Fibre-optic observation of volcanic tremor through floating ice sheet resonance

Andreas Fichtner[1], Sara Klaasen[1], Sölvi Thrastarson[1], Yesim Cubuk-Sabuncu[2], Patrick Paitz[1] & Kristin Jonsdottir[2]

[1]ETH Zurich
[2]Icelandic Meteorological Office

Fibre-optic observation of volcanic tremor through floating ice sheet resonance

Evening view of the caldera of Grimsvötn, where a 12 km long fibre-optic cable currently records volcanic earthquakes with unprecedented spatial resolution.

Morning impression of the research huts at Grimsfjall, the highest point of Grimsvötn's crater rim, where the fibre-optic interrogator is currently running.

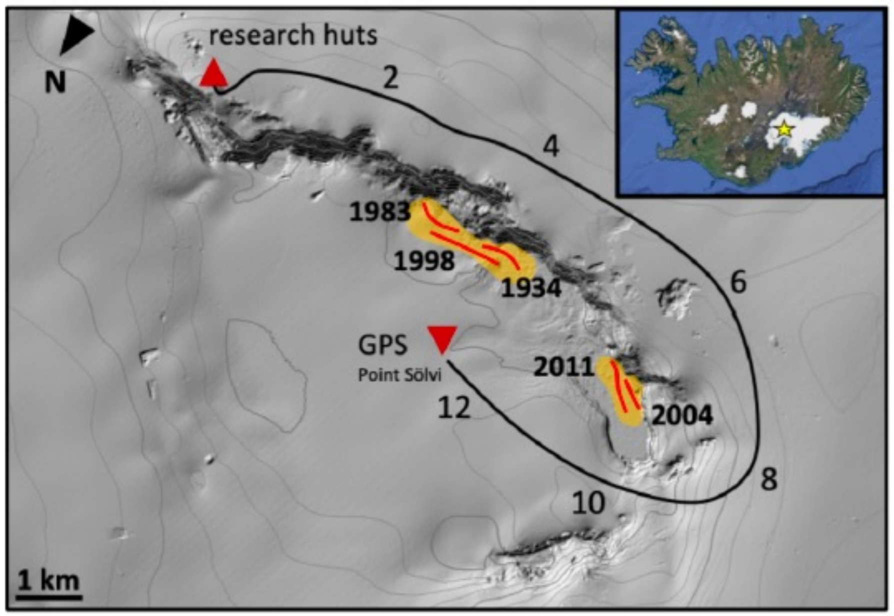
Grimsvötn in May 2021

We present results from a large fibre-optic seismology experiment at Grimsvötn volcano, Iceland. Covered completely by Europe's largest glacier, Vatnajökull, Grimsvötn is among Iceland's largest and most active volcanoes. The pictures on this slide show a view across the 10 km wide caldera of Grimsvötn during sunset (left) and the research huts at the highest point of the crater rim, where our DAS interrogator was located during the experiment (right).

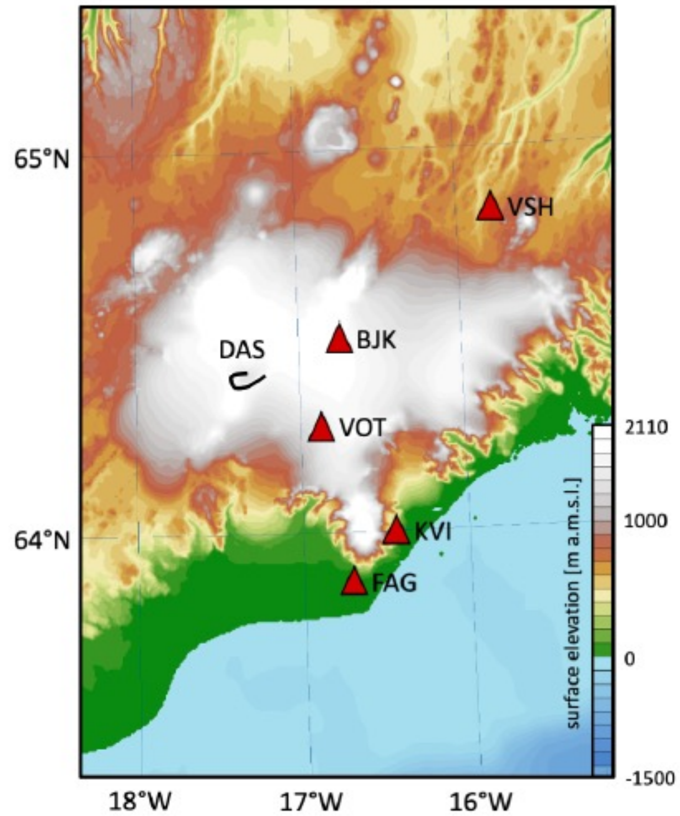
Setup

Experimental arrangement

a) Grimsvötn topography and DAS cable geometry



b) DAS and station map



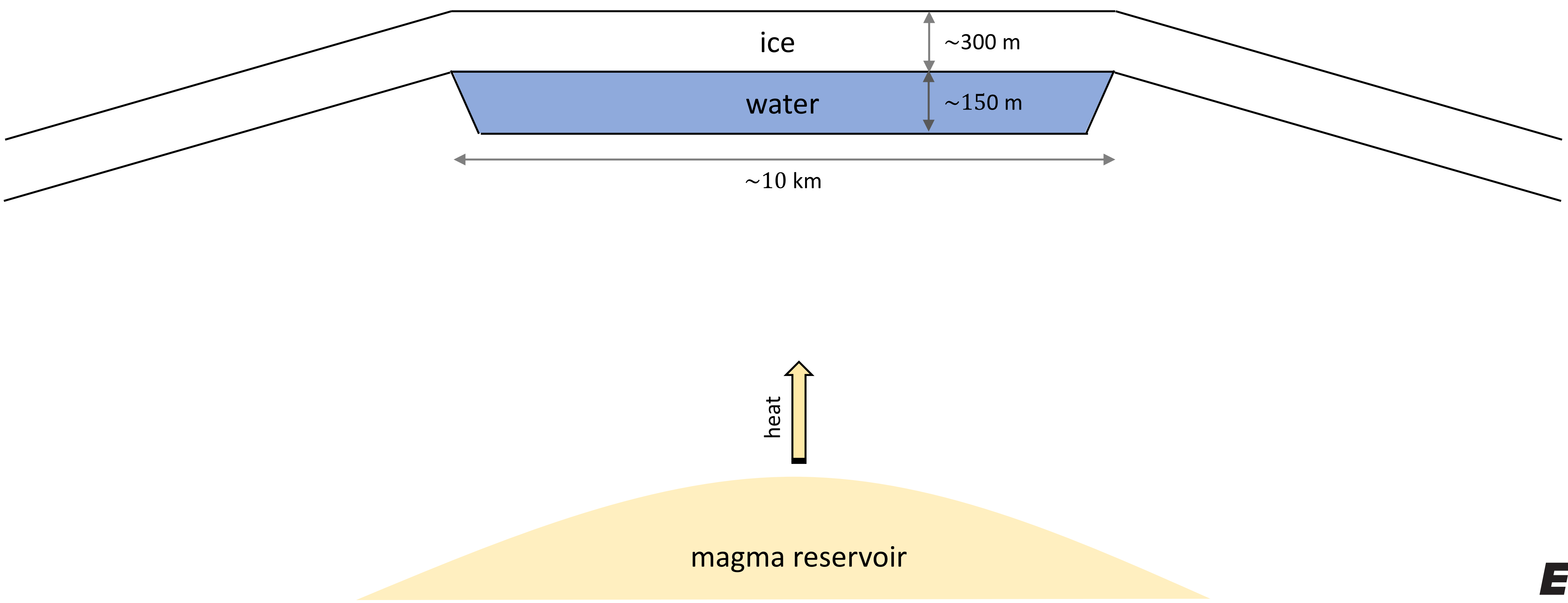
- Nearly 13 km of fibre-optic cable along the caldera of Grimsvötn.
- Recording of surface deformation during 3 weeks in May 2021.
- Channel spacing: 8 m.

