Leveraging Railway Telecommunications Fibers with Distributed Acoustic Sensing

Authors

Daniel Bowden & Pascal Edme *(ETHZ/FOSlab)*

With contributions from

Sanket Bajad *(Indian Institute of Science)*

Scott Keating *(ETHZ/SWP)*

Frédérick Massin *(SED)*

John Clinton *(SED)*

Elliot James Fern *(SBB)*

ETH Zürich, 25.06.2026

Summary

This pilot project evaluated the feasibility of using existing railway telecommunications fibers as Distributed Acoustic Sensing (DAS) arrays for large-scale subsurface characterization and monitoring. A DAS interrogator was connected to existing railway fibers in Valais and continuous measurements were acquired over several weeks.

The study successfully demonstrated that train-generated vibrations can be exploited to recover near-continuous subsurface shear-wave velocity models over more than 30 km of railway. The resulting models show good agreement with available geotechnical information and highlight zones of soft sediments and lateral geological variability.

Beyond geotechnical characterization, the project demonstrated real-time data streaming, integration with Swiss Seismological Service workflows, and the potential for railway telecommunications fibers to support infrastructure monitoring, train characterization, natural hazard detection, and rapid-response deployments following disruptive events.

The results suggest that existing railway fiber infrastructure could evolve into a multi-purpose sensing network supporting geotechnical characterization, infrastructure management, hazard monitoring, and future railway asset-management applications.

Table of Contents

1. Introduction 4
2. DAS deployment and data acquisition 5
  2.1 Study Area 5
  2.2 Deployment Concept 7
  2.3 DAS configuration 7
  2.4 Channel Mapping 9
  2.5 Ground Coupling 10
  2.5 Data Management and Real-Time Streaming 11
  2.5 Train signatures 12
3. Subsurface Characterisation 15
  3.1 Conventional Workflow 15
    3.1.1 Ambient Noise Cross-Correlation 15
    3.1.2 Dispersion Measurement (MASW / Slant Stack) 17
    3.1.3 McMC Inversion 18

3.2 Refinements in the Context of Train-Dominated Vibrations 20
3.2.1 Testing Conventional Signal Processing Improvements 20
3.2.2 Evaluating the Effect of Additional Stacking 21
3.2.3 Exploring directionality of seismic sources 22
3.2.4 Isolating Train Sources 23
3.2.5 Automated Dispersion Curve Selection 26
3.2.6 Testing a Symmetric Variational Autoencoder (SymVAE) 27
3.3 Subsurface Model 30
3.4 Key findings for Subsurface Characterization 33
3.5 Repeated Measurements and Change Detection 33
4. Additional Monitoring Applications and Future Opportunities 35
4.1 Natural Hazard Monitoring 35
4.2 Collaboration with the Swiss Seismological Service 36
4.2.1 Integration with Operational Monitoring Workflows 36
4.2.2 Opportunistic science 37
4.3 Responsive Monitoring and Rapid Infrastructure Assessment 37
4.4 Railway Infrastructure and Train Health Monitoring 38
4.5 Mobile / Agile High-Resolution Surveys 38
5. Proposed Follow-Up Activities 41
6. Conclusions 42
7. References 43
Appendix A: Related publications from this work 45
Appendix B: Additional comparison with CPTs 46

1. Introduction

This report documents the research conducted under agreement ETH ID30033 between Allianz Fahrweg and ETH Zurich, involving the Fiber Optic Sensing Laboratory (FOSlab) and the Swiss Seismological Service (SED).

The long-term performance, maintenance requirements, and resilience of railway infrastructure are strongly influenced by the mechanical properties of the shallow subsurface. Variations in soil stiffness, sediment thickness, groundwater conditions, and geological structure can affect track performance, influence degradation rates, and increase vulnerability to natural hazards. Understanding these subsurface conditions is therefore an important component of railway asset management.

Conventional geotechnical investigations provide valuable information but are typically localized, time-consuming, and expensive to deploy over large portions of a railway network. As a result, detailed subsurface information is often only available at selected sites, while network-scale characterization remains challenging.

At the same time, railway corridors are increasingly equipped with extensive telecommunications infrastructure, including fiber-optic cables running alongside the tracks. Distributed Acoustic Sensing (DAS) technology transforms these fibers into dense arrays of virtual vibration sensors, capable of continuously recording ground motion over tens of kilometres from a single interrogation unit. Existing telecommunications fibers therefore represent a potentially powerful and cost-effective sensing approach that can be leveraged without requiring the installation of additional sensors in the field.

The primary objective of this project was to evaluate the feasibility of using existing railway telecommunications fibers for large-scale subsurface characterization. In particular, the project investigated whether seismic vibrations generated by passing trains and ambient environmental sources could be exploited to estimate shallow shear-wave velocity (Vs) structures along railway corridors. Such information is directly relevant to the identification of soft ground conditions, lateral geological variations, and zones that may warrant further geotechnical investigation.

Beyond subsurface characterization, the project also discusses the broader monitoring capabilities enabled by DAS. The exceptional spatial coverage provided by fiber-optic sensing allows continuous observation of train-generated vibrations along large sections of the railway network. These observations may support future developments in infrastructure monitoring, train characterization, detection of anomalous vibration behaviour, and the long-term assessment of changes in ground conditions.

An additional objective was to assess the potential value of railway fiber networks for seismic and natural-hazard monitoring. Real-time seismic observations collected along the large railway network could contribute to earthquake monitoring and improve situational awareness following potentially damaging events. Furthermore, many hazards relevant to railway operations (including landslides, rockfalls, debris flows, and snow avalanches) generate seismic signals that can be detected by distributed fiber-optic sensing systems. Railway telecommunications networks therefore represent a promising platform not only for geotechnical characterization, but also for broader environmental and hazard-monitoring applications.

To investigate these opportunities, a DAS interrogator was connected to existing telecommunications fibers along railway corridors in the Valais. Continuous measurements were acquired over several weeks and analysed using a range of geophysical and signal-processing techniques. Particular emphasis is placed on the use of train-generated vibrations as a source of seismic energy for subsurface imaging.

This report describes the DAS deployment and acquisition, the development of subsurface characterization workflows adapted to train-dominated environments, the resulting geotechnical interpretations, and a number of additional monitoring applications enabled by the technology. The results demonstrate that existing railway telecommunications fibers can successfully support both large-scale geotechnical characterization and continuous monitoring applications. In addition to producing detailed subsurface velocity models, the pilot test highlighted opportunities for real-time monitoring, infrastructure assessment, and future network-scale as well as local and agile sensing strategies. Recommendations and perspectives for future research and development are discussed. In brief, the project illustrates how existing railway telecommunications infrastructure can evolve into a multi-purpose sensing network supporting both operational and scientific objectives.

2. DAS deployment and data acquisition

2.1 Study Area

The study was conducted along line 100 railway in the Valais, Switzerland, using existing telecommunications fibers deployed along the track. A DAS interrogator was installed in a technical facility in Vernayaz and connected to two dark-fiber segments: one extending northwest toward Vevey, and a second extending northeast toward Sierre. The Rhône Valley provides an attractive test environment for railway-scale subsurface characterization. The corridor spans a wide range of geological and environmental settings, including alluvial sediments, urbanized areas, industrial zones, river crossings, and bedrock-controlled sections. Such variability is expected to influence the mechanical properties of the shallow subsurface and therefore the seismic wavefield recorded by the fiber.

The primary focus of this report is the northwestern fiber segment between Vernayaz and Vevey Previous investigations in this corridor identified significant lateral variations in sediment properties, particularly in the St. Triphon–Aigle region, where geotechnical investigations and cone penetration tests (CPTs) have been conducted. The area has also been the subject of recent geophysical studies related to geothermal exploration and seismic hazard assessment, providing independent datasets against which DAS-derived subsurface models can be compared. The second fiber segment toward Sierre was used primarily to evaluate the capability of the DAS system to monitor multiple fibers simultaneously and to explore additional applications related to seismic and environmental monitoring. **Figure 1** provides an overview of the monitored fiber network and the corresponding study area.

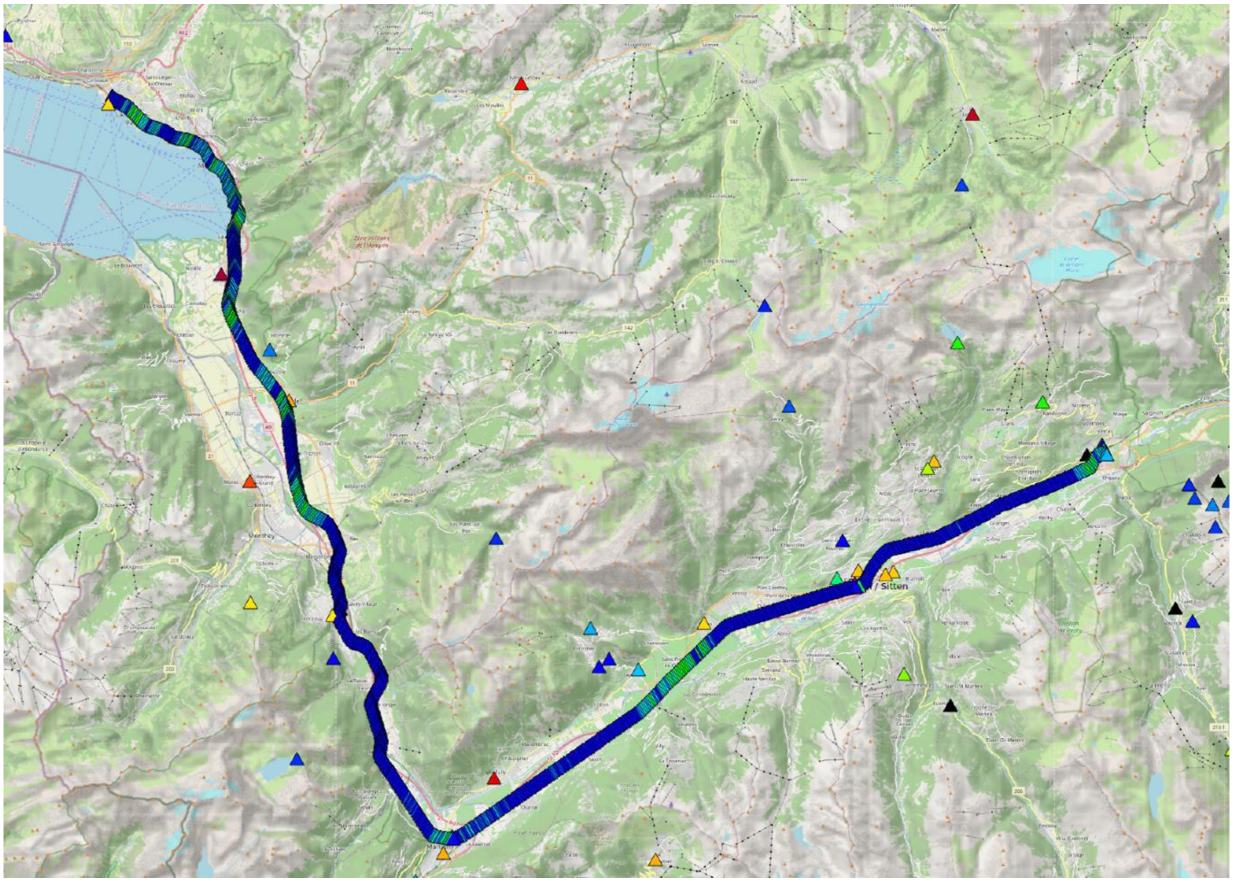


Figure 1: Overview of recorded fibers, with triangles indicating locations of nearby SED seismic stations.

2.2 Deployment Concept

The objective of the deployment was to evaluate whether existing railway telecommunications fibers could be rapidly converted into large-scale sensing infrastructure with minimal disruption to railway operations. Access was provided by Frederic Martin and his team to two unused (dark) telecommunications fibers within a technical facility in Vernayaz. A portable DAS interrogator was connected directly to 2 existing 50 km long fibers. The DAS installation was completed within approximately two hours.

As shown in **Figure 2**, the deployment occupied only a small footprint within the technical facility and required limited supporting equipment, consisting primarily of the interrogator unit, external storage, a communication modem (SED router) enabling setting to be done remotely. The compact nature of the setup demonstrates the practicality of deploying DAS systems within railway telecommunications facilities.

From an operational perspective, one of the key advantages of the technology is that a single interrogator can monitor tens of kilometres of existing fiber infrastructure. This enables large-scale measurements without installing dedicated sensors in the field and significantly reduces deployment effort compared with conventional geophysical surveys. The deployment therefore served not only as a scientific experiment, but also as a practical demonstration of how existing railway telecommunications infrastructure can be transformed into a distributed sensing network suitable for geotechnical characterization and continuous monitoring applications.

2.3 DAS configuration

The measurements were acquired using a Sintela Onyx Peta interrogator measuring dynamic strain rate along two fibers by repeatedly transmitting coherent laser pulses and analysing the backscattered optical signal. Several acquisition parameters govern the trade-off between spatial resolution, sensing range, and signal quality. The most important are the gauge length, channel spacing, and sampling frequency. Throughout the project, gauge lengths between 6 m and 24 m were tested, with corresponding channel spacings between 3 m and 12 m. The selected channel spacing was approximately half the gauge length, to avoid spatial aliasing of the measured wavefield. Data were typically recorded at a sampling frequency of 200 Hz, providing sufficient bandwidth for both train-generated vibrations and local seismic signals.

The acquisition parameters were selected to maximize the useful sensing range while preserving the spatial resolution required for subsurface characterization. Using the selected configuration, high-quality observations were obtained over approximately 30–40 km range. Increasing spatial resolution through shorter gauge lengths, denser channel spacing, or higher sampling frequencies is possible, but generally comes at the expense of sensing distance and data volume. Note that the ETHZ upgraded Onyx Peta system now enables the interrogation over approximately twice the range without signal quality nor spatial resolution degradation (i.e. 2x 100km; in principle and to be tested).

For the subsurface characterization presented later in this report, the chosen configuration (6m gauge length) provided an effective compromise between spatial coverage, signal quality, and operational practicality. The resulting dataset consists of thousands of virtual sensing channels distributed continuously along the railway corridor, enabling geotechnical investigations at an unprecedented spatial scale.

Figure 2: DAS deployment in the telecommunications facility at Vernayaz. The Sintela Onyx interrogator was connected to 2 existing railway telecommunications fibers and operated directly from its transport case. System configuration and remote access were provided through a laptop and an independent 4G router. The setup doesn't require much space and can be deployed rapidly within existing railway infrastructure facilities.

Key Takeaway: The DAS acquisition parameters must balance sensing range and spatial resolution. The configuration adopted in this study enabled continuous monitoring over tens of kilometers while maintaining sufficient resolution for shallow subsurface characterization.

2.4 Channel Mapping

A key requirement for interpreting DAS measurements is the ability to associate individual channels with physical locations along the railway line. Because telecommunications fibers typically contain slack loops at stations and access points, the distance reported by the DAS interrogator does not directly correspond to railway chainage or geographic position.

For this study, channel mapping was established mainly using train movements observed along the route. By correlating train signal at known stations, a relationship between fiber distance, railway chainage, and geographic location was constructed.

The procedure was applied in detail along the fiber segment toward Vevey, which forms the basis of most analyses presented in this report. The resulting mapping (**Figure 3**) enables direct comparison of DAS observations with railway assets and independent geotechnical investigations. The final positional accuracy is estimated to be on the order of 20 metres, which is sufficient for the large-scale characterization and monitoring objectives considered here.

