T3.4-P8

Resonance Seismometry: A toolbox for OSI

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Resonance Seismometry

Besides aftershock monitoring, resonance seismometry is listed in the CTBT as passive seismological method for On Site Inspection (OSI). The objective is nuclear verification through detection of resonances, static structural anomalies and monitoring of temporal changes of subsurface properties caused by an underground nuclear explosion (UNE). During an expert meeting in November 2015 at the CTBTO several techniques have been listed, to be tested for this purpose including those relying on cavity resonances.
The table summarizes the methods, the causative features that are aimed to be detected as UNE-indicators and the seismic sources that are used. Besides a cavity, the expected structural anomaly in the subsurface comprises also rubble and spall zones, which can be used as targets for seismological exploration.

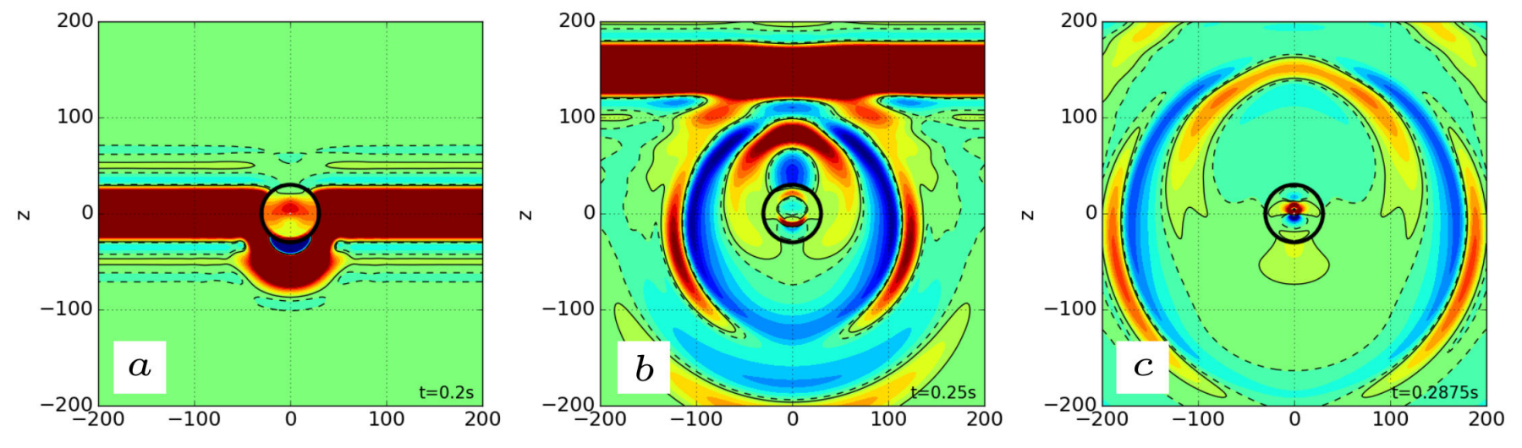
We are aiming at an evaluation of the proposed methods by the investigation of the complex wave field interactions at an UNE test site through forward modeling and analysis of data collected at a natural analogue site. Data have been provided by the OSI division of the CTBTO.

Table of passive seismic methods for OSI (condensed version)