ETH Seismology & Wave Physics

For this experiment we deployed nearly 13 km of fibre-optic cable along and within the caldera of Grimsvötn, as shown in the figure to the left. Using a Silixa iDAS, we recorded surface deformation for 3 weeks in May 2021. The channel spacing was 8 m. The figure to the right shows the position of the cable in relation to several broadband seismic stations in southern Iceland, which will play an important role in the subsequent analyses.

Setup

Schematic cross section

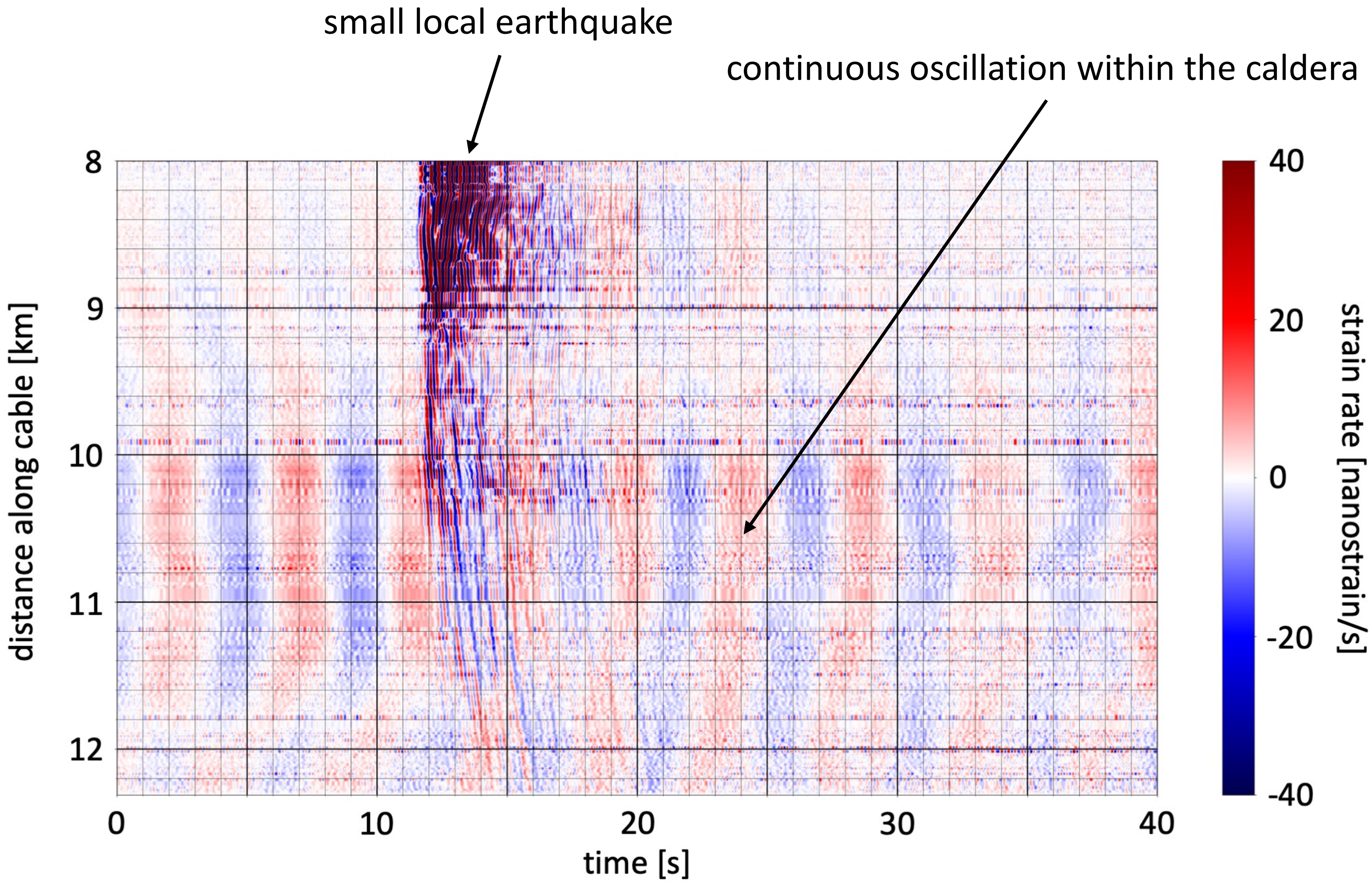


Seismology & Wave Physics

A cartoon of the geologic setting at Grimsvötn is shown on this slide. A deep magma reservoir provides heat that maintains a subglacial lake, which, at the time of the experiment, had a depth of around 150 m. The overlying ice sheet is around 300 m thick.