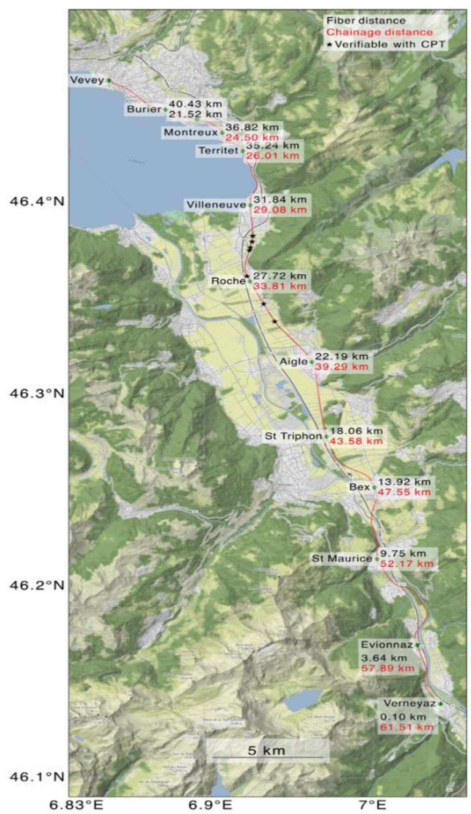


Figure 3: Focusing on the N-S running Fiber between Vernayaz and Vevey. Black distances indicate our system's measurements along the fiber from Vernayaz. Red distances correspond to chainage distances. Black stars corresponds to local Vs measurements obtained by CPTs (provided by James Fern).

2.5 Ground Coupling

The quality of DAS measurements depends on the mechanical coupling between the fiber-optic cable and the surrounding ground. In dedicated geophysical surveys, fibers can potentially be buried/installed to maximize coupling and ensure accurate recovery of ground deformation.

In this study, measurements were performed using pre-existing telecommunications infrastructure, where coupling conditions vary along the railway (**Figure 4**). In most locations, the fiber was installed in lateral ducts alongside the track, while in some sections the cable was visibly in temporary protective conduits at the surface.

Variations in coupling primarily affect the amplitude of recorded signals. For the subsurface characterization workflow developed in this study, this is generally not critical, as the analysis relies primarily on the travel times and dispersion characteristics of seismic waves rather than their absolute amplitudes. However, coupling conditions may become more important for future applications involving quantitative vibration monitoring or infrastructure condition assessment.

Key Takeaway: Although coupling conditions vary along the corridor, the quality of the recorded wavefield was sufficient for the geotechnical characterization objectives of this study.

Figure 4: *Examples of fiber conditions along the monitored railway corridor. Most sections (left) consist of buried telecommunications cables installed alongside other utilities, whereas some locations (right) showed cables positioned at the surface within temporary ducts. These differences may influence local coupling conditions and recorded signal amplitudes.*

2.5 Data Management and Real-Time Streaming

A major challenge associated with DAS monitoring is the large volume of data generated. Depending on the acquisition parameters, daily data volumes ranged from several tens to several hundreds of gigabytes. While such volumes can be accommodated during temporary deployments, long-term operational monitoring requires efficient strategies for data reduction, visualization, and transmission.

To partially address this challenge, FOSlab is developing a visualization and monitoring framework designed to transform dense DAS datasets into lightweight, information-rich products suitable for real-time applications. As part of this effort, the DAS interrogator is configured to perform on-board processing and generate downsampled band-averaged Power Spectral Density data images in real time. Rather than transmitting very heavy raw waveforms, the system continuously computed sparse representations of the seismic wavefield, which can be streamed to ETH Zurich for conversion into RGB images, in which three frequency bands are assigned to the Red, Green, and Blue channels of the image, allowing both amplitude and frequency content to be visualized simultaneously.

The resulting representation provides an intuitive overview of activity along tens of kilometres of fiber, enabling rapid identification of trains, seismic events, and other sources of vibration. Beyond visualization, the approach converts large waveform datasets into promising compact image products for automated monitoring, pattern recognition, and machine-learning workflows. In addition to supporting remote system monitoring, the RGB representation provides a powerful tool for exploring railway vibrations and identifying unusual behaviour. Variations in signal intensity, frequency content, or spatial extent may be tracked continuously and could provide useful indicators of changes in train health, infrastructure conditions, or environmental activity.

Figure 5 illustrates an example of real-time RGB monitoring, showing approximately 35 km of railway fiber over a 10-minute period, on which trains maps into a clear white (i.e. broadband). The rich spatial and spectral content of these signatures suggests that railway fiber networks may benefit from such light-weight approach, including infrastructure monitoring, train characterization, and potentially anomaly detection.

Key Takeaway: FOSLAB develops a system that converts in real-time the dense data into light-weight rich images. Combining different frequency ranges gives an immediately interpretable feed that could be used for state-of-health monitoring for example.

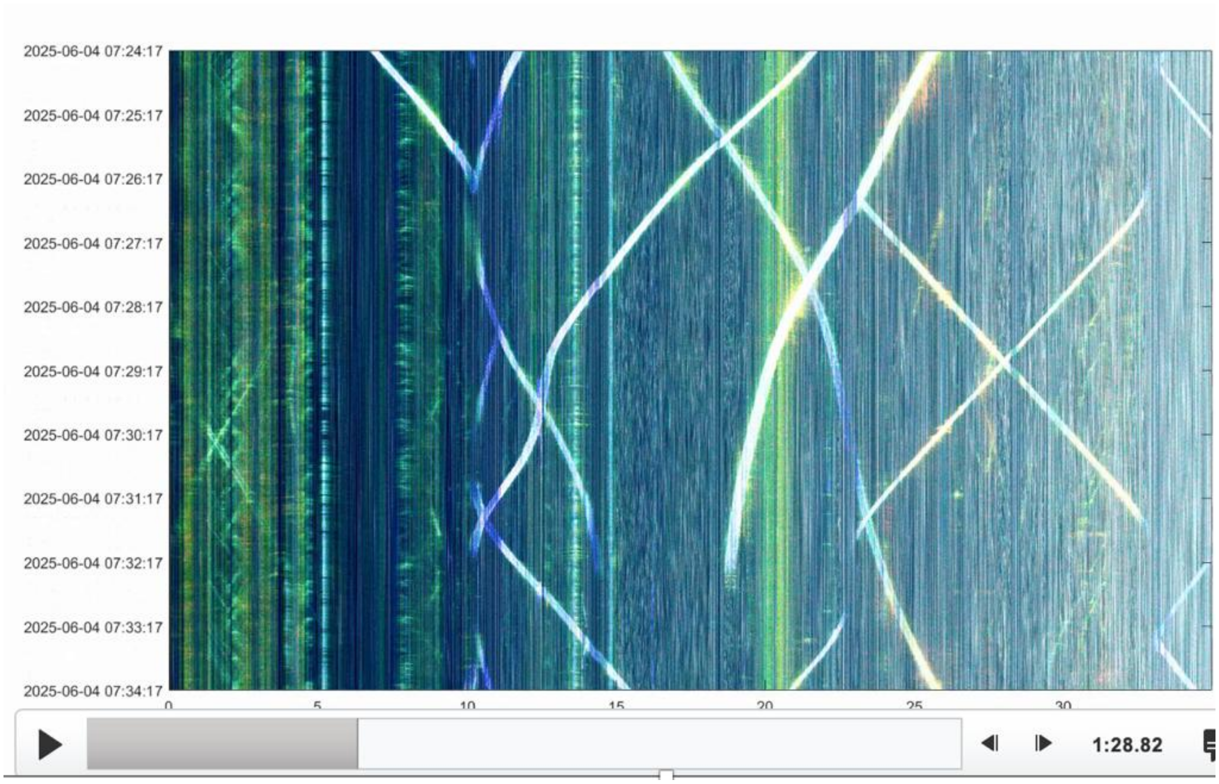


***Figure 5**: RGB representation example (snapshot of a movie). This shows the PSD data (red [0 2]Hz, Green [2 20]Hz, Blue [20 200]Hz) over ~35 kilometers and 10 minutes, with light-weight images streamed to a workstation at ETH then assembled and displayed as RGB to emphasize frequency content and variation in real time.*

2.5 Train signatures

The RGB representation introduced above provides a convenient initial overview of activity along the railway line, enabling selected regions of interest to be further investigated (using the raw strain-rate measurements). **Figure 6** shows an example of a train strain low-frequency signal ([0 20] Hz) extracted from one of the regions highlighted in the RGB monitoring products. Individual train components can be distinguished within the DAS recordings, with repeated patterns corresponding to successive bogies and wagons. The spatio-temporal continuity of the measurements enables these signatures to be tracked over distances of several kilometres. The low-frequency content associated with passing trains is particularly clear and provides a direct visualization of the interaction between the train, track, and surrounding ground. Such observations suggest that (more easily manageable) low-frequency DAS measurements may provide useful information not only on train traffic but also on local site response and infrastructure condition.

Figures 6 to 8 demonstrate that railway vibrations contain substantially more information than is typically accessible from conventional point sensors. The yellow regions visible in the RGB representation often correspond to locations where high-frequency train-generated vibrations locally persist beyond the immediate vicinity of the train. Such behaviour may indicate local amplification effects and therefore motivates further investigation of subsurface conditions. Those yellow regions in the RGB representation highlights part of the data exhibits prominent fast seismic signals emitted from the train itself (e.g. around 9 km beyond 04:26:20 UTC time in Figure 6). This is the part of the data which proves to be the most relevant for the MASW approach discussed in more details later. Differences in train composition, weight, speed, loading conditions produce distinct signatures within the DAS data. Similarly, variations in the propagation of vibrations along the line may reflect changes in ground conditions or coupling between the railway infrastructure and the subsurface.

Key Takeaway: Low-frequency DAS observations motivate both the geotechnical analyses presented in the following sections and future investigations into train characterization and infrastructure monitoring applications.

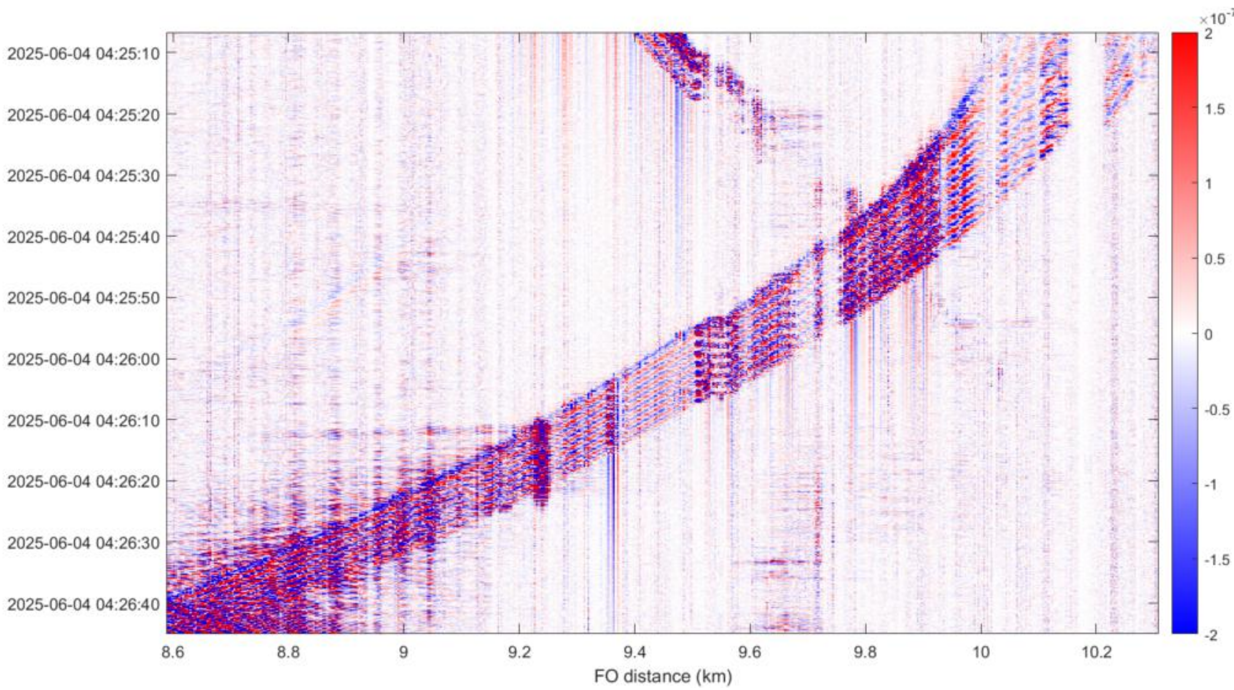


***Figure 6**: Example of a passing train, with strain rate filtered between 2 and 20 Hz.*

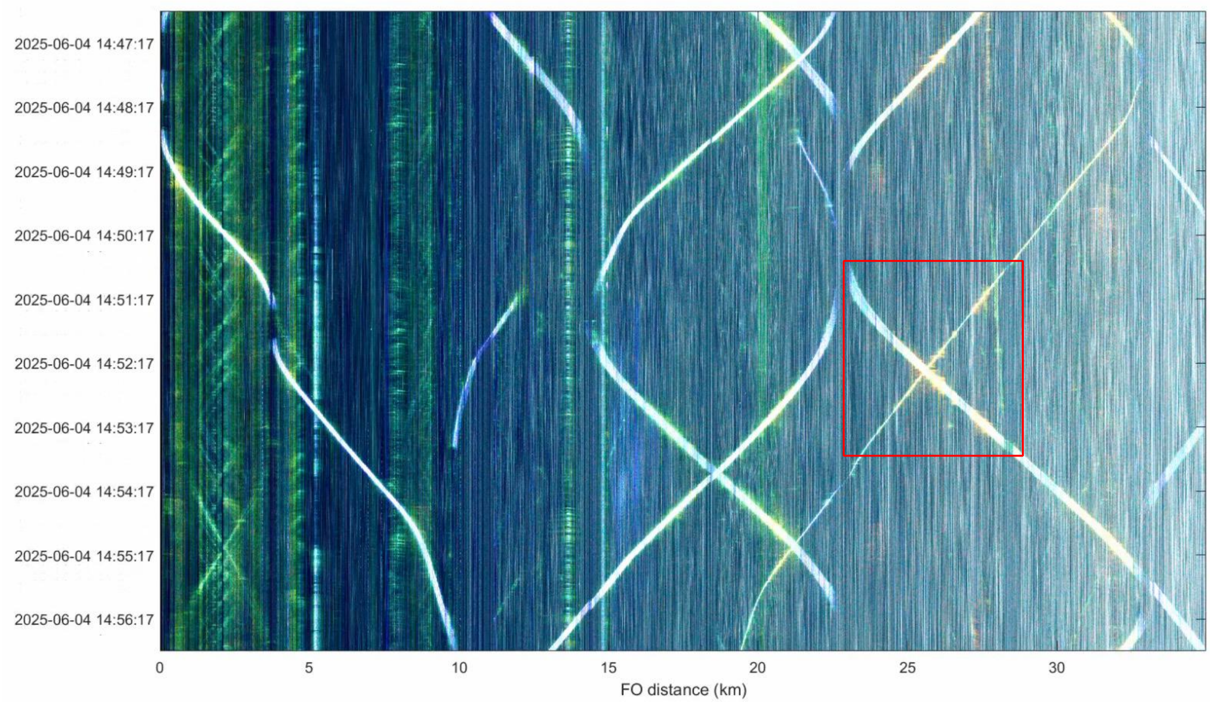


Figure 7: *An example of several passing trains, some of distinctly different length or weight. The red box indicates a region of interest, where yellow pixels highlighting broadband seismic signals propagating more strongly away from the train.*

