Deliverable

[D2.3: Report on all DAS field deployments]

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Summary

This final report summarises the setup and major results of all Distributed Acoustic Sensing (DAS) experiments conducted within the RISE project. They roughly fall into three categories: (i) urban, (ii) volcano-glacial, and (iii) submarine environments. In all cases, we find that the experiments are logistically easily feasible, and that they provide new insight into the seismicity of the respective systems. The ensemble of experiments confirms the added value of DAS in seismic monitoring, especially under conditions where dense networks of conventional seismometers may be difficult to install and maintain.

1. DAS Overview

DAS technology facilitates the use of standard fibre optic cables as dense seismic arrays, using interferometry to detect miniscule variations in strain along on the fibre. DAS allows this strain to be detected at regular intervals along the fibre (down to tens of centimetres), meaning that a single fibre may act as thousands of inline strain detectors. The measurement principle of DAS is summarised in Figure 1.

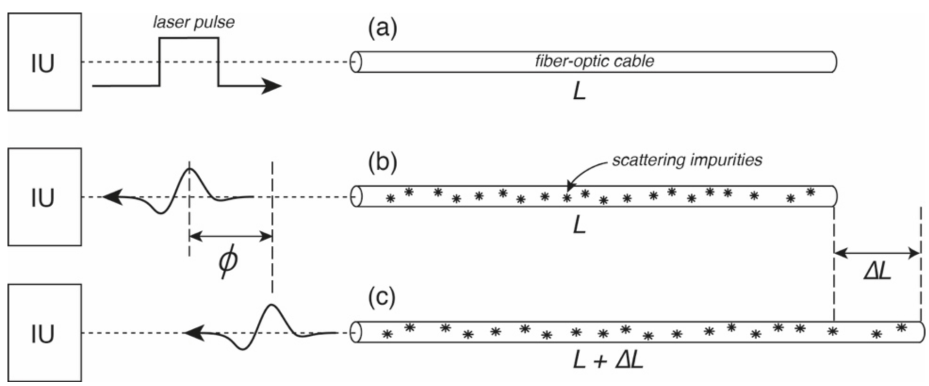
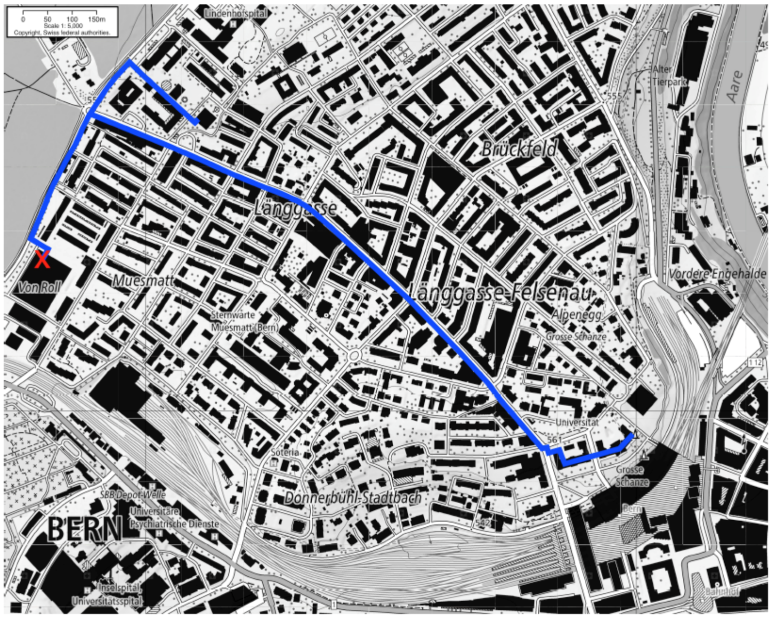


Figure 1: Measurement principle of DAS. An interrogation unit (IU) sends laser pulses into an optical fibre. At imperfections, part of the signal is scattered back and registered by the IU. Deformation of the fibre leads to a phase delay of the back-scattered pulses, which can then be translated into a spatially distributed strain measurement.

This technology has the potential to be extremely useful for monitoring seismic activity in urban environments for two main reasons: (1) the deployment of an array of traditional seismometers in urban areas can be extremely difficult due to dense infrastructure; (2) telecommunication networks almost always contain dark fibres – currently unused fibres that are installed for future expansion of the network / in case other fibres fail. The locations of these fibres are usually well mapped by the owners of the network. This means that it is possible to connect a DAS interrogator to the end of one of these dark fibres and create an instant urban seismic array, avoiding the need to install a likely sparse network of traditional seismometers.

2. Urban Environments I: The Bern Pilot Experiment

In November 2019, we collected seismic data over a period of two weeks, using dark fibre beneath Bern, Switzerland. The layout consisted of 3 km of fibre in a T configuration (Figure 2), with the light signal reflected at the far end of the cable and returned through a second fibre, giving twice the 3 km layout.



Blue line = fibre; Red cross = DAS interrogator location

Figure 2: Layout of the telecommunication cable used in the pilot DAS experiment. The total length is around 6 km (3 km back and forth).