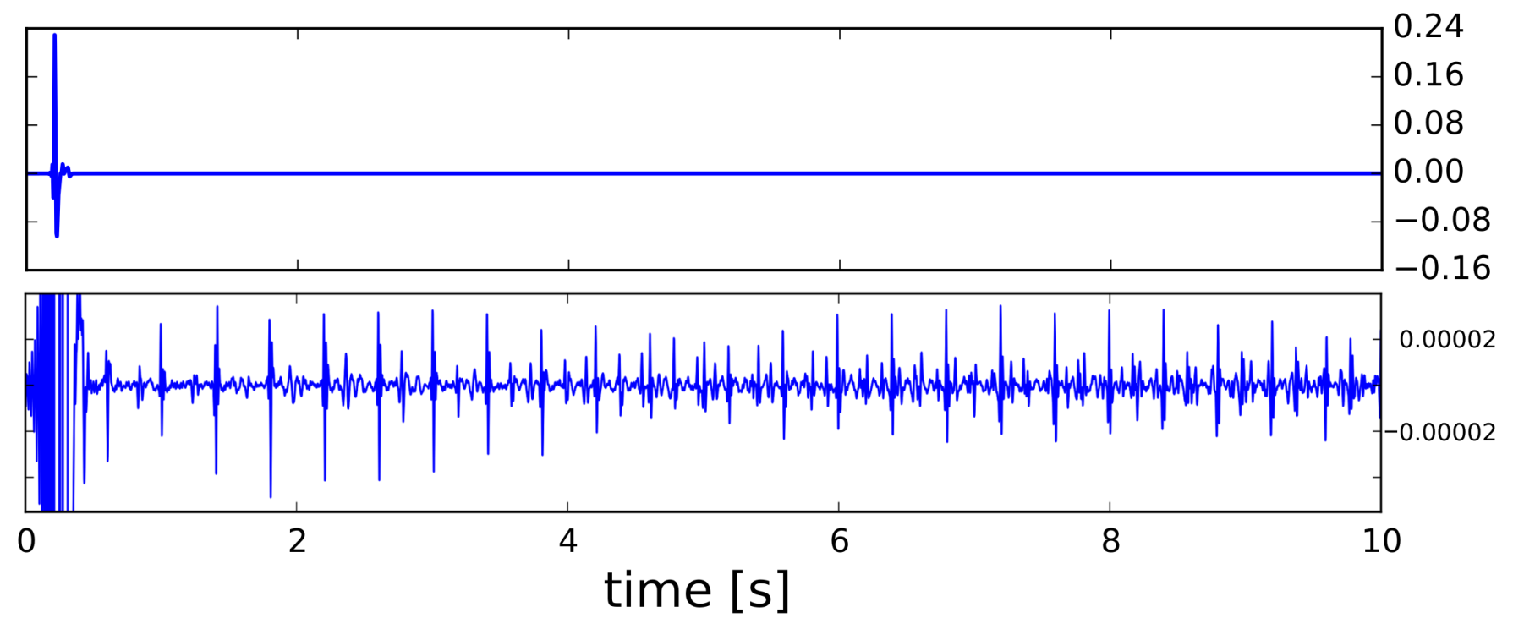
	Noise Power Spectrum			Noise: Surface wave dispersion (SPAC,FK)	Deterministic Sources	Interferometry		
	Background change	Distinct frequencies	H/V analysis			Surface wave tomography	Body wave tomography	Temporal changes
Measuring what?	Increased power density in certain frequency ranges measured close to GZ compared with more distant stations	Spatial change in spectral amplitude of narrow frequency ranges	Spatial change in amplitude ratio of horizontal and vertical components Rayleigh wave ellipticity	Surface wave dispersion Shear velocity-depth profile	Spatial variation of: attenuation, incidence angle,conversions coda characteristics, polarization, dispersion, correlation,…	Surface wave dispersion, Shear velocity-depth profile 3D-tomographic Shear velocity model	Body wave tomography, Diffractions, Reflections	Velocity change, Attenuation, Decorrelation
Causative feature	Local modification of noise field by near-surface effects	Resonance of cavity/rubble zone or spall layer	Near-surface variations (spall) or deeper features (rubble/fracture zone)				Deeper features: rubble/fracture-zone, cavity	Healing of fractures, Ground water changes, Stress relaxation, Consolidation
Source of seismic energy	Processes around chimney / rubble zone or static effects on ambient noise	Original energy from teleseismic events or ambient noise	Passive or active surface wave source		Teleseismic, regional and local events (incl. body and surface waves)	Ambient noise		

Modelling Cavity Resonances

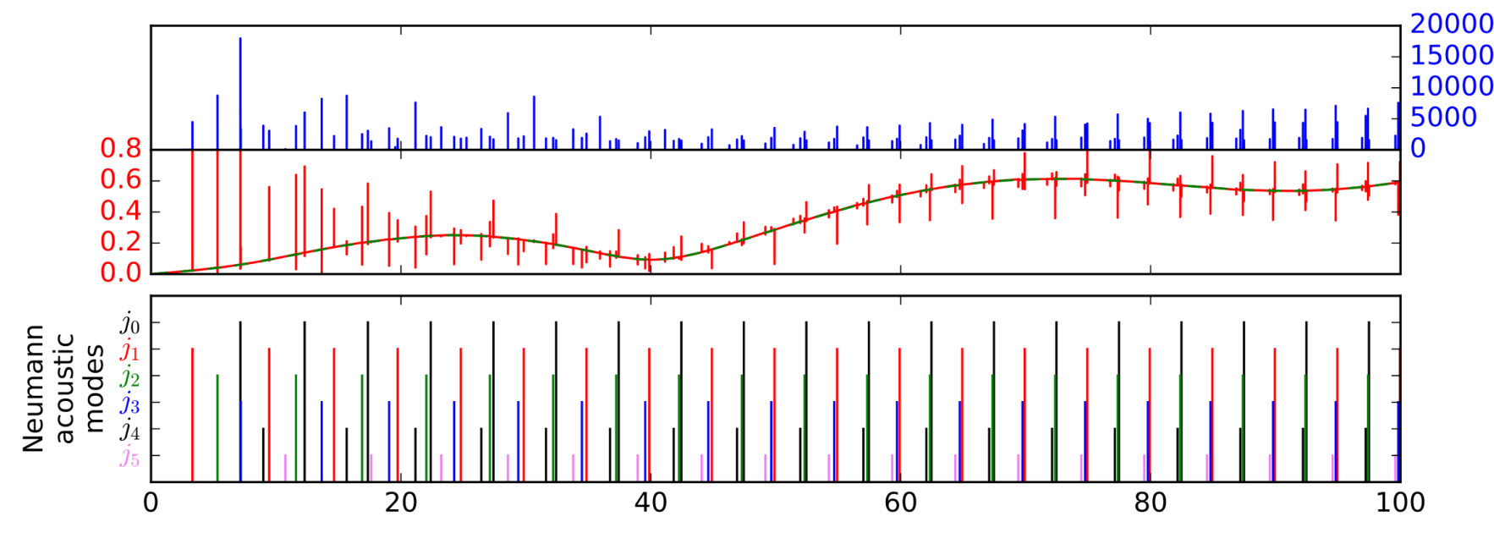
The wave field interaction of a plane P-wave with an air filled cavity is modeled using an analytical solution (Korneev and Johnson, 1993). The seismic wave field is reflected at the cavity and transmitted in the acoustic air-filled domain.



