subtracted. Lower diagram: No noise reduction (based on the reference coils) is applied.

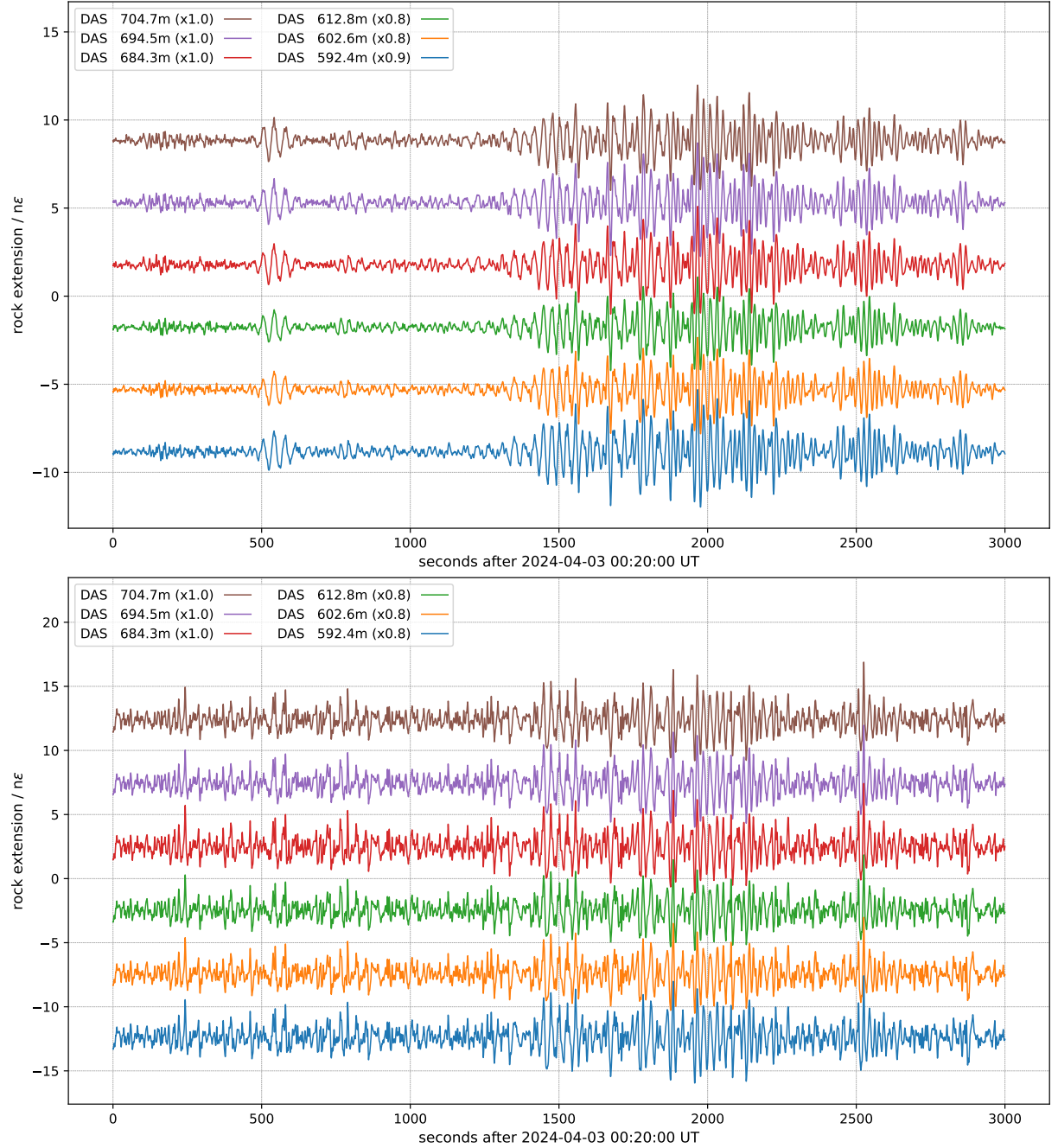


Figure S18: Residuals of waveforms recorded with the OptoDAS with respect to the BFO strainmeters. The upper and lower diagram correspond to those in Fig. S17. Please note that the amplitude scale in each of the diagrams is adjusted to the signal amplitude.