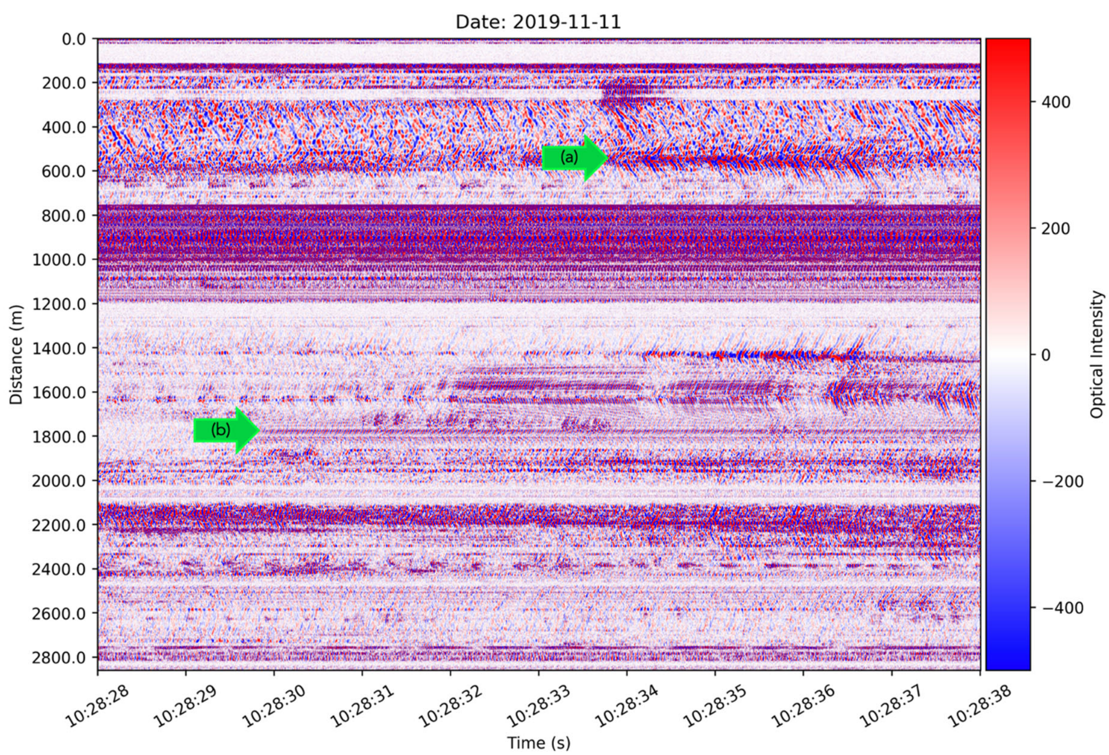


Figure 3: A typical 10 s record section of the Bern DAS data. Arrow (a) marks the signal produced by a driving car. The fishbone structure is due to surface waves emanating from the car. From these, the Rayleigh wave phase velocity can be inferred directly. Arrow (b) is the fibre deformation caused by a leaf blower. The fact that such a weak signal can be detected easily by the telecommunication fibre that was not at all installed for this purpose attests to the high sensitivity of the measurement system. When converted to strain rate, we see that deformation at the level of few nanostrain/s can usually be recorded.

Data were recorded with a 10 m gauge length, 2 m channel spacing and sampling rate of 200 Hz, producing ~1.5 TB of data. This installation was likely to detect ground motion primarily caused by traffic, as well as construction, large machinery, and subsurface installations that may be close to the fibre (e.g., water pipes). A typical record section is shown in Figure 3.

While the layout of the cable was known, the locations of the individual fibre channels were not. Therefore, we carried out a tap test using sequences of 5 jumps on the pavement, matching measured GPS locations to the channel at which the jumps were seen (Figure 4). Using interpolation, this allowed for the assignment of all usable channels to a physical location, facilitating future spatial analysis of the data.

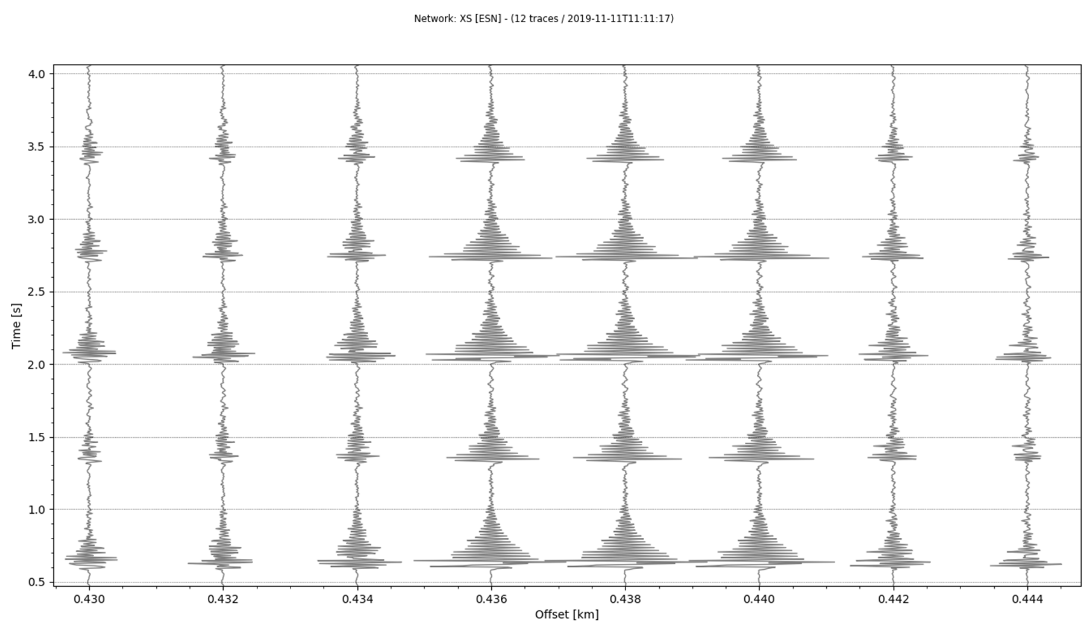


Figure 4: Strain rate recordings at selected DAS channels for the human jumps on the pavement. The figure shows 5 consecutive jumps that produce very similar waveforms. The temporal moveout and amplitude variations can be used to constrain near-surface structure, as explained below.

The data from the Bern experiment are complex and have a large volume, which turns their analysis into a non-trivial data science problem. Below, we present a collection of preliminary results, that we are in the process of consolidating into a multi-scale model of the near surface.

Figure 5 (left) shows a typical anthropogenic noise correlation computed from night time strain rate data. While a clear deterministic wavefront with a nearly linear moveout is easily visible, the correlation waveforms are obviously more complex than in regional-scale applications at lower frequencies. Most importantly, not all of the wavefronts are propagating forward. Some propagate in opposite direction, suggesting the presence of significant scattering and associated backward propagation. Likely scatterers include, for instance, the basements of large buildings.