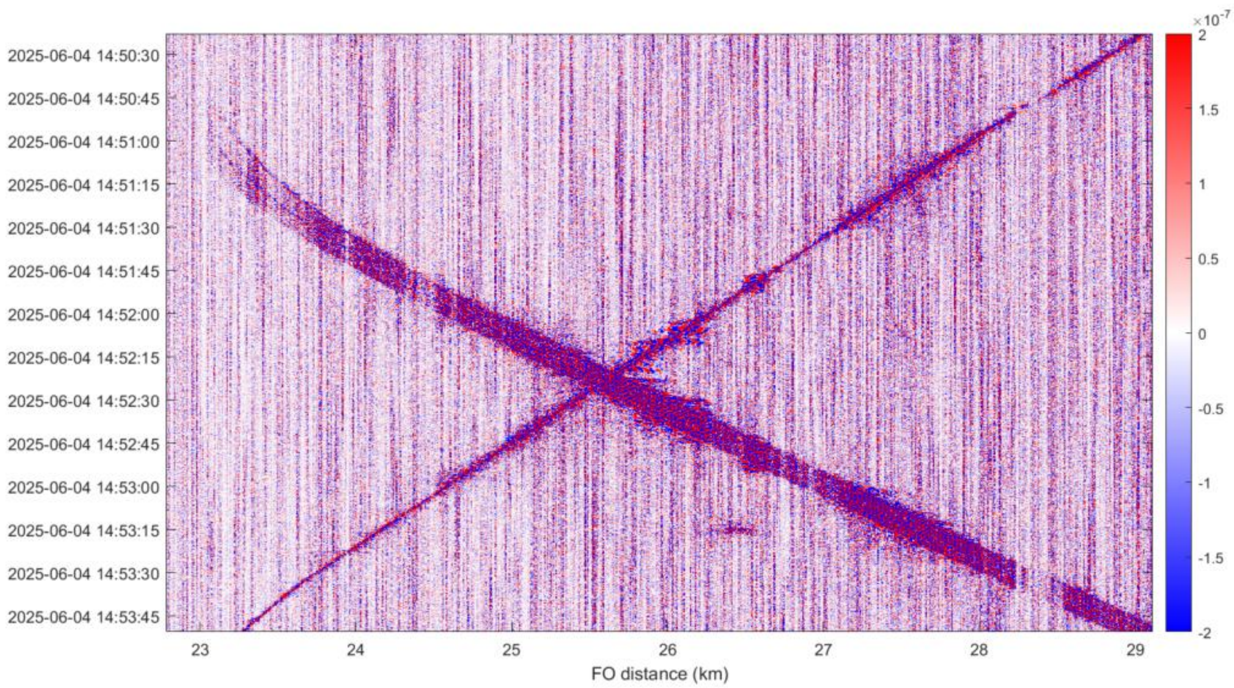


Figure 8: *A zoomed-in example corresponding the red box in* ***Figure*** *7.*

3. Subsurface Characterisation

The main objective of this project was to evaluate the capability of DAS measurements acquired on existing railway telecommunications fibers to characterize the shallow subsurface and identify variations in ground conditions along the railway. This is based mostly on analysis of Rayleigh-wave propagation and dispersion, under the workflow generally referred to as Multichannel Analysis of Surface Waves (MASW: Park et al., 1999). Such information is relevant to railway asset management, as variations in sediment properties and soil stiffness can influence vibration propagation, track performance, and long-term infrastructure stability.

DAS-based MASW subsurface characterization has proven effective in a variety of environments. Previous studies have demonstrated the ability to recover shallow velocity structures over the upper tens to hundreds of metres and relate them to local geology, sedimentary structure, and near-surface mechanical properties (e.g., Ajo-Franklin et al., 2019; Lai et al., 2024; Smolinski et al., 2024). In some cases, these velocity models have been used for earthquake site-response characterization and validated against earthquake observations (Bowden et al., 2026), while in others they have provided constraints on glacier structure and subsurface fluid content (Lanteri et al., 2025).

The typical subsurface characterization workflow consists of three principal stages: extraction of coherent surface-wave signals, measurement of surface-wave dispersion characteristics, and inversion of the resulting dispersion curves to obtain one-dimensional shear-wave velocity at a location. Repeating the process at multiple locations then enables to construct a continuous image of subsurface variations along the profile.

3.1 Conventional Workflow

We first evaluated the conventional workflow based on continuous ambient noise analysis (both environmental noise and train-generated signals), before introducing several adaptations specifically developed for train-dominated environments. The objective was to establish a baseline processing chain and evaluate how effectively existing methodologies could be transferred to railway telecommunications fibers. The workflow consists of three principal stages described in the next sub-sections.

3.1.1 Ambient Noise Cross-Correlation

The first step of the workflow involves seismic interferometry, with the objective of constructing virtual shot gathers suitable for subsequent dispersion analysis. Each DAS channel is cross-correlated with its neighbours to recover surface waves propagating along the railway corridor (Shapiro and Campillo, 2004; Smolinski et al., 2024).

The underlying principle is that while any individual fluctuation within the ambient seismic wavefield may be difficult to interpret, correlating many hours or days of recordings between two locations isolates signals that are common to both. In this way, the travel times and propagation characteristics of seismic waves travelling between two points can be recovered. Repeating this procedure for many channel pairs produces virtual-source gathers that form the basis for subsequent dispersion analysis and shear-wave velocity inversion.

Ideally, the ambient seismic wavefield would be diffuse and homogeneous, in which case cross-correlation would accurately recover the complete seismic response between any two channels (Tsai, 2009). Direct stacking of all available noise windows has formed the basis of several successful DAS-based subsurface characterization studies, including recent work at ETH (Bowden et al., 2026; Smolinski et al., 2024).

In the ideal case, the correlation gather would exhibit a clear “X” pattern. From the central reference channel, correlations can be observed both northward (positive distances) and southward (negative distances). In each direction, a causal branch at positive time lags corresponds to seismic waves propagating away from the reference channel toward more distant locations, while an acausal branch at negative time lags corresponds to waves travelling from distant channels back toward the reference location. For diffuse and homogeneous noise sources propagating through a laterally uniform, approximately one-dimensional subsurface, the four branches of the correlation gather would be identical and perfectly symmetric. Deviations from this idealized pattern therefore provide insight into asymmetries in the source distribution, wave propagation, or subsurface structure.

Two ambient-noise correlation results are shown in **Figure 9**. In some portions of the railway corridor, this conventional workflow performed well, resulting in clear Rayleigh-wave arrivals suitable for subsequent analysis (panel A). In other locations (panel B), however, the background seismic wavefield was strongly biased, and the resulting correlations converged to something other than a simple ballistic surface wave. This behaviour suggested that the assumptions underlying conventional ambient-noise interferometry were not always satisfied and motivated a more detailed investigation of the railway wavefield.

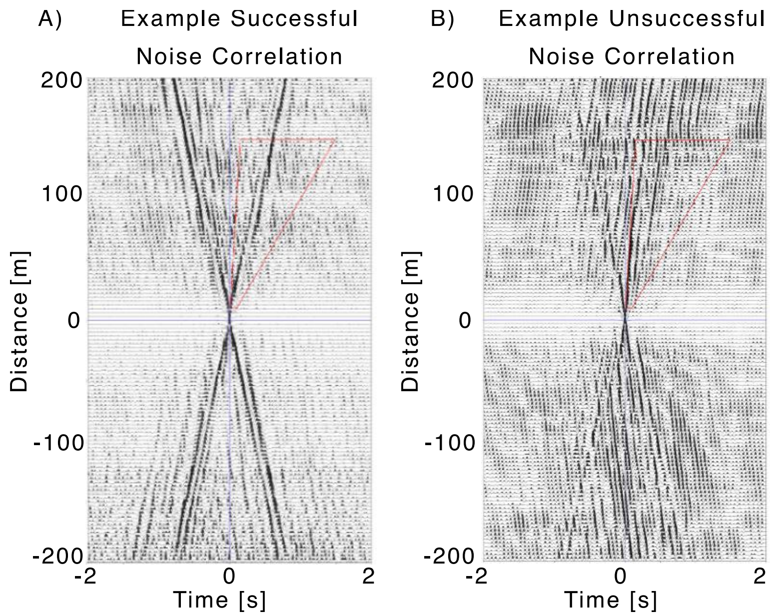


Figure 9*: Example record sections resulting from cross correlating one channel with it's neighbors. Panel A comes from a location roughly 19.7 kilometers away from the interrogator and is relatively clean and interpretable. Panel B is an example of a location where pure noise correlations were less successful, coming from a location roughly 20.1 km from the interrogator.*

3.1.2 Dispersion Measurement (MASW / Slant Stack)

Once virtual shot gathers have been obtained through interferometry, the next step is to quantify how surface-wave velocity varies with frequency. This phenomenon, known as dispersion, arises because different frequencies sample different depths within the subsurface. Low frequencies penetrate deeper and are therefore influenced by deeper geological layers, whereas higher frequencies are primarily sensitive to shallower materials.

To extract this information, the virtual shot gathers are transformed into the frequency-velocity domain using slant stacking. The method systematically tests a range of propagation velocities by applying corresponding phase shifts to each seismic trace before summation. The dominant velocity maps as the one producing the most coherent stacking of the wavefield, appearing as a peak in the resulting frequency-velocity image. **Figure 10** presents two dispersion spectra examples, corresponding to the correlation gathers shown in Figure 9. In one case, a clear and continuous dispersion trend can be identified and measured (giving the dispersion curve), while in the other the result is too ambiguous for reliable analysis. Such examples highlight the sensitivity of the conventional workflow to the characteristics of the underlying seismic wavefield.

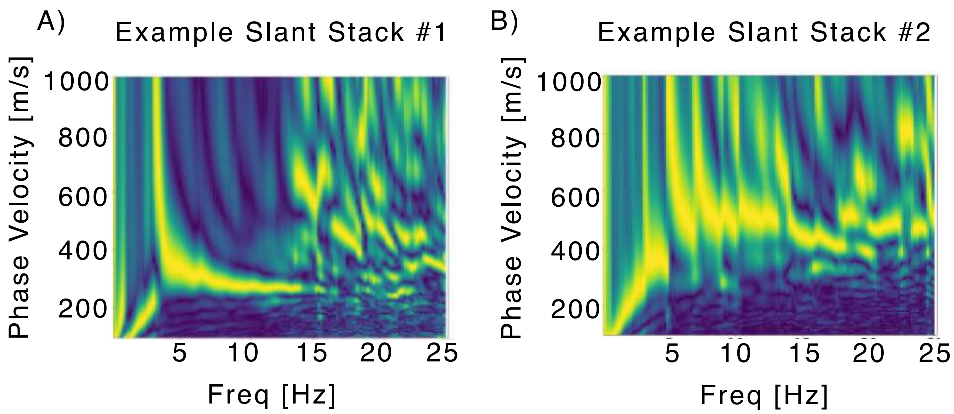


***Figure 10**: Dispersion images corresponding to Panels A and B from the record sections above. Again, panel A showed clearly interpretable Rayleigh waves between 5 and 15 Hz, while panel B may show surface waves but would be too poor in quality to be interpreted.*

3.1.3 McMC Inversion

The final stage of the workflow consists of converting the measured dispersion curves into estimates of subsurface shear-wave velocity (Vs). This is achieved using a Markov Chain Monte Carlo (McMC) inversion approach, in which candidate subsurface models are repeatedly generated, their theoretical dispersion curves computed, and their fit to the observations evaluated. Our inversion uses the BayHunter package (Dreiling and Tilmann, 2019) for sampling and Computer Programs in Seismology (Herrmann, 2013) for forward modelling.

A total of one million models were explored for each location. After discarding an initial burn-in phase, the remaining models form an ensemble of acceptable solutions (the posterior distribution). Rather than producing a single velocity profile, this approach provides both a preferred model and an estimate of uncertainty as a function of depth. Well-constrained depths are characterized by a narrow range of acceptable models, whereas larger variability indicates greater uncertainty.

Figure 11 shows an example inversion result at approximately 15.8 km distance from the interrogator. The observed Rayleigh-wave dispersion picks are shown in Panel A, while Panel B presents the ensemble of compatible velocity models. The mean profile (green) is used as the preferred solution, while the dashed lines indicate one standard deviation and provide a measure of uncertainty. In this example, the velocity structure is best constrained between approximately 5 and 20 m depth, with uncertainty increasing both very near the surface and below roughly 40–50 m.

Constraining higher-order Rayleigh-wave modes can significantly improve the inversion, particularly in the shallow subsurface. Although such modes are often more difficult to identify, they exhibit greater sensitivity to near-surface layers. Figure 10 illustrates how including the first higher mode reduces model uncertainty, especially within the upper few metres most relevant to railway geotechnical applications.

The inversion framework is based on the transdimensional approach of Bodin et al. (2012), in which the number of layers is itself treated as a model parameter. For this project, a modified pseudo-transdimensional formulation was adopted in which several layers were explicitly retained within the upper 5 m. This adaptation was introduced to better resolve shallow structures of particular interest and to avoid underestimating uncertainty in the near surface.

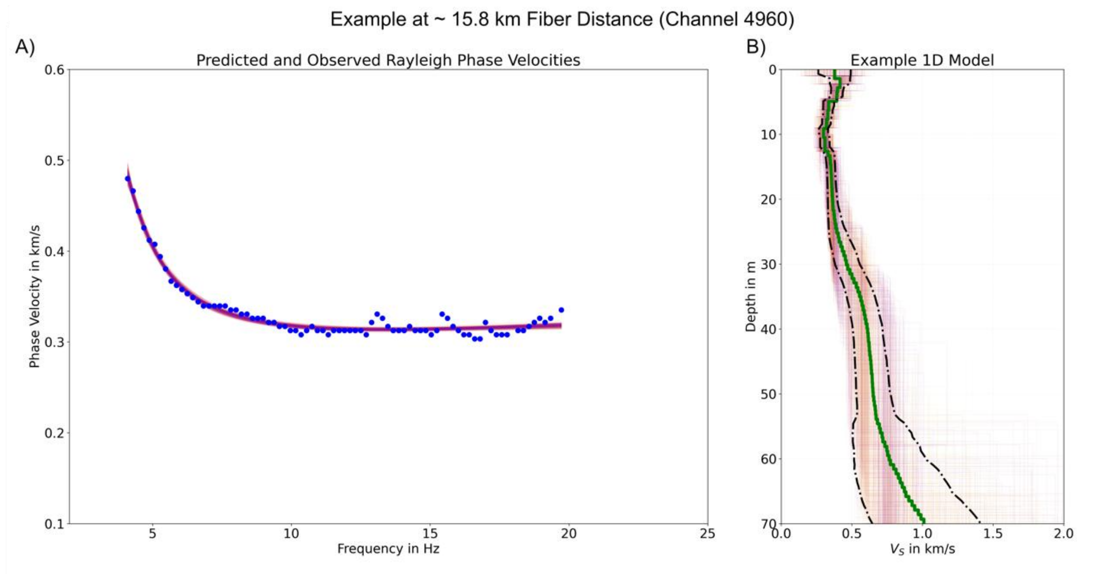


Figure 11*: Example of the 1D Vs Modelling. Given a set of dispersion curve picks (blue dots in Panel A), a range of 1D models are proposed (panel B). For each 1D model proposed, synthetic dispersion curves and a corresponding misfit are calculated. The ensemble of models shown in Panel B all represent feasible solutions, and give an estimate of uncertainty.*