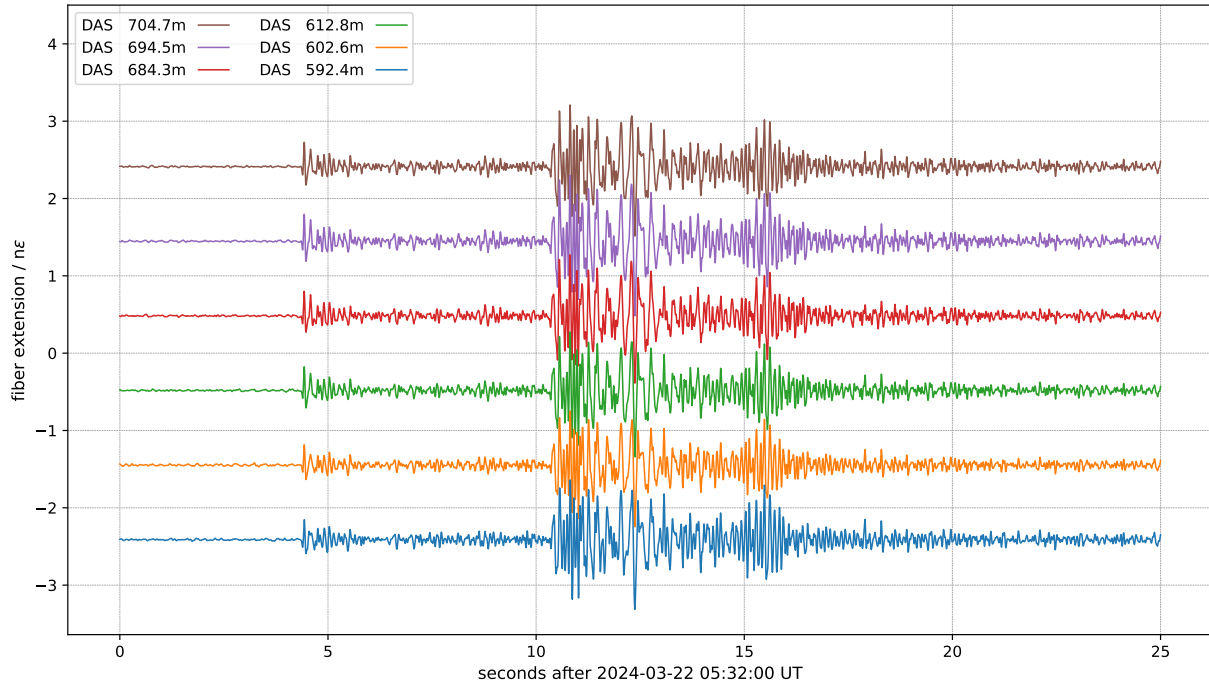


Figure S19: Waveform comparison for the Albstadt earthquake (see Table 2) recorded with the OptoDAS. All signals are band-passed to frequencies from 3 Hz to 18 Hz. Optical channel offsets (all traces located in the ‘Vorstollen’) are given in the legend. Extension represents ‘fiber strain’. The average signal recorded on the reference coils is subtracted.

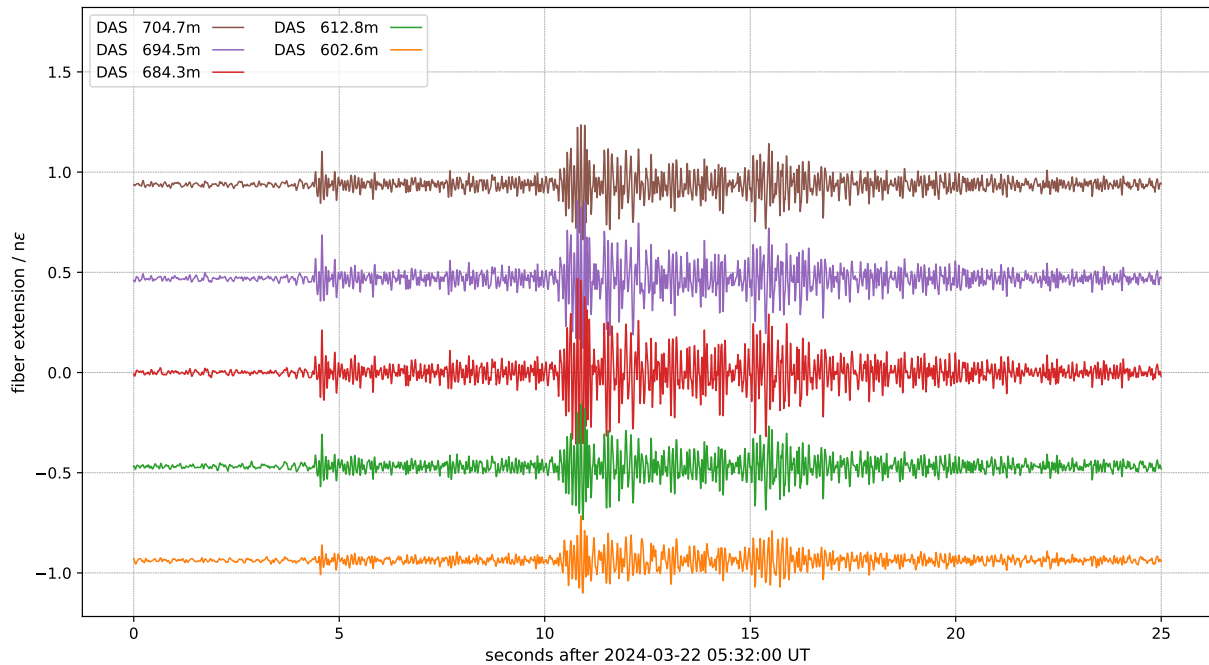


Figure S20: Residuals of waveforms recorded for the Albstadt earthquake (see Table 2) with the OptoDAS. Residuals are computed with respect to the channel of smallest offset in Fig. S19. Please note that the amplitude scale in each of the diagrams is adjusted to the signal amplitude.

