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Distributed Acoustic Sensing from mHz to kHz: Empirical Investigations of DAS Instrument Responses

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Abstract

With the upside of high spatial and temporal sampling even in remote or urban areas using existing fiber-optic infrastructure, Distributed Acoustic Sensing (DAS) is in the process of revolutionising the way we look at seismological data acquisition. However, recent publications show variations of the quality of DAS measurements along a single cable. In addition to site- and orientation effects, data quality is strongly affected by the transfer function between the deforming medium and the fiber, which in turn depends on the fiber-ground coupling and the cable properties. Analyses of the DAS instrument response functions in a limited part of the seismological frequency band are typically based on comparisons with well-coupled conventional seismometers for which the instrument response is sufficiently well known to be removed from the signal.

Here, we extend the common narrow-band analyses of DAS instrument responses to a wide range of experiments covering a frequency range of five orders of magnitude ranging from ~4000 s period to frequencies up to ~100 Hz.

I. Introduction

Distributed Acoustic Sensing (DAS) is a method to measure **in-line strain or strain-rate** a long a **fibre-optic cable** – generating a distributed high resolution sensor array both in space and time [1]. To **quantify the data quality of DAS** compared to conventional sensing methods in ground monitoring, such as geophones and seismometers, we need to identify **the transfer function between ground motion and strain along the cable – the instrument response.**

In theory, the DAS instrument response is flat for wavelengths down to close to the gauge-length, which is the measurement length over which the strain is calculated [2]. In practice however, deviations from this perfectly flat instrument response have been observed in the past [2].

II. Instrument Response Calculations

We define the instrument response function ***T*** of a single DAS channel at location ***x*** as the ratio of the amplitude spectrum of the observed wavefield *u* to the amplitude spectrum of the true ground motion *g*, both in the direction of ***e***. Note that equation (1) only holds if the spectrum of the true ground motion is non-zero within the investigated frequency range from ω_1 to ω_2 .

$$T_{\mathbf{e}}\Big|_{\omega_1}^{\omega_2} = \frac{u_{\mathbf{e}}(\mathbf{x},\omega)}{g_{\mathbf{e}}(\mathbf{x},\omega)}\Big|_{\omega_1}^{\omega_2} \qquad (1)$$

We evaluate the instrument response of DAS for amplitude and phase responses separately. For the amplitude response we look at the response after eq. (1) in dB as $20log_{10}(T_e)$ and for the phase response we look at the complex angle of T_e . The ground motion estimates come from reference measurements of instruments with known responses.
An example of amplitude and phase response of DAS for an earlier study is visualized below in **Fig. 1** [2].