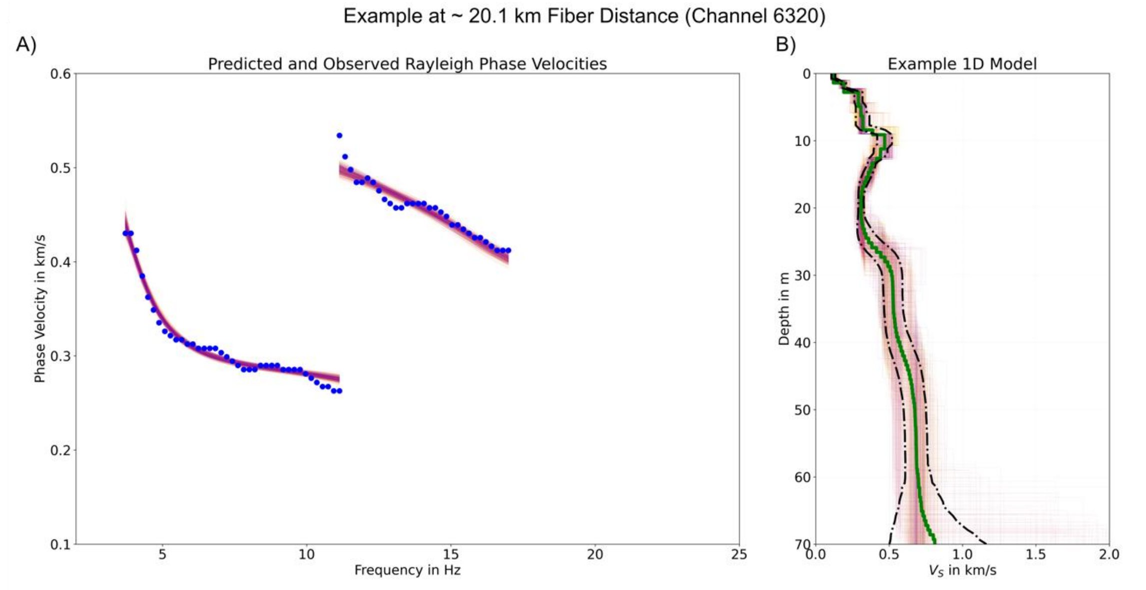


***Figure 12**: A different example of 1D modelling, as in the figure above. Here, a higher mode was interpreted, and we see that this helps constrain the 1D model, especially in the shallower subsurface.*

3.2 Refinements in the Context of Train-Dominated Vibrations

The workflow described above has been successfully applied in a variety of DAS projects and provides a robust framework for subsurface characterization. However, the railway environment presents several unique challenges. Unlike conventional ambient-noise studies, the recorded wavefield is dominated by train-generated vibrations that are highly directional, spatially localized, and strongly time-dependent. While these characteristics violate some of the assumptions underlying classical seismic interferometry, they also provide opportunities. Trains generate large amounts of seismic energy on a daily basis and therefore constitute a persistent and repeatable source of excitation distributed along the railway network. The following sections describe several investigations undertaken to better understand and exploit these railway-specific wavefield characteristics.

3.2.1 Testing Conventional Signal Processing Improvements

The first hypothesis considered was that the poor quality of some correlation gathers resulted from limitations in the signal processing workflow. Numerous studies have shown that preprocessing can improve ambient-noise interferometry by suppressing transient events and reducing spectral imbalances within the seismic wavefield (Bensen et al., 2007; Girard and Shragge, 2020).
Several commonly used preprocessing approaches were therefore evaluated, including one-bit normalization, running time-domain normalization, spectral whitening, and combinations thereof. **Figure 13** illustrates the impact of these different processing strategies on the resulting correlation

gathers. Overall, spectral whitening provided the largest individual improvement (panel F), while the combination of time- and frequency-domain normalization generally produced the clearest results.

Despite these improvements, problematic sections of the railway corridor remained problematic. Locations that already exhibited coherent Rayleigh-wave arrivals generally became slightly clearer, whereas locations with poor or ambiguous correlations rarely became interpretable. The results suggest that signal processing alone cannot explain the observed variability in data quality and that other factors, likely related to the source distribution itself, play a dominant role.

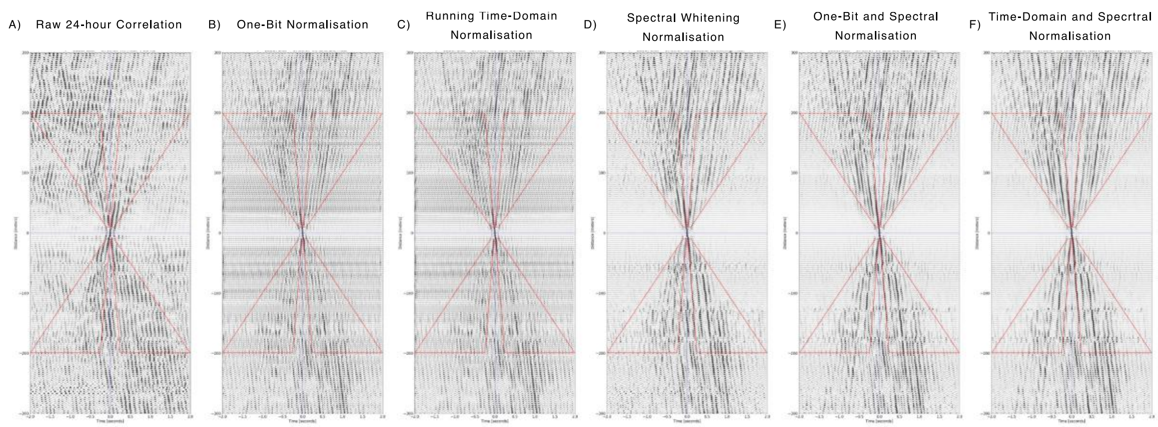


***Figure 13**: Examples of the cross-correlations extracted from a single source channel, repeated with different pre-processing steps to enhance signal quality.*

3.2.2 Evaluating the Effect of Additional Stacking

A second hypothesis was that the quality of the interferometric response was limited by insufficient averaging in time. Ambient-noise interferometry typically benefits from longer recording durations, as additional stacking suppresses incoherent noise and enhances signals common to both channels.

To evaluate this possibility, correlation functions were computed using progressively longer recording periods, ranging from a single day to several days of continuous observations. **Figure 14** compares representative examples obtained after one and nine days of stacking. Additional stacking produced modest improvements in signal clarity and reduced the level of incoherent background noise. However, the overall character of the correlation gathers remained largely unchanged. Locations exhibiting clear Rayleigh-wave arrivals after one day generally remained interpretable after longer stacking periods, while locations with poor or ambiguous responses showed little improvement.

These results indicate that the limitations observed in certain sections of the railway corridor are not primarily caused by insufficient recording duration. Instead, they point toward a more fundamental issue related to the nature and distribution of the seismic sources, motivating the investigation of source directionality discussed in the following section.

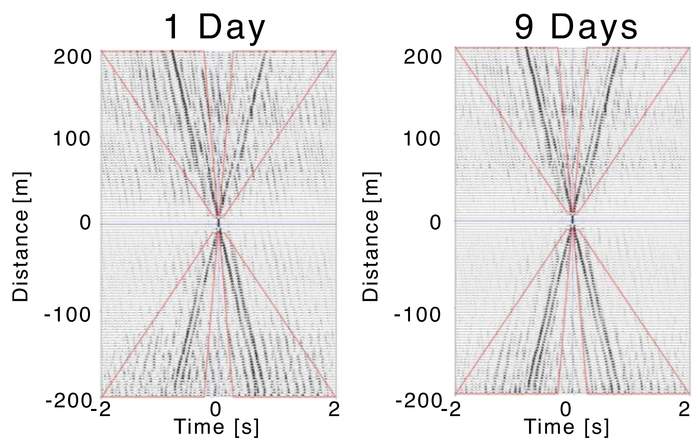


Figure 14*: Example of the cross correlations extracted by averaging additional time. Although stacking over 9 days cleans up the result a little bit, the results were considered marginal and not worth the extra time in terms of recording and computation.*

3.2.3 Exploring directionality of seismic sources

We next sought to better understand the origin of the seismic energy recorded along the railway corridor and verify that the recovered dispersion curves were indeed associated with Rayleigh waves propagating along the fiber. While train traffic was expected to dominate the wavefield, we wanted an automated way to identify the direction of the dominant energy source at each location. For each virtual source position, the observed frequency-velocity dispersion image was compared against synthetic Rayleigh-wave responses generated for approximately 100 possible source azimuths. The source direction providing the best match between observations and predictions was then identified.

Figure 15 summarizes the results along the railway corridor. As expected, most locations show dominant energy arriving from azimuths close to 0° or 180°, consistent with train-generated vibrations propagating along the railway line. A few sections, however, exhibit anomalous source directions, indicating the presence of off-line anthropogenic or environmental sources.
The main value of this analysis is the identification of locations where conventional ambient-noise assumptions are violated. In the presence of a strong off-axis source, Rayleigh or Love waves can reach the fiber with apparent velocities significantly different from the true subsurface velocity, resulting in unusually fast or otherwise difficult-to-interpret dispersion curves. The identification of such locations motivated the train-isolation workflow described in the following section.
Beyond source characterization, the approach offers two advantages over conventional MASW processing: it does not assume that the dominant source is aligned with the fiber, and it operates directly in frequency-velocity space, eliminating the need for manual dispersion-curve picking.

The methodology is currently being further developed by another Senior Researcher in the SWP group, Scott Keating, and a draft manuscript is being prepared.

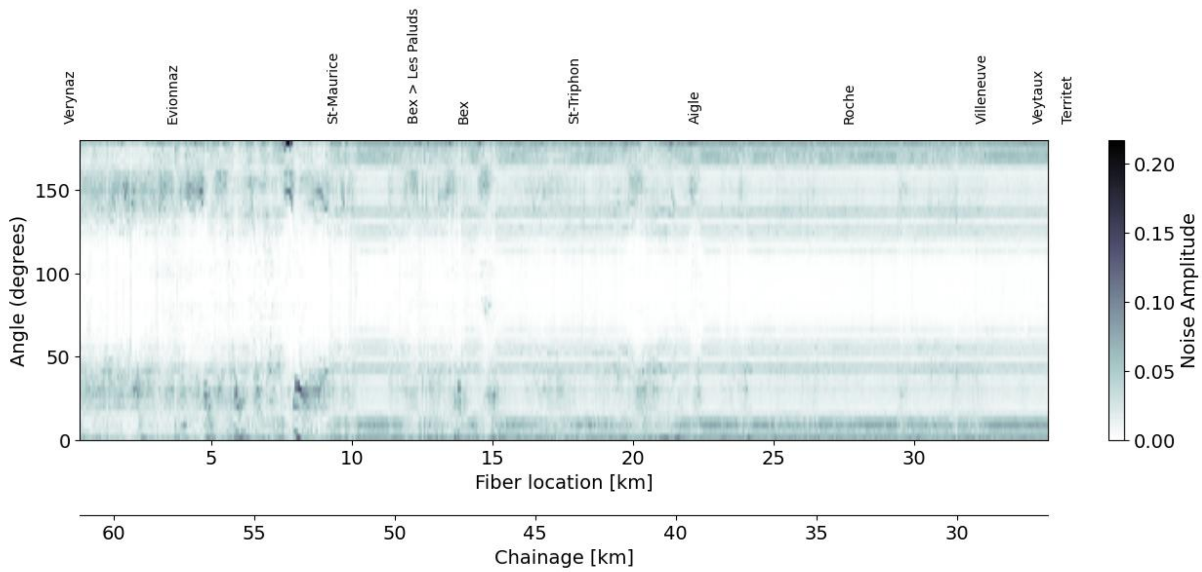


Figure 15*: Testing the goodness-of-fit when modelling dispersion images, for sources from different azimuths. Most locations along the fiber show strongest signals at 0 or 180 degrees, most likely corresponding to train excitations, but a few places (e.g. at ~ 8k) showed anomalous sources of seismic vibrations.*

3.2.4 Isolating Train Sources

It became clear that trains represent the most energetic and persistent seismic source available along the railway corridor. Rather than treating these signals as noise, we investigated how they could be isolated and used directly for subsurface characterization.

To achieve this, we implemented an automated window-selection workflow based on the approach of Cunha Teixeira et al. (2025). The objective was to identify coherent seismic waves propagating away from passing trains while excluding the highly complex wavefield observed directly beneath the train itself. In addition to concerns regarding source complexity, very large strain amplitudes can occasionally approach the dynamic limits of the DAS measurement system, making near-source observations less suitable for quantitative analysis.

The workflow operates in the frequency-wavenumber (FK) domain. Continuous DAS recordings are divided into small overlapping time-space windows (of 5 seconds by 100 meters), and an FK transform is applied to each. By comparing the energy propagating in opposite directions along the fiber, windows exhibiting a strong directional signal can be automatically identified. In practice, this corresponds to the seismic wavefield radiated ahead of and behind passing trains.
Figure 16 shows an example. The automated workflow successfully identifies coherent wave packets propagating northward and southward away from the train while avoiding the chaotic wavefield (in grey) directly associated with the train passage. Depending on location and traffic conditions, the procedure identifies (only) hundreds to thousands of suitable windows per day.

The results demonstrate that train-generated vibrations can be isolated automatically and used as a repeatable source of seismic energy. More importantly, they suggest that railway operations themselves may provide a persistent excitation source for large-scale subsurface characterization, reducing reliance on the assumptions of conventional ambient-noise interferometry

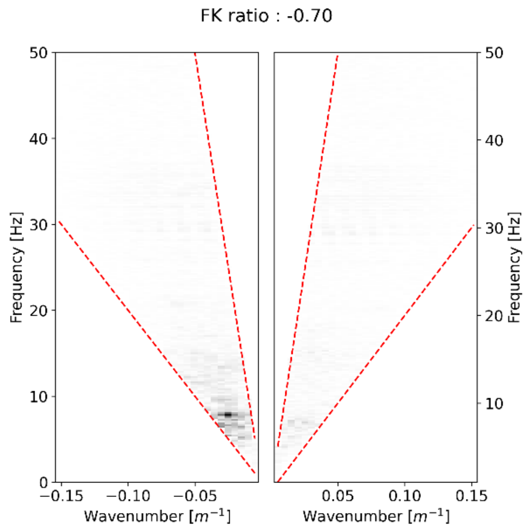


***Figure 16**: An example FK-transform from one tile of data. In this case, stronger energy was observed corresponding to the left side or negative wavenumbers, indicating seismic waves were propagating southward along the line. This was likely a moment in time where a train was nearby causing strong vibrations to propagate in one direction.*

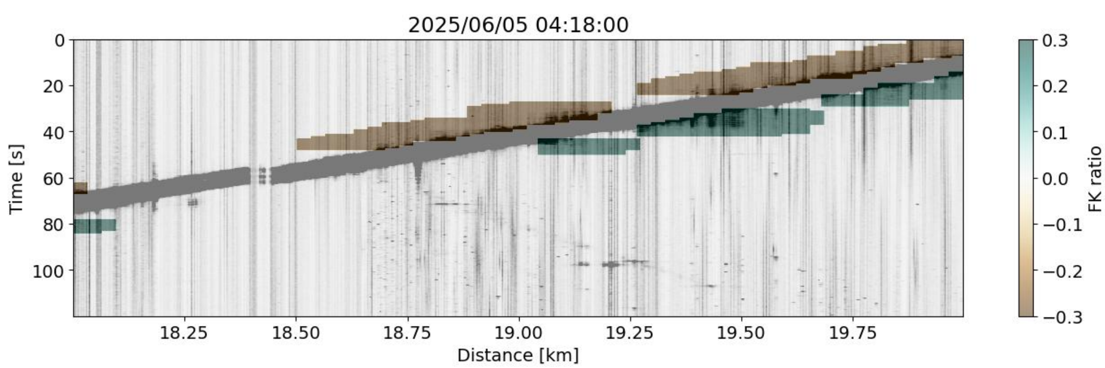


***Figure 17**:Example window picking near a passing train. The automated workflow isolated southward propagating (brown) or northward propagating (green) signals, while avoiding the chaotic seismic wavefield directly beneath the train.*

The FK-based window selection successfully identified periods dominated by directional seismic energy. However, not all selected windows were associated with trains. As shown in **Figure 17**, while the majority of selected windows track train passages, additional directional sources were observed at several locations along the fiber, consistent with the azimuthal analysis presented in the previous section.