A look at the data

40 s of data from May 7

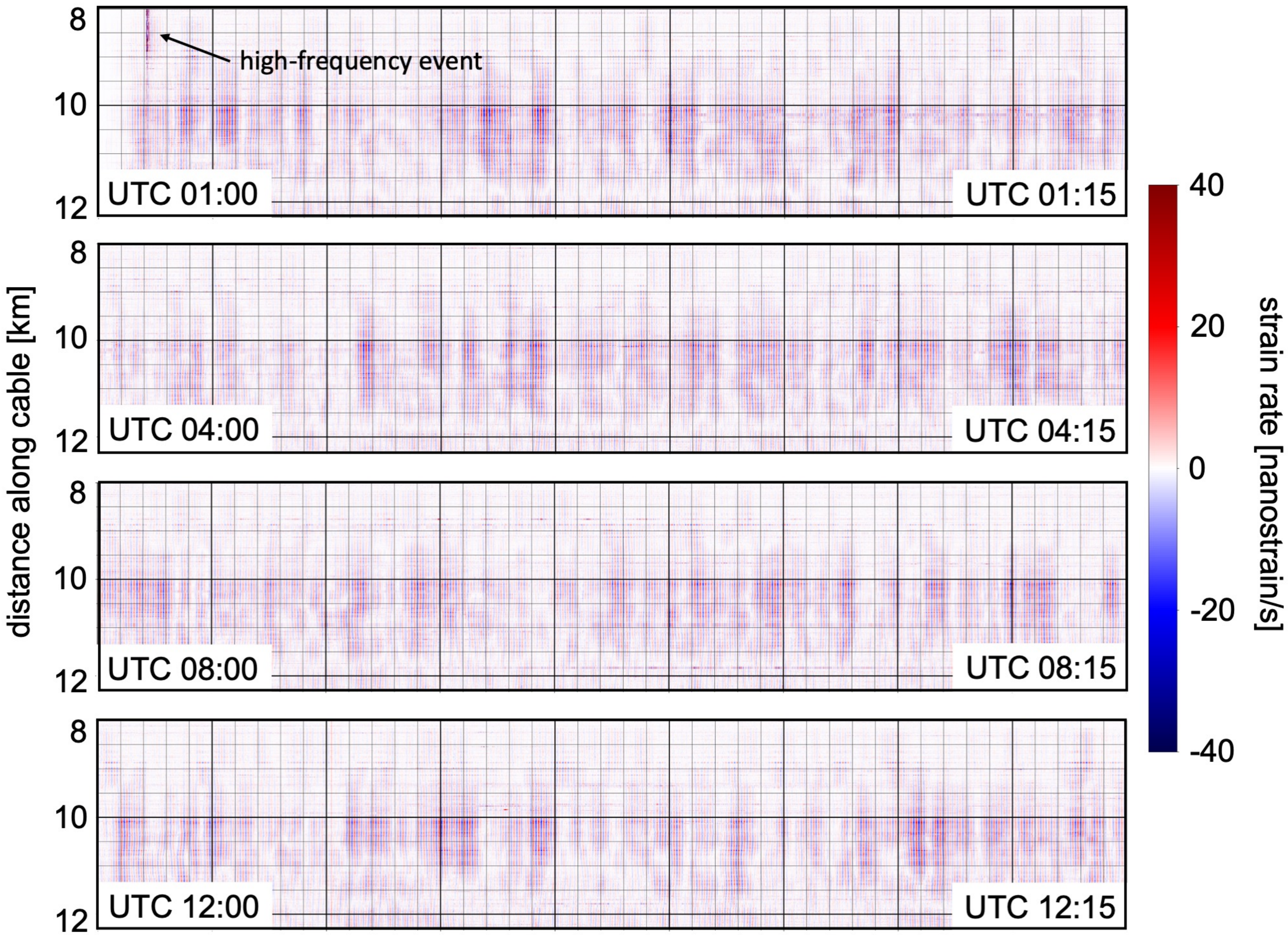


ETH Seismology & Wave Physics

This figure shows a typical DAS recording along the last 4 km of the cable, which is located inside the caldera. A small local earthquake with frequencies above 5 Hz dominates the strain rate recording, with amplitudes above 100 nanostrain/s. In the background, we clearly see an almost monochromatic oscillation with a period of roughly 5 s. We will look at this more closely in the following slides.

A look at the data

Snapshots of 12 hours of data from May 7

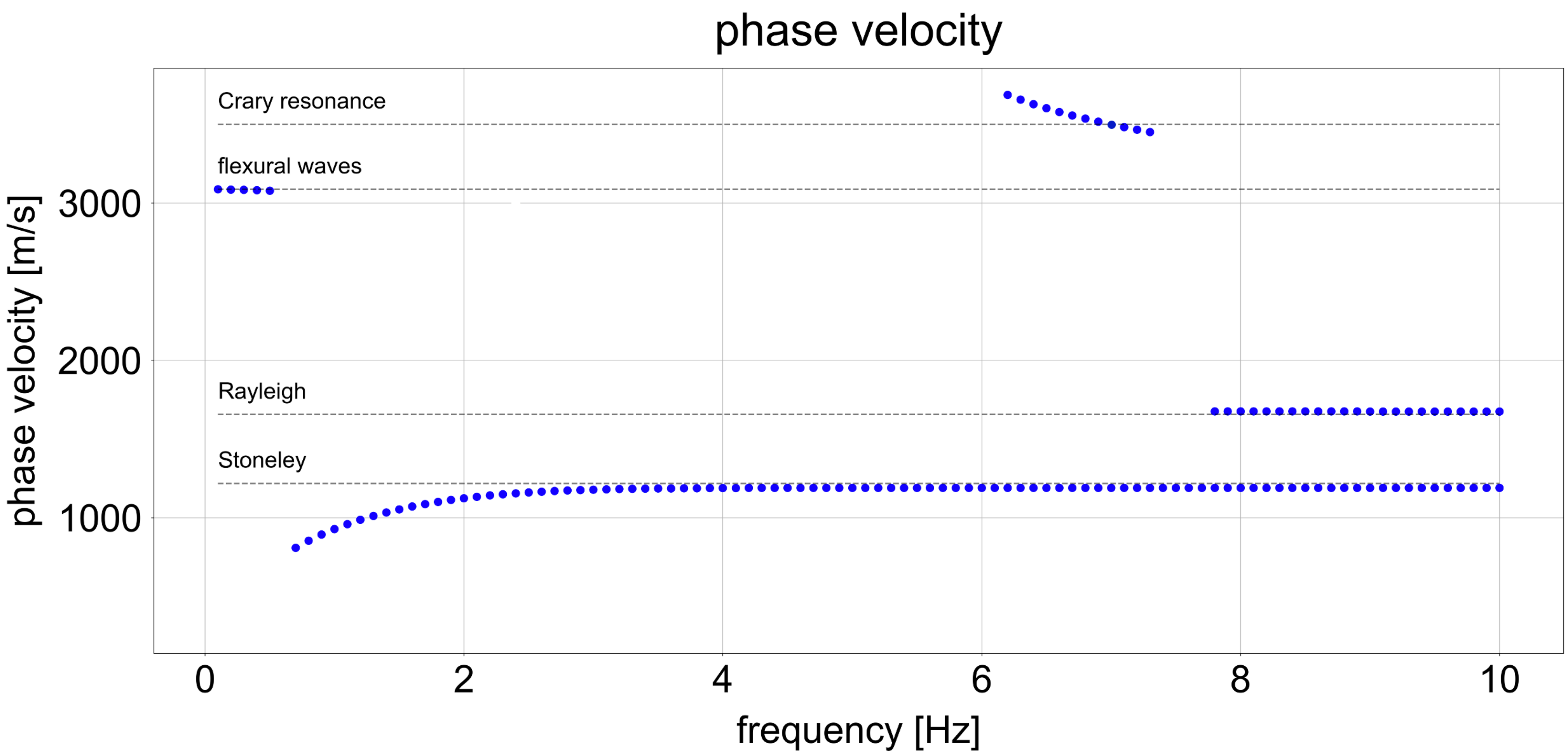


- Grimsvötn's caldera oscillates continuously.
- Oscillation frequency: ~0.2 Hz.
- What kind of wave could that be?

ETH Seismology & Wave Physics

We expand our view from just 40 s on the previous slide to half a day on this slide. Evidently, these oscillations are persistent, and their amplitude varies just slightly during the first half of 7 May 2021. Obviously, Grimsvötn's caldera is oscillating continuously. What kind of wave could that be?