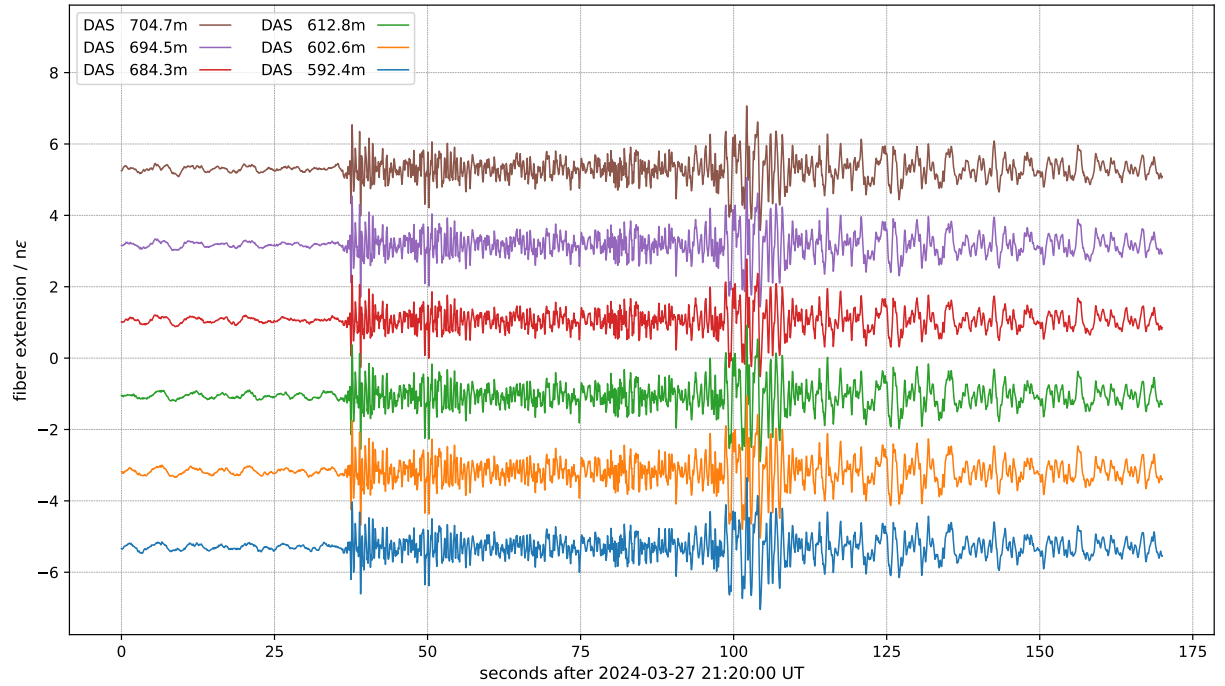


Figure S21: Waveform comparison for the Italy earthquake (see Table 2) recorded with the OptoDAS. All signals are band-passed to frequencies from 0.2 Hz to 8 Hz. Optical channel offsets (all traces located in the ‘Vorstollen’) are given in the legend. Extension represents ‘fiber strain’. The average signal recorded on the reference coils is subtracted.

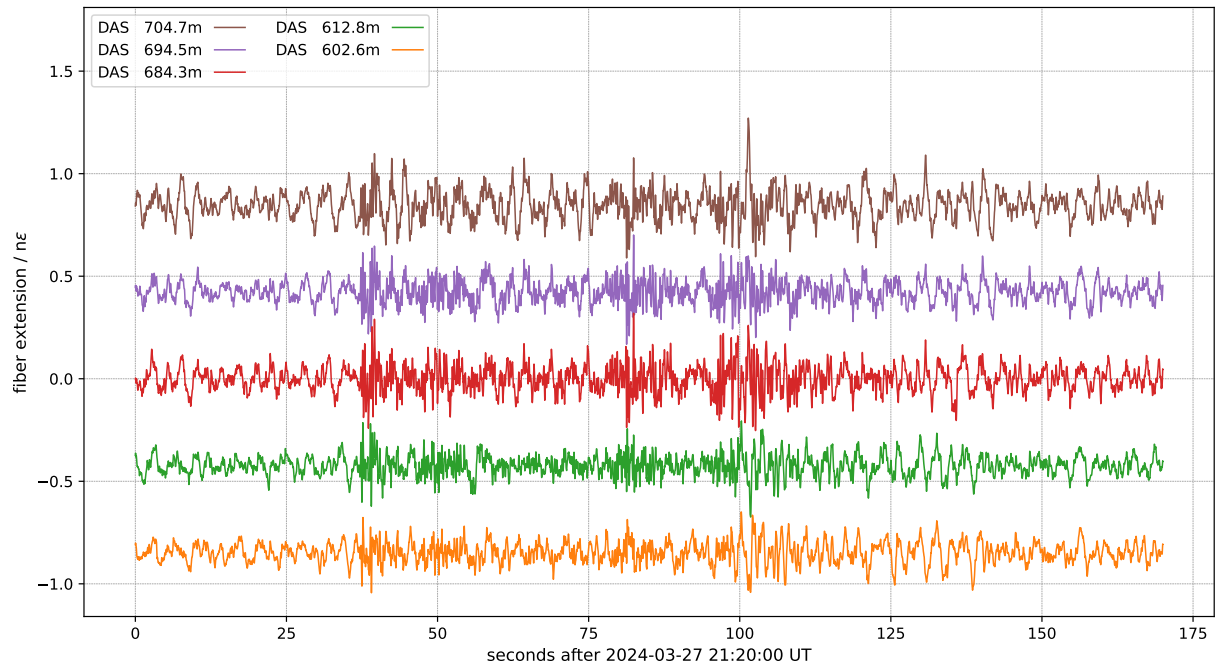


Figure S22: Residuals of waveforms recorded for the Italy earthquake (see Table 2) with the OptoDAS. Residuals are computed with respect to the channel of smallest offset in Fig. S21. Please note that the amplitude scale in each of the diagrams is adjusted to the signal amplitude.

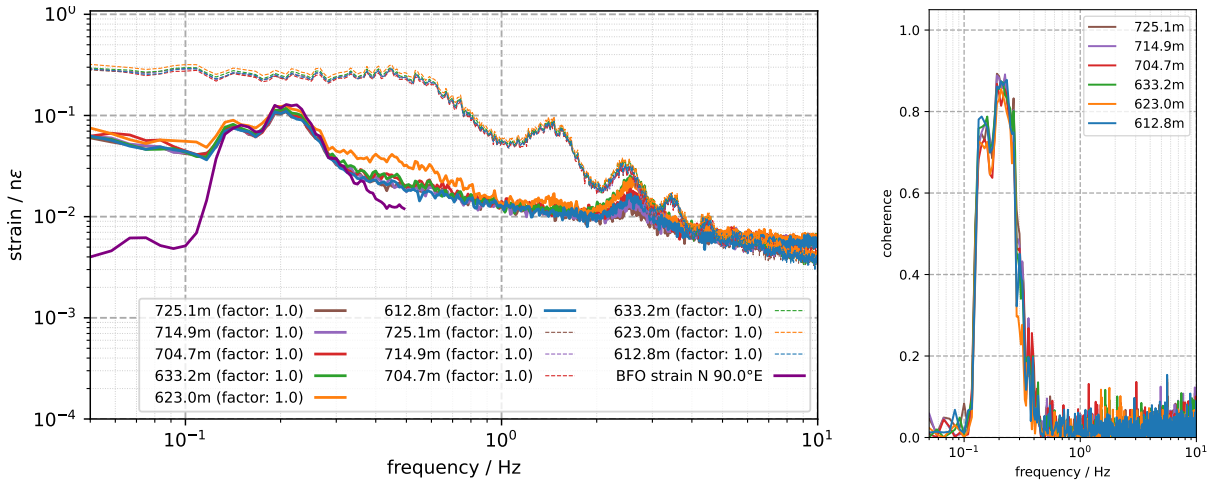


Figure S23: Analysis of the background signal on 2024-03-08 1 UTC to 2 UTC for recordings of the ASN Op-toDAS: rms amplitude in 1/6 decade (left, see section 4.1 by Forbriger, 2023) and magnitude-squared coherence (Carter et al., 1973, their eq. 2) with respect to the BFO strainmeter data (right). The 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. Signal amplitudes are not further scaled to correct for ‘strain transfer rate’ (factor: 1.0).