To further isolate train-generated signals, an additional energy-based criterion was introduced. Because seismic amplitudes vary substantially both along the fiber and throughout the day, a simple RMS threshold proved insufficient. Instead, we used the ratio between the Root-Mean-Square (RMS) amplitude and the Median Absolute Deviation (MAD), which more robustly identifies periods of unusually strong seismic activity relative to the local background.

Figure 18 illustrates the resulting selection for a short train passage. The combined FK and RMS/MAD criteria successfully isolate strong wavefields propagating away from the train while rejecting the complex and highly energetic signals observed directly beneath it.
Although the combined selection substantially reduces the number of usable windows, the resulting observations are significantly cleaner and more interpretable. Even after applying both criteria, most locations along the fiber still yield several hundred high-quality windows per day suitable for analysis.

Key Takeaway: Combining amplitude and directionality criteria enables robust selection of train-generated seismic waves, while avoiding the chaotic near-field underneath the train itself. The resulting correlations and MASW dispersions are better constrained. The process is time consuming but fully automated.

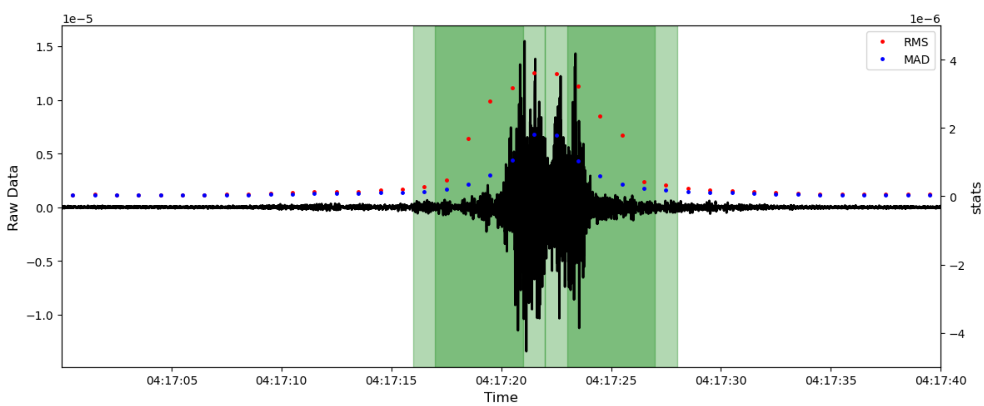


***Figure 18**: Window selection based on a ratio of total amplitude (RMS) and level of variability or chaoticness (MAD).*

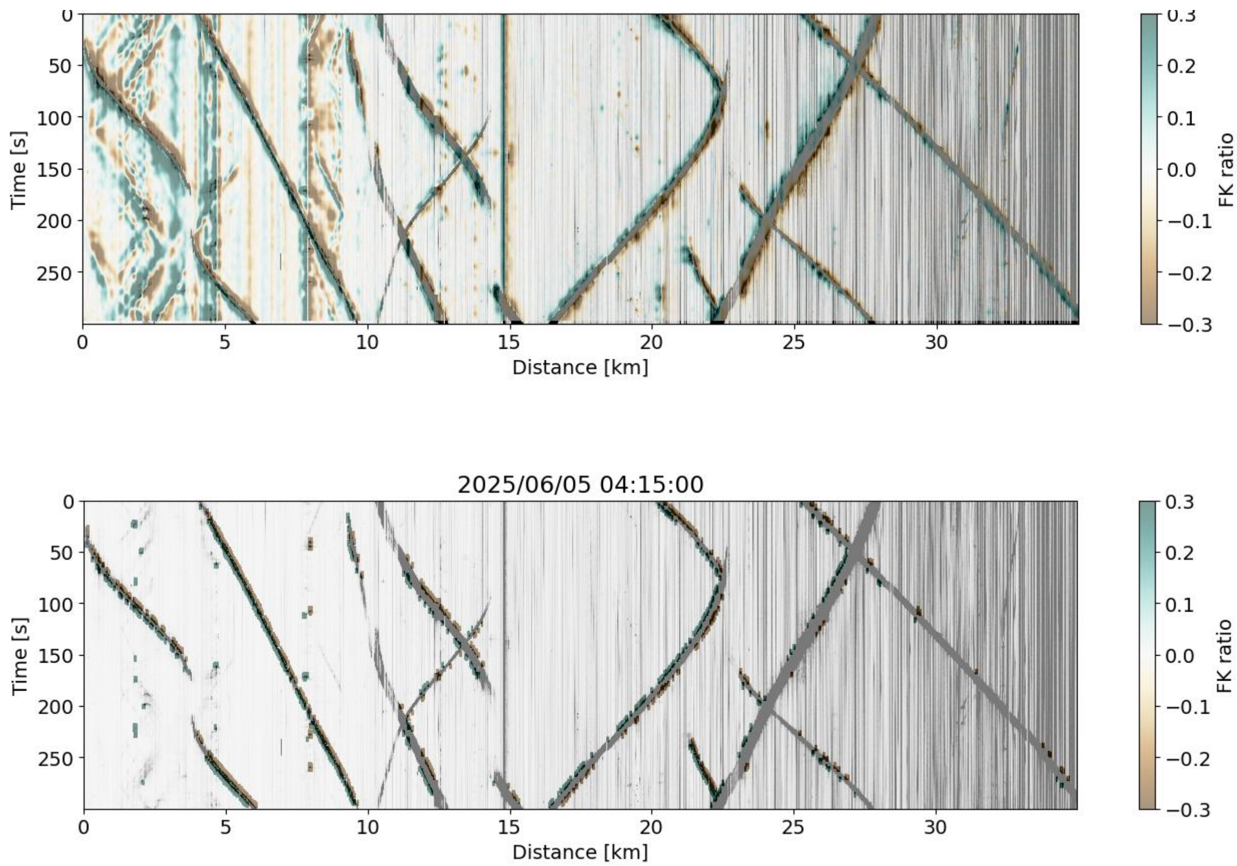


***Figure 19**: A 5 minute window of data, with raw DAS signals in greyscale. Colored windows indicate selected time windows to be used for cleaner stacking. Top panel shows all time windows from the FK-based directionality analysis. The bottom panel shows selections under both FK-based and energy-based criteria, and indicates the combination is effective at mostly isolating train-dominated seismic waves.*

3.2.5 Automated Dispersion Curve Selection

One of the most time-consuming steps in the workflow is the interpretation and picking of Rayleigh-wave dispersion curves. After isolating train-dominated windows, performing the interferometric analysis, and applying the slant-stack transform, each virtual source location produces a frequency-velocity image similar to those shown in **Figure 11**. Processing the several thousand dispersion images generated in this study required multiple days of manual effort.

With the prospect of repeated measurements through time, or deployment along additional railway corridors, we investigated approaches for automating this process. We implemented a version of the MUltiple SIgnal Classification (MUSIC) algorithm adapted to identify dominant signals in the frequency-wavenumber domain. The method uses Singular Value Decomposition (SVD) to separate signal and noise subspaces, allowing coherent dispersion trends to be identified more robustly than conventional peak-picking approaches.

In addition to automatically identifying the dominant Rayleigh-wave mode, the algorithm provides an estimate of the robustness of each pick as a function of frequency. This enables low-confidence picks to be discarded automatically while retaining only the most reliable measurements for inversion. An example is shown in **Figure 20,** where the automated MUSIC-based picks closely reproduce the manually interpreted dispersion curves and capture the main features of the wavefield. While manual interpretation required many hours of work, the automated workflow processed the full dataset in only a few minutes, demonstrating a promising route toward large-scale and repeatable railway monitoring.

Key Takeaway: FOSlab implemented an algorithm for automated dispersion curve picking, saving days of manual analysis. The output agrees with manually interpreted picks.

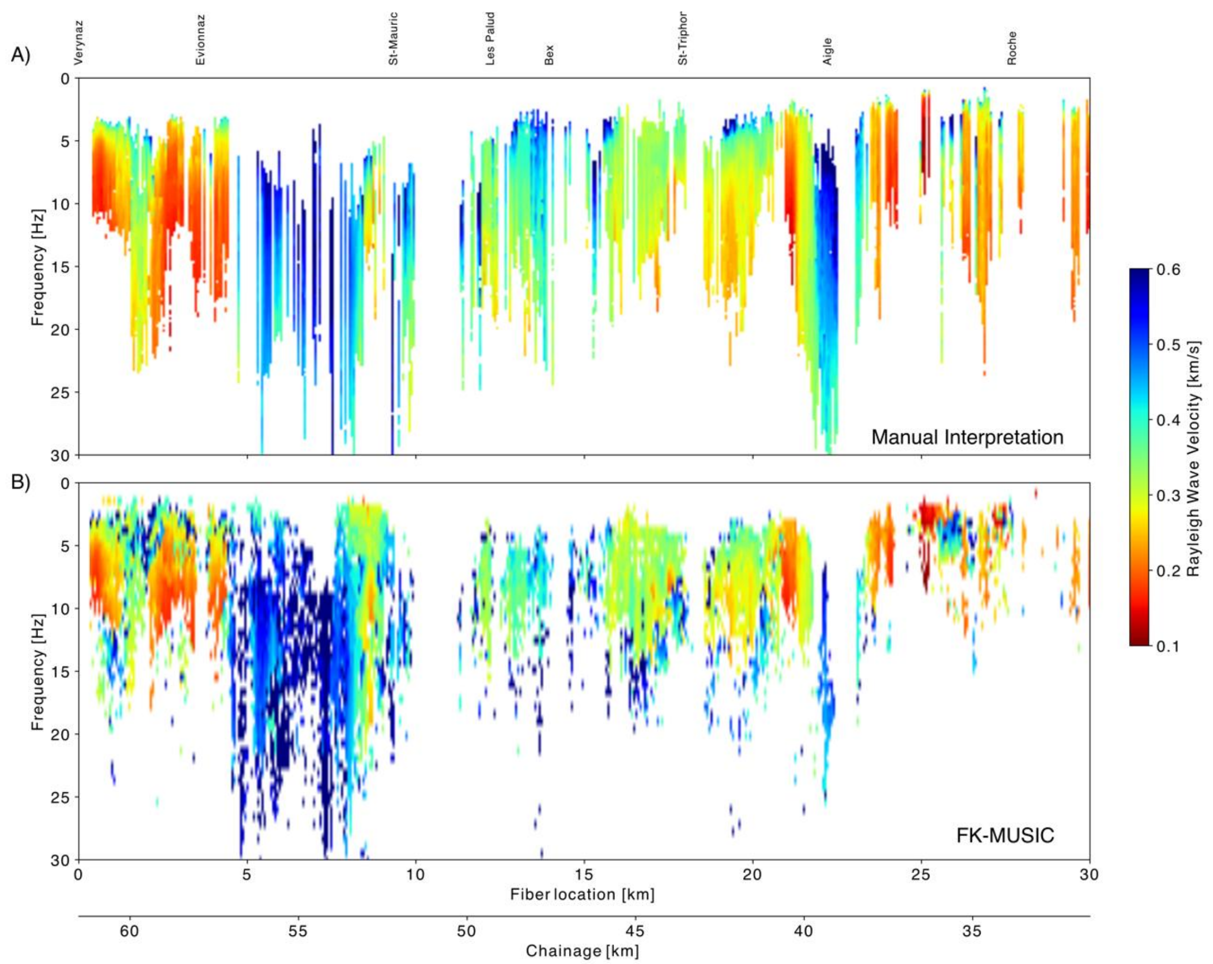


Figure 20*: (A) Manually interpreted dispersion curves from the MASW workflow. Different frequencies were used based on what could be robustly interpreted, and some areas were excluded on the basis of unclear or uninterpretable images. (B) The same dispersion data but automatically identified by the FK-MUSIC algorithm.*

3.2.6 Testing a Symmetric Variational Autoencoder (SymVAE)

An alternative to the signal processing steps discussed in the previous section to isolate train-dominated signals is to use a Machine Learning approach. The very dense set of DAS observations make the task well suited to ML or computer vision approaches. A PhD student visiting ETH (SWP/FOSlab) in 2025 had particular experience in this domain, and set up a Symmetric Variational Autoencoder (SymVAE) to identify time windows of interest for extracting robust Rayleigh waves (Bajad and Bharadwaj 2025).

The SymVAE approach is a specialized version of what may colloquially be called a “U-Net”, where observations are compressed through a neural network to only a few latent bits of information (the “encoder”), and a symmetric decompression (“decoder”) recovers a clean version of the original input. While often used for data cleaning, the approach specifically tested here uses only the compressed bits of information to sort data into different clusters that share common wavefield characteristics. Stacking the observations within each cluster then provides a robust representation of the dominant seismic signals present.

As per the standard approach described at the beginning of this section, one-minute segments of DAS data were cross-correlated and fed into the SymVAE network yielding several clusters. Upon manual inspection of the different clusters, one or two showed dominant Rayleigh waves that could be used for subsurface imaging. **Figure** below shows one such example, and it was manually determined that panels C and D showed the cluster with the most robust measure of Rayleigh waves.

Inspection of the contributing time windows showed that these clusters were overwhelmingly associated with train passages (**Figure 22**), independently confirming the conclusions reached through the signal-processing-based workflow described in the previous section. The results of the SymVAE algorithm show promise and are currently being prepared for a journal article. Application to the whole line is not complete at the time of this report, as ultimately further testing and fine-tuning are needed.