Waves in a floating ice sheet

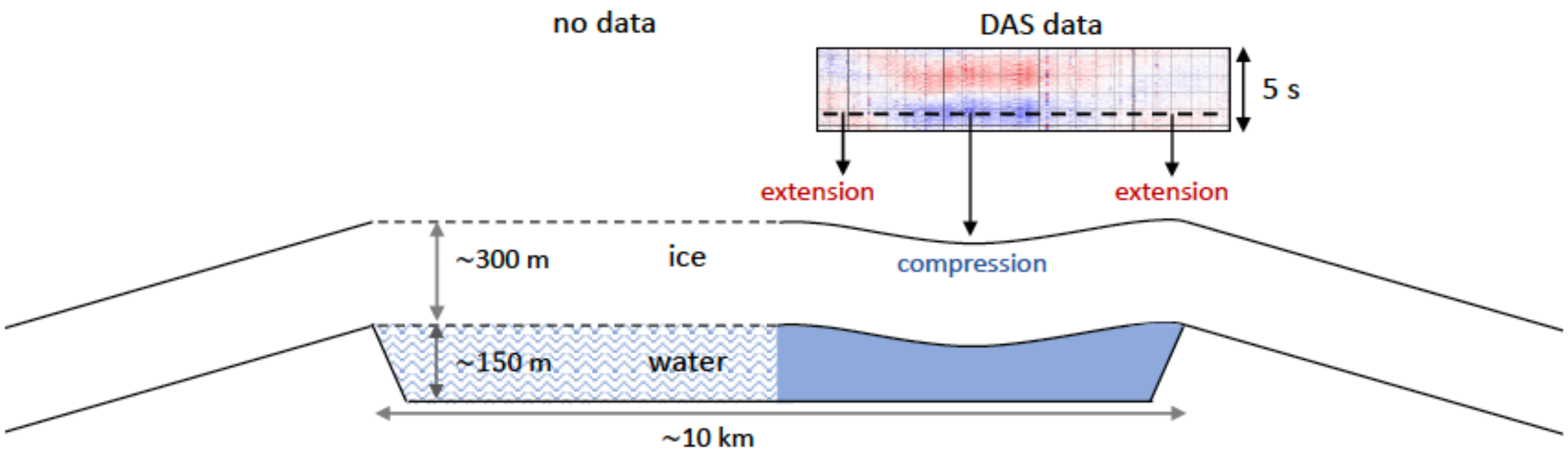


At frequencies around 0.2 Hz, all waves are flexural waves.

Waves in floating ice sheets have been studied extensively. This figure shows the phase velocities of various kinds of waves in a 300 m thick ice sheet. At the low frequencies that we are interested in, Rayleigh, Stoneley and Crary waves cannot exist. Hence, we must be observing some kind of flexural waves within the ice sheet, i.e., oscillatory ice sheet bending. (The effects of coupling to gravity waves in the water and to the solid Earth are omitted here, for simplicity.)

Setup

Schematic cross section

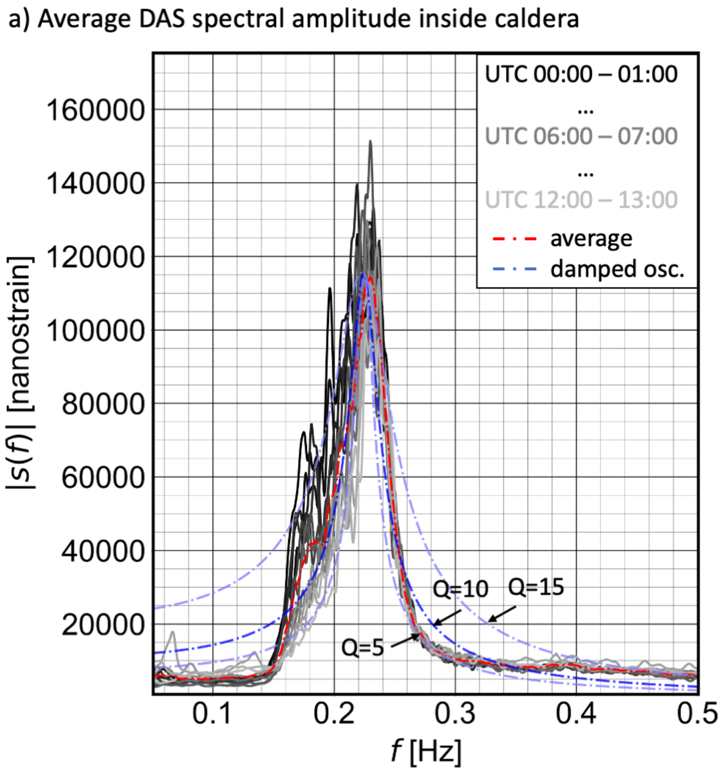


- Every ~5 s, the ice sheet moves ~0.5 m up and down.
- Could it be that ambient vibrations (caused by ocean waves) excite the ice sheet?

ETH Seismology & Wave Physics

A closer look at the DAS data nicely shows that large-scale compression related to down-warping is accompanied by extension near the edge of the oscillating part of the ice sheet. The oscillation period of around 5 s suggests that ambient seismic noise might be a driving force of this phenomenon. Let us take a closer look at this.

Spectrograms on 7 May 2021



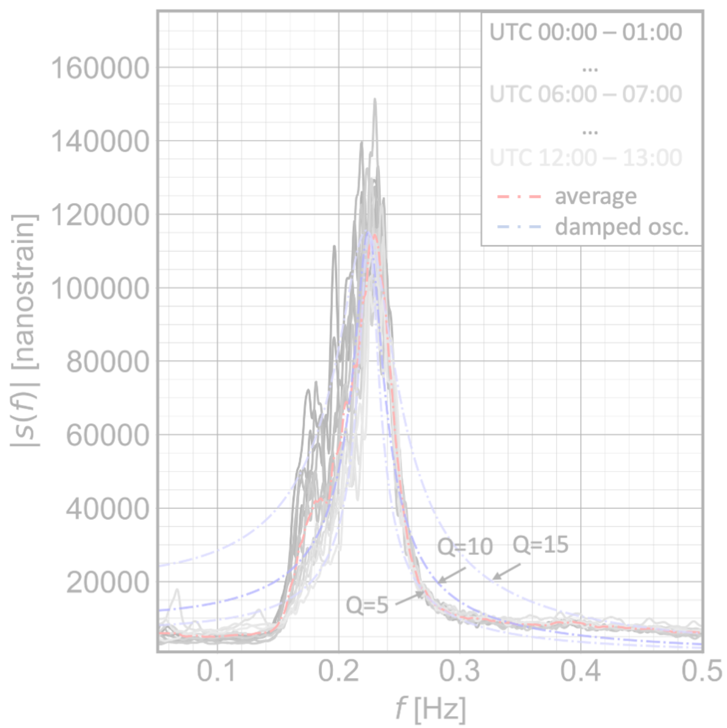
- Ice sheet oscillations have very narrow spectral peak.
- It resembles the spectrum of a damped harmonic oscillator with $Q\sim15$.
- On 7 May 2021, the spectrum hardly varies over time.

ETH Seismology & Wave Physics

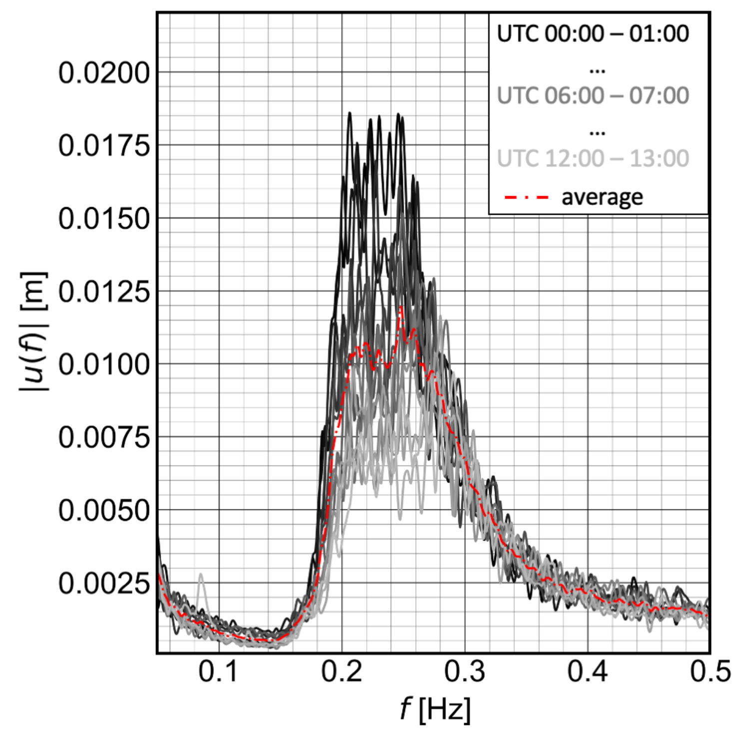
In this figure we see the average spectral power of the DAS channels within the Grimsvötn caldera as a function of time. [Shading from black to light grey corresponds to hourly bins from midnight to midday on 7 May 2021.] The spectral speak is very narrow, and its amplitude hardly varies over time. The shape of the amplitude spectrum can be approximated closely by the spectrum of a simple damped harmonic oscillator with Q around 15.