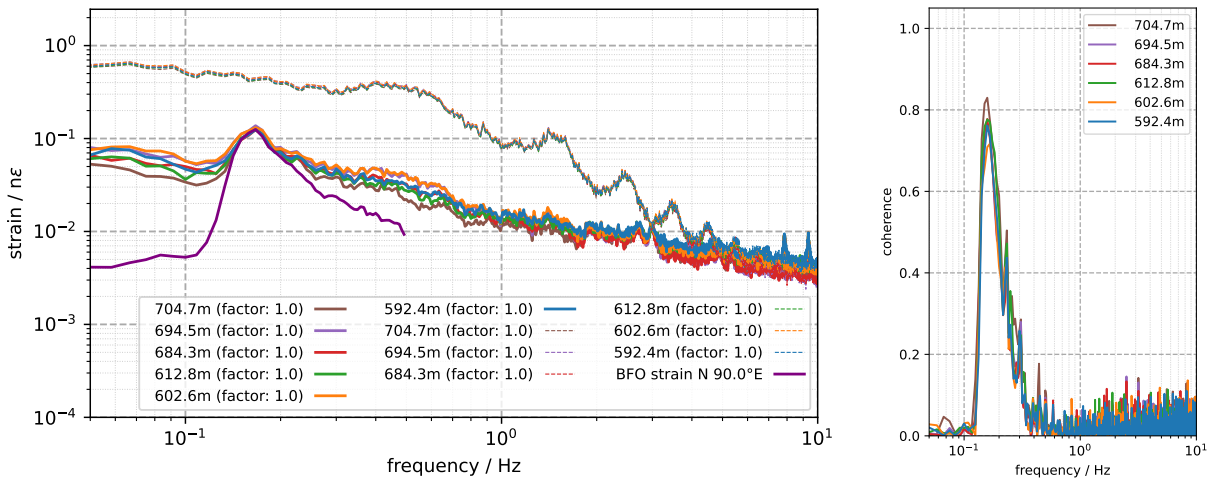


Figure S24: Analysis of the background signal on 2024-03-26 1 UTC to 2 UTC for recordings of the ASN Op-toDAS: rms amplitude in 1/6 decade (left, see section 4.1 by Forbriger, 2023) and magnitude-squared coherence (Carter et al., 1973, their eq. 2) with respect to the BFO strainmeter data (right). The 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. Signal amplitudes are not further scaled to correct for ‘strain transfer rate’ (factor: 1.0).

S5.6 Terra15 Treble+

Table S6: Parameters used by the Terra15 Treble+ interrogator when processing the data in the unit. Where the data file headers specify more digits, the values have been rounded to three digits.

Manufacturer:	Terra15
Model:	Treble+
Firmware Version:	6.4.0rc9
Optical wavelength:	1550 nm
Pulse width:	equals gauge length
Pulse rate:	25.5 kHz
Refractive index of the fiber:	1.47
Opto-elastic correction factor:	1 (changed to 0.78 in the preprocessing)
Gauge length (GL):	49.8 m
Spatial sampling interval:	9.80 m
Temporal sampling interval:	0.51 ms
Primarily recorded quantity:	velocity to be converted to strain-rate