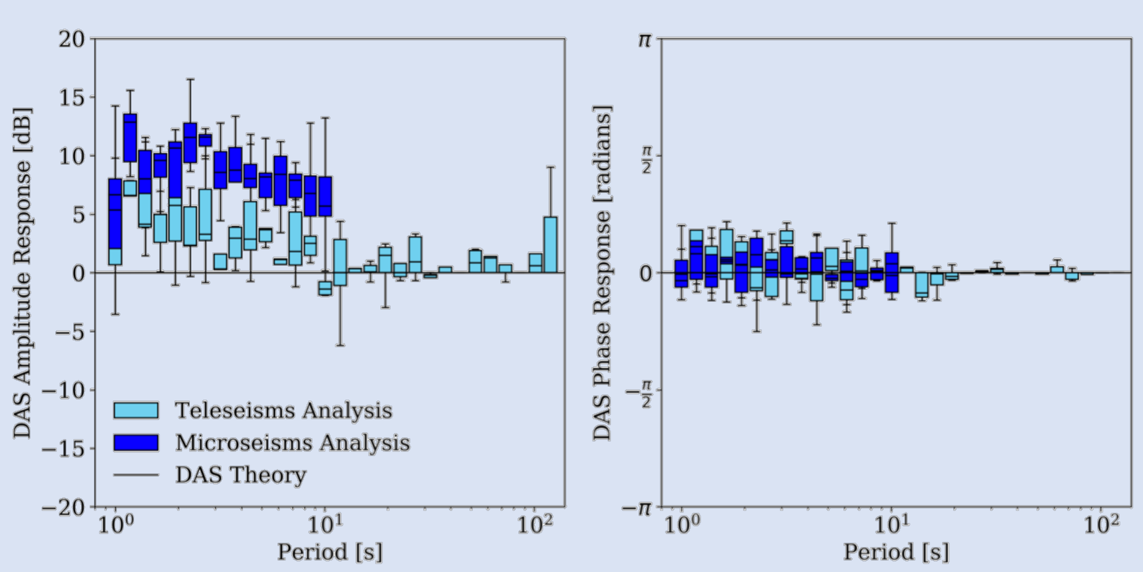

Figure 1: DAS amplitude and phase response. The response was calculated for teleseismic signals as well as microseismic signals for the lower frequencies. The black lines at 0 dB and 0 radians indicate the theoretical DAS responses for the investigated signals. Figure from [2].

Recent studies showed that the instrument response for teleseismic frequencies is reasonably flat for the frequencies of interest (1/100 to 1 Hz) [2]. To cover a larger bandwidth and various fiber installation scenarios, we extend the narrow-band analyses to multiple experiments conducted in Switzerland throughout 2018 and 2019.

III. Experiment Overview

We conducted a wide range of experiments for which we will calculate the instrument responses in section V. The experiments include (1) hydraulic injection tests in a borehole and (2) earthquake recordings in a tunnel at the Grimsel Test Site, (3) an active source experiment on an agricultural field close to Yverdon-les-Bains and icequake recordings on Rhonegletscher in the Swiss Alps. Each experiment had reference measurements to compare DAS to. For an overview see **Fig. 2**.

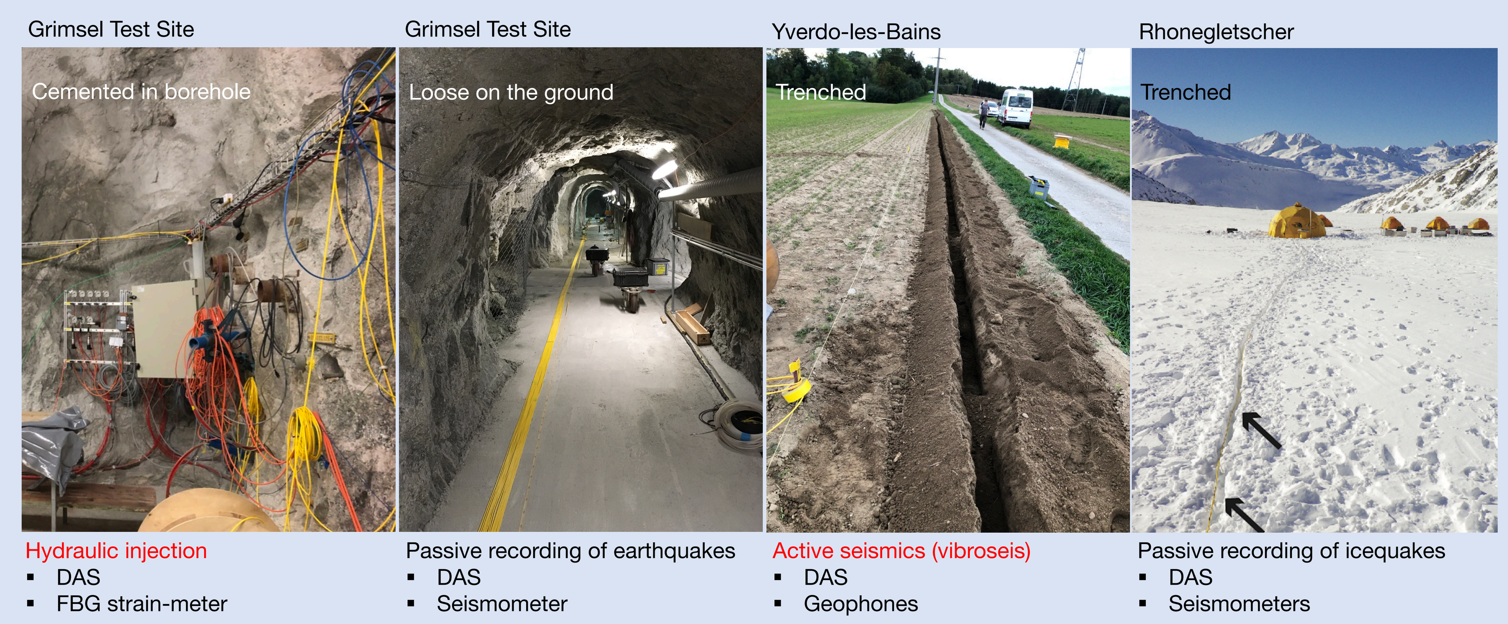

Figure 2: Impressions of the experiments conducted to compare instrument responses. The reference measurements include FBG strainmeters, seismometers and geophones. For the fiber installation type, see the subfigures. For more information on the Grimsel Test Site, see [3].