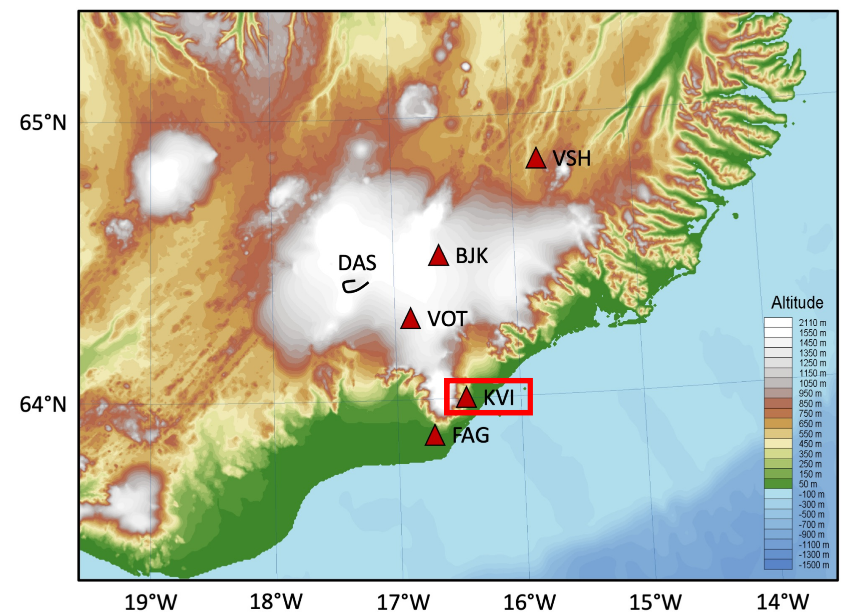
Spectrograms on 7 May 2021

a) Average DAS spectral amplitude inside caldera



b) Average spectral amplitude at KVI





- Ice sheet oscillations have very narrow spectral peak.
- It resembles the spectrum of a damped harmonic oscillator with $Q \sim 15$.
- On 7 May 2021, the spectrum hardly varies over time.

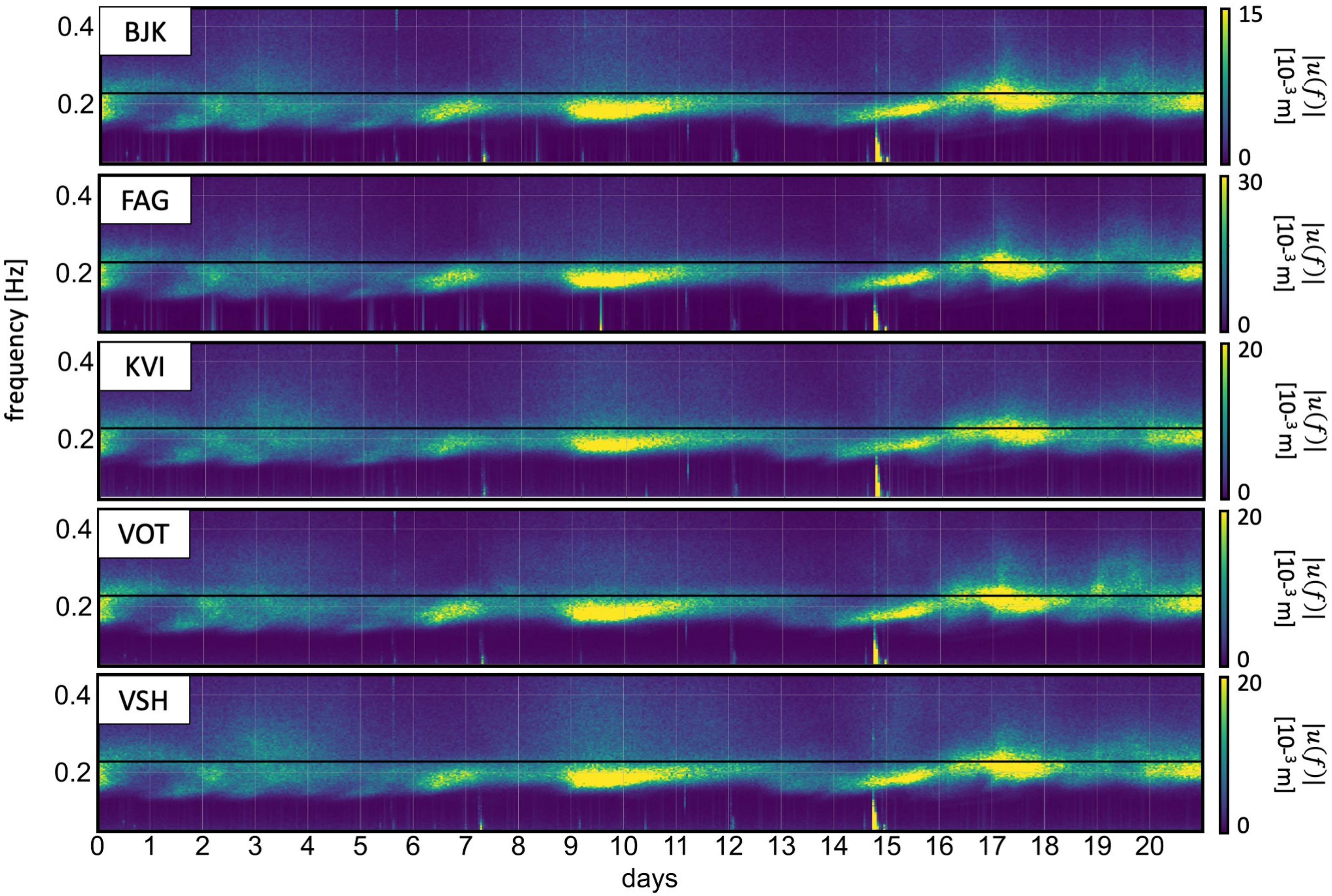
- Ambient vibrations at coastal station KVI have a broader spectrum.
- The spectral amplitude varies by a factor of ~3 within only 12 hours!