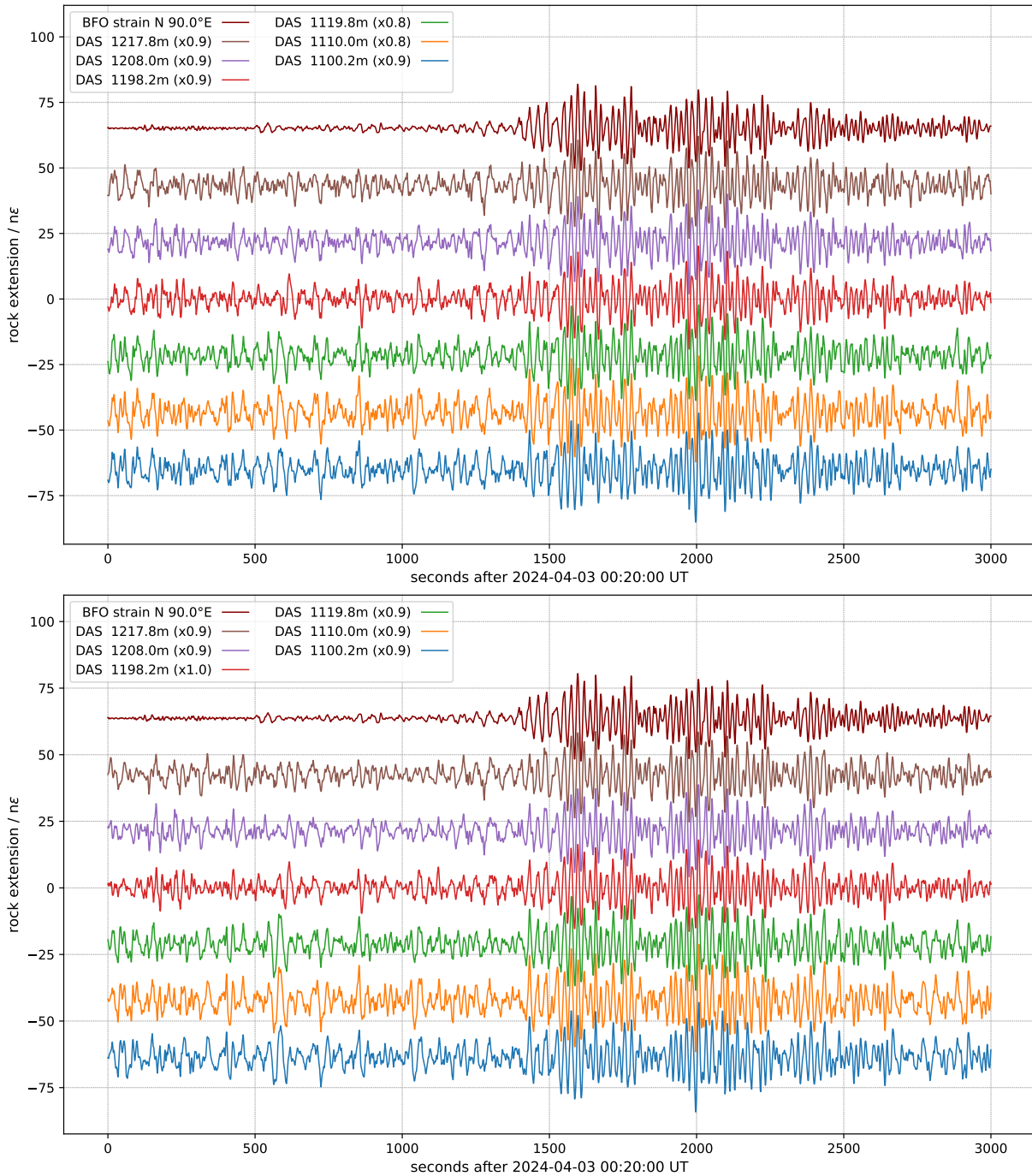


Figure S25: Waveform comparison for the Taiwan earthquake (see Table 2) recorded with the Treble+. The traces are vertically shifted for better visibility of details. The S-phase arrives at about 2024-04-03 00:21 UTC. The P-phase (not shown) does not exceed the noise level. Rayleigh waves arrive after 1300 s on the time scale. All signals are band-passed to frequencies from 20 mHz to 200 mHz. The top trace is the signal from the BFO strainmeters in N90°E azimuth. The other six traces are recorded by the Treble+ in the ‘Vorstollen’. Optical channel offset and amplitude scaling factors are given in the legend, where the scaling factors are the reciprocal regression coefficients with respect to the strainmeter (RCS). Upper diagram: The average signal recorded on the reference coils is subtracted. Lower diagram: No noise reduction (based on the reference coils) is applied.