IV. Data and Processing

Before the Instrument response was calculated, all data was converted to the same observed quantity and filtered within the same frequency band. The workflow is visualized in **Fig. 3** and example waveforms of raw and processed data is shown in **Fig. 4**. GTS denotes Grimsel Test Site.

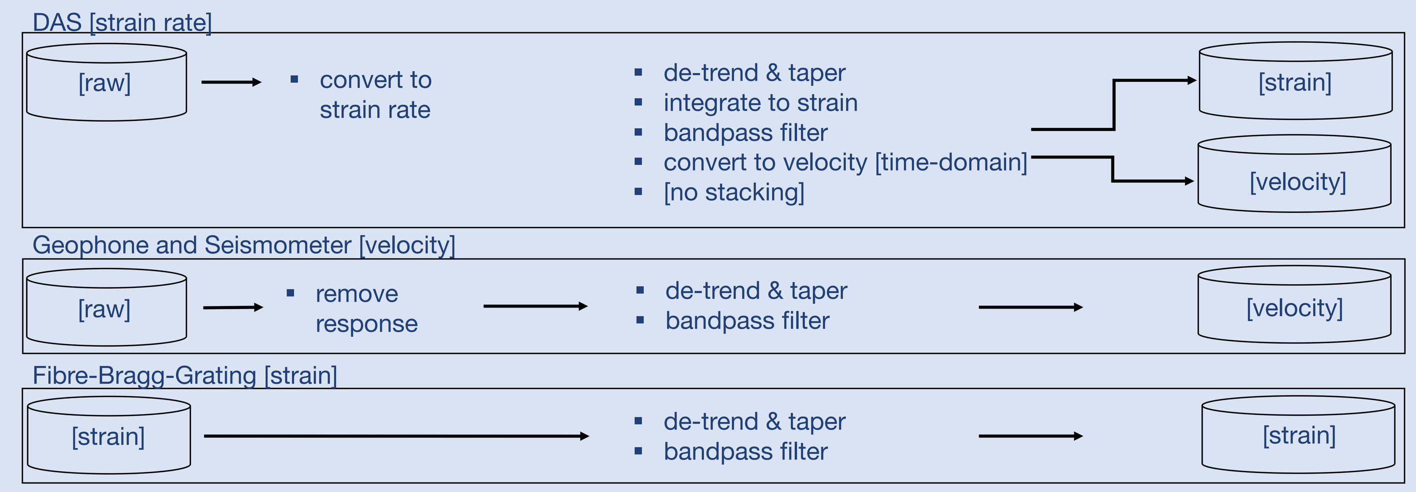

Figure 3: Processing workflow for DAS (top) and reference data (middle and bottom). The reference data is either from FBG strain meters [strain] or from geophone or seismometer recordings [velocity].