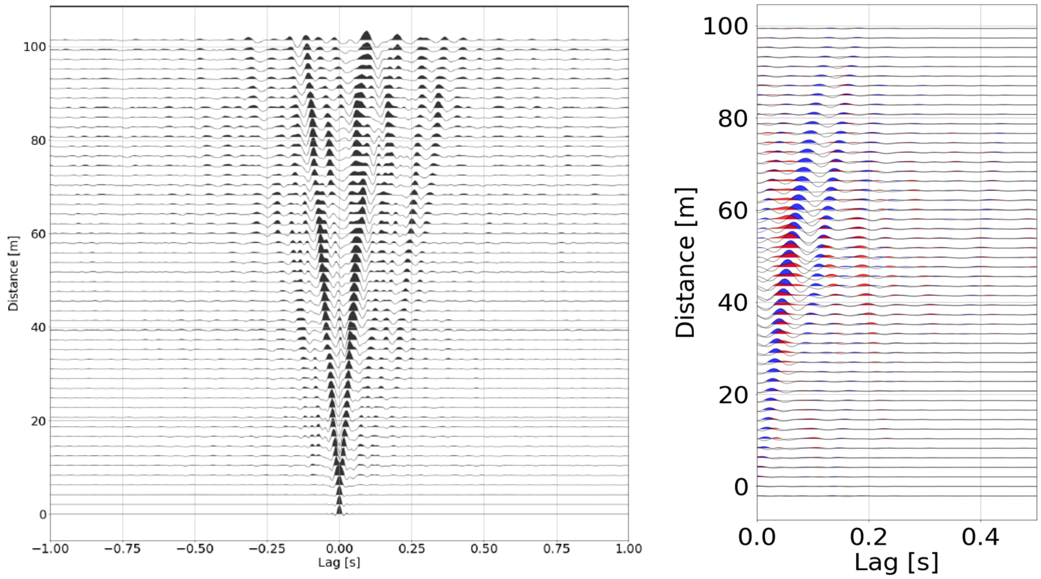


Figure 5: Left: A typical anthropogenic noise correlation with channel pairs separated by up to 100 m. The recording contains visible back-scattered energy. Right: f-k filtered version of the original correlations (blue) with back-scattered energy (red) removed.

The presence of back-scattered energy requires an additional pre-processing step, prior to the estimation of dispersion curves. To eliminate reflected waves, we apply an f-k filter. A typical result is shown in Figure 5 (right).

The f-k-filtered noise correlation permit the extraction of stable dispersion curves in the frequency range from around 8 - 22 Hz. As DAS data is collected as evenly-spaced channels along the fibre, we are able to use a slant-stack method, rather than looking at single traces cross-correlated with one another. This slant stack method is the same as the MASW (Multichannel Analysis of Surface Waves) method that is often applied in exploration seismology contexts.

We produce dispersion images for each 100 m record section, using each DAS channel as a virtual source. These dispersion images are generally clearest from 10 – 20 Hz, and indicate that the subsurface phase velocity is around 600 m/s. A dispersion curve is picked from each dispersion image, corresponding to the maxima of the heatmap image at each frequency.

The dispersion images very consistently display a sharp Rayleigh wave phase velocity reduction from >800 m/s to <600 m/s for frequencies above approximately 14 Hz. Combined with the nearly constant phase velocities above 14 Hz, this hints at the presence of a nearly homogeneous low-velocity layer with a thickness of roughly 20 m, below which a high-velocity material is located.

These qualitative inferences can be confirmed with a rigorous dispersion curve inversion, some results of which are shown in Figure 6. The inverse algorithm is based on a probabilistic trial and error that produces a large ensemble of plausible subsurface models that contain uncertainty information.

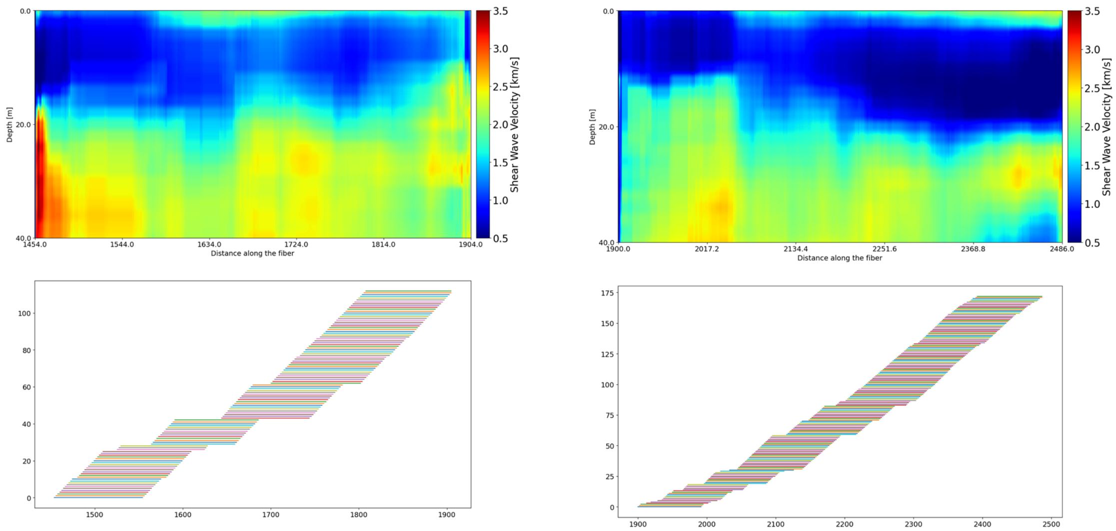


Figure 6: Shear wave velocity in the upper 40 m for the top and bottom segments of the street in Bern where the fibre-optic cable was deployed. Estimated vertical resolution is around a few metres, horizontal resolution is in the few tens of metres range.

A journal publication on this pilot experiment is in preparation.