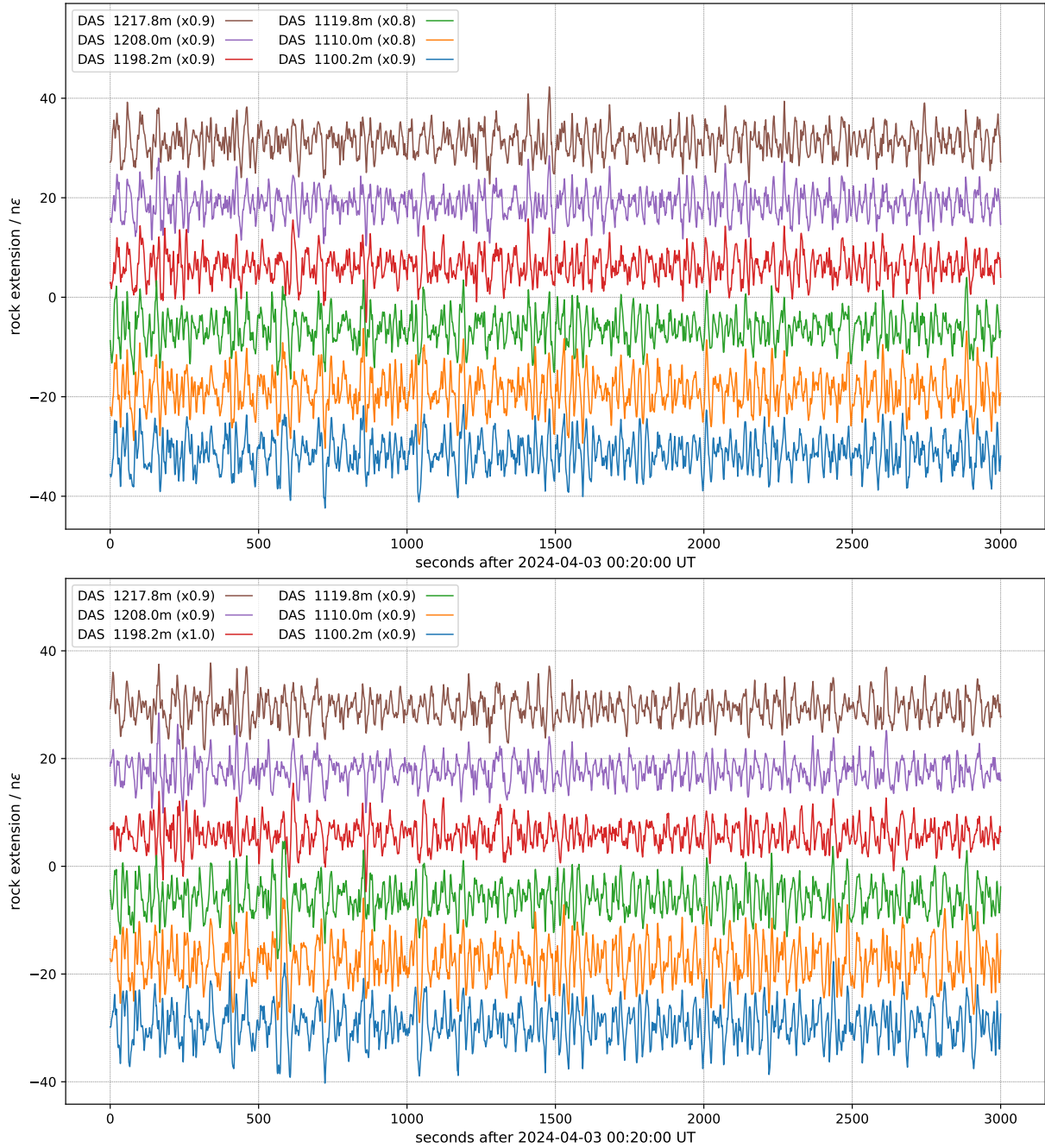


Figure S26: Residuals of waveforms recorded with the Treble+ with respect to the BFO strainmeters. The upper and lower diagram correspond to those in Fig. S25. Please note that the amplitude scale in each of the diagrams is adjusted to the signal amplitude.

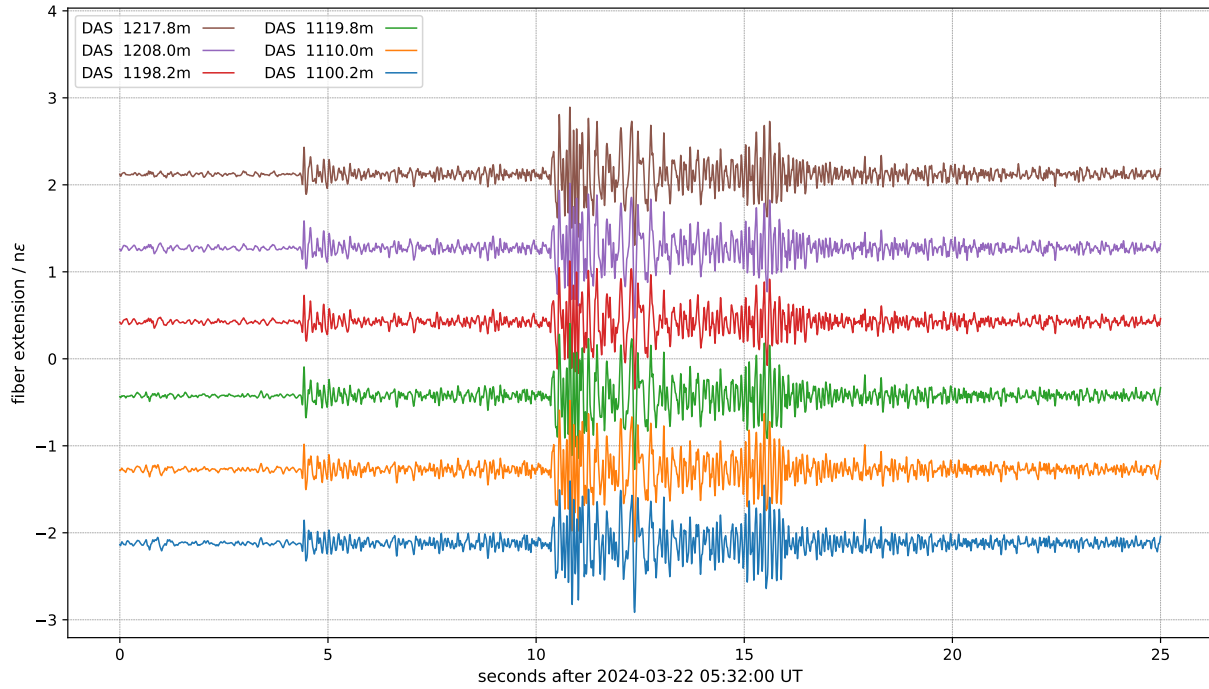


Figure S27: Waveform comparison for the Albstadt earthquake (see Table 2) recorded with the Treble+. All signals are band-passed to frequencies from 3 Hz to 18 Hz. Optical channel offsets (all traces located in the ‘Vorstollen’) are given in the legend. Extension represents ‘fiber strain’. No noise reduction (based on the reference coils) is applied.