The scattered wave is dominated by the primary scattered pulse. Zooming into the coda of the primary scattered wave yields a repeating signal from internal reverberations of the acoustic cavity.



In the spectral domain those internal reverberations cause resonance peaks, which occur inside (blue) and outside (red) of the cavity. The acoustic resonance frequencies f_{nm} correspond to acoustic Neumann eigenmodes of the cavity.



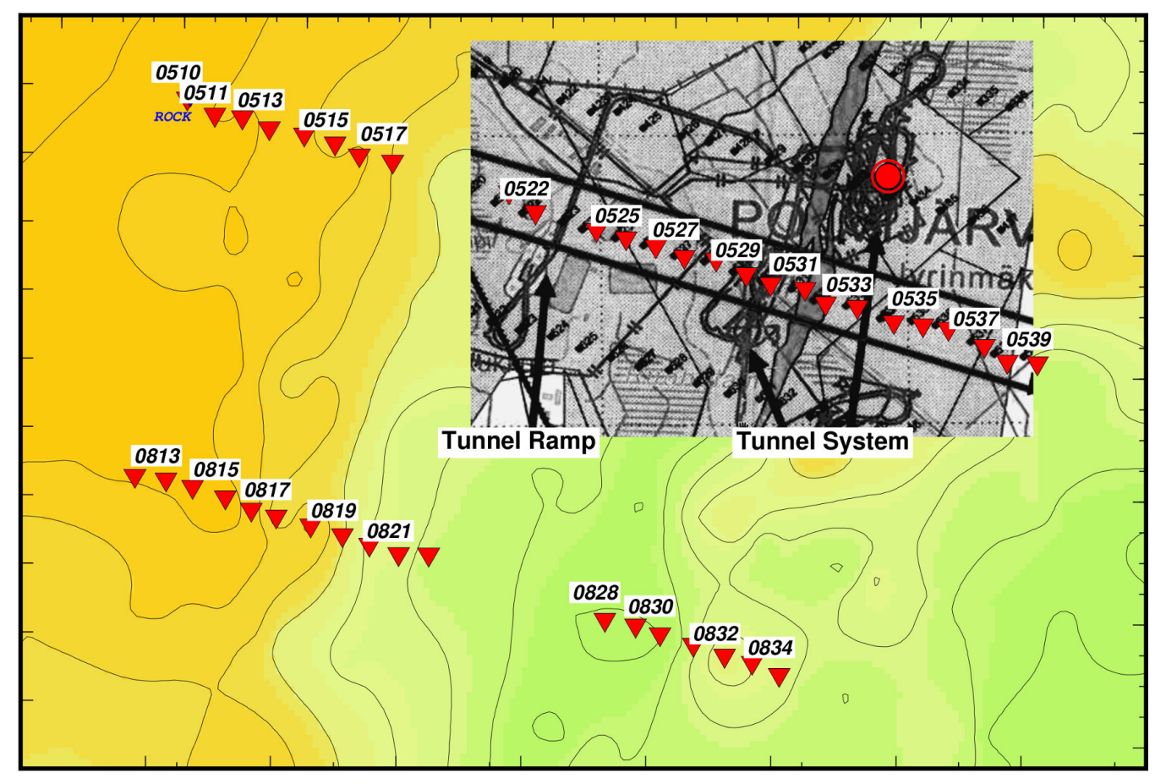
$$f_{nm} = j'_{nm} v_p / (2\pi R)$$

j_{nm}: spherical Bessel function
v_p: acoustic velocity inside cavity

Schneider et al.: **Seismic resonances of spherical acoustic cavities**, Geophysical Prospecting (2017) doi:10.1111/1365-2478.12523