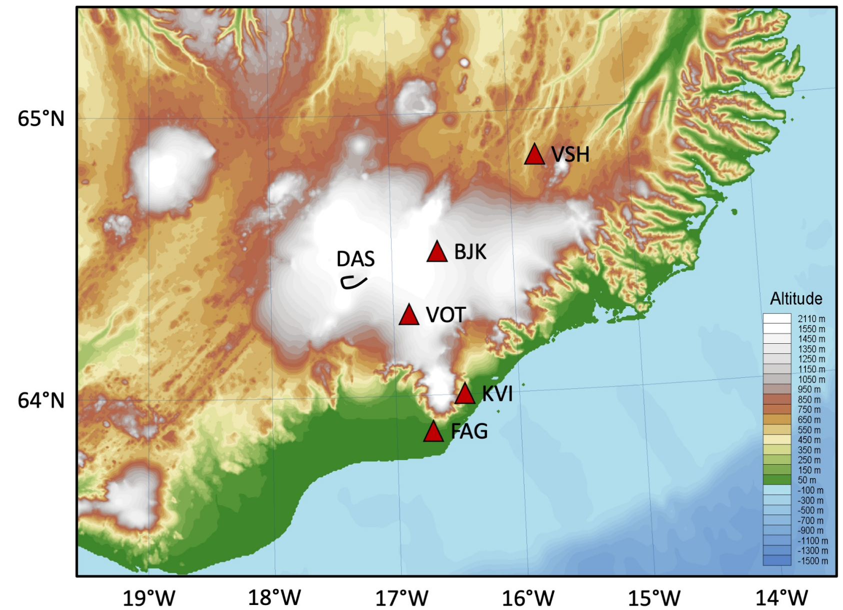
Seismology & Wave Physics

The spectrum at Grimsvötn is significantly different from the spectrum recorded at the coastal station KVI, which is certainly dominated by ambient seismic noise of oceanic origin. At KVI, the spectral peak is significantly broader, and its amplitude varies by a factor or about 3 within only 12 hours. This already suggests that ambient noise is at least not the only driving force of the ice sheet oscillations.

Spectrograms over 3 weeks

- Spectrograms of ambient vibrations at stations in southern Iceland are remarkably similar!

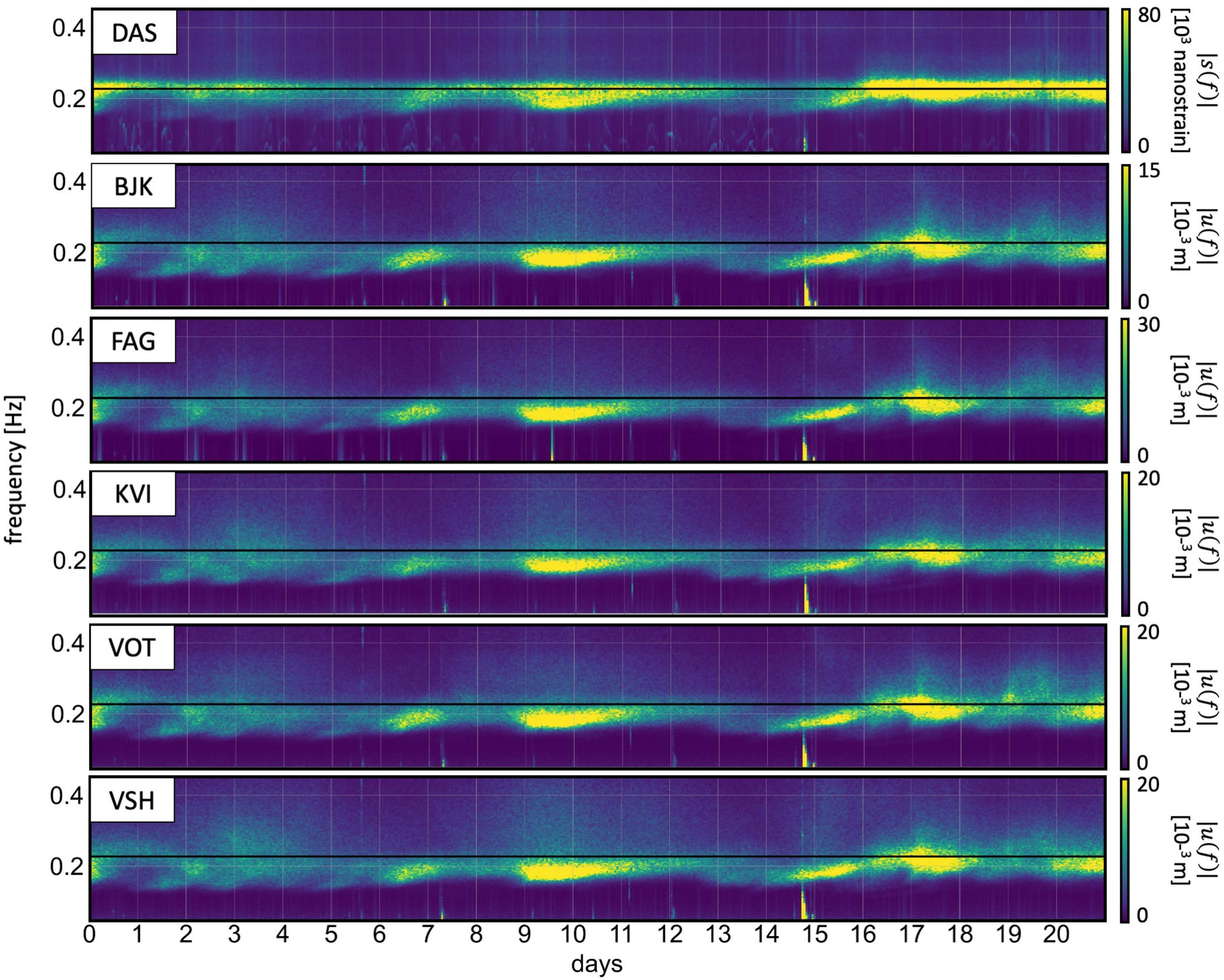




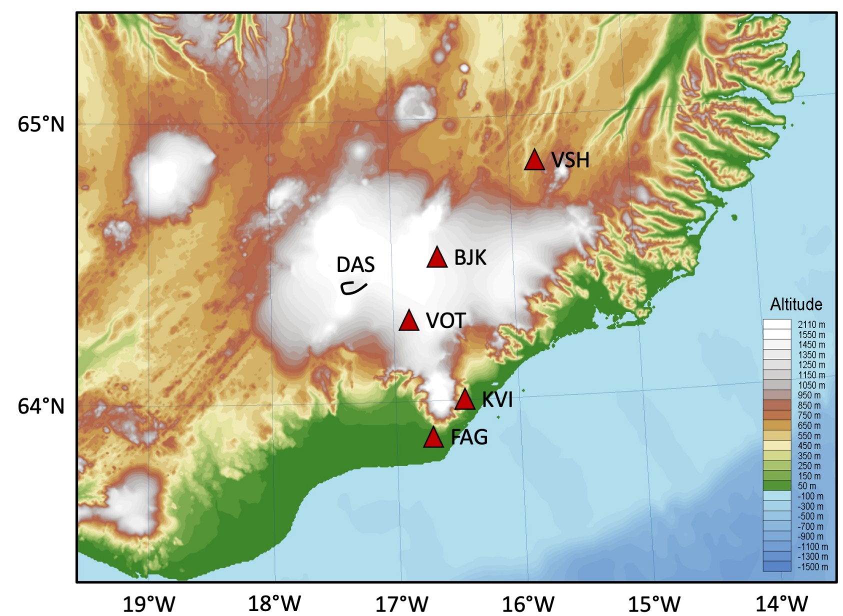
ETH Seismology & Wave Physics

The amplitude spectrum at KVI is remarkably similar to the amplitude spectra at other broadband stations in southern Iceland, as we see in the figure to the right. This holds not only on 7 May 2021, but during the complete 3 weeks of the experiment. Clearly, the ambient seismic field in southern Iceland is quite homogeneous.