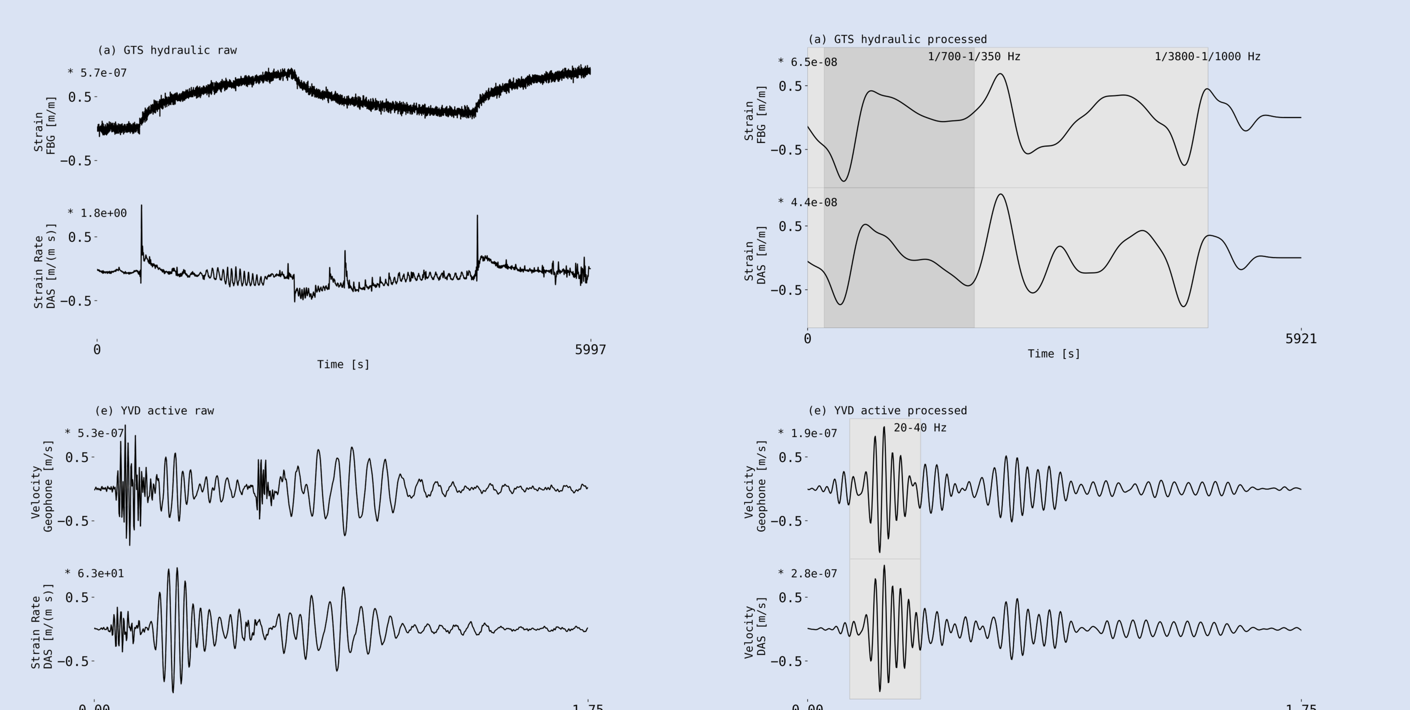

Figure 4: Examples of raw (left) and processed data (right) for the hydraulic injection (a) and the active seismics experiment (e). The reference data (FBG and geophone measurements) are plotted in the top subplots whereas DAS data are plotted in the bottom subplots. The grey area indicates the window in which the response is calculated.

V. Results: Instrument Response Estimates

After preprocessing, the instrument response is calculated from DAS and reference measurements. The amplitude and phase responses are visualized in **Fig. 5** for the different experiments within their corresponding frequency ranges.