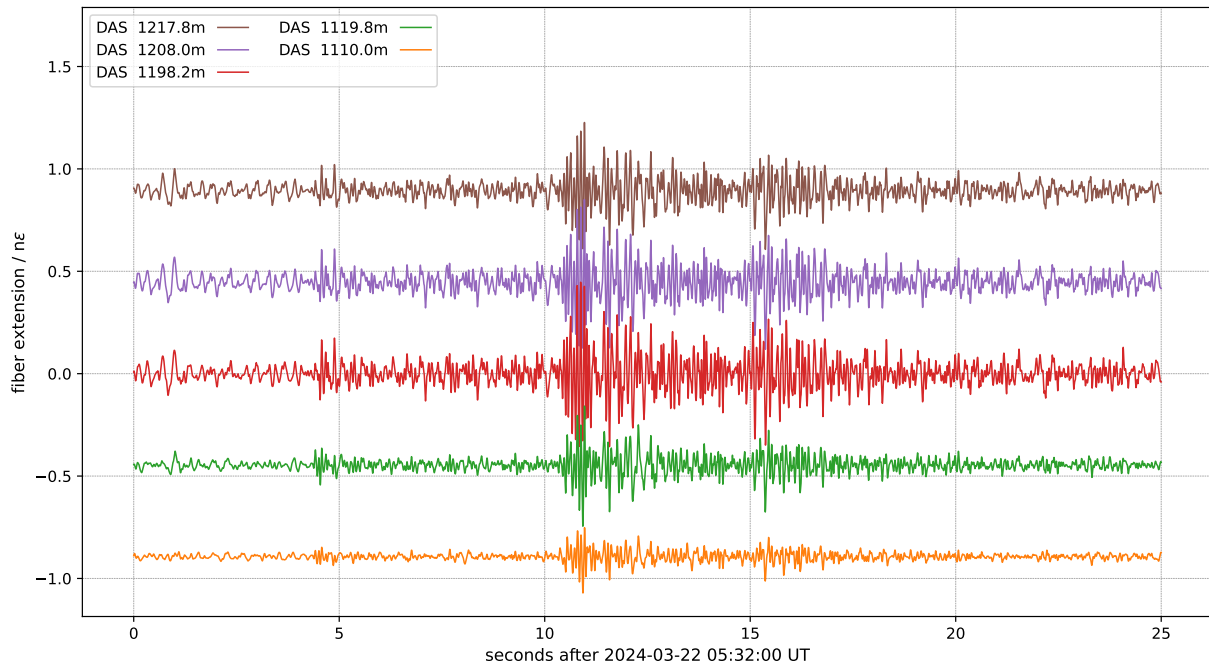


Figure S28: Residuals of waveforms recorded for the Albstadt earthquake (see Table 2) with the Treble+. Residuals are computed with respect to the channel of smallest offset in Fig. S27. Please note that the amplitude scale in each of the diagrams is adjusted to the signal amplitude.

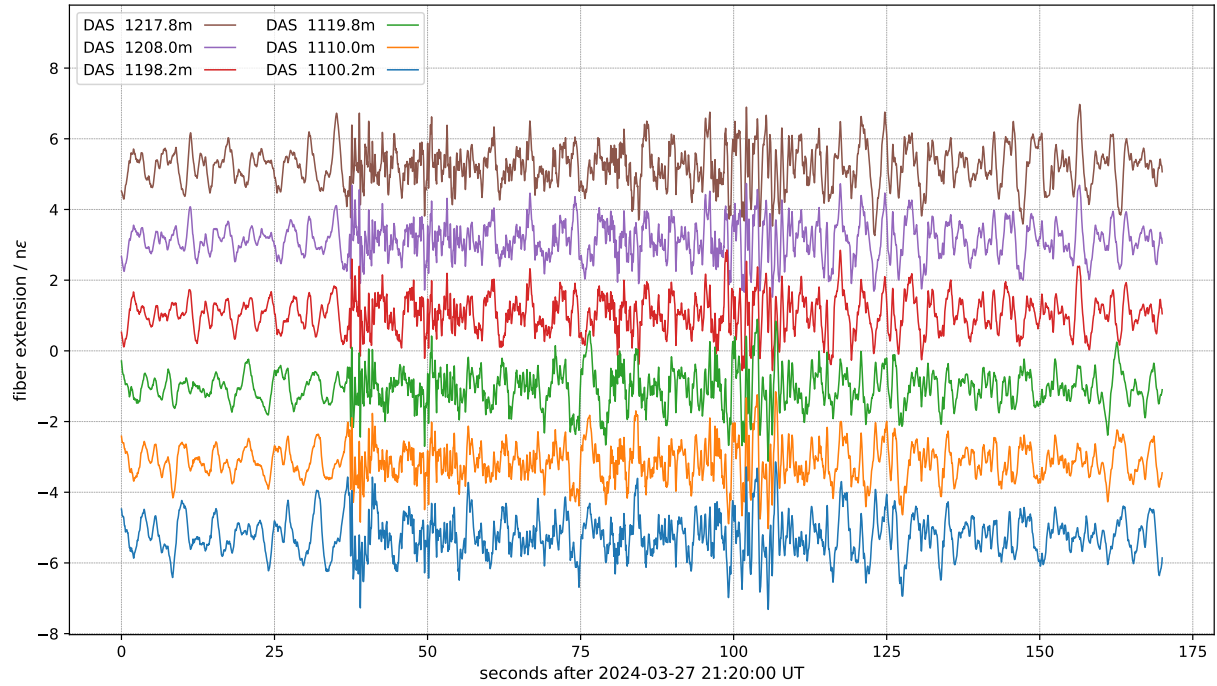


Figure S29: Waveform comparison for the Italy earthquake (see Table 2) recorded with the Treble+. All signals are band-passed to frequencies from 0.2 Hz to 8 Hz. Optical channel offsets (all traces located in the ‘Vorstollen’) are given in the legend. Extension represents ‘fiber strain’. No noise reduction (based on the reference coils) is applied.