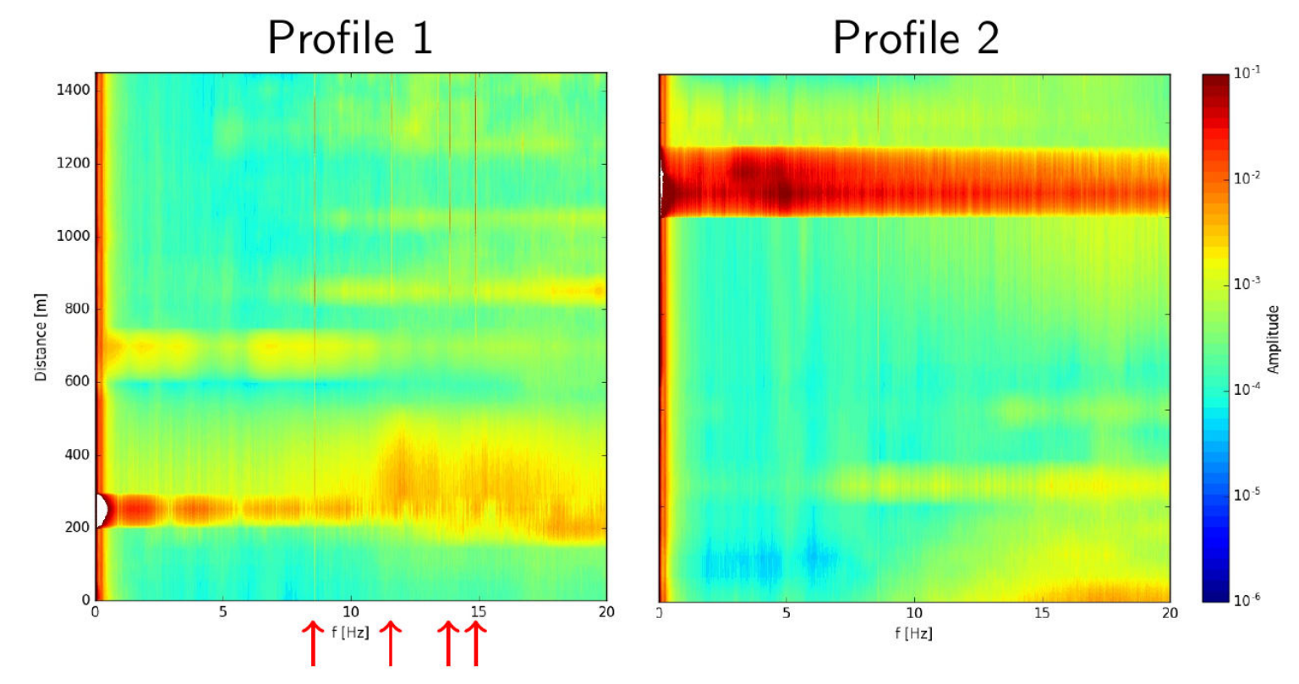
Kylylahti Dataset

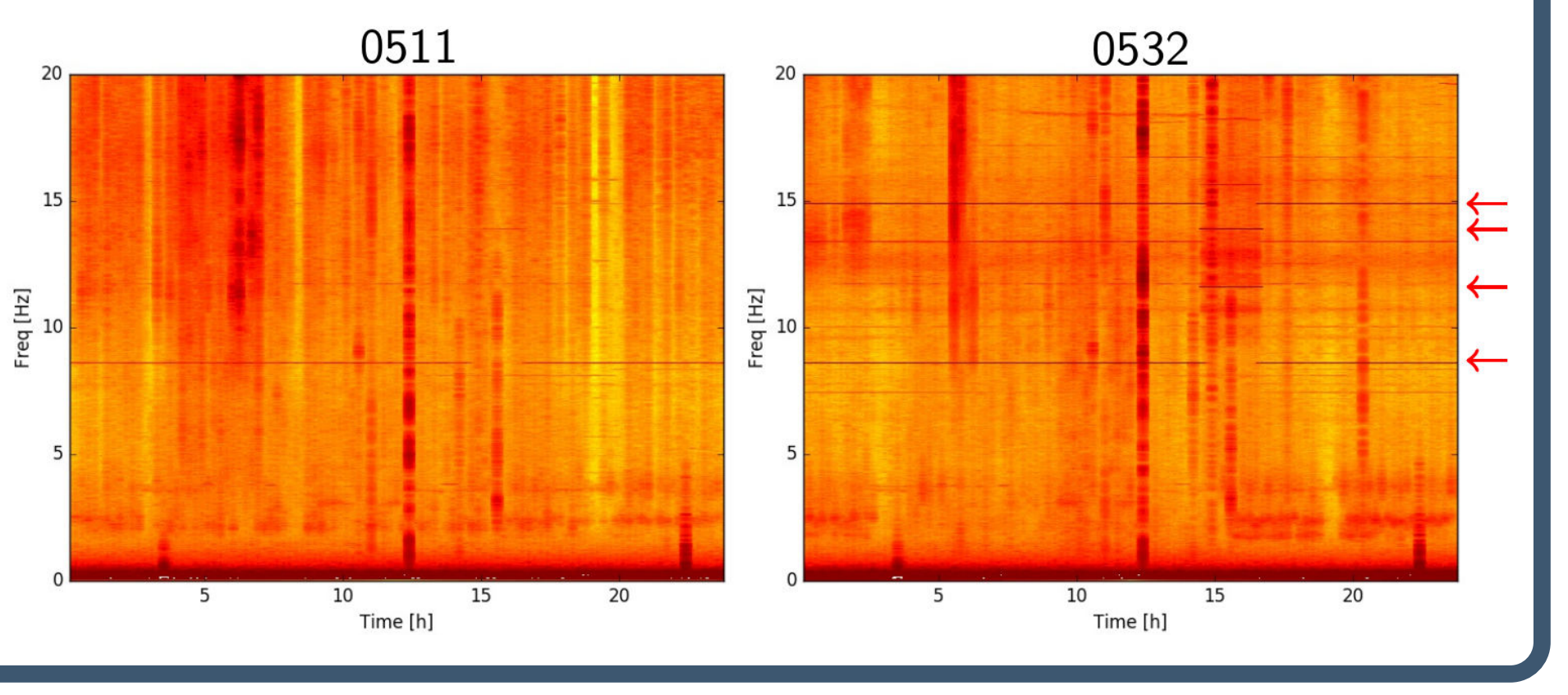
The seismological institute of the University of Helsinki (P. Lindblom et al.) collected seismic data using the SAMS instrumentation (3C-Lennartz, 1Hz) at the active Kylylahti mine in Finland. The data have been collected along two profiles for a duration of 34 days in August/September 2016. The northern profile is crossing a tunnel system and a tunnel ramp, which