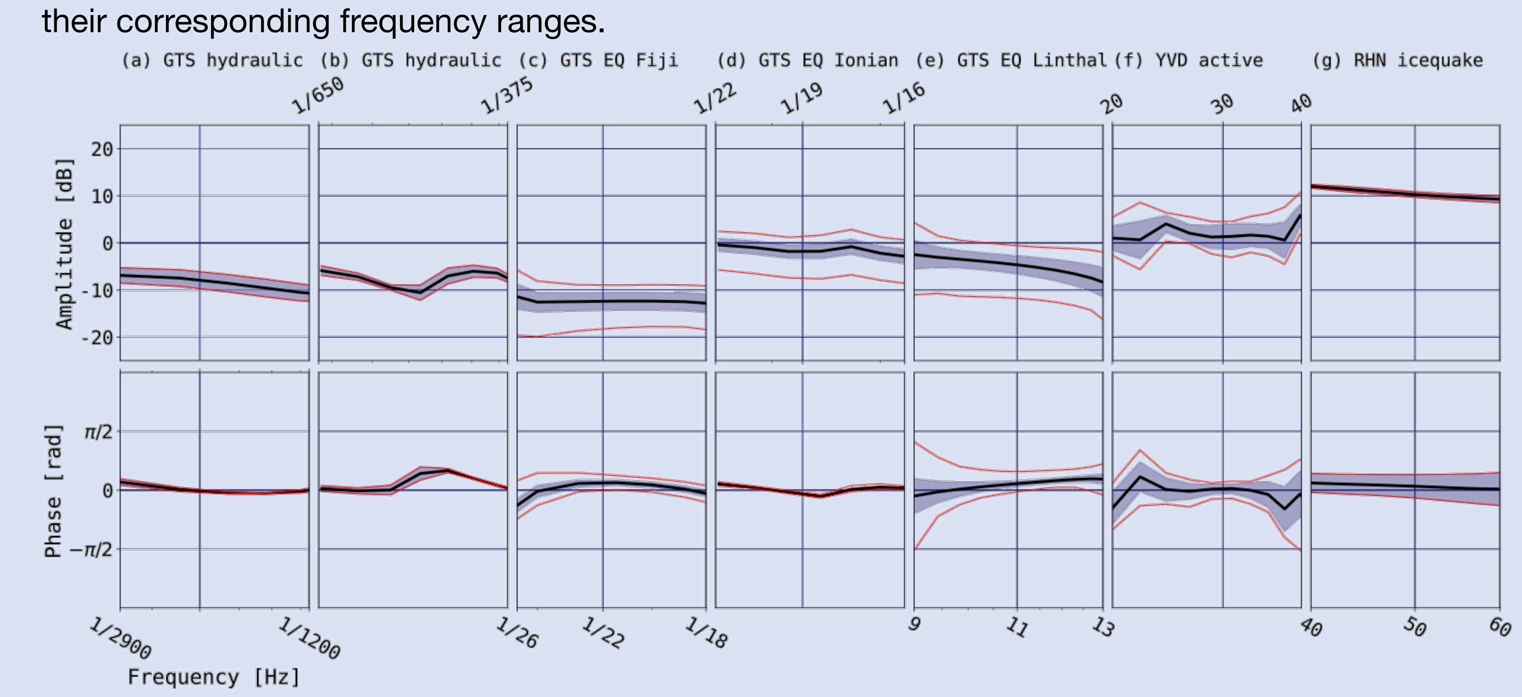

Figure 5: Estimated amplitude (top) and phase responses (bottom) for all available DAS channels for the experiments introduced in section III. GTS denotes the Grimsel Test Site, YVD the Yverdon-les-Bains site and RHN the Rhoneglestcher site. there are 3 different earthquake recordings (denoted EQ) at the GTS, two teleseismic events from Fiji (d=16800 km) and the Ionian Sea (d=1300km) and a regional earthquake with an origin close to Linthal (d=60km). The black line indicates the mean of the response, the shaded area the data within the standard deviation and the red lines indicate the maxima and minima of the response of the individual DAS channels.

The main observations include:
- The amplitude responses do vary more than phase response.
- There seems to be a small frequency trend: the higher the frequencies, the higher the response.
- The variations in amplitude and phase response are on the order of magnitude of the responses from [2] (see **Fig. 1**).

VI. Discussion

There are many possible explanations for the deviations from a perfectly flat instrument response, including:
- Instrument effects like optical noise.
- Assumptions and approximations on the calculation of the responses introduce errors. Examples include incorrect phase velocity estimates when converting from strain to velocity.
- The reference measurements do not represent true ground motion.
- Differences in subsurface properties and instrument installation. An example here is Rhoneglacier where the reference measurement is in ice approx. 3 m below the snow cover and the fiber optic cable is installed in snow. Site-amplification effects could be possible in such a scenario, hence higher amplitudes on DAS compared to the seismometer.
- Sub wavelength heterogeneities can have a an impact on strain recordings [4].

It is important to emphasize that the implementation of strain recordings into existing geophysical workflows can help overcome many assumptions and approximations and hence could yield a better ground motion estimate than velocity-equivalent DAS data.

Conclusion

The initial results presented in this conference contribution suggest that the amplitude and phase information of DAS recordings are sufficient for conventional geophysical methods such as event localisation, full-waveform inversion, ambient noise tomography and even event magnitude estimation. Despite the promising initial results, further engagement by the DAS community is required to evaluate the DAS performance and repeatability among different interrogation units and study sites.

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