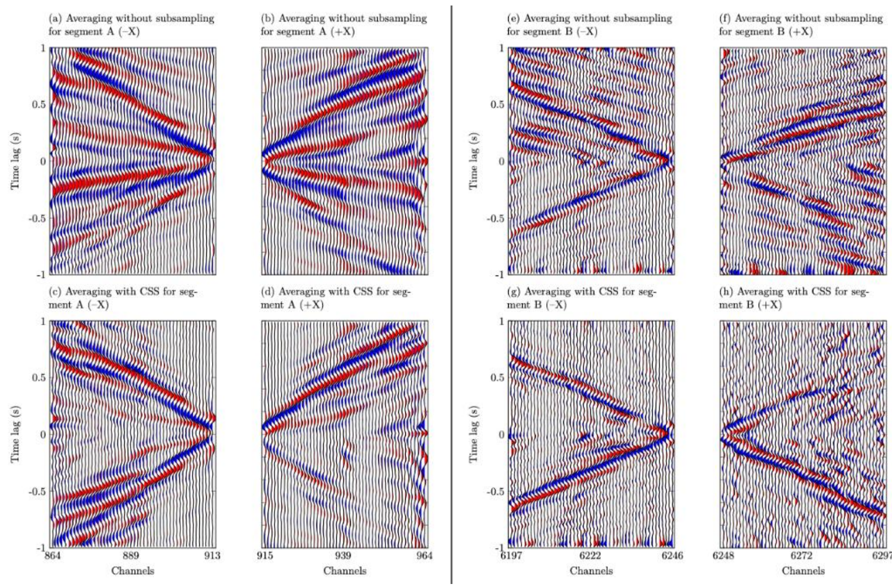


Figure 21*: Different approaches to stacking or averaging cross-correlated data. Panels (a) and (b) show the standard approach of averaging all time windows. Other panels show different clusters identified by the SymVAE algorithm, for which only raw data in those clusters were stacked.*

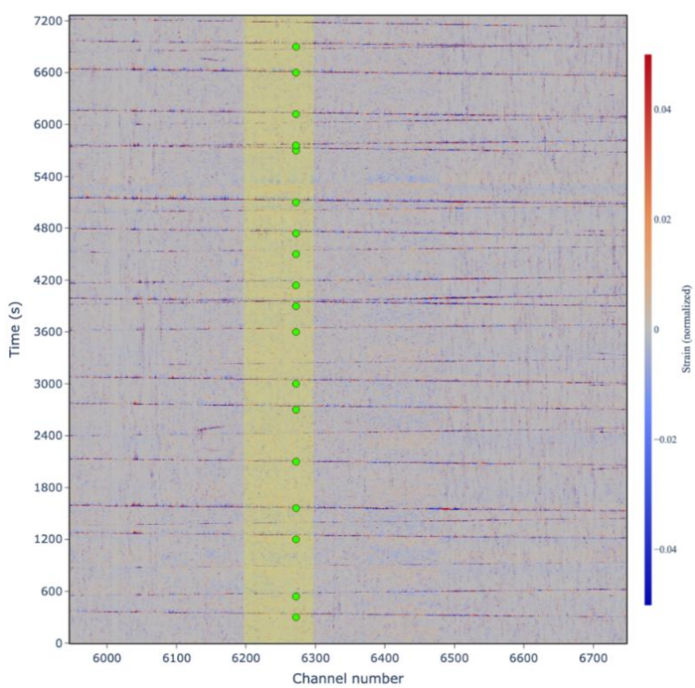


Figure 22*: 2 hours of DAS data with green dots indicating the 1-minute time-windows that contributed to the robust Rayleigh wave observations from the SymVAE algorithm. Every one indeed corresponds to a passing train.*

3.3 Subsurface Model

Using the Rayleigh-wave dispersion observations described above, one-dimensional shear-wave velocity (Vs) profiles were estimated along the railway corridor using the McMC inversion workflow presented in Section 3.1.3. Because each dispersion measurement was derived from a slant-stack window approximately 150 m long, neighbouring Vs profiles usually overlap. In such cases, overlapping models are averaged to improve robustness. Where only one measurement was available, the resulting model was distributed over the corresponding spatial extent. Combining all observations yields the nearly continuous 2D subsurface model shown in **Figure 23**.

Each individual Vs profile is associated with its own uncertainty as a function of depth. However, while these uncertainties can be quantified at the profile level, interpreting and visualizing them consistently within a continuous 2D section remains challenging, particularly where multiple overlapping inversions contribute to the final model.

Several notable features emerge from the resulting cross-section. First, strong lateral velocity contrasts are observed at a number of locations. While geological units often vary gradually, the railway corridor itself can vary sharply with bridges, villages, or tunnel section. As a result, adjacent portions of the fiber may sample markedly different geological environments, producing abrupt changes in the recovered velocity structure.

The model also reveals several regions characterized by relatively low shear-wave velocities extending beyond 20 m depth. These are interpreted as soft soils or unconsolidated sediments and are considered robust features as they are independently supported by the observed slow dispersion values and the inversion output. In a number of locations, very deep sediments are observed, notably in the regions southwards of Saint-Triphon at chainage distances less than 46 km. While the deeper extents of our models are more uncertain, very deep and very slow materials are again supported by the dispersion curves (**Figure 20)**.

In at least one area of particular interest, the inversion results can be compared against independent Cone Penetration Test (CPT) measurements (**Figure 24 and 25**). Several CPT locations coincide with recovered Vs profiles retrieved within the section around Aigle and Roche (chainage 28–38 km) which is known to contain soft sediments, silts, and other unconsolidated materials, and therefore identified as a region of geotechnical interest. The agreement between the DAS-derived velocity models and the CPT observations is generally encouraging. In some cases (e.g., CPT3c and CPT11), the correspondence is particularly strong. In others (e.g., CPT5, CPT6, and CPT7), the DAS-derived velocities are somewhat higher, although the overall trends and relative variations remain consistent. These comparisons provide independent validation of the ability of railway telecommunications fibers to recover meaningful subsurface information over large spatial scales.

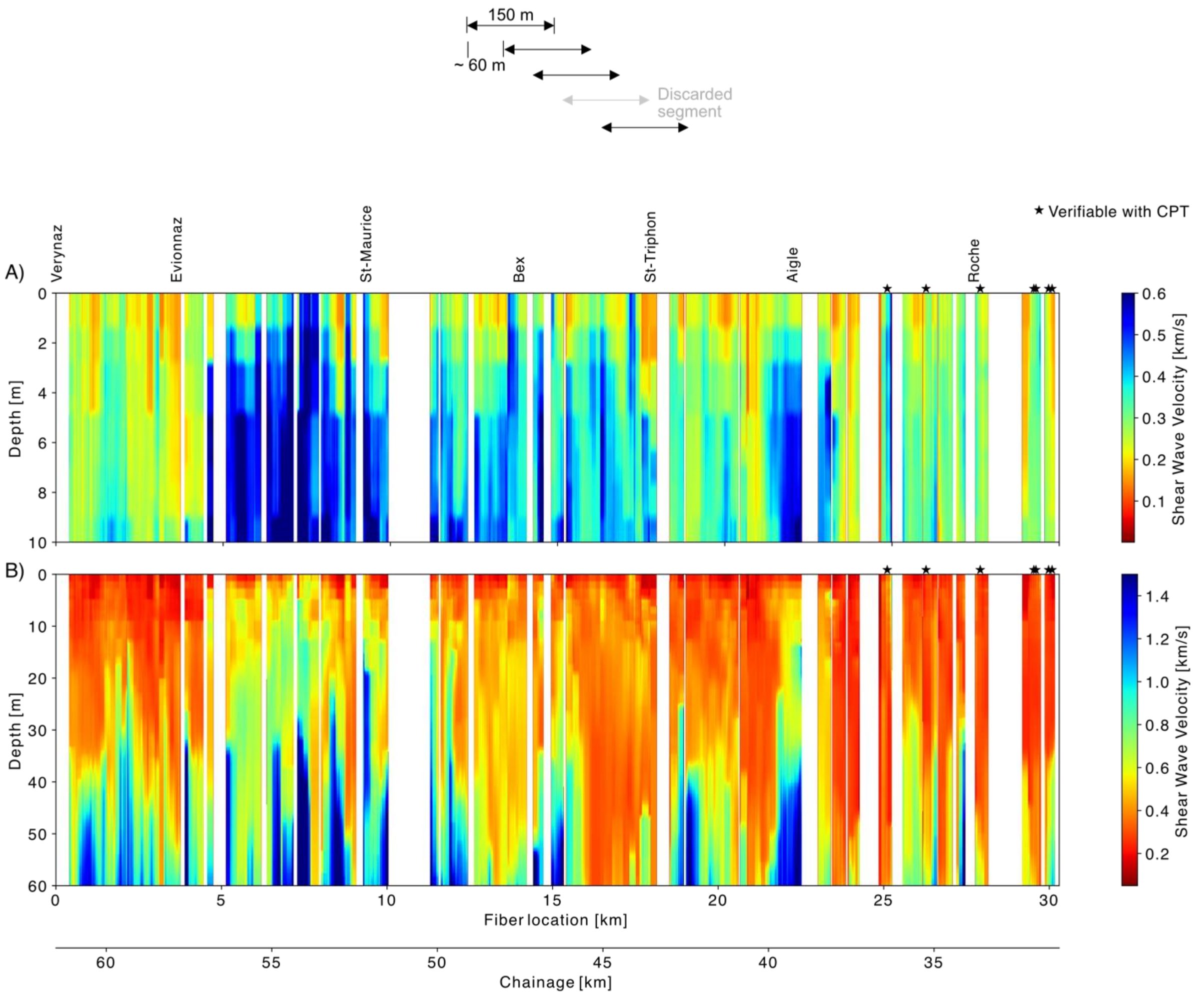


Figure 23*: Recovered 2D velocity model along the study area. (A) shows only the top 10 m, while (B) shows the top 60 m with a wider color range. In both cases, white gaps were left where the data was unpickable or uninterpretable. Black stars indicate locations for which velocities from CPT measurements were present.*

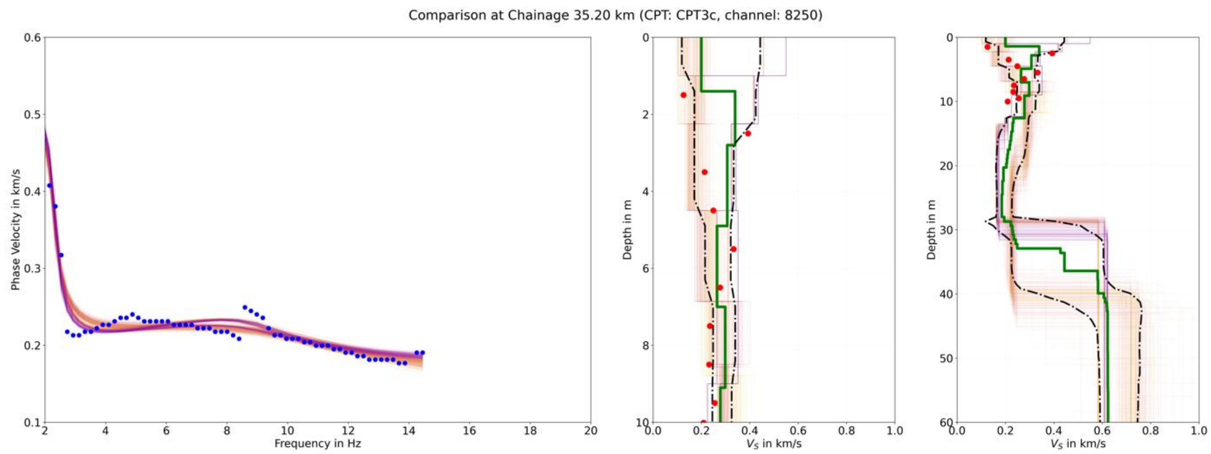


Figure 24: *Comparison to CPT observations. The right panel shows MASW recovered Vs profile in green, with +/- 1 standard deviation of the ensemble of possible models in black dashed lines. Red dots indicate the CPT Vs estimates.*

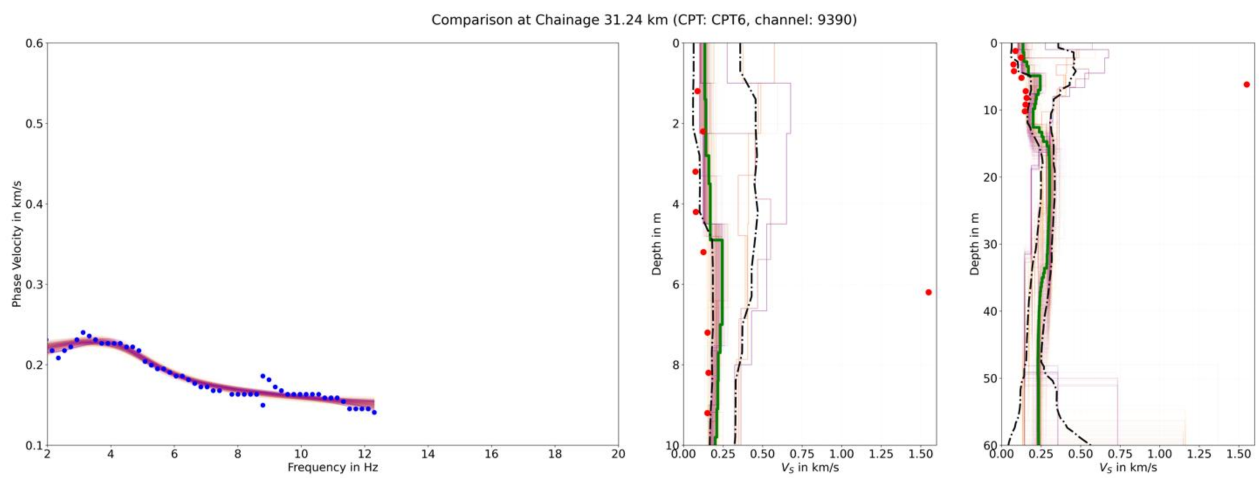


Figure 25: *Comparison to CPT observations. Curves are the same as above. Here, the agreement between our MASW mean model and the CPT measurements is poorer, though still within the range of plausibility indicated by the spread of models.*

3.4 Key findings for Subsurface Characterization

The analyses presented in this section demonstrate that existing railway telecommunications fibers can be successfully leveraged for large-scale subsurface characterization using DAS. The principal findings are:

- Railway telecommunications fibers provide sufficient data quality for MASW-based subsurface imaging. Approximately 100 km of railway fiber were acquired during the project, demonstrating the scalability of the approach. While the present study focused on approximately 30 km of high-quality observations, next-generation DAS interrogators are expected to extend the effective sensing range to hundreds of kilometres while maintaining the spatial resolution required for geotechnical applications.
- Train traffic represents the dominant source of seismic energy. Rather than being a limitation, these vibrations can be exploited as a persistent and repeatable seismic source for subsurface characterization.
- Conventional ambient-noise workflows are not always optimal in railway environments. Directional source effects and non-diffuse wavefields can bias standard interferometric approaches.
- Railway-specific processing significantly improves robustness. Source-direction analysis, train isolation, automated dispersion picking, and machine-learning approaches all contributed to more reliable subsurface imaging.
- The resulting Vs models reveal significant lateral variations in subsurface conditions. Several regions characterized by low seismic velocities were identified, indicating the presence of soft soils or unconsolidated sediments.
- Independent CPT measurements broadly validate the DAS-derived velocity models. The observed agreement demonstrates that existing telecommunications fibers can recover meaningful geotechnical information at railway-network scale.

Overall, the project demonstrates that existing railway fiber infrastructure can be transformed into a low-cost geotechnical sensing network, capable of providing continuous subsurface information over tens of kilometres with minimal disruption to railway operations.

3.5 Repeated Measurements and Change Detection

The subsurface model presented above represents a snapshot of ground conditions during the deployment period. However, one of the principal advantages of leveraging existing railway telecommunications fibers is the ability to repeat such measurements at low cost and with minimal operational impact.

Once a processing workflow has been established, the same railway line could (should?) be surveyed repeatedly to detect changes in subsurface properties through time. Unlike conventional geotechnical investigations, which are often limited to isolated campaigns or discrete locations, DAS could be a particularly convenient approach. Previous studies have demonstrated that repeated surface-wave measurements can detect changes in groundwater conditions, sediment saturation, permafrost degradation, and other environmental processes that influence seismic velocities. Similar approaches have also been used to monitor evolving geotechnical conditions and characterize the response of the subsurface following natural or anthropogenic disturbances. For railway applications, repeated measurements could potentially be used to identify progressive changes in embankments, monitor the impact of construction activities, assess seasonal variations in groundwater conditions, or track the evolution of known problematic areas. Locations identified in the present study as exhibiting particularly low shear-wave velocities may represent natural candidates for future monitoring efforts.

The workflow developed during this project was designed with repeatability in mind. Automated train selection, dispersion extraction, and velocity inversion provide a foundation for comparing measurements acquired at different times and identifying meaningful deviations from baseline conditions. While no dedicated time-lapse experiment was performed within the scope of the present project, the results establish a baseline subsurface model against which future surveys can be compared.