yield a possible target for testing the Resonance Seismometry methods.



Presence of distinct frequencies

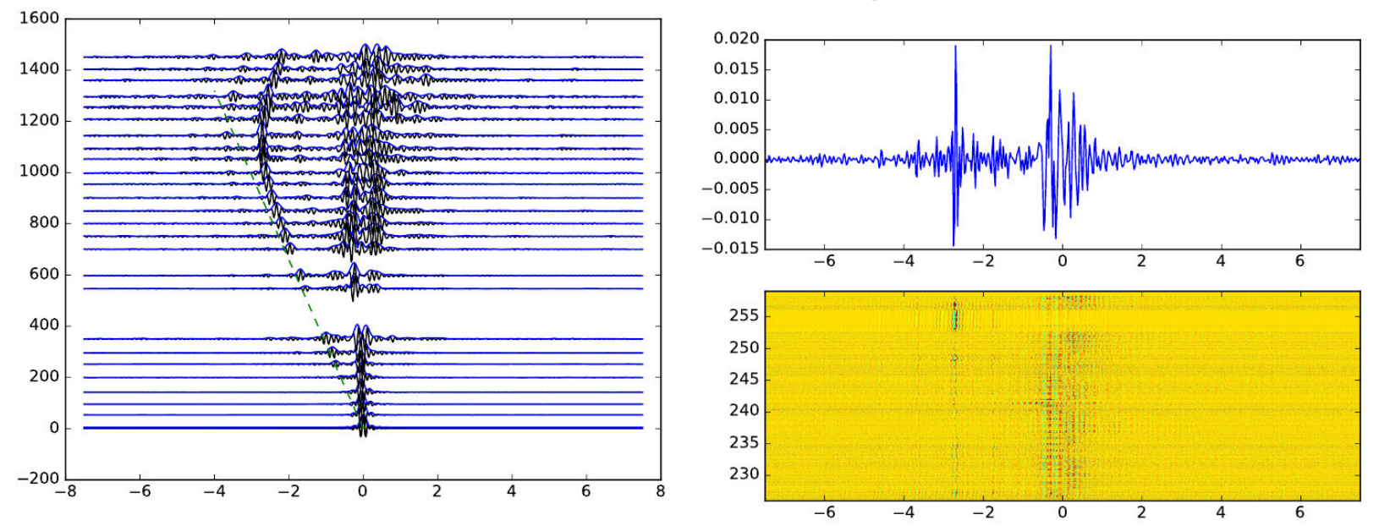
Spatial spectrograms show the presence of sharp spectral peaks at the northern profile (Profile 1). Temporal spectrograms of single stations reveal the anthropogenic origin of the peaks. Left: Spatial spectrograms computed for 24h of data (Aug 31 2016). Right: Temporal spectrograms for stations 0511 and 0532.