3. Urban Environments II: The Athens Experiment

In September 2021, we travelled to Athens, Greece, to conduct a DAS experiment in collaboration with OTE (the Hellenic Telecommunications Organisation S.A.). This experiment ran for one month, and utilised ca. 23 km of in-situ telecommunication fibre in the North-East suburbs of Athens (Figure 7), producing around 20 TB of data.

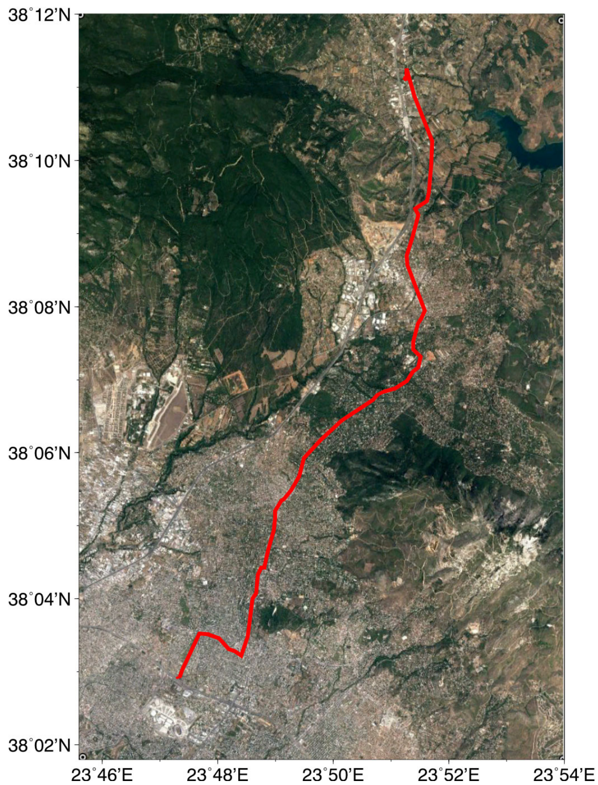


Figure 7: Map showing the layout of the DAS line within Athens, Greece. The interrogator was situated at the bottom right of the image, in North-East Athens, with the DAS line following the roads out of the city, into the suburbs.

The purpose of this deployment was to determine the extent to which DAS using dark fibre may be beneficial in urban environments exposed to significant seismic hazard – both in terms of the ability of DAS to capture earthquake signals, and for the purpose of understanding the shallow subsurface structure using DAS data. We also aim to assess the potential benefit of the incorporation of DAS within regional seismic networks.

In a preliminary analysis of the data, we are able to observe a large number of seismic events, across a range of magnitudes and distances. These include the Mw 6.3 2021 Lasithi Earthquake that occurred over 400 km away, off of the coast of Crete (Figure 8). We were also able to record small, local events with magnitudes of less than 1, as well as see clear moveout and separation of P- and S-wave arrivals (Figure 9), for events that were favourably oriented in relation to the layout of the DAS fibre.

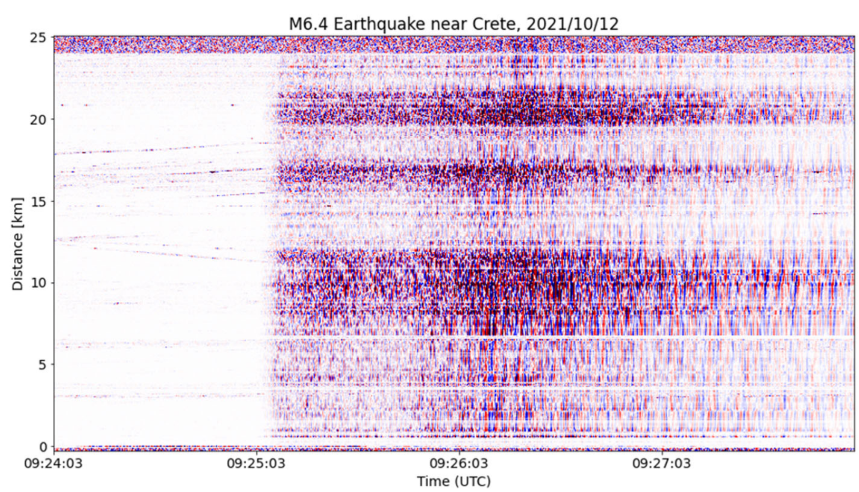


Figure 8: Plot showing the 2021 Lasithi Earthquake as seen in the DAS data. The P-wave arrival is clearly seen just after 09:25:03 UTC. The faint diagonal lines seen prior to this are the signals of cars travelling along the road on top of the DAS line.

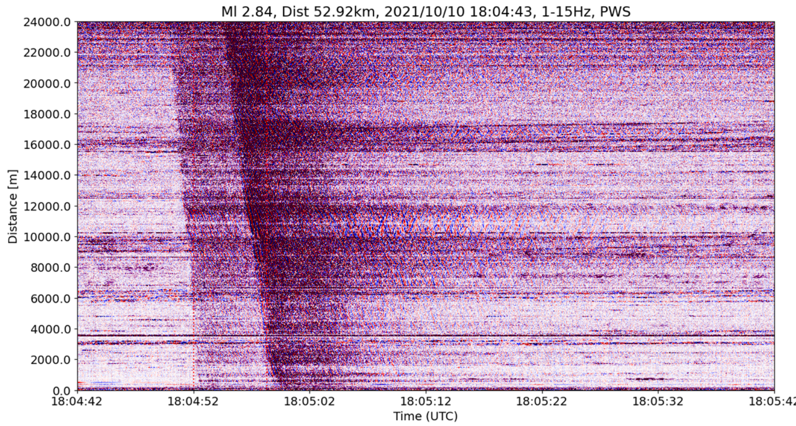


Figure 9: An example of an event showing distinct P- and S-wave wavefronts, as well as move-out along the DAS line. The red vertical lines correspond to predicted P- and S-wave arrival times.