Key Takeaway: The ability to transform existing railway telecommunications fibers into a continuously available geotechnical monitoring system represents one of the most promising long-term opportunities identified during this work. DAS measurements could also be used to quantify the contribution of different train types to railway infrastructure wear and deterioration.

4. Additional Monitoring Applications and Future Opportunities

Although the primary objective of this project was subsurface characterization, the deployment also demonstrated a range of additional capabilities relevant to railway operations, natural hazard monitoring, and national seismic monitoring. Many of these applications leverage the same DAS infrastructure and processing workflows developed for geotechnical imaging, highlighting the potential value of railway telecommunications fibers as multi-purpose sensing networks.

4.1 Natural Hazard Monitoring

Many of the natural hazards monitored by the Swiss Seismological Service (SED) are also directly relevant to railway infrastructure. Earthquakes, landslides, rockfalls, debris flows, and avalanches can all damage railway assets or disrupt operations, often with little warning. The dense spatial sampling provided by DAS offers a unique opportunity to detect and characterize such events over large areas using existing telecommunications infrastructure.

Previous work within ETH and other institutions has demonstrated the ability of DAS systems to detect and classify a wide range of natural hazards, including avalanches, rockfalls, debris flows, and glacier-related processes. Many of these events generate characteristic seismic wavefields that can be identified using approaches similar to those developed in this project.

Although no major earthquake occurred within the monitored corridor during the deployment period, several transient geophysical events were recorded, including regional seismicity, quarry blasts, and the seismic waves generated by the Blatten landslide collapse. These observations demonstrate both the sensitivity of the system and its ability to capture events occurring over a wide range of distances and magnitudes.

The combination of real-time monitoring, automated processing, and existing telecommunications fibers suggests that DAS can contribute to both hazard detection and post-event assessment. In addition to identifying the occurrence of an event, the same infrastructure could potentially be used to evaluate resulting changes in ground conditions through repeated subsurface characterization measurements, as discussed in Section 3.5.

While substantial development and validation remain necessary before operational deployment, the results of this project support the broader concept of railway telecommunications fibers serving as distributed environmental and hazard-monitoring networks in addition to their primary communications role.

4.2 Collaboration with the Swiss Seismological Service

The pilot deployment also provided an opportunity to explore how railway DAS observations could complement the operational and scientific activities of the Swiss Seismological Service (SED). Beyond the specific objectives of railway subsurface characterization, the project served as a testbed for integrating large-scale DAS observations into existing seismic monitoring workflows and evaluating their potential value for earthquake and hazard monitoring.

4.2.1 Integration with Operational Monitoring Workflows

From August to October 2025, 917 individual channels from the DAS deployment were streamed in real time to the SED and incorporated into the national seismic monitoring infrastructure. The objective of this experiment was threefold: (1) to demonstrate stable long-term streaming of large DAS datasets; (2) to integrate DAS observations into standard seismic monitoring software; and (3) to evaluate whether DAS observations could contribute to earthquake detection and location.

The test proved successful. Real-time streaming using a standard 5G connection provided sufficient bandwidth and remained stable throughout the deployment. The DAS observations were converted into the standard miniSEED format, archived alongside conventional seismic observations, and integrated into the SeisComP monitoring platform. Sensor metadata, including channel locations and acquisition parameters, were incorporated into the existing infrastructure, allowing DAS observations to be visualized and analysed using the same tools employed for the national seismic network.

Initial tests demonstrated that DAS observations can contribute useful information for earthquake analysis, particularly for events occurring close to the fiber. The experiment also established the technical foundations required for future operational deployments involving substantially larger numbers of DAS channels.

The ability to stream, archive, visualize, and process DAS observations within existing seismic monitoring systems represents an important step toward broader operational use of fiber-optic sensing technologies.

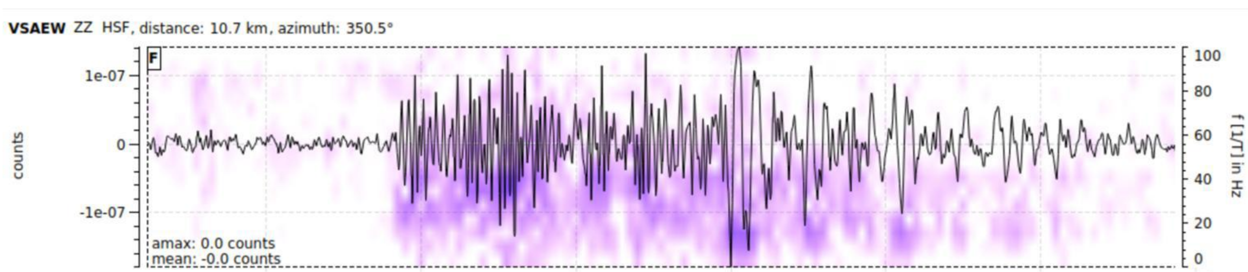


Figure 26*: One example channel from the fiber recordings streamed in real-time to the SED's servers. This data was incorporated into regular workflows to complement the existing network of seismic stations across Switzerland.*

4.2.2 Opportunistic science

In addition to its operational value, the pilot test created opportunities for scientific investigations unrelated to the original objectives of the project. Because the DAS observations were continuously available and readily accessible, they could be incorporated into other ongoing research activities within the SED.

One example was a large geothermal monitoring experiment in the Lavey-les-Bains region where geophysical monitoring is used to identify suitable geothermal resources and to distinguish naturally occurring seismicity from seismicity potentially associated with geothermal operations. As part of this effort, the railway DAS observations complemented a dense network of 271 three-component seismometers was deployed across the valley. The combination of conventional seismic stations and dense DAS measurements provide an unusually rich dataset for characterizing the local seismic wavefield and subsurface structure. Analysis of these observations is ongoing and has already contributed to scientific results published by Obermann et al. (2026).

This example illustrates a broader benefit of railway DAS deployments: once the data infrastructure is established, the observations can support a wide range of scientific and operational objectives beyond those originally envisioned. Existing railway telecommunications fibers therefore represent not only a monitoring asset for railway operators, but also a valuable resource for geoscience research and national monitoring activities.

4.3 Responsive Monitoring and Rapid Infrastructure Assessment

The deployment demonstrated that DAS systems can be installed rapidly and operated remotely using existing telecommunications infrastructure. Following earthquakes, landslides, rockfalls, floods, derailments, or other disruptive events, a DAS interrogator could potentially be connected to a nearby railway fiber and begin providing measurements within hours. Such deployments could complement conventional inspections by providing dense observations over tens of kilometres of railway. In addition to monitoring ongoing seismic activity, the measurements could be used to assess changes in subsurface conditions or identify sections of infrastructure requiring further investigation.

The Swiss Seismological Service already operates rapid-response monitoring systems following significant earthquakes. Future collaborations between SBB, ETH/FOSLAB, and the SED could investigate whether similar workflows can be extended to railway telecommunications fibers, providing rapid situational awareness following disruptive events. The technical foundations required for such deployments (including real-time streaming, remote operation, and integration into existing monitoring systems) were successfully demonstrated during this project.

4.4 Railway Infrastructure and Train Health Monitoring

While the primary objective of this project was subsurface characterization, the recorded DAS observations clearly demonstrate that railway telecommunications fibers contain a wealth of information related to train traffic and infrastructure behaviour. Throughout the deployment, train passages represented the dominant source of seismic energy and generated highly repeatable wavefield signatures observable over tens of kilometres of fiber.

Several examples presented earlier in this report show that individual bogies, axle groups, and train passages can be identified directly within the DAS observations. These measurements contain information not only on train position and speed, but also on how vibrations are transferred between the train, track, and surrounding ground.

Beyond train detection itself, the data reveal spatial variations in vibration amplitude and frequency content along the railway. Such variations may reflect differences in subsurface conditions, track structure, ballast condition, bridges, tunnels, switches, or other infrastructure elements. Continuous or repeated observations could therefore be used to identify locations that behave differently from their surroundings or that evolve through time.

A particularly attractive future direction is condition monitoring. Rather than attempting to model every train individually, repeated observations of the same train operating along the same route could be compared through time. Changes in vibration signatures may provide indicators of wheel defects, wheel out-of-roundness, uneven loading, track degradation, or evolving infrastructure conditions. Similar concepts have already been demonstrated using conventional vibration sensors and could potentially be adapted to DAS measurements.

The FOSlab RGB monitoring approach may provide a practical foundation for such applications. Train signatures, track responses, and unusual vibration patterns could be visualized in real time and transmitted at low bandwidth. Combined with automated signal processing and machine-learning approaches, this may open the possibility of continuously screening large railway networks for anomalous behaviour.

Although these applications remain largely unexplored, they may ultimately represent one of the most valuable outcomes of railway DAS monitoring. Existing telecommunications fibers could evolve into permanent sensing networks capable of simultaneously monitoring trains, track infrastructure, subsurface conditions, and natural hazards using a single sensing platform.

4.5 Mobile / Agile High-Resolution Surveys

While the results presented in this report demonstrate the ability of DAS to characterize subsurface conditions over tens of kilometres of railway, some applications may benefit from a different acquisition strategy focused on shorter distances and higher spatial resolution.

In the present deployment, acquisition parameters were optimized for an interrogation range exceeding 30 km. While this approach proved effective for imaging the upper tens of metres of the subsurface, it is less well suited to resolving very shallow features or highly localized infrastructure issues. In such situations, a more targeted mode of operation may be preferable.

Because DAS interrogators can be portable and be connected at many railway facilities, it would be possible to temporarily deploy the system on selected fiber segments and acquire data at higher spatial resolution over shorter distances. Based on the results obtained during this project, we expect that useful subsurface models could often be recovered from only a few hours to a few days of recording.

Such surveys could support a variety of applications, including detailed investigations of bridges, tunnels, switches, embankments, stations, construction sites, or locations identified as problematic. The same train-generated seismic sources exploited in this study could provide the required energy without the need for dedicated active seismic sources.

This capability creates a natural complement to the large-scale monitoring concepts discussed throughout this report. Railway telecommunications fibers can be used both as permanent monitoring systems covering extensive portions of the network and as rapidly deployable tools for focused, high-resolution investigations wherever additional information is required.

5. Proposed Follow-Up Activities

The pilot project successfully demonstrated the feasibility of railway DAS monitoring and identified several promising directions for future work.

1. Advanced Railway Wavefield Analysis
Several observations made during the pilot project warrant further investigation. These include the potential use of Doppler shifts from passing trains, exploitation of low-frequency quasi-static deformations generated by train loads, and direct observation of propagating surface waves (gradiometry) as alternatives or complements to conventional ambient-noise interferometry. Such approaches may improve shallow subsurface characterization while reducing data volumes and processing requirements.

2. Railway Infrastructure and Train Health Monitoring
Investigate the capability of DAS to distinguish different train types and develop automated workflows for train classification. Repeated observations of the same trains could potentially be used to detect wheel defects, wheel out-of-roundness, uneven loading, or other indicators of train condition. Similarly, repeated measurements may reveal evolving conditions in tracks, ballast, switches, bridges, tunnels, or embankments, providing a foundation for infrastructure condition monitoring.

3. Repeatability and Time-Lapse Monitoring
Repeat selected surveys over periods of months to years to quantify the sensitivity of DAS-derived subsurface models to seasonal groundwater variations, construction activities, and long-term geotechnical changes. Establish baseline conditions and assess the feasibility of operational change detection along railway corridors.

4. Quantitative Geotechnical Interpretation
The 2D velocity model presented in this report represents the mean of a large ensemble of McMC solutions. Future work should focus on propagating and visualizing uncertainty estimates at network scale, integrating CPT and geological information, and translating DAS-derived velocity models into engineering-relevant indicators that can support infrastructure management and decision-making.

5. Responsive Monitoring and Hazard Response
Demonstrate rapid deployment of DAS systems following earthquakes, landslides, floods, rockfalls, or other disruptive events. In collaboration with the Swiss Seismological Service, evaluate the feasibility of integrating railway DAS observations into existing rapid-response monitoring workflows and aftershock deployments, while simultaneously supporting rapid infrastructure assessment.

6. Network-Scale and Agile Monitoring Strategies
The present deployment demonstrated that more than 100 km of railway telecommunications fiber can be acquired using a single DAS interrogator. However, the high-resolution analyses presented in this report required acquisition parameters that limited the effective sensing range to approximately 2x 30 km. Recent developments in DAS interrogator technology (recently acquired by ETHZ) enable in principle to significantly extend this range to 2x100 km, while maintaining the spatial resolution required for geotechnical applications.

Future work could therefore investigate optimal strategies for combining very large-scale monitoring with targeted high-resolution investigations. One approach would consist of routine network-scale surveys covering extensive portions of the railway system to identify regions of interest, unusual behaviour, or evolving geotechnical conditions. These observations could then guide the deployment of mobile interrogators at nearby railway access points to acquire even higher-resolution and quality measurements over shorter distances.

Such hybrid strategy would provide both broad network coverage and detailed local characterization using the same railway fiber infrastructure, therefore at low cost. The combination of extended sensing range and agile targeted deployments would ultimately provide a cost-effective approach to obtain very detailed information where its is most needed while maintaining continuous awareness across large portions of the network.

6. Conclusions

This project demonstrated the feasibility of using DAS and existing railway telecommunications fibers for large-scale subsurface characterization and monitoring. More than 30 km of railway corridor were successfully investigated, resulting in a near-continuous shear-wave velocity model validated against independent geotechnical information where available.

A key outcome of the study was the recognition that train traffic represents a powerful and repeatable seismic source. Rather than treating train-generated vibrations as noise, dedicated processing workflows were developed to isolate and exploit them for subsurface imaging. These railway-specific approaches significantly improved the robustness and scalability of the methodology.

Beyond geotechnical characterization, the project demonstrated real-time data streaming, integration with Swiss Seismological Service monitoring systems, and the potential for rapid-response deployments following disruptive events. The observations also revealed promising opportunities for infrastructure monitoring, train health assessment, natural hazard monitoring, and long-term change detection.

Taken together, the results suggest that railway telecommunications fibers can evolve from passive communication assets into multi-purpose sensing networks capable of simultaneously supporting geotechnical characterization, infrastructure monitoring, hazard assessment, and scientific investigations. The combination of existing fiber infrastructure, improving DAS technology, and automated processing workflows creates a unique opportunity to develop monitoring capabilities at scales that would be difficult or prohibitively expensive to achieve using conventional instrumentation alone.
The work presented here should therefore be viewed not only as a successful proof of concept, but also as the foundation for a broader programme of railway sensing and monitoring activities that could deliver value to both railway operators and the wider geoscience community.

7. References

Ajo-Franklin, Jonathan B., Shan Dou, Nathaniel J. Lindsey, Inder Monga, Chris Tracy, Michelle Robertson, Veronica Rodriguez Tribaldos, Craig Ulrich, Barry Freifeld, Thomas Daley, and Xiaoye Li. 2019. "Distributed Acoustic Sensing Using Dark Fiber for Near-Surface Characterization and Broadband Seismic Event Detection." *Scientific Reports* 9(1):1328. doi:10.1038/s41598-018-36675-8.

Bajad, Sanket Narayan, and Pawan Bharadwaj. 2025. "Symmetric Autoencoders for Retrieving Void-Generated Ringing Modes and Backscatter from Vehicle Seismic Noise." *Geophysics* 90(5):KS109–24. doi:10.1190/geo2024-0409.1.

Bensen, G. D., M. H. Ritzwoller, M. P. Barmin, A. L. Levshin, F. Lin, M. P. Moschetti, N. M. Shapiro, and Y. Yang. 2007. "Processing Seismic Ambient Noise Data to Obtain Reliable Broad-Band Surface Wave Dispersion Measurements." *Geophysical Journal International* 169(3):1239–60. doi:10.1111/j.1365-246X.2007.03374.x.