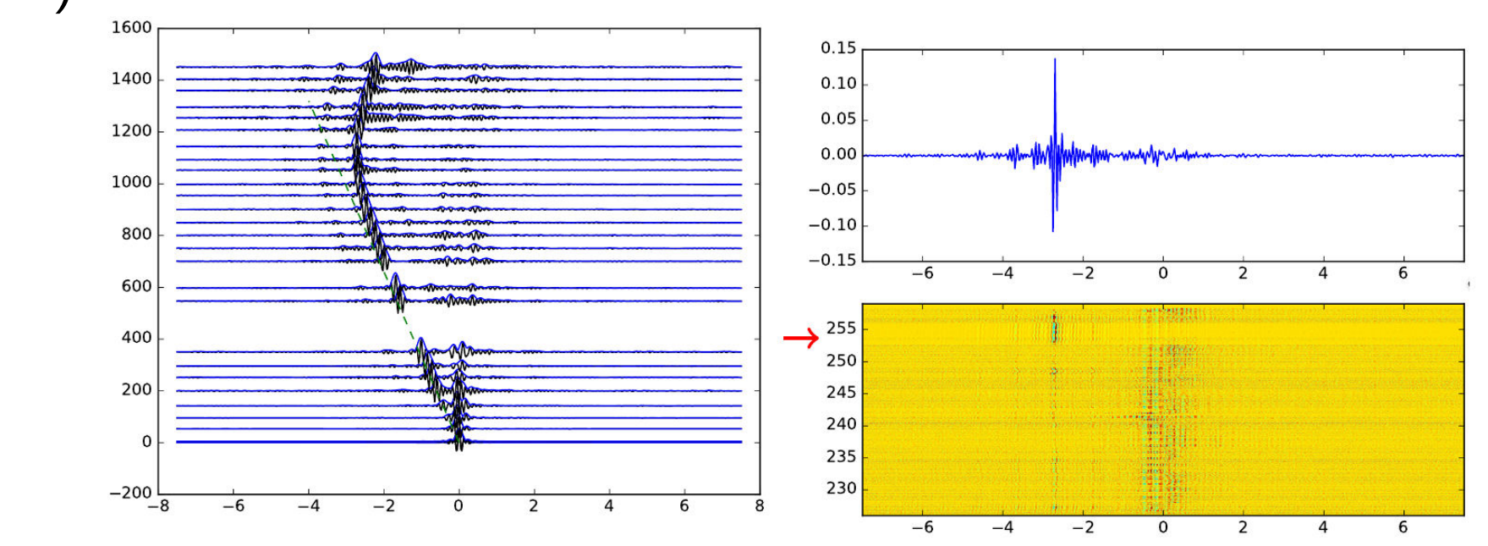




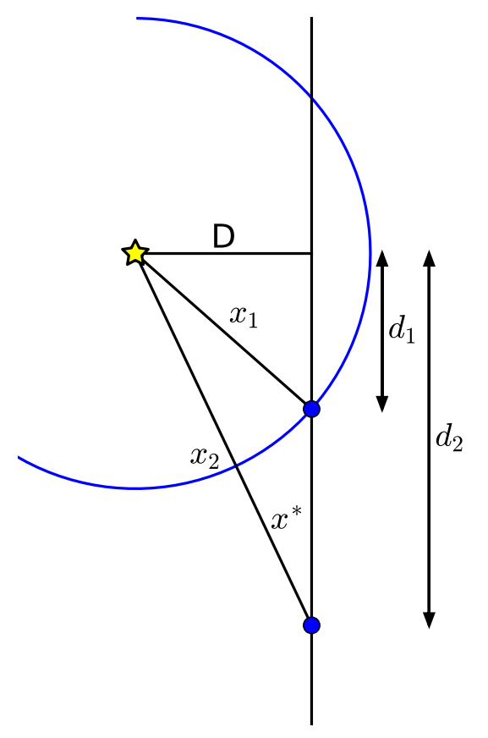
Ambient Noise Cross-Correlation

Cross correlation of ambient noise records revealed a strong non-transient source, which is dominating the cross correlations on a couple of days (Sep 08 - Sep 10 2016).