The Athens experiment also offered the unique opportunity to compare the quite well-established DAS technology to an emerging mode of fibre-optic deformation sensing based on phase transmission. While our experiment was running in the OTE Academy, a group of fibre-optic engineers from various universities in and around Athens deployed a proto-type transmission system based on microwave frequency dissemination. While such systems only provide integrated measurements, they are capable of covering much larger distances than DAS, possibly in the range of thousands of kilometres. The comparison of DAS and the new proto-type is very promising, and it led to a series of publications that we could not foresee at the beginning of the project (Bogris et al., 2022; Fichtner et al., 2022a,b; Bowden et al., 2022).

4. Volcano-Glacial Environments I: Mt. Meager

One of the suspected niches of DAS is in environments where dense arrays of conventional seismometers cannot be deployed or maintained easily. Volcano-glacial environments fall into this category.

On Mt. Meager in British Columbia, we performed the first DAS experiment on a glacier-clad active volcano, together with colleagues from the University of Calgary. In total, we deployed around 3 km of fibre-optic cable on a ridge, near the summit of Mt. Meager, which is Canada's most active volcano, with high geothermal potential. Around 2 km of the cable were trenched into the glacier that partly covers the northern flank of Mt. Meager (Figure 10).

The experiment on Mt. Meager ran for around 1 month. The data reveal a previously unknown level of seismicity, including, on some days, several hundred detectable events. Many of those are nearly perfect repeaters, with waveform correlation coefficients reaching 0.98. Furthermore, most of the events are located within clusters, possibly caused by localized geothermal activity (Figure 11).

Another aspect of previously unknown seismicity at Mt. Meager includes long-lasting, low-frequency tremor, also most likely of geothermal origin (Figure 12).

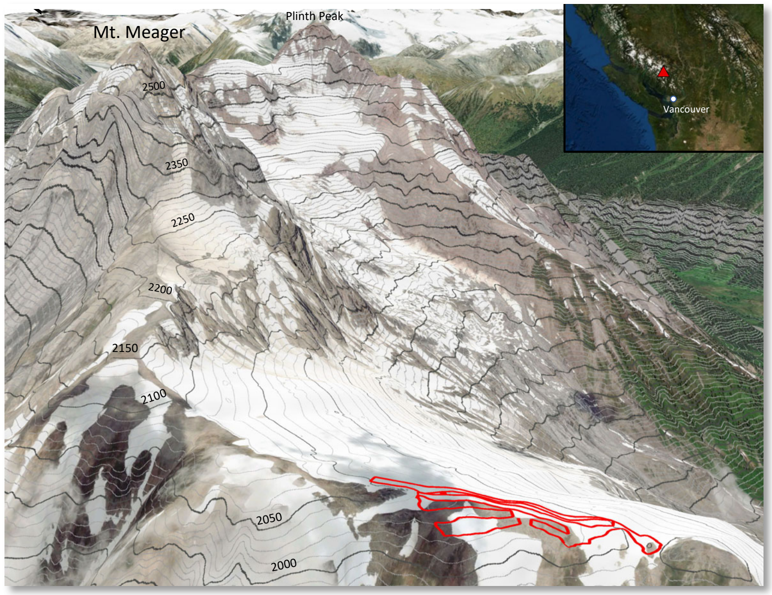


Figure 10: Cable layout on Mt. Meager. The total length is around 3 km.

In addition to painting an entirely new picture of Mt. Meager's activity, this experiment also demonstrates that DAS experiments are logistically possible in harsh terrain where the installation of traditional seismometer arrays with similar coverage in space and frequency would be close to impossible.

The complete results have been published in Klaasen et al. (2021).

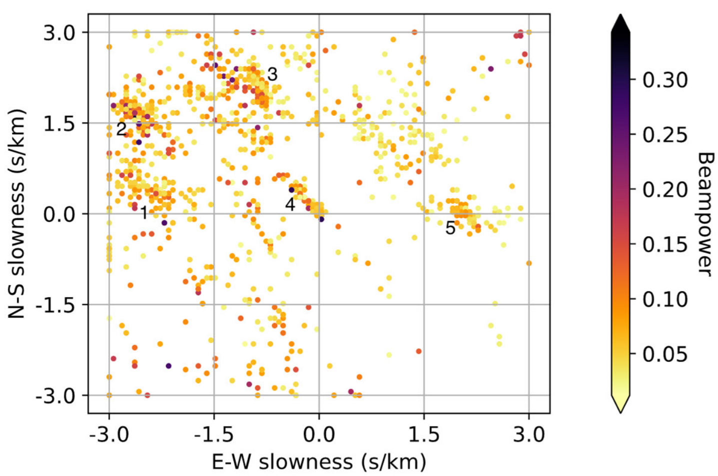


Figure 11: Clusters of seismic events identified by beamforming of the Mt. Meager DAS data.

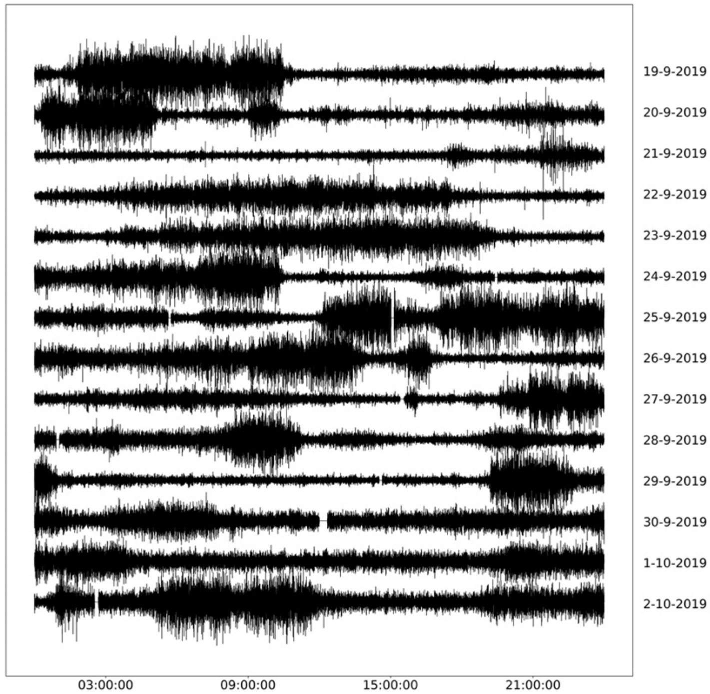


Figure 12: Example of volcanic tremor recording at Mt. Meager.