Bodin, T., M. Sambridge, K. Gallagher, and N. Rawlinson. 2012. "Transdimensional Inversion of Receiver Functions and Surface Wave Dispersion." *Journal of Geophysical Research: Solid Earth* 117(B2):2011JB008560. doi:10.1029/2011JB008560.

Bowden, Daniel, Ali Shaikhsulaiman, Simon Grieder, Ebru Bozdağ, Ali Özgün Konca, Semih Ergintav, Esra Ertan, Evrim Yavuz, Muhammed Ünlü, and Andreas Fichtner. 2026. "Shallow Modeling and Site-Amplification From Telecommunications Fibers in Istanbul." *Geophysical Research Letters* 53(11):e2025GL121011. doi:https://doi.org/10.1029/2025GL121011.

Cunha Teixeira, José, Ludovic Bodet, Marine Dangeard, Alexandrine Gesret, Amélie Hallier, Agnès Rivière, Audrey Burzawa, Julio José Cárdenas Chapellín, Marie Fonda, Ramon Sanchez Gonzalez, Amine Dhemaied, and Joséphine Boisson Gaboriau. 2025. "Nondestructive Testing of Railway Embankments by Measuring Multi-Modal Dispersion of Surface Waves Induced by High-Speed Trains with Linear Geophone Arrays." *Seismica* 4(1). doi:10.26443/seismica.v4i1.1150.

Girard, Aaron J., and Jeffrey Shragge. 2020. "Automated Processing Strategies for Ambient Seismic Data." *Geophysical Prospecting* 68(1):293–312. doi:10.1111/1365-2478.12794.

Herrmann, R. B. 2013. "Computer Programs in Seismology: An Evolving Tool for Instruction and Research." *Seismological Research Letters* 84(6):1081–88. doi:10.1785/0220110096.

Jennifer Dreiling and Frederik Tilmann. 2019. "BayHunter - McMC Transdimensional Bayesian Inversion of Receiver Functions and Surface Wave Dispersion." *GFZ Data Services*. V. 1.0. doi:https://doi.org/10.5880/GFZ.2.4.2019.001.

Lai, Voon Hui, Meghan S. Miller, Chengxin Jiang, Yan Yang, Fabrizio Magrini, Zhongwen Zhan, and Herb McQueen. 2024. "Passive Seismic Imaging of Urban Environments Using Distributed Acoustic Sensing: A Case Study from Melbourne, Australia." *The Seismic Record* 4(4):308–17. doi:10.1785/0320240031.

Lanteri, Ariane, Scott Keating, Lars Gebraad, Sara Klaasen, Marta Pienkowska-Côte, Olaf Eisen, Andrea Zunino, Kristín Jónsdóttir, Coen Hofstede, Dimitri Zigone, and Andreas Fichtner. 2025. "Seismic Constraints on Glacier Density." *Scientific Reports* 15(1):42259. doi:10.1038/s41598-025-26440-z.

Obermann, Anne, Marc Grandjean, Jonas Simon Junker, and Pascal Edme. 2026. "Large N-Array and DAS around the Lavey Geothermal Reservoir in Switzerland in Challenging Topographic Settings." *Geophysical Journal International* 245(1):ggag063. doi:10.1093/gji/ggag063.

Park, Choon B., Richard D. Miller, and Jianghai Xia. 1999. "Multichannel Analysis of Surface Waves." *GEOPHYSICS* 64(3):800–808. doi:10.1190/1.1444590.

Shapiro, N. M., and M. Campillo. 2004. "Emergence of Broadband Rayleigh Waves from Correlations of the Ambient Seismic Noise." *Geophysical Research Letters* 31(7):2004GL019491. doi:10.1029/2004GL019491.

Smolinski, Krystyna T., Daniel C. Bowden, Patrick Paitz, Felix Kugler, and Andreas Fichtner. 2024. "Shallow Subsurface Imaging Using Challenging Urban DAS Data." *Seismological Research Letters* 96(1):168–81. doi:10.1785/0220240052.

Tsai, Victor C. 2009. "On Establishing the Accuracy of Noise Tomography Travel-Time Measurements in a Realistic Medium." *Geophysical Journal International* 178(3):1555–64. doi:10.1111/j.1365-246X.2009.04239.x.

Appendix A: Related publications from this work

Paper: Obermann, Anne, Marc Grandjean, Jonas Simon Junker, and Pascal Edme. 2026. "Large N-Array and DAS around the Lavey Geothermal Reservoir in Switzerland in Challenging Topographic Settings." Geophysical Journal International 245(1):ggag063. doi:10.1093/gji/ggag063.

Conference oral presentation: Seismological Society of America, April 2026: *Subsurface Characterization Along Rail Lines – Distributed Acoustic Sensing in the Swiss Alps.* Bowden, D., Bajad, S. N., Fern, E. J., Fichtner, A., Bharadwaj, P., Edme, P.

Conference poster presentation: European Geophysical Union, May 2026: *Coherent Source Subsampling of Seismic Noise for Distributed Acoustic Sensing in the Swiss Alps. Sanket Bajad, Daniel Bowden, Pawan Bharadwaj, Elliot James Fern, Andreas Fichtner, and Pascal Edme*

Conference poster presentation: European Geophysical Union, May 2026: *Leveraging Railway Fiber-Optic Networks with DAS: Multi-Scale Opportunities.* Pascal Edme, Daniel Bowden, Frederick Massin, Anne Obermann, sanket Bajad, John Clinton, and James Fern

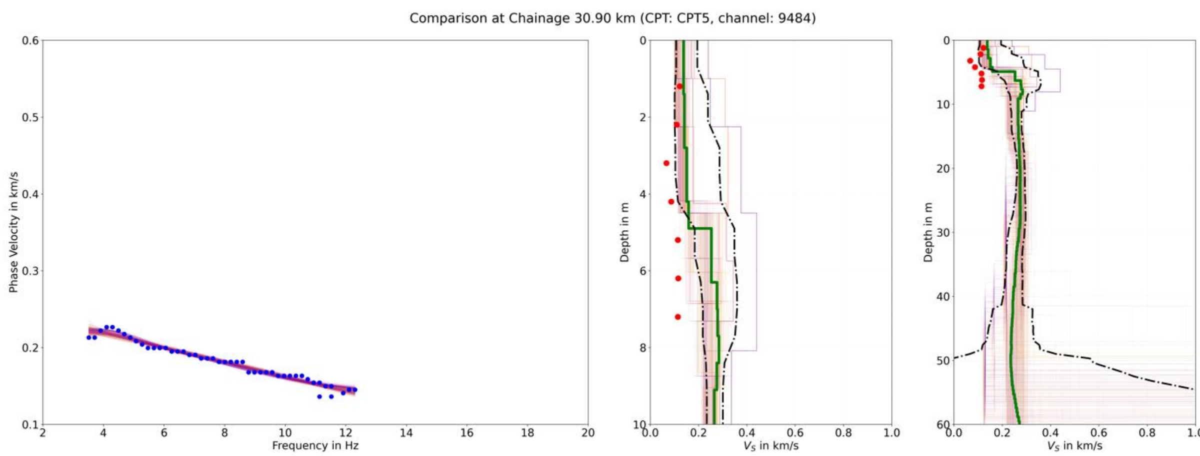
At least 3 additional journal publications are in prep or planned:

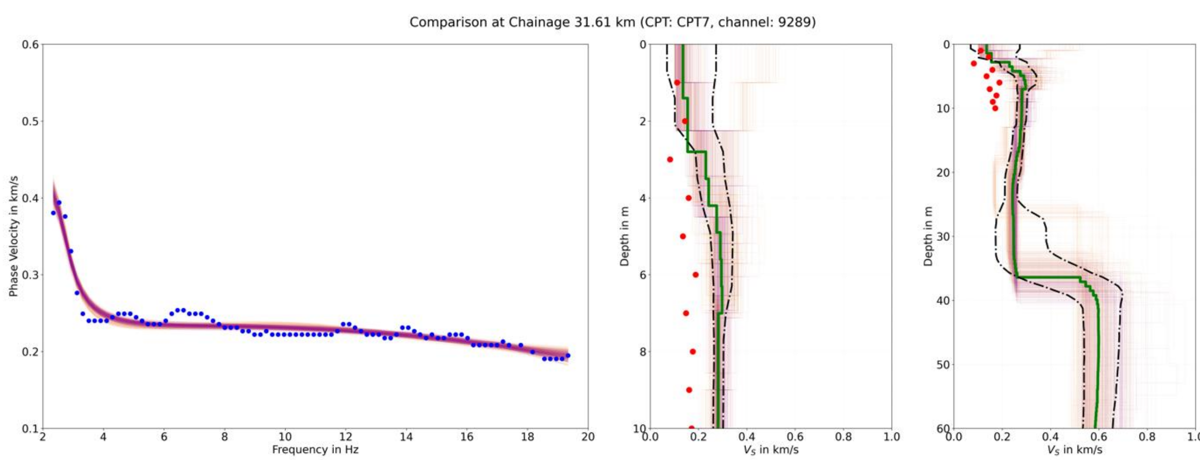
- From Sanket Bajad, covering the application of the Machine Learning SymVAE approach.
- From Scott Keating, covering the multi-azimuthal and picking free implementation of subsurface Rayleigh wave modelling
- From Daniel Bowden, covering the project generally and subsurface characterisation (i.e., similar in content to this report)

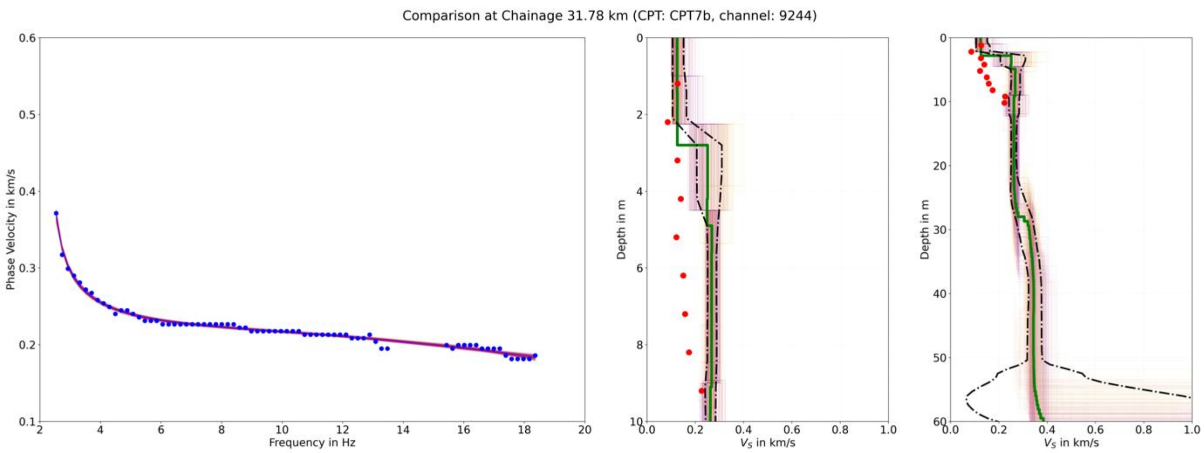
Appendix B: Additional comparison with CPTs

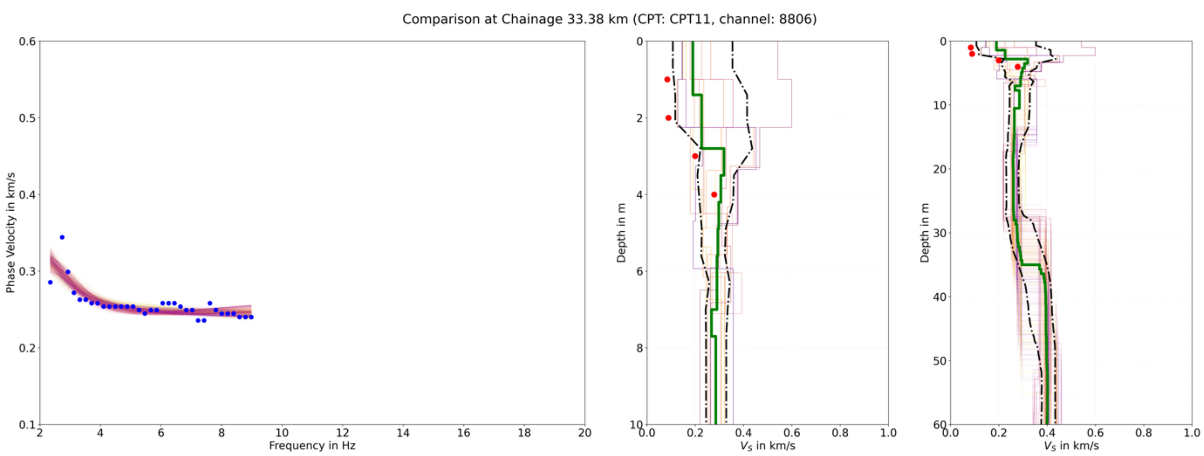
In addition to the 2 CPT comparisons shown earlier in the document, 5 other locations were identified where a MASW recovered 1D profile corresponded to the location of a CPT study. The remaining 5 comparisons are shown below.

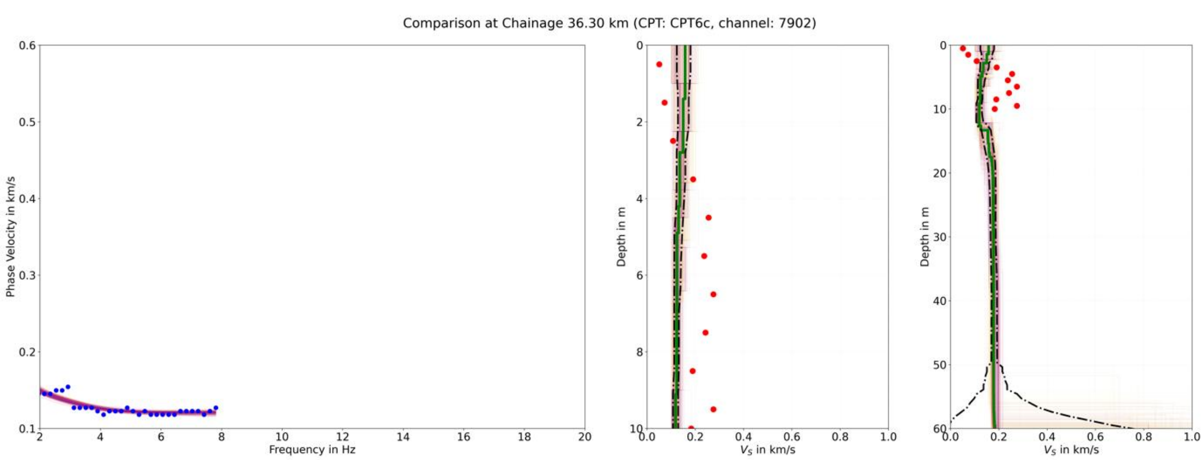
In cases where the recovered Vs profile does not agree with the CPT observations, the Vs profile consistently overpredicts velocities.






Comparison at Chainage 31.78 km (CPT: CPT7b, channel: 9244)
Phase Velocity in km/s
Frequency in Hz
Depth in m
V_S in km/s


Comparison at Chainage 33.38 km (CPT: CPT11, channel: 8806)
Phase Velocity in km/s
Frequency in Hz
Depth in m
V_S in km/s


Comparison at Chainage 36.30 km (CPT: CPT6c, channel: 7902)
Phase Velocity in km/s
Frequency in Hz
Depth in m
V_S in km/s