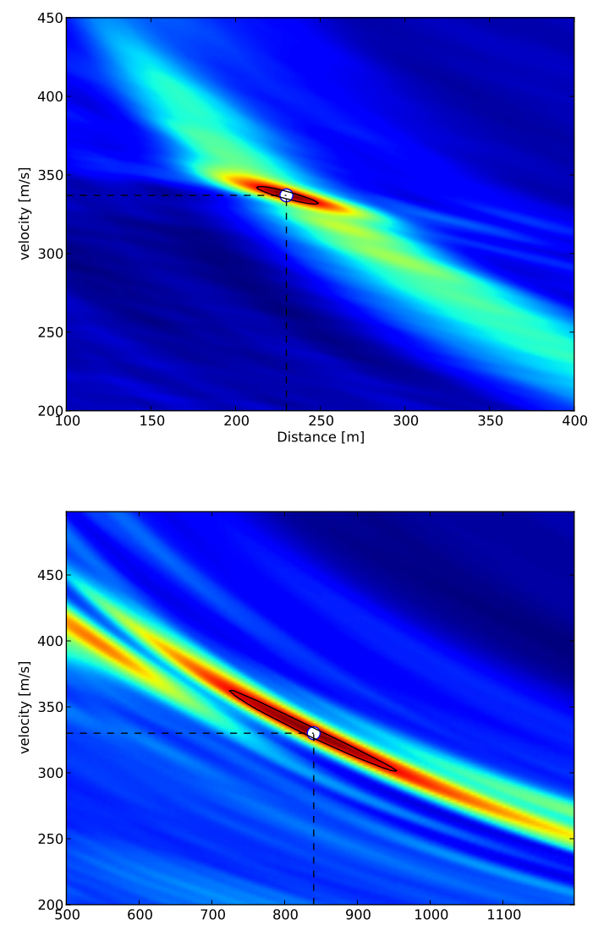


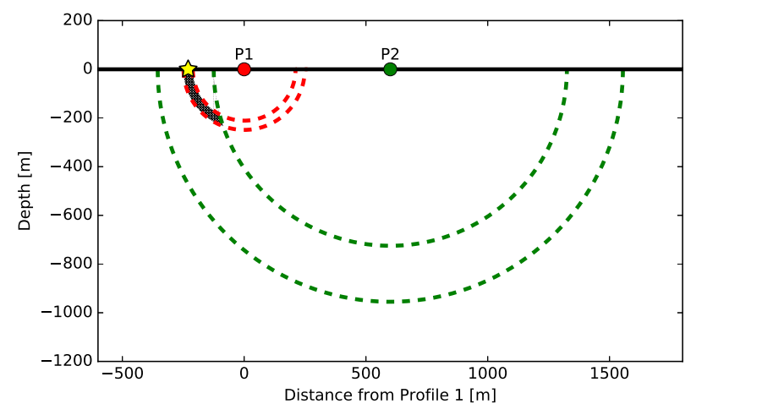
Location of non-transient source



The distance D of the source and the propagation velocity v are determined for both profiles by a slant-stack of the cross-correlations. The traces are aligned by shifting with the lagtime t_l. The final location of the acoustic source is depicted on the satellite image and the red dot in the station map.

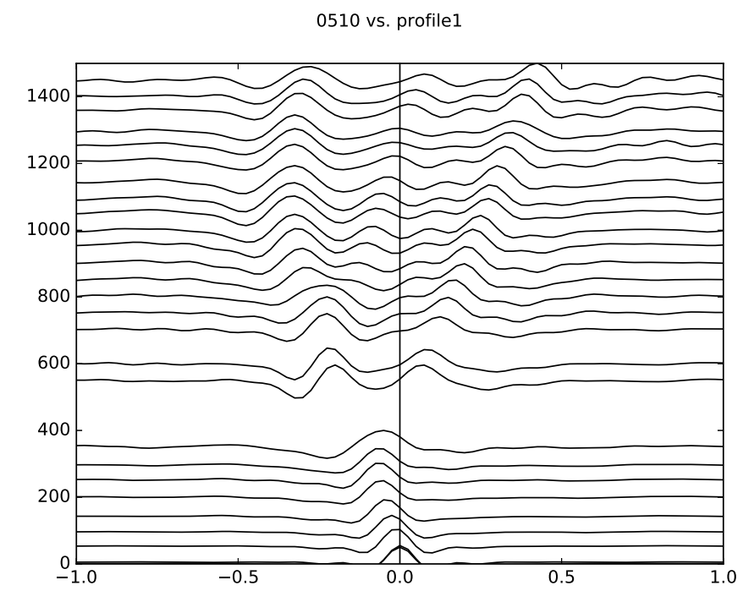
$$t_l = \frac{\sqrt{D^2 + d_1^2} - \sqrt{D^2 + d_2^2}}{v}$$