5. Volcano-Glacial Environments II: Grimsvötn

Encouraged by the results from Mt. Meager, we performed the so far largest DAS experiment on an active volcano, Grimsvötn, in Iceland (Klaasen et al., 2022). Almost completely covered by the Vatnajökull ice cap, Grimsvötn is the most active volcano of Iceland, on a decadal time scale. Using a specially designed sled, we trenched more than 12 km of cable in the ice, half way around and into the caldera (Figure 13).

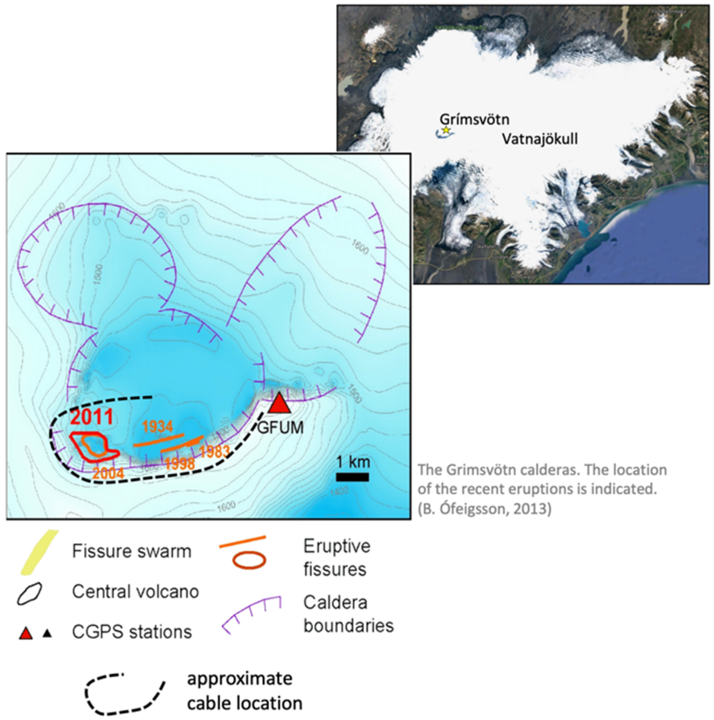


Figure 13: Geography and cable layout on Grimsvötn, Iceland.

Figure 14 shows a typical recording from Grimsvötn, focusing on the last 4 km of the cable, located within the caldera. The low-frequency signal is due to resonance of the ice sheet, which is floating atop a subglacial lake. This resonance is most likely excited by volcanic tremor but also has an ambient noise contribution (Fichtner et al., 2022c). Superimposed is the high-frequency signal of a local earthquake.

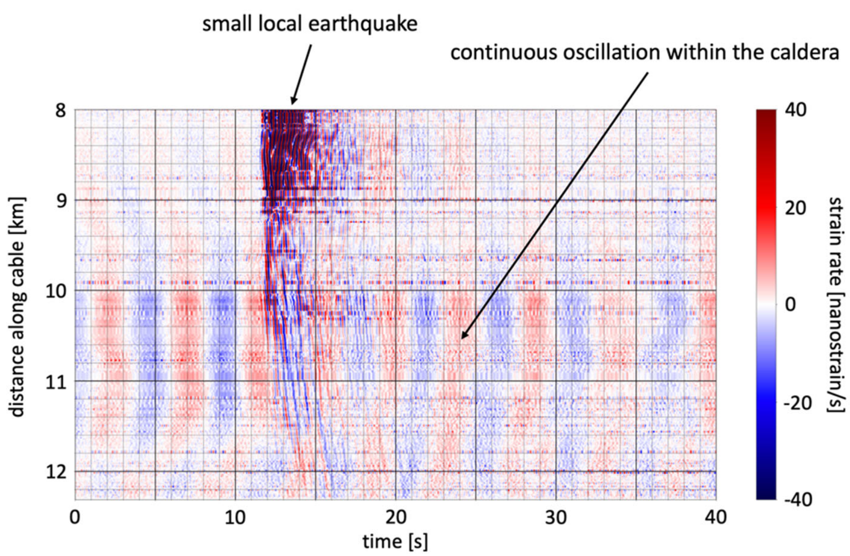


Figure 14: Typical recording from Grimsvötn, showing caldera resonance at low frequencies around 0.2 Hz, superimposed by a high-frequency local event at >10 Hz.

We detect a total of 1828 transient events, averaging between 50 – 150 per day, using a method specifically developed for DAS data which is based on image processing techniques (Thrastarson et al., 2022). We locate these events in a probabilistic framework using a Hamiltonian Monte Carlo code that takes the data uncertainty into account. With these locations, we can apply the local magnitude scale to the events detected with DAS, revealing b-values greater than 1. Figure 15 shows the respective locations, their uncertainties, and local magnitudes of all located events with respect to the fibre-optic cable, and Figure 16 shows the local magnitude scale of all events.

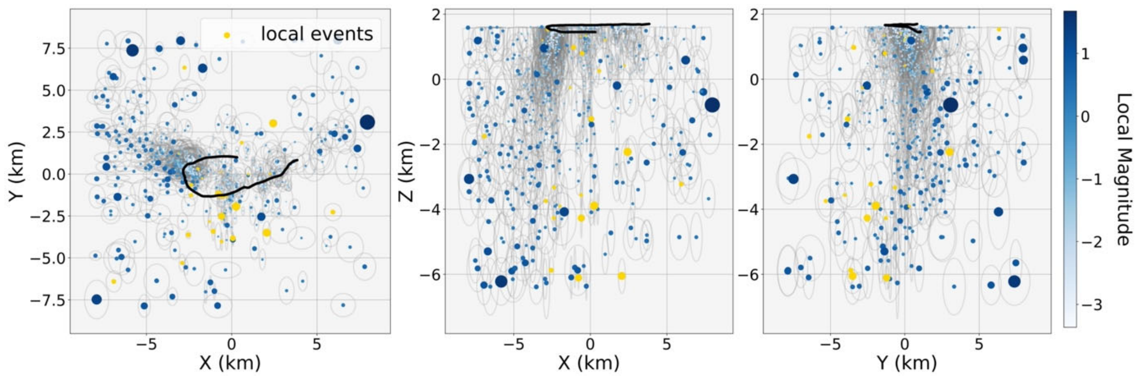


Figure 15: The locations of all detected events are scattered around the fiber-optic cable. The gray ellipses surrounding each location indicate the uncertainty in the location, and the size and blue color correspond to the local magnitude of each event. The events indicated in yellow are recorded by both our DAS network, and the national catalog of the Icelandic Meteorological Office.

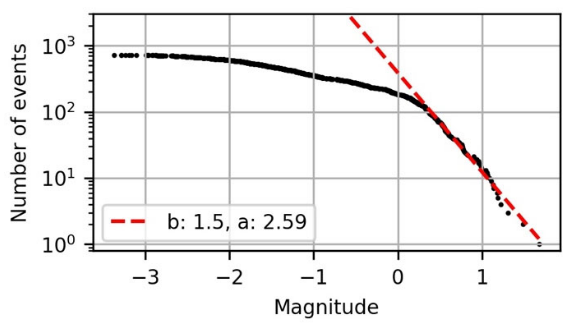


Figure 16: The Gutenberg-Richter distribution of all events on the SIL magnitude scale reveals a b-value near 1.5 over a range of magnitudes between -3.4 and 1.7.

The Grimsvötn experiment perfectly exemplifies the logistic feasibility of large-scale DAS experiments in environments where comparable arrays of conventional seismometers are impossible to install, also for financial reasons. In both the Mt. Meager and the Grimsvötn experiments, the effective cost per channel (including cable and deployment costs) is around 10 Euros. Keeping in mind that the bandwidth of our iDAS ranges from mHz to kHz, comparable broadband sensors would be orders of magnitude more expensive.

The results of the experiment at Grímsvötn furthermore underline the potential of DAS on subglacial volcanoes. This experiment highlights both insights into the Grímsvötn volcanic system, and improvements that could further develop DAS as a volcano monitoring tool.

6. Submarine Environments: Santorini

The Christiana-Santorini-Kolumbo (CSK) rift in Greece is one of the most critical volcanic fields in Europe, having produced more than 100 explosive eruptions during the last 400,000 years. It hosts several volcanic centres, including the extinct Christiana Volcano and associated seamounts, the Santorini caldera with its intra-caldera Kameni Volcano, the Kolumbo Volcano, and 25 other submarine cones that constitute the Kolumbo submarine volcanic chain. Natural hazards associated with the CSK rift pose significant threats to the Eastern Mediterranean region, including earthquakes, subaerial or submarine volcanic eruptions, volcanic gas release, tsunamis due to eruptions or submarine landslides and potential aviation disruptions due to volcanic ash plumes.

During this submarine DAS pilot experiment, we connected an iDAS from Silixa to an optical telecommunication fibre provided by the Greek telecommunication company COSMOTE. The optical fibre extends from the building of COSMOTE in Thira, to Ios, an island to the North of Santorini. The first 12 km of the cable are deployed along the roads of Santorini, and the remainder of the 45 km long fibre-optic cable has been trenched into the sea floor. The submarine part of the cable passes nearby (~5 km) the Kolumbo volcano. The installation and configuration of the IU, as well as the experiment as a whole, have been without any major interruptions. The fibre-optic cable does not have any unexpected loss of light, and we were able to sample at least the first 35 km of the cable for seismic signals. Beyond 35 km, the noise floor becomes too high to record earthquakes, and the tap tests performed in Ios were not visible in the data. This, however, is to be expected, as the maximum interrogation distance of currently available DAS units is generally below 40 km.

From October 18 to December 17, 2021, we collected around 55 TB of seismic data, with a sampling frequency of 1000 Hz, and a channel spacing of 8 m. A first visual analysis suggests that the experiment was very successful. A detailed survey of the data is work in progress. Preliminary results are presented below in Figure 17.

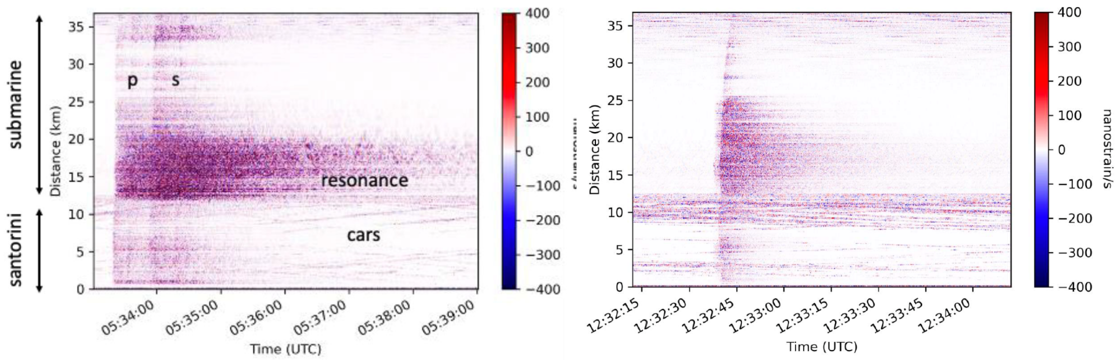


Figure 17: Typical submarine DAS recordings of a local (left) and regional (right) earthquake.

The catalogue of detected events with DAS at Santorini, while not complete, also reveals additional events that were below the detection threshold of the national network of Greece. Figure 18 shows a comparison of all the events detected by the DAS network, and of the events recorded by both the DAS network and the national network. On most days, we can record additional events with the DAS experiment.

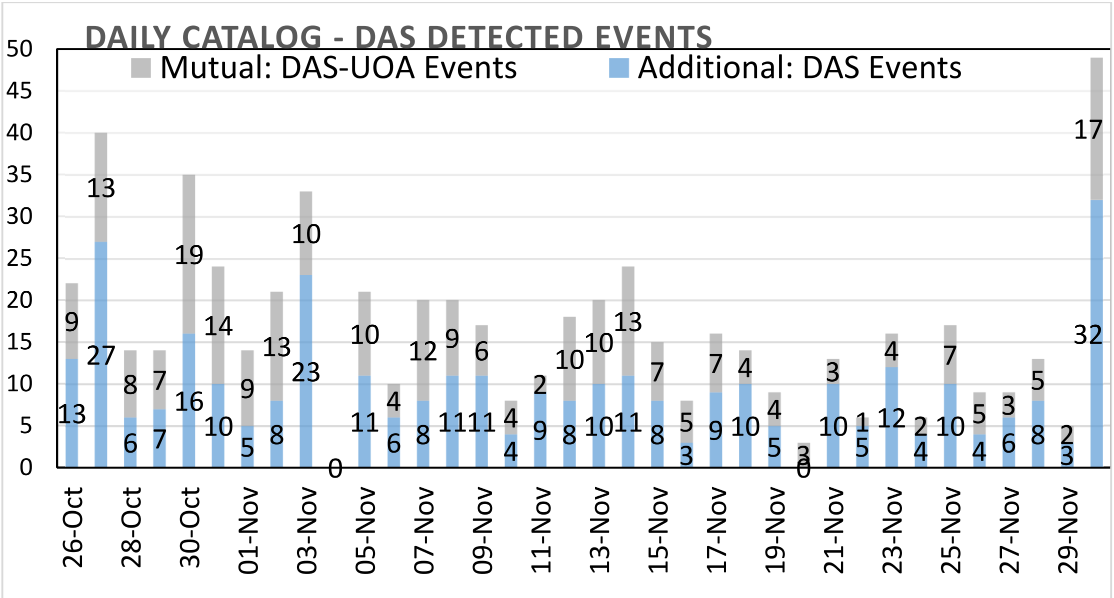


Figure 18: The DAS catalogue complements the catalogue from the University of Athens. The blue bars indicate the amount of events detected by the DAS system, and the grey bars show the number of events detected by both the DAS system and the national network.

Again, within the context of this deliverable, the most important conclusion is easy logistic feasibility combined with high data quality, sufficient for seismic event detection and characterisation.

7. Conclusions

Two major conclusions can be drawn from this series of DAS experiments:

1. Logistic feasibility: All experiments were logistically feasible, regardless of the environment. On volcanoes and glaciers, equipment could be transported with helicopters, and trenching the cable was doable with reasonable effort. In urban and submarine environments, we used pre-installed telecommunication cables. Attaching the DAS interrogator to these cables was nearly effortless, and support from local authorities and telecom companies was generally great.

2. Seismicity: In all experiments we discovered previously unknown types and levels of seismic activity. On Grimsvötn, for example, we detected nearly 2 orders of magnitude more events than the regional seismometer network. On both Grimsvötn and Mt. Meager we found new forms of seismic tremor, partly related to geothermal activity. In Athens we were able to detect low-magnitude urban seismicity, and in Bern the anthropogenic noise data provide a subsurface model with metre-scale resolution.

In summary, our results confirm the usefulness of DAS for seismic monitoring in a wide range of environments.

8. Publications

The following is a list of publications related to the RISE project:

Bowden, D., Fichtner, A., Nikas, T., Bogris, A., Simos, C., Smolinski, K., Koroni, M., Lentas, K., Simos, I., Melis, N. S., 2022. *Linking distributed and integrated fibre-optic sensing.* Geophysical Research Letters, 49, doi:10.1029/2022GL098727.

Bogris, A., Nikas, T., Simos, C., Simos, I., Lentas, K., Melis, N. S., Fichtner, A., Bowden, D., Smolinski, K., Mesaritakis, C., Chochliouros, I., 2022. *Sensitive seismic sensors based on microwave frequency fiber interferometry in commercially deployed cables*. Scientific Reports, 12, doi:10.1038/s41598-022-18130-x.

Fichtner, A., Bogris, A., Nikas, T., Bowden, D., Lentas, K., Melis, N. S., Simos, C., Simos, I., Smolinski, K., 2022a. *Sensitivity kernels for transmission fiber optics*. Geophysical Journal International, 231, 1040-1044, doi:10.1093/gji/ggac238.

Fichtner, A., Bogris, A., Nikas, T., Bowden, D., Lentas, K., Melis, N. S., Simos, C., Simos, I., Smolinski, K., 2022b. *Theory of phase transmission fibre-optic sensing*. Geophysical Journal International, 231, 1031-1039, doi:10.1093/gji/ggac237.

Fichtner, A., Klaasen, S., Thrastarson, S., Cubuk-Sabuncu, Y., Paitz, P., Jonsdottir, K., 2022c. *Fiber-optic observation of volcanic tremor through floating ice sheet resonance*. The Seismic Record, 2, 148-155, doi:10.1785/0320220010.

Klaasen, S., Paitz, P., Lindner, N., Dettmer, J., Fichtner, A., 2021. *Distributed Acoustic Sensing in volcano-glacial environments – Mount Meager, British Columbia*. Journal of Geophysical Research, 126, doi:10.1029/2021JB022358.

Klaasen, S., Thrastarson, S., Fichtner, A., Cubuk-Sabuncu, Y., Jonsdottir, K., 2022. *Sensing Iceland's most active volcano with a «buried hair»*. EOS, 103, doi:10.1029/2022EO220007.

Thrastarson, S., Torfason, R., Klaasen, S., Paitz, P., Cubuk-Sabuncu, Y., Jonsdottir, K., Fichtner, A., 2022. *Detecting seismic events with computer vision: Applications for fiber-optic sensing.* Earth and Space Science Open Archive, doi:10.1002/essoar.10509693.1.