Spectrograms over 3 weeks



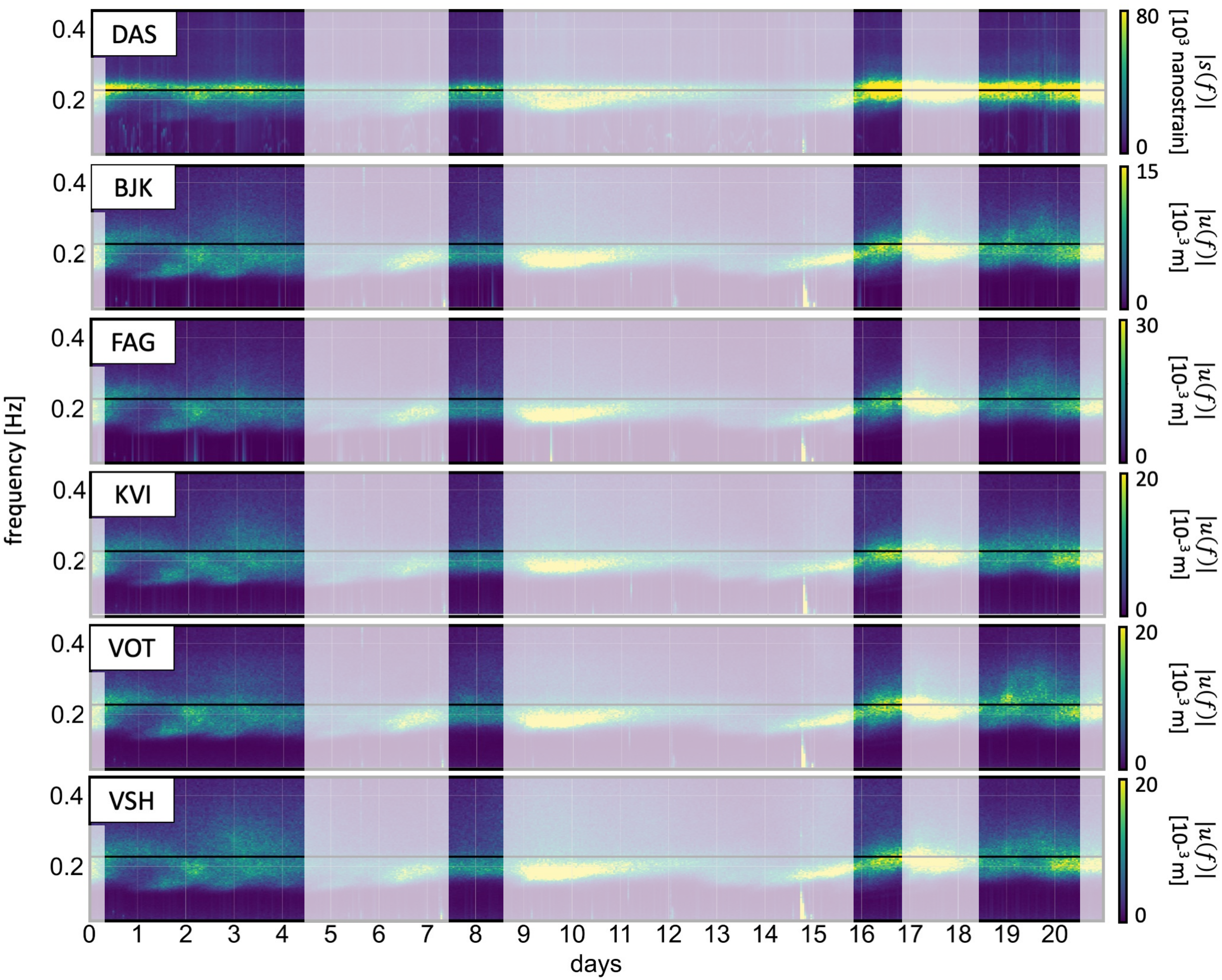
- Spectrograms of ambient vibrations at stations in southern Iceland are remarkably similar!
- Overall, they correlate with the spectrogram of the ice sheet oscillations.
- However …



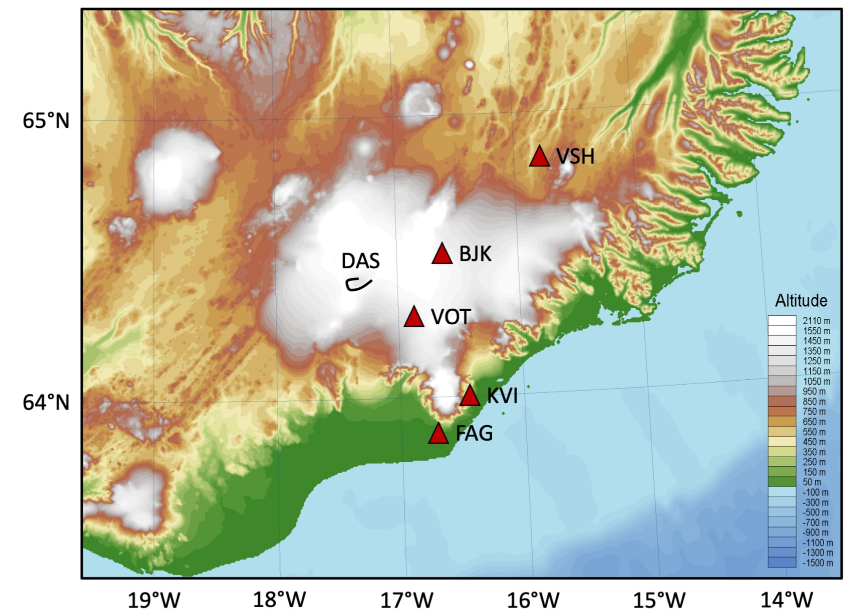
ETH Seismology & Wave Physics

The DAS channels in the Grimsvötn caldera exhibit spectral characteristics that are similar to those of ambient noise at the broadband stations. However …

Spectrograms over 3 weeks



- Spectrograms of ambient vibrations at stations in southern Iceland are remarkably similar!
- Overall, they correlate with the spectrogram of the ice sheet oscillations.
- However, there are exceptions, as seen before:



ETH Seismology & Wave Physics

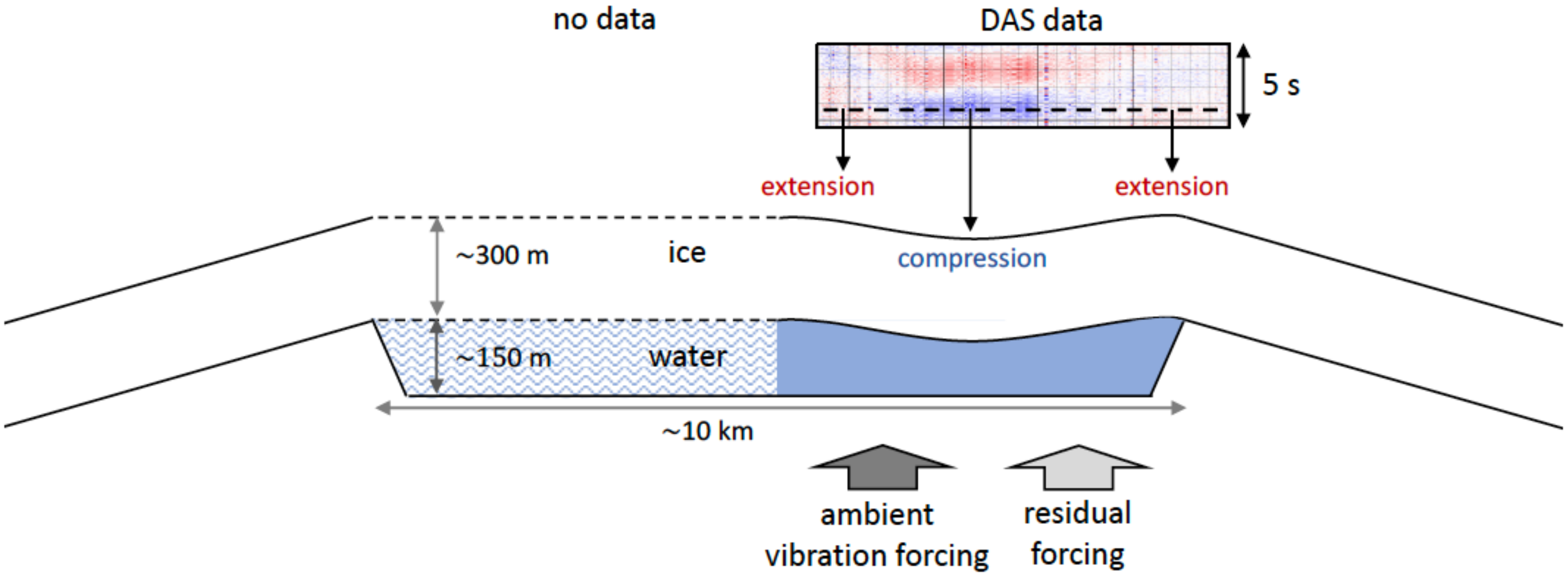
… , as we have seen before, there are times when the amplitudes of the ice sheet oscillations and the ambient noise field are clearly not correlated. Some of these periods are highlighted here. For example, around day 16 – 17 of the experiment, the amplitude of the ice sheet oscillation is high, whereas the ambient noise amplitudes are relatively low.

A simple model

The ice sheet as a 1D damped harmonic oscillator

Ice sheet oscillations can only partly be explained by ambient vibration forcing.

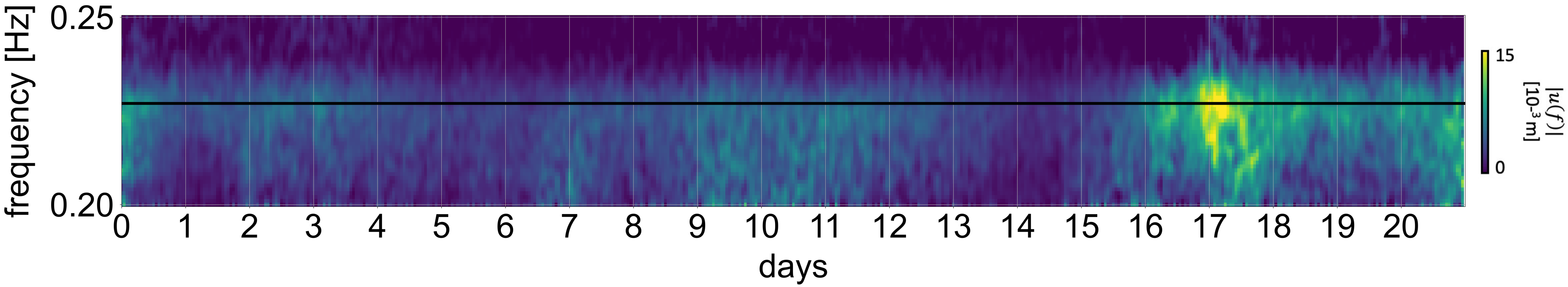
What are the minimum forces required to explain the observations?



Knowing that the ice sheet approximately behaves likes a 1D damped harmonic oscillator, we can build a simple model. For this, we assume that the oscillator is driven by (1) ambient noise, the properties of which we know from the broadband seismic stations, (2) some residual forces that remain to be estimated.

Minimum residual forces

Estimating $f_{residual}$ through a series of linear inverse problems:

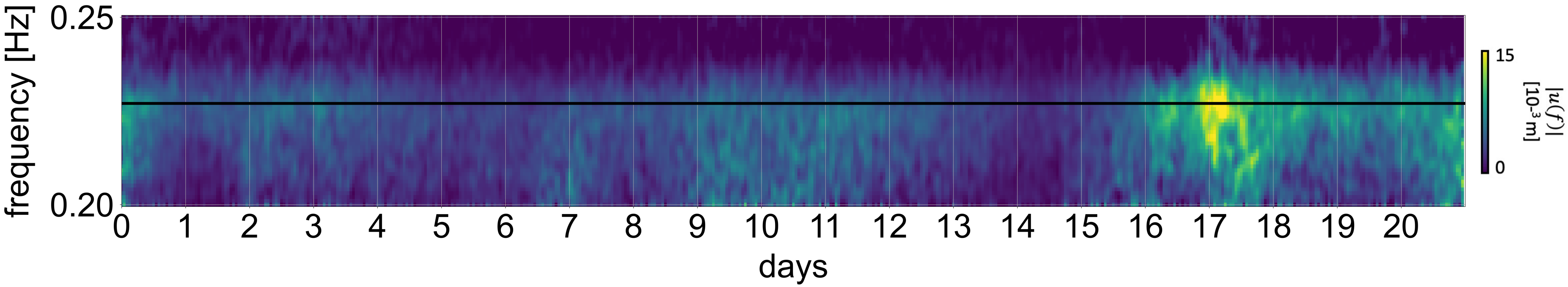


ETH Seismology & Wave Physics

We can estimate the minimum residual forces by solving a series of linear inverse problems. The resulting spectrogram of these minimum residual forces is shown in this figure.

Minimum residual forces

Estimating $f_{residual}$ through a series of linear inverse problems:



Low-frequency forces are required to act almost continuously on the ice sheet.

ETH Seismology & Wave Physics

Clearly, some low-frequency forces are required to act nearly continuously in order to keep the ice sheet oscillations at the observed level.

Conclusions

- Continuous low-frequency sources are most easly explained in terms of **volcanic tremor**.
- Consistent with [visible] **geothermal** activity and the known volcanic activity of Grimsvötn.
- Ice sheet resonance acts as an amplifier that makes otherwise invisible forces visible. **Natural loudspeaker**.
- This may offer new, and somewhat exotic, opportunities for volcano **monitoring**.

For more details:

Fichtner et al., 2022. "Fiber-optic observation of volcanic tremor through floating ice sheet resonance". *The Seismic Record*, under review.

ETH Seismology & Wave Physics

These residual forces are most plausibly explained in terms of volcanic tremor that excites the ice sheet. This is in agreement with geothermal and volcanic activity at Grimsvötn. A particularly interesting aspect of this phenomenon is that the floating ice sheet acts like a natural loudspeaker that amplifies tiny signals that would otherwise not be observable. This may offer interesting opportunities for the monitoring of other ice-covered volcanoes.