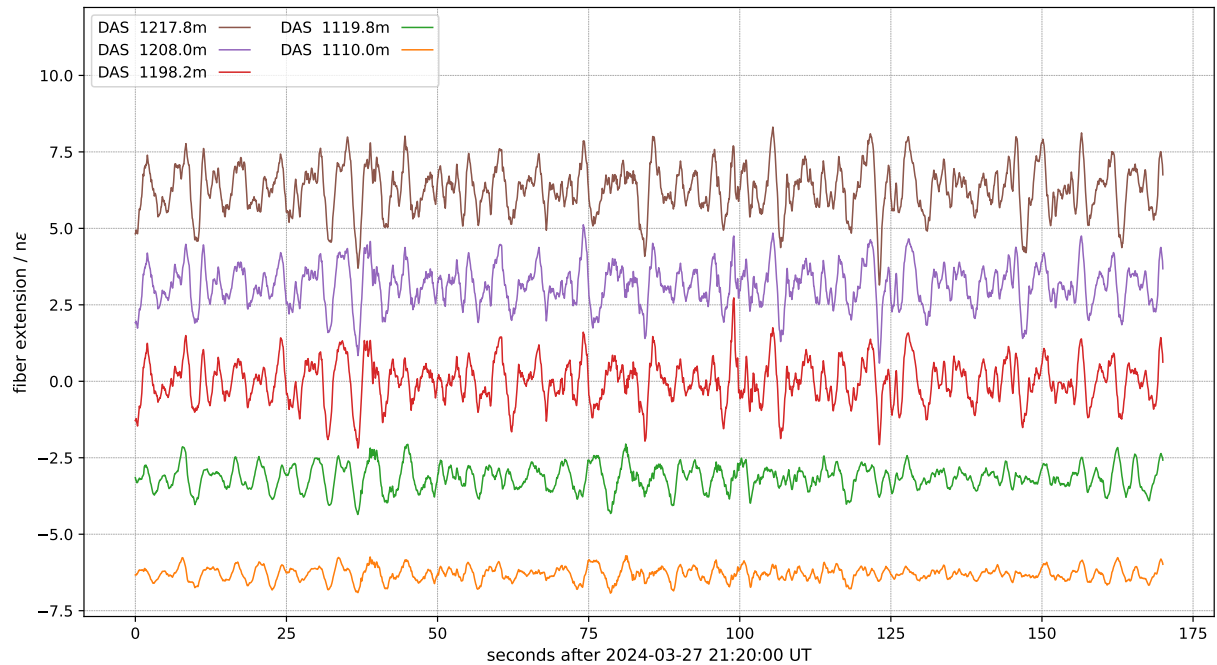


Figure S30: Residuals of waveforms recorded for the Italy earthquake (see Table 2) with the Treble+. Residuals are computed with respect to the channel of smallest offset in Fig. S29. Please note that the amplitude scale in each of the diagrams is adjusted to the signal amplitude.

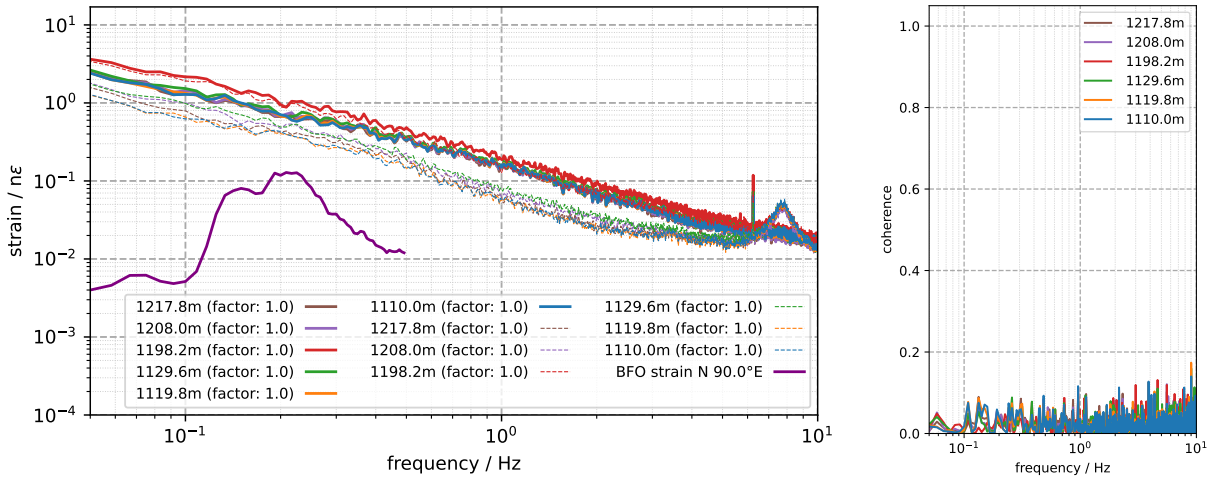


Figure S31: Analysis of the background signal on 2024-03-08 1 UTC to 2 UTC for recordings of the Terra15 Treble+: rms amplitude in 1/6 decade (left, see section 4.1 by Forbriger, 2023) and magnitude-squared coherence (Carter et al., 1973, their eq. 2) with respect to the BFO strainmeter data (right). 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. Signal amplitudes are not further scaled to correct for ‘strain transfer rate’ (factor: 1.0).

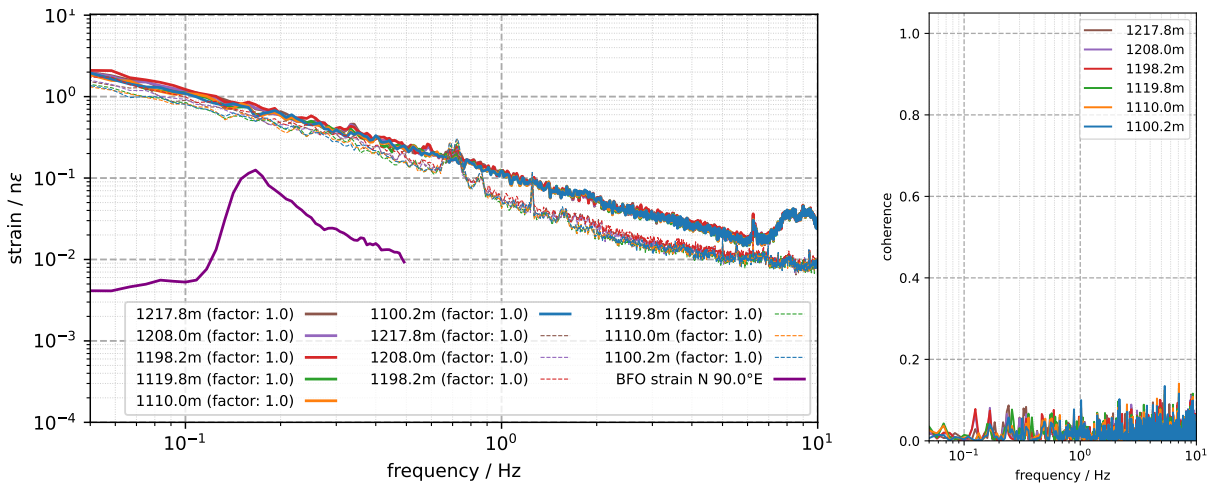


Figure S32: Analysis of the background signal on 2024-03-26 1 UTC to 2 UTC for recordings of the Terra15 Treble+: rms amplitude in 1/6 decade (left, see section 4.1 by Forbriger, 2023) and magnitude-squared coherence (Carter et al., 1973, their eq. 2) with respect to the BFO strainmeter data (right). 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. Signal amplitudes are not further scaled to correct for ‘strain transfer rate’ (factor: 1.0).

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