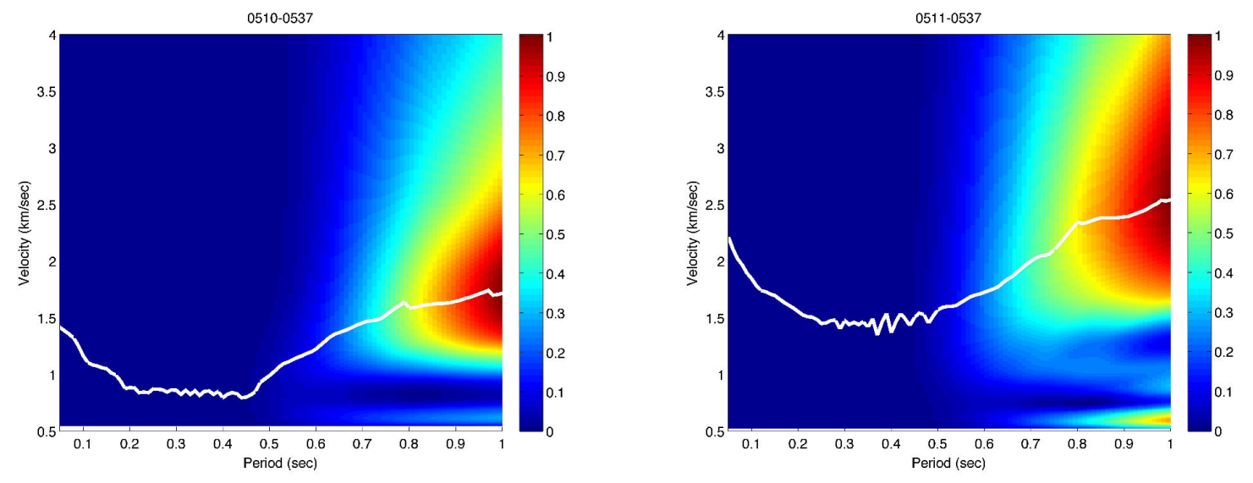


Ambient Noise Dispersion Analysis

Standard ambient noise cross correlation work flow for surface wave retrieval has been applied (spectral whitening, cross correlation of subtraces (15 Min.), stacking). Subtraces with transient signals and days with strong local non-transient sources are discarded. Right: cross correlations of station 0510 with all other stations of the northern profile, filtered with a bandpass filter of 1-7 Hz.

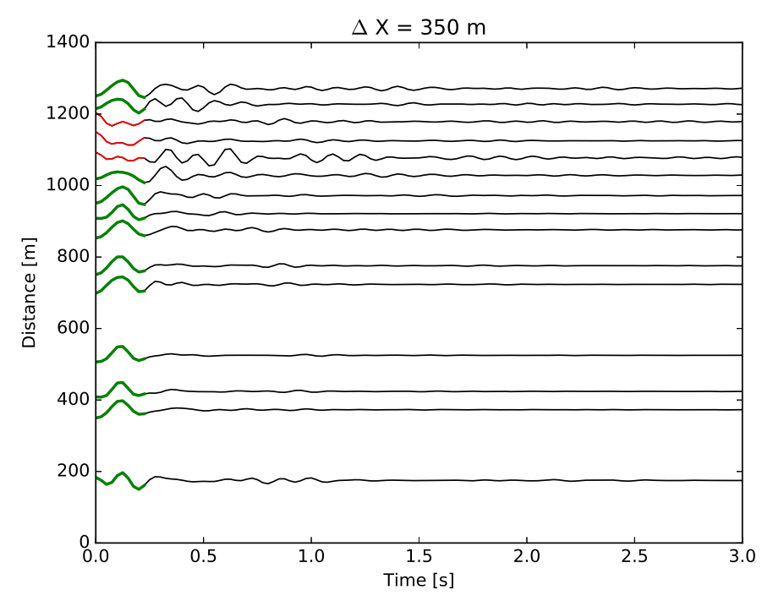


Dispersion analysis of the surface waves retrieved from ambient noise cross correlation is done by frequency-time analysis (FTAN) Right: preliminary dispersion curve results for station pairs 0511-0537 and 0511-0539 .



Blockage of surface wave phase

For equidistant station spacing of 350 m along the profile, cross correlations retrieve a surface phase at 0.12 s (corresponding to 2917 m/s). Right: Cross-correlations filtered between 3 and 9 Hz. The Y-axis shows the midpoint location of each station pair. Between 1050 m and 1150 m the surface wave vanishes. It might been blocked by underground structure.



H/V - Analysis

northern profile:

The spectral ratio of the averaged horizontal components and the vertical components have been computed using GEOPSY (M. Wathelet et al.). Windows of 15s have been selected automatically from 24h data by a STA/LTA anti-trigger. For STA and LTA windows of 1s and 30s, windows with 0.18 < STA/LTA < 2.5 were used for the computation.

southern profile: