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Nikhef

Shallow subsurface characterization using high frequency ambient noise at Terziet, Limburg

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An array of 183 vertical component 5 Hz geophones deployed between Nov. 12 – Dec 06, 2020

- Array covers an approximate area of 7x7 sq. km
- Approximate station separation of about 300-400 m

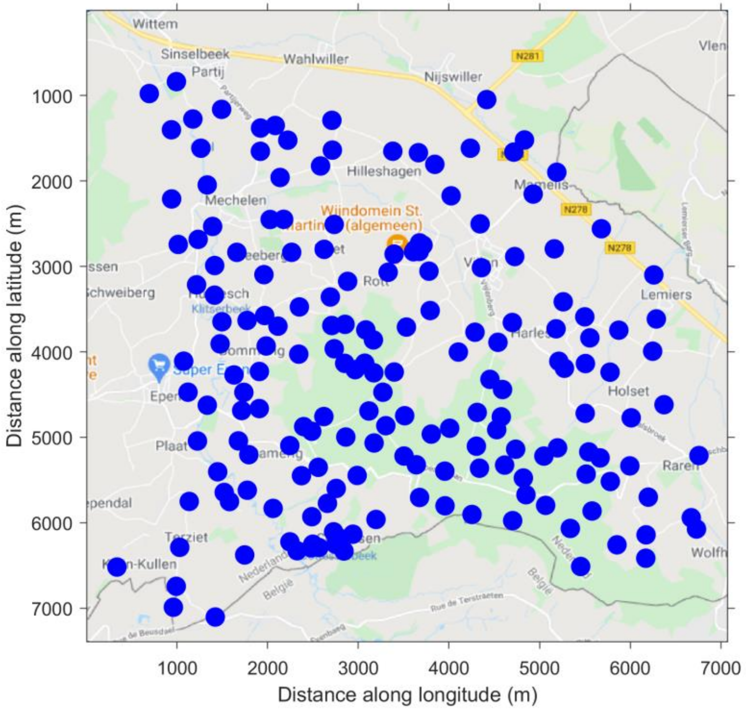
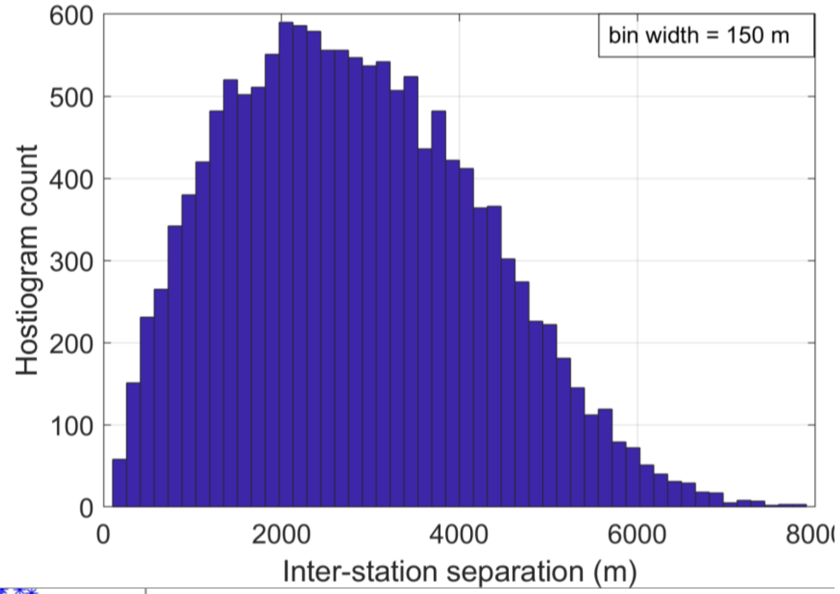
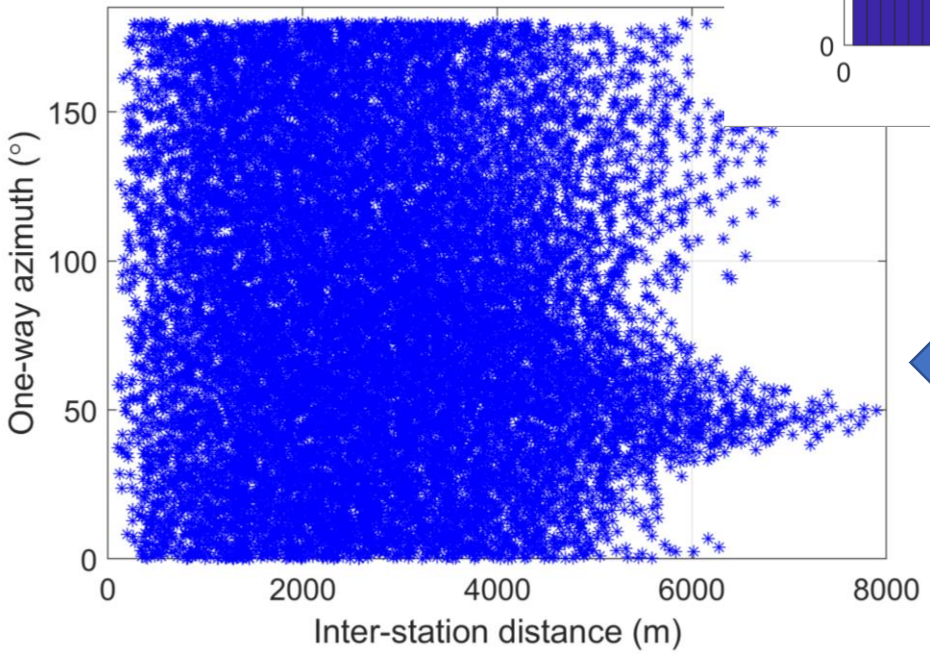


Figure: Sensor locations overlaid on a map of the region

- Adequate station-pairs with interstation distances in the range 1 – 4.5 km for array analysis and interferometry at low frequencies

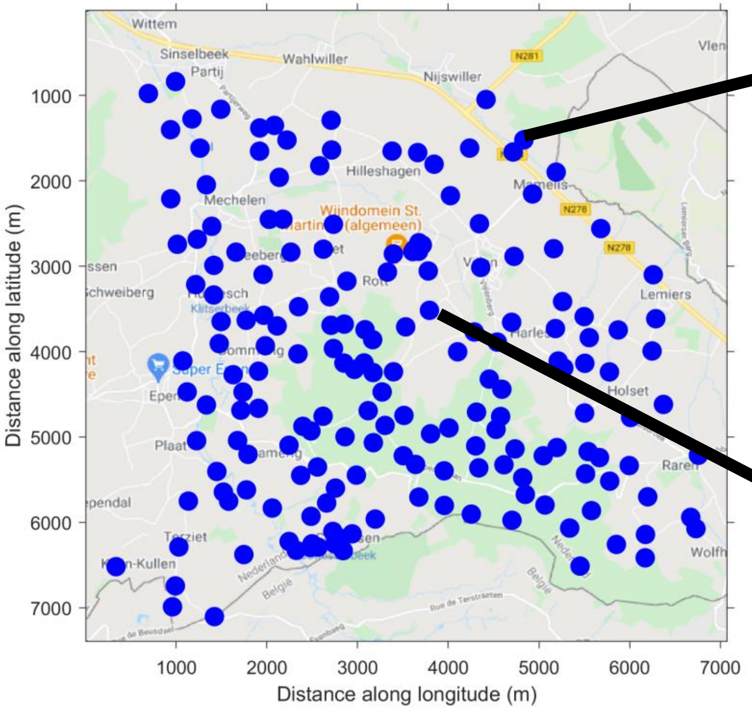




- Good azimuthal coverage for all inter-station distances up to 6 km which is important for tomography

Noise PSD characteristics(>1 Hz)

- PSD parameters:
  - Window length – 600 s (50 Hz)
  - Overlap length – 300 s
  - Windowing function
    - Tukey, $\alpha = 0.1$



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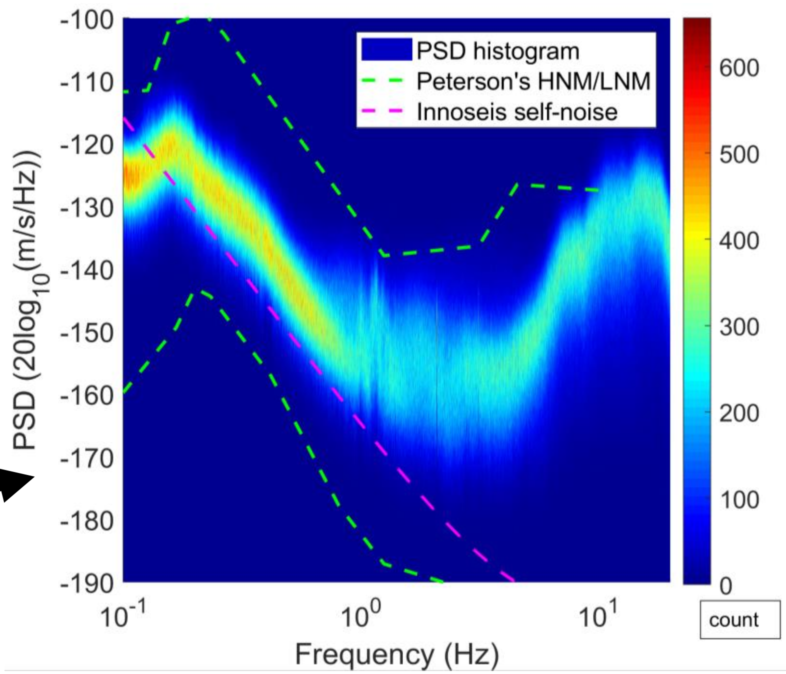
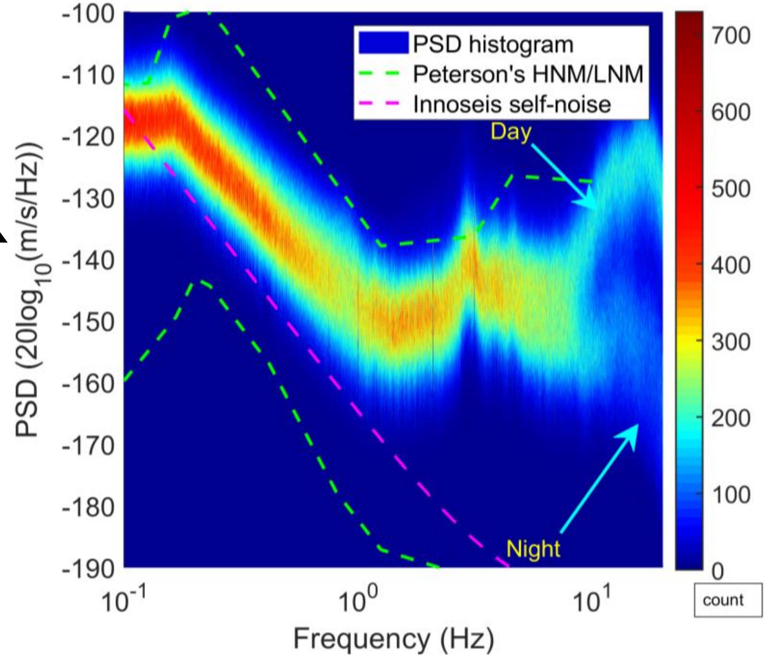


- Station Z2KWA stationed in the vicinity of highway N-278 measures a persistent high-level of ambient noise
- No significant day-night variation is observed
- Noise below 1 Hz **"might"** be sensor self-noise limited

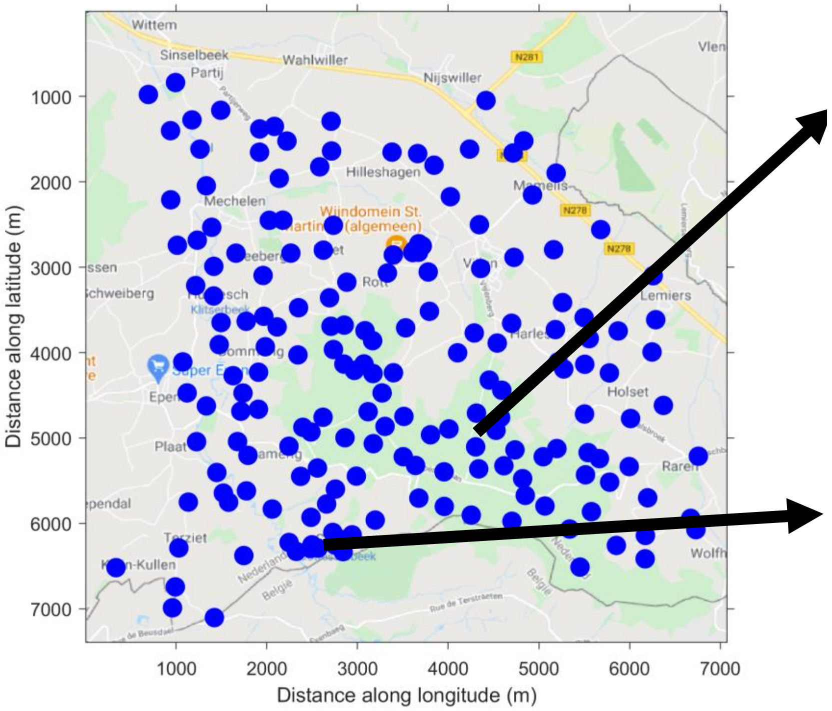


- Station ZCM4A stationed in the vicinity of a local road and exhibits a typical day and night variation
- A variation of about 40 dB in power is observed

Related Literature: McNamara & Buland 2004, Groos & Ritter, 2009

Noise PSD characteristics(>1 Hz)

- Figure below showing two stations situated away from anthropogenic noise sources like roads, industrial noise etc



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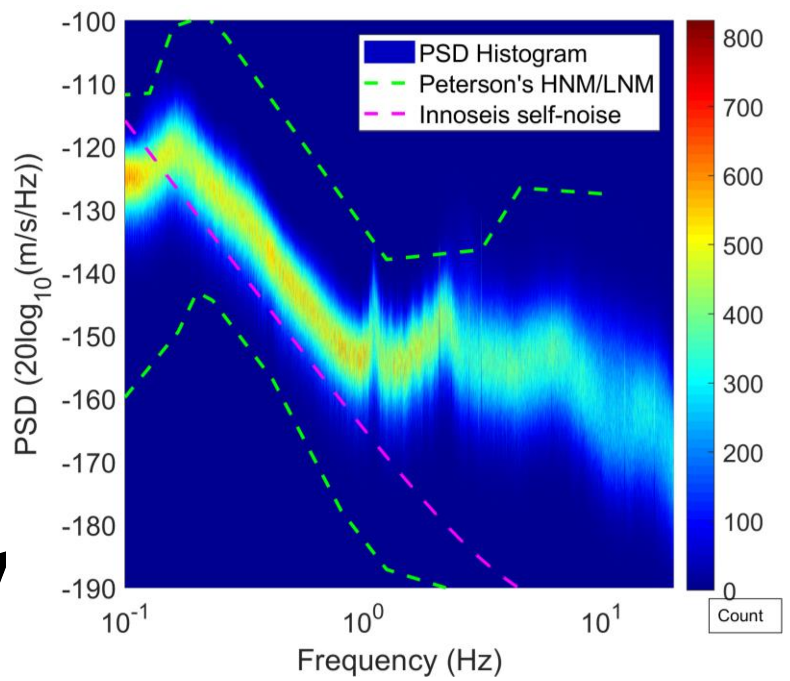
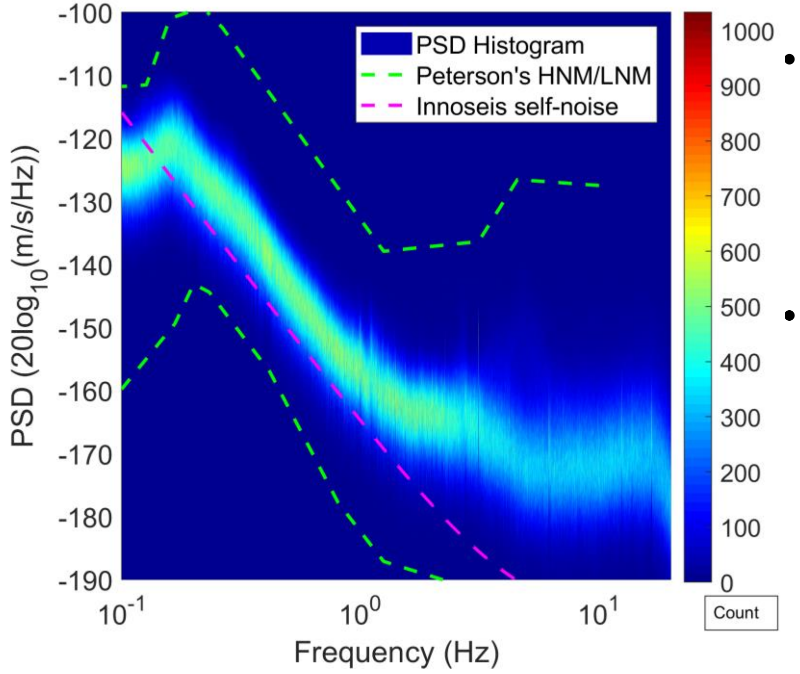


- Station ZQO1A stationed in Vijlenerbos shows low-level of anthropogenic noise
- No dominant day-night variation
- Broad spectral peaks at 1.2 Hz, 2.3 Hz, and 3.1 Hz originating from windmills are visible
- The drop in noise below 0.2 Hz is due to pre-filtering applied to the data during instrument-response removal

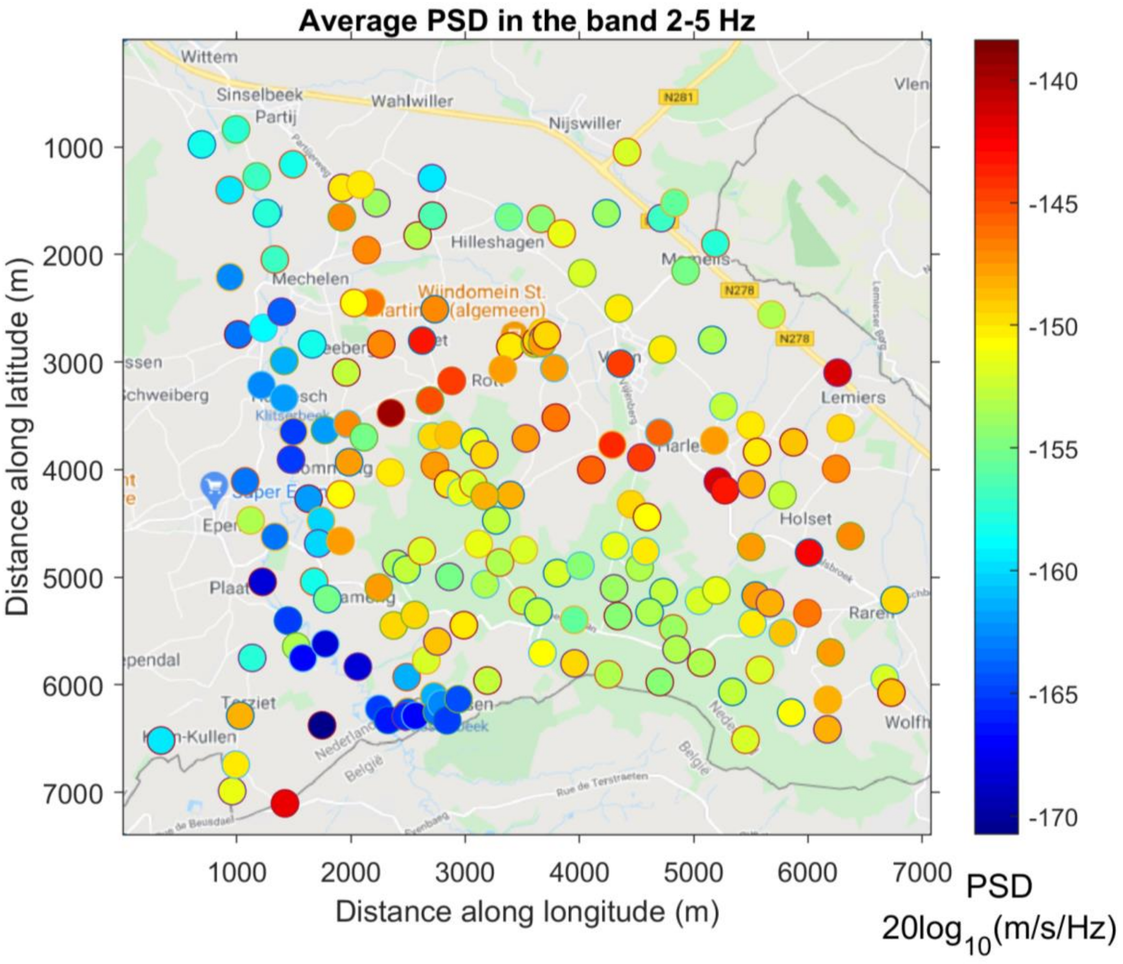


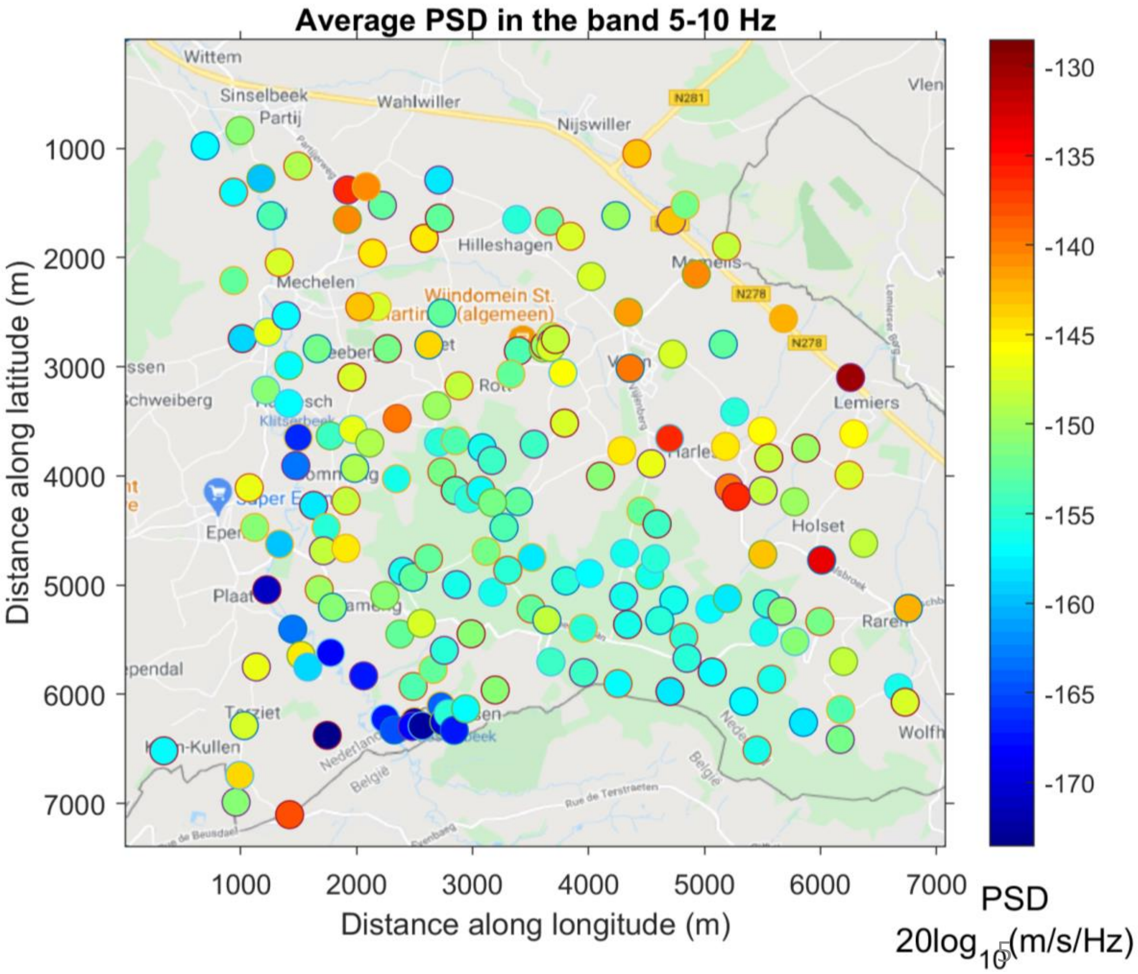
- Station YCQGA stationed at Cottessen measures a low-level of ambient noise and about 50 dB lower in power as compared to noisy stations
- The station is located at a site with only a few meters of soft soil, resulting in little amplification of surface-generated anthropogenic noise

Related Literature: Seo, 1997

Spatial variation of average PSD in the frequency band 2-5 Hz and 5-10 Hz

- Spatial variation of PSD of about 30 dB observed in the band 2-5 Hz
- This variation increases to about 50 dB for the band 5-10 Hz
- Low-levels of anthropogenic noise observed at hard-rock sites and ***valley-like setting (Panzera et al 2011)***

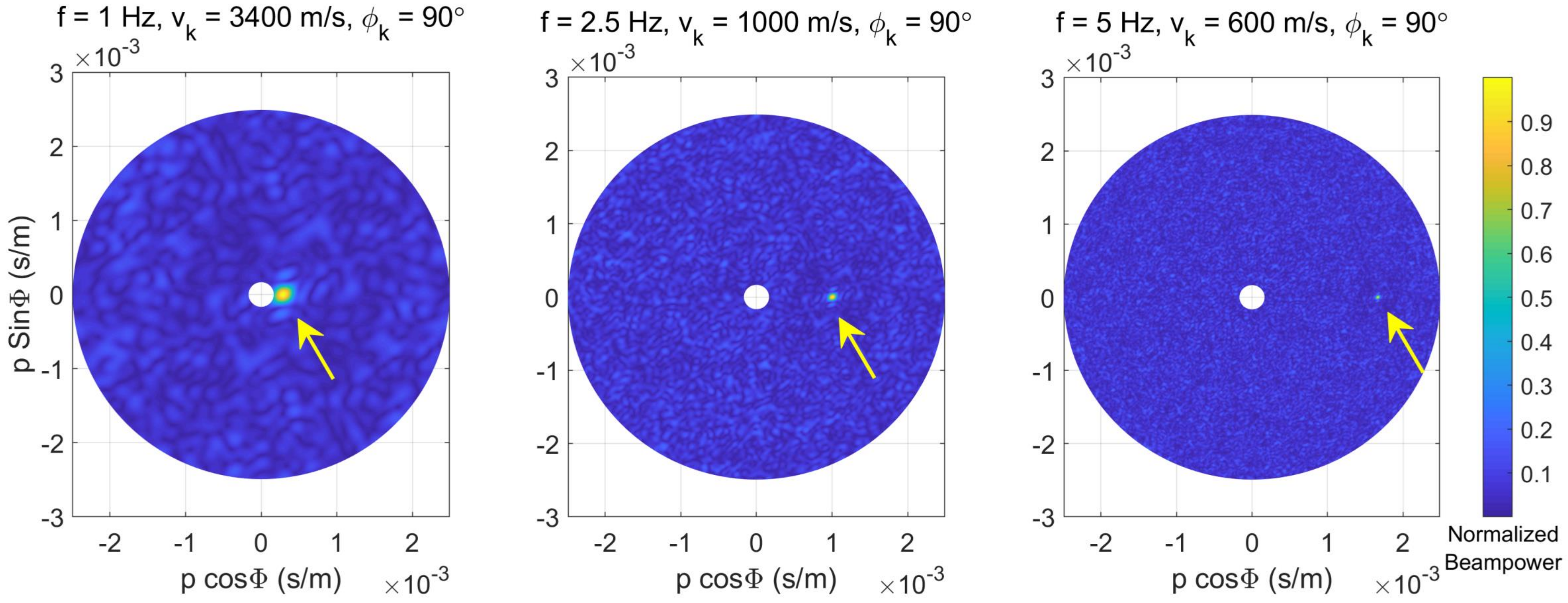




Array processing

Theoretical array response – Given plane wave incidence under conditions that the wave suffers no attenuation during propagation, the array can sample up to 5 Hz and velocities of about 600 m/s

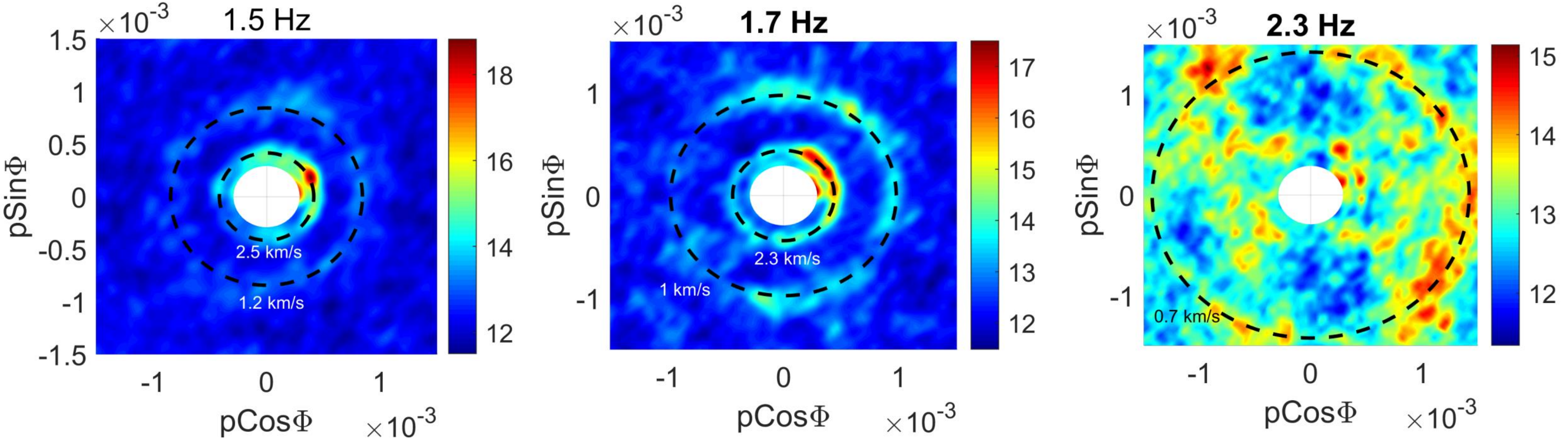
- $AR_{TH}(v_k, \phi_k, f) = A(f) \times a_k^*(f)$, where $A(f) = [a_0(f), a_1(f), \dots \dots a_{N_P N\_\phi}(f)]$, and $a_k(f) = [e^{2\pi f j \tau_{0,k}}, e^{2\pi f j \tau_{1,k}}, \dots \dots., e^{2\pi f j \tau_{M,k}}]$, and $j = \sqrt{-1}$, " $*$ " represents complex conjugate
- $\tau_{m,k} = x_m p_k cos\phi_k + y_m p_k sin\phi_k$, (x_m, y_m) are the coordinates of the $\mathrm{m^{th}}$ station



Related Literature: *Lacoss et al, 1969*

Ambient noise beamforming

- Estimating beampower corresponding to different values of speed and azimuth of wave propagation helps infer about the dominant propagation mode of coherent plane waves propagating through an array of seismometers
- $BP(v_k, \phi_k, f) = a_k(f) R_{xx}(f) a_k^*(f)$, where $a_k(f) = \left[e^{2\pi j f \tau_{0,k}}, e^{2\pi j f \tau_{1,k}}, \dots \dots ., e^{2\pi j f \tau_{M,k}}\right]$ and $\tau_{M,k} = x_M p_k cos\phi_k + y_m p_k sin\phi_k,\ p_k = 1/v_k; R_{xx}(f)$ is the frequency domain data covariance matrix of size $M \times M$ where M represents the number of stations



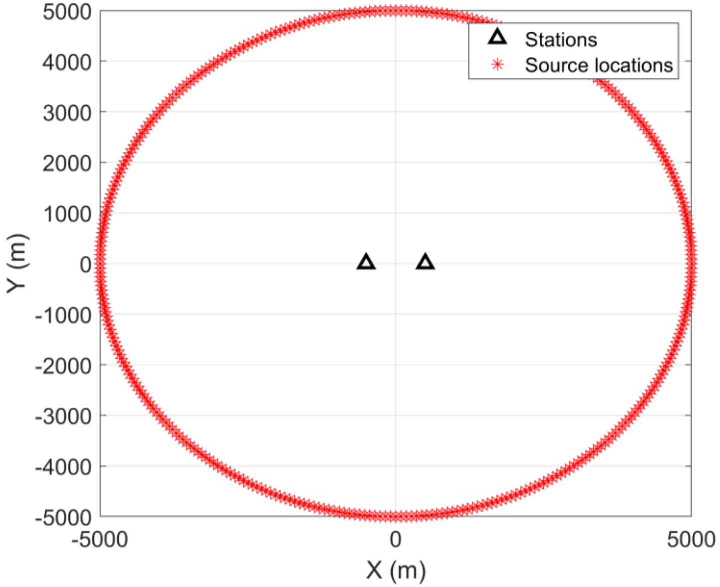
- A dominant first overtone observed besides a relatively weaker fundamental mode
- Noise illumination – dominantly North-East
- Beampower SNR reduces drastically above 2 Hz – lack of coherent noise

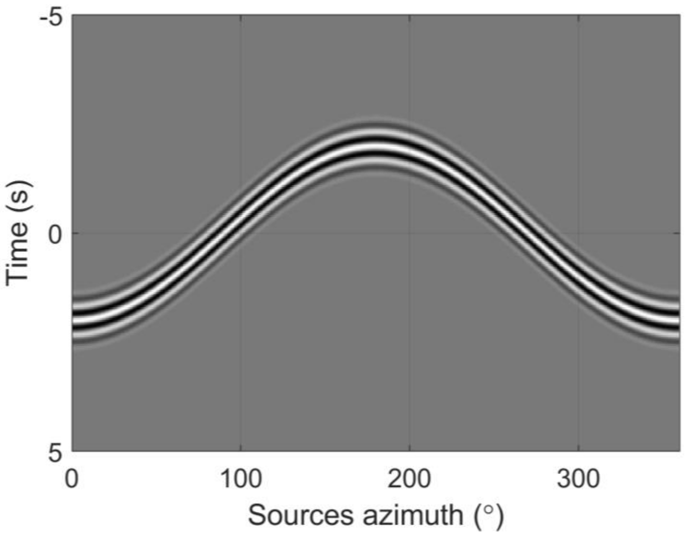
Related Literature: Chmiel et al, 2019

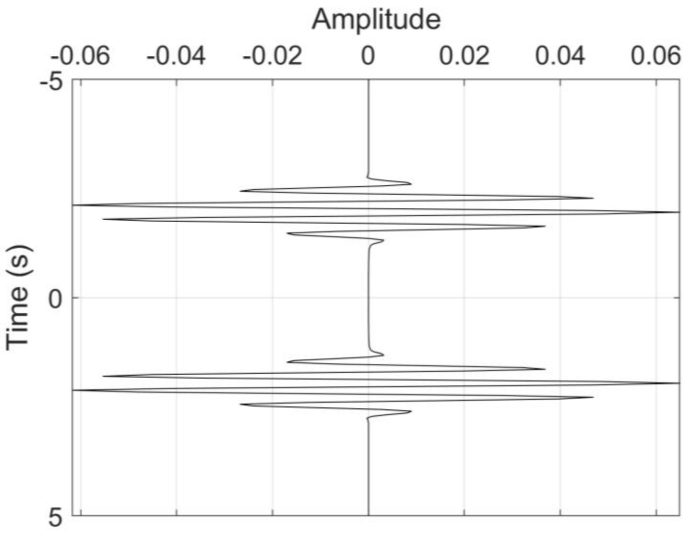
Ambient noise interferometry

Principle of ambient noise interferometry : Ensemble average of seismic noise correlations over a sufficiently long measurement period approximates to the Green's function of the propagation medium (EGF)

- $EGF = -\frac{d}{2dt}(C_{AB}(t) + C_{AB}(-t))$ Wapenaar 2004, Weaver and Lobkis 2006







- An isotropic illumination:
  - Actual distribution of sources at all azimuths
  - Diffuse wavefield
    - Inhomegeneity of the medium
    - Coda-wave interferometry

- A theoretical realization of noise seismograms measured for a propagation speed of 500 m/s at 3 Hz
- Station separation of 1000 m
- Sinusoidal behavior – Plane wave

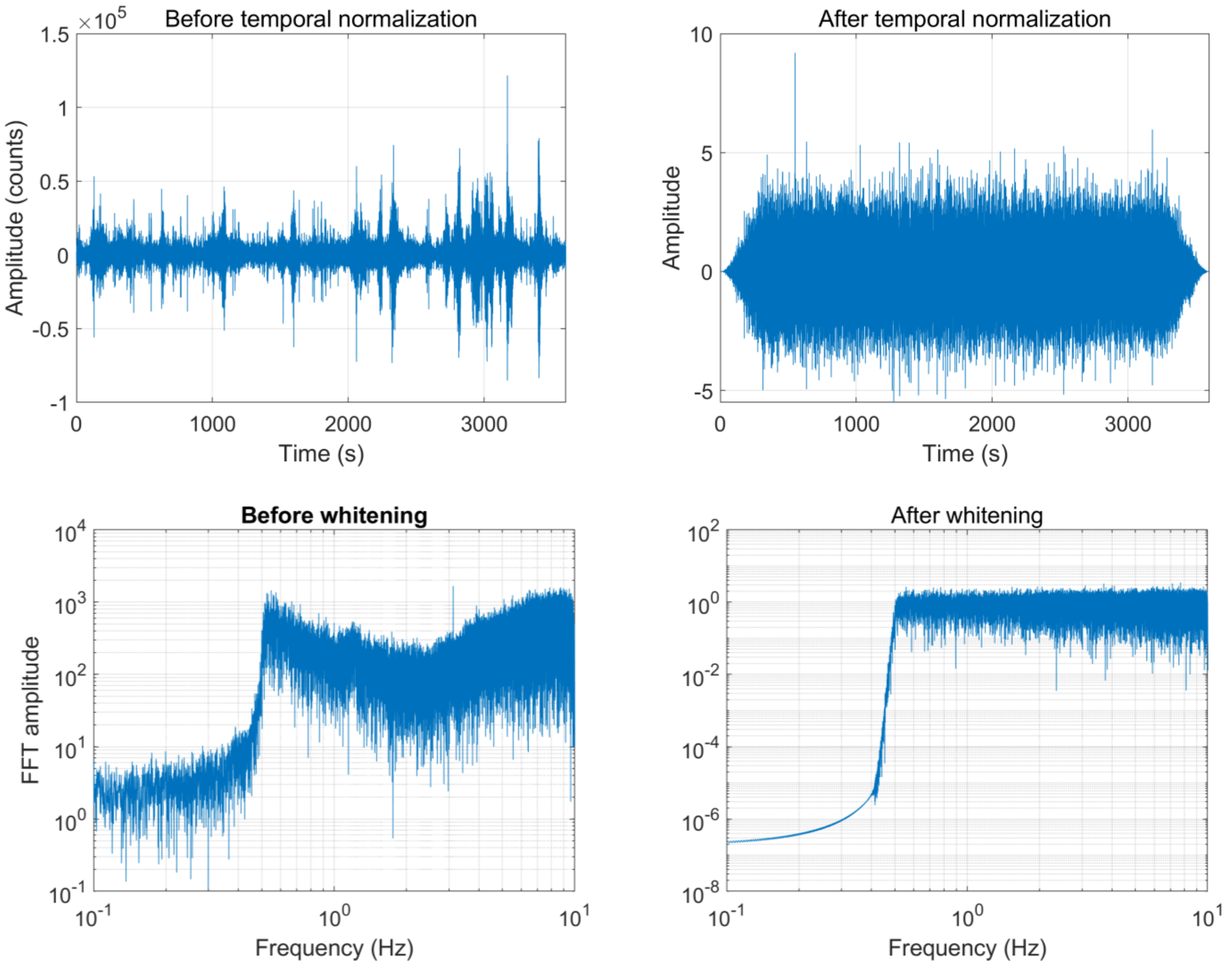
- Phases cancel for $180 - \theta_{\mathrm{FZ}} > \phi > 0 + \theta_{FZ}$ and $360 - \theta_{\mathrm{FZ}} > \phi > 180 + \theta_{FZ}$
- θ_{FZ} is the Fresnel angle where constructive interference occurs

Related Literature: *Yao and van der Hilst 2009*, *Yao, van der Hilst, de Hoop, 2006*

Data preprocessing : In order to diminish amplitude irregularities between stations and reduce impact of directional sources of noise in the data like earthquakes, we perform data preprocessing using temporal normalization and spectral whitening

- A running average temporal normalization is performed following
  $x_{norm}(t) = \frac{x(t)}{\Sigma_{\mathrm{m=t-}\delta t}^{t} x(m)}$; we chose $\delta t = 10\ s$
- Spectral normalization is performed by dividing the spectra with smoothed version of it,
  $X_{white}(f) = \frac{X(f)}{\Sigma_{\mathrm{m=f-}\delta f}^{f+\delta f} X(m)}$; we chose $\delta f = 0.001\ Hz$
- Additionally, a Tukey window with $\alpha = 0.1$ is used prior to cross-correlating

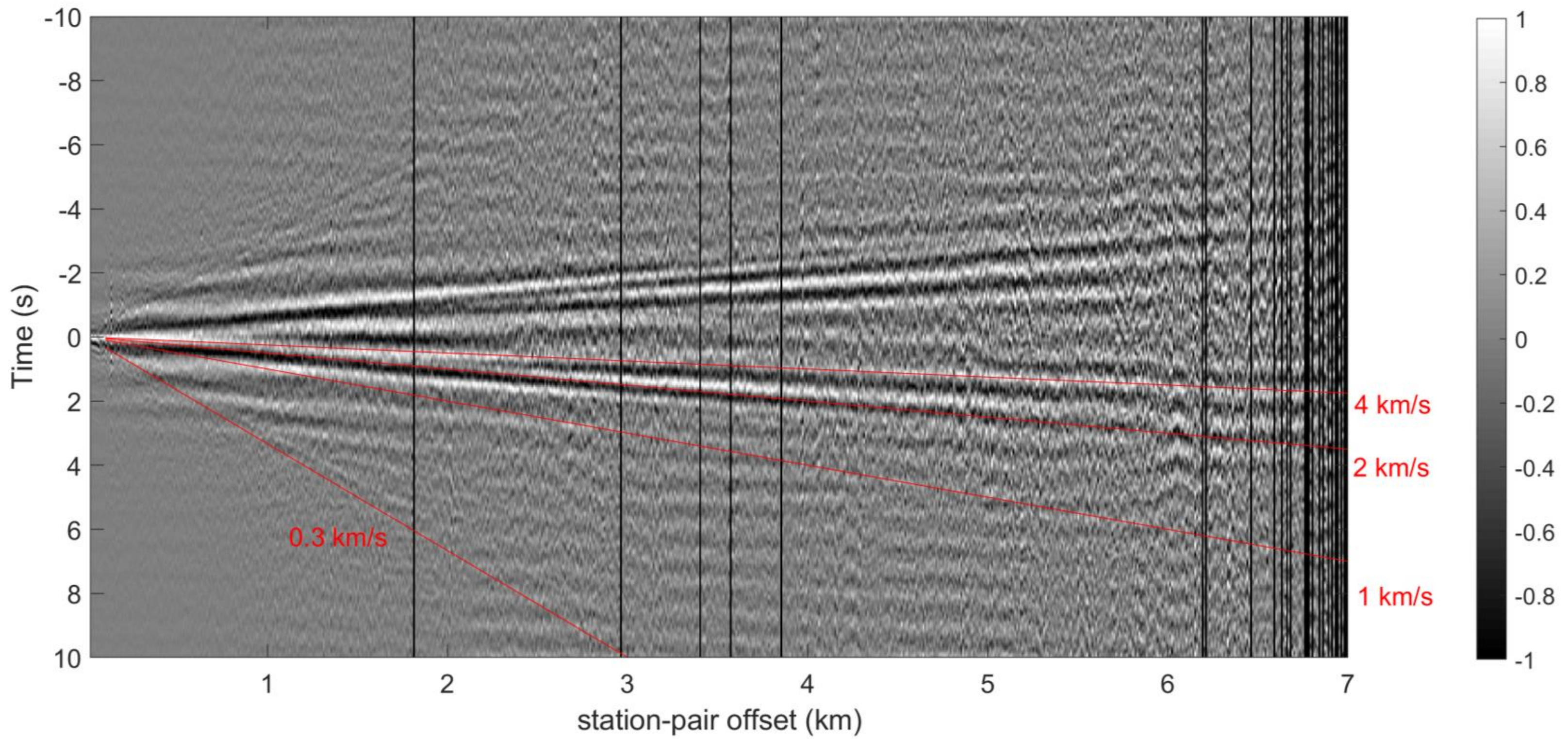
- We process the data in one-hour segments
  - Larger data-segments are useful for reducing effect of directional noise
  - On the contrary more ensemble averages are desired for convergence to Empirical Green's function
  - We found one-hour segments to perform well (Seats et al 2012)

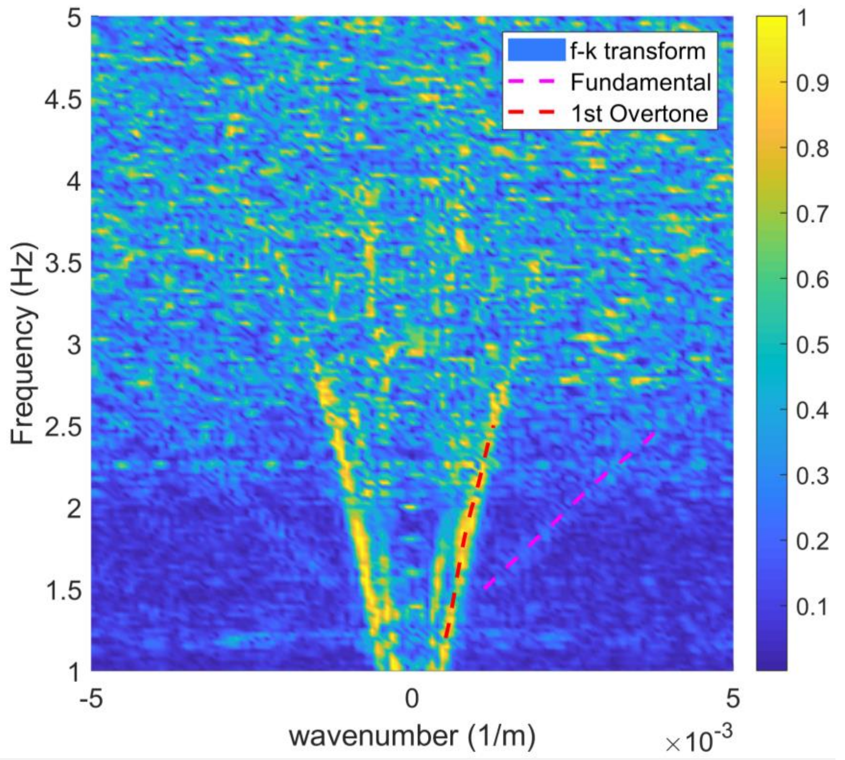


Related Literature: Bensen et al 2007

Virtual noise gather

- Time-domain cross-correlations between station pairs are assembled in 25 m inter-station distance bins
- Although an azimuthal averaging occurs, but such a representation is important to appreciate the multimodal nature of surface waves at the site





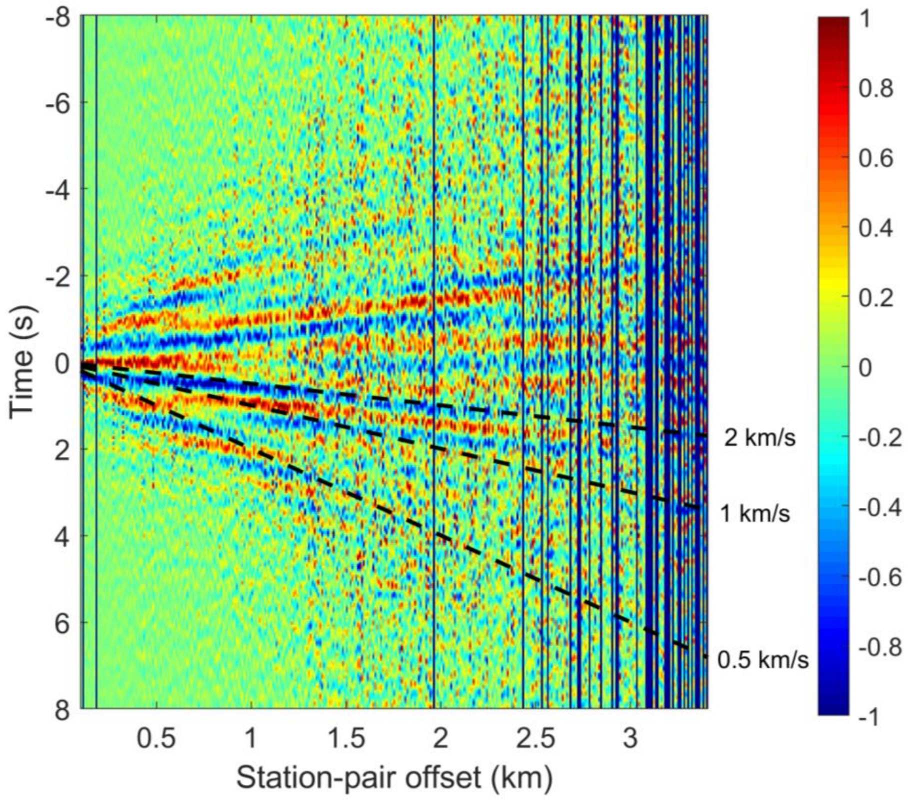
- A symmetric nature of the CCF emerges – courtesy the azimuthal averaging
- Fast propagating higher order surface-wave modes at group speeds of 1-3 km/s (propagate deeper and prominently delineated at larger offsets)
- A weak fundamental mode is recovered (300-400 m/s) for shorter offsets

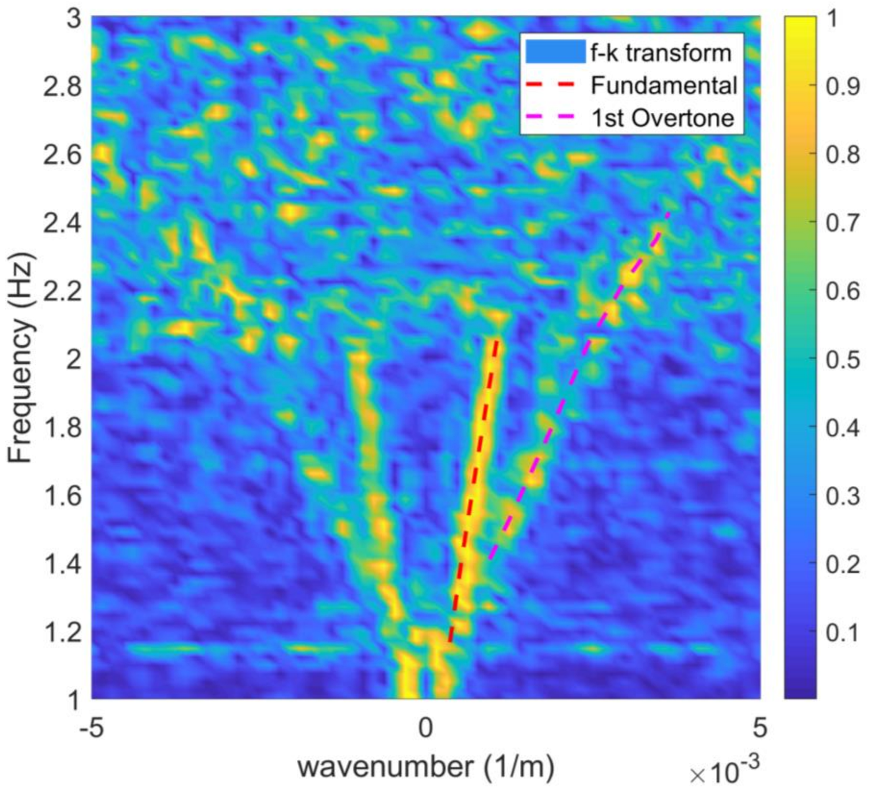
- The two different modes can be identified in the frequency-wavenumber domain
- Also establishes the fact that above 2.5 Hz, coherence diminishes drastically

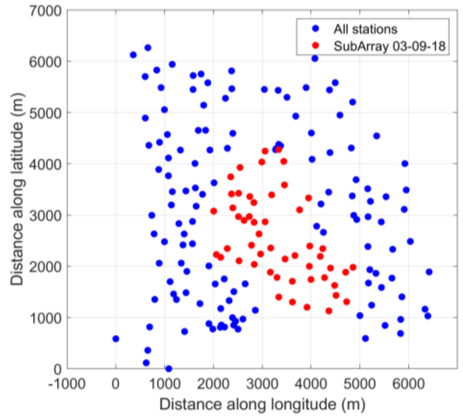
Related Literature: Mordret et al 2013, Chmiel et al 2019, Roux et al 2016

Appreciating the multimodal nature – using subarrays

- A subarray processing is employed as a check to verify the presence of multiple modes







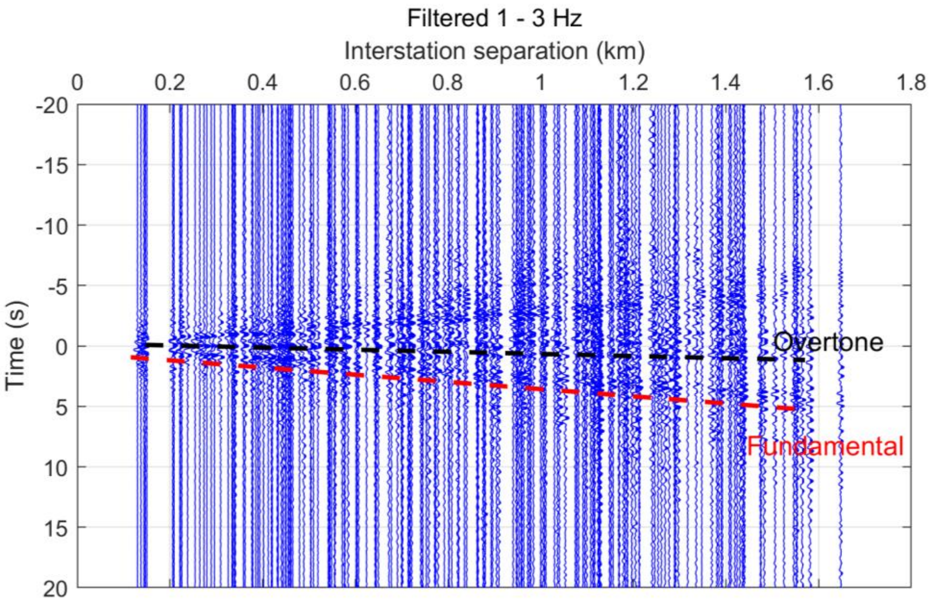
- A subgroup of stations for which both the modes are observed

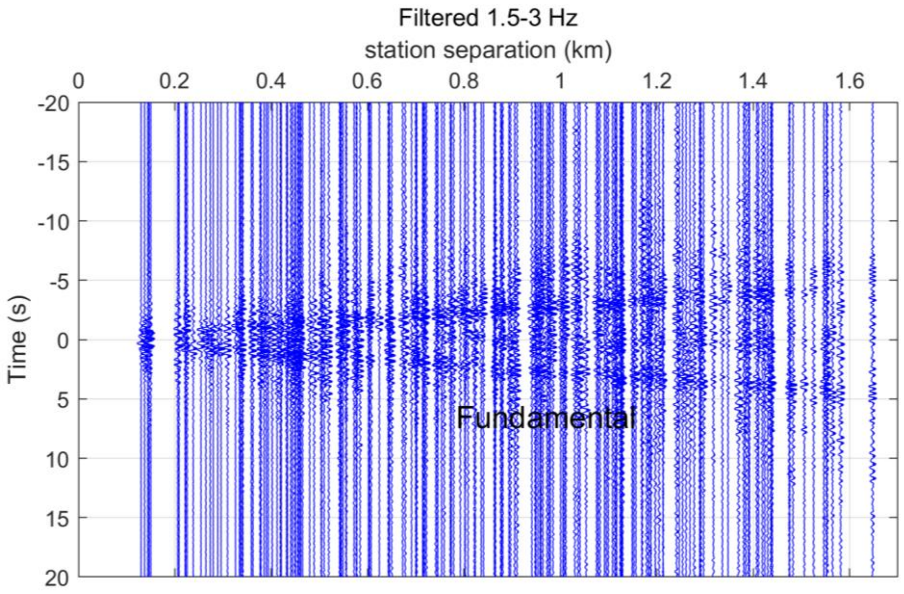
- Majority of station-pairs with interstation-offset greater than a kilometer is dominated by the first overtone of surface waves
- Also, the first overtone is dominated for frequencies between 1-2 Hz; while the fundamental is marginally stronger for frequencies greater than 2 Hz → **More in next slide**

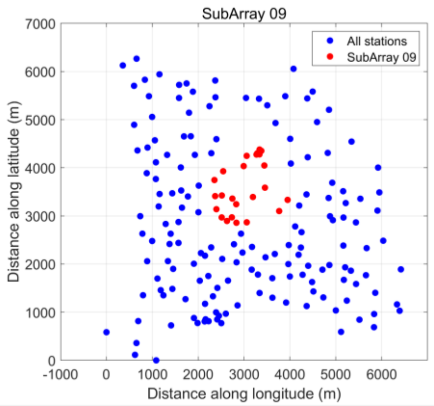
Related Literature: Spica et al 2018

Multimodal nature and frequency bands of interest

- For example, in subarray 09, cross-correlation gathers in frequency band 1.0-1.5 Hz is dominated by the first overtone and for frequencies between 1.5-2.5 Hz the fundamental mode dominates







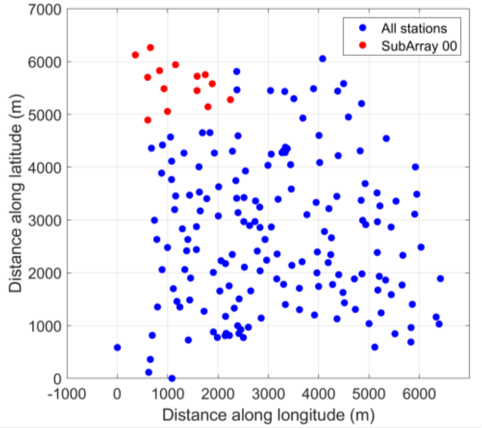
- A subgroup of stations for which both the modes are observed

- An intuitive next step is do perform cross-correlation beamforming and obtain phase velocity distribution in different sub-arrays

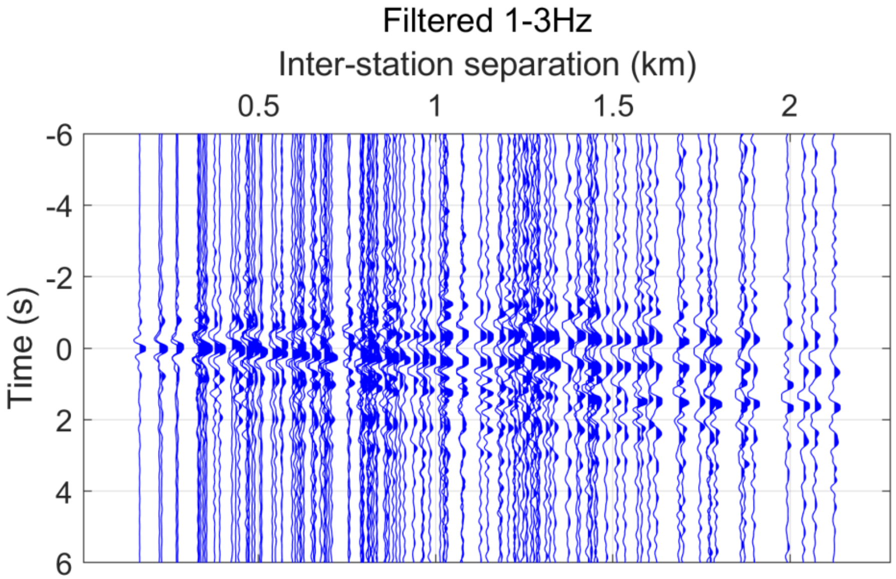
Related Literature: Spica et al 2018

Cross-correlation beamforming

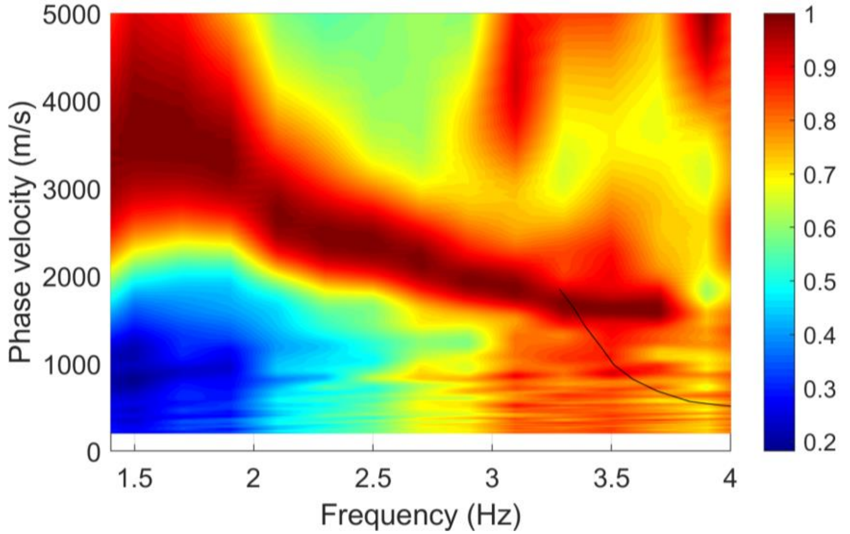
- We divide the area into several overlapping sub-arrays and obtain an initial estimate of sub-array phase velocities
- $P(f,p,\phi) = \Sigma_{i=1}^{N} X_i(f) e^{2\pi j f d_i \boldsymbol{k}}$, where $X_i(f)$ is the Fourier transform of the cross-correlation corresponding to the i^{th} station pair, d_i is distance between the station-pair and $\boldsymbol{k} = [pcos\phi \; psin\phi]$ is the wave-vector



- A subgroup of stations for which the first overtone dominates



- It is important to observe the causal contribution of the CCF due to directional bias in the noise source distribution



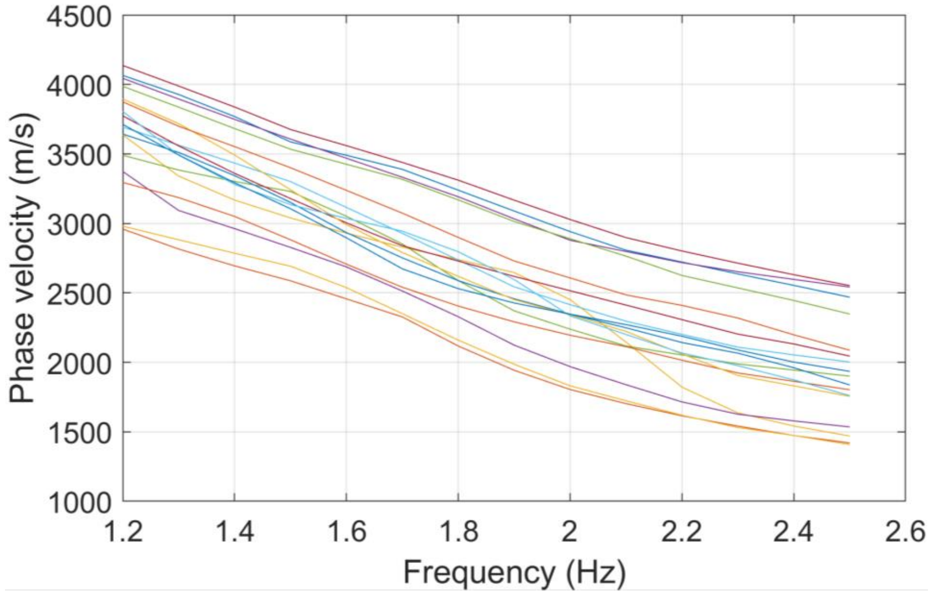
- Phase velocities range between 2-4 km/s and a dispersive nature is observed
- This process is repeated for 18 of such overlapping subarrays

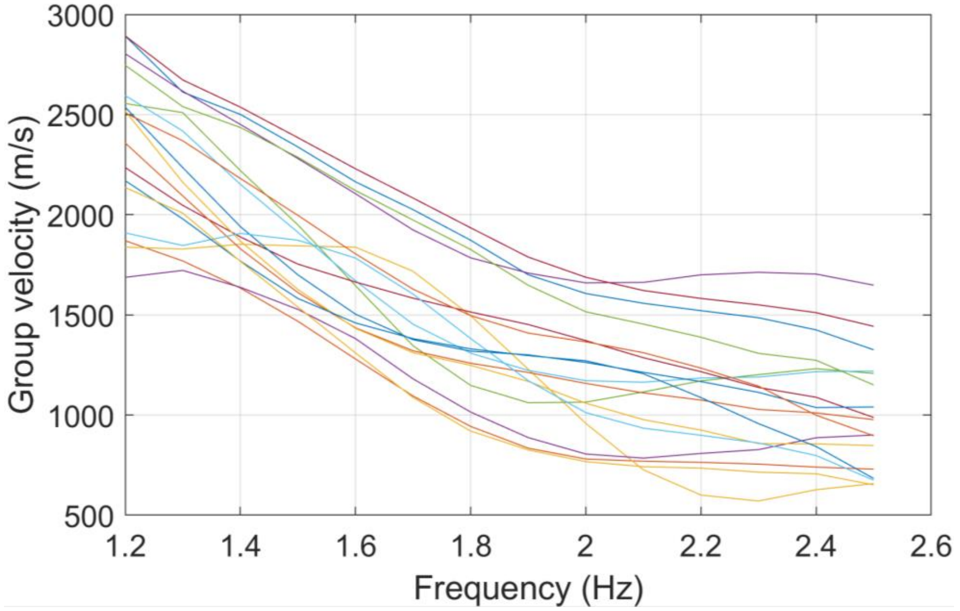
more in next slide

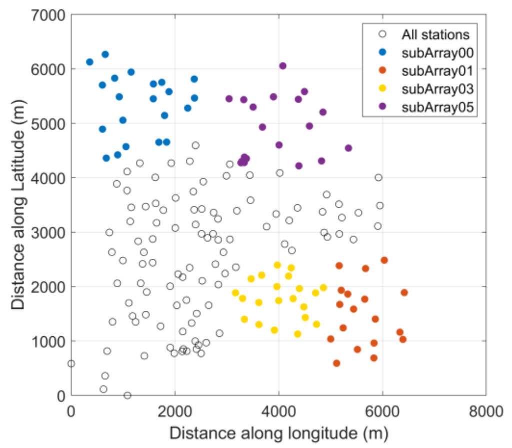
Related Literature: Ruigrok et al 2017

Cross-correlation beamforming – subarray phase and group velocities

- Each subarray extends about 2x2 sq km and overlaps with surrounding arrays







- Different subarray locations

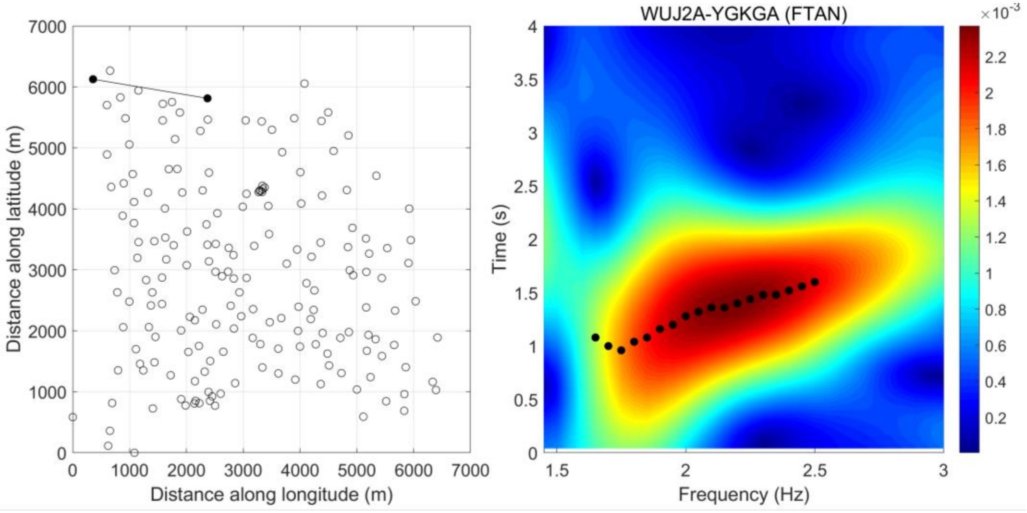
- Phase velocities show significant changes in velocity between subarray
- Significant lateral inhomogeneity in the medium
  - Something to consider while doing tomography
  - An easy way to obtain a 3D model is to invert each of this dispersion curves and interpolate
    - Philosophical differences among peers (DBF, Boue et al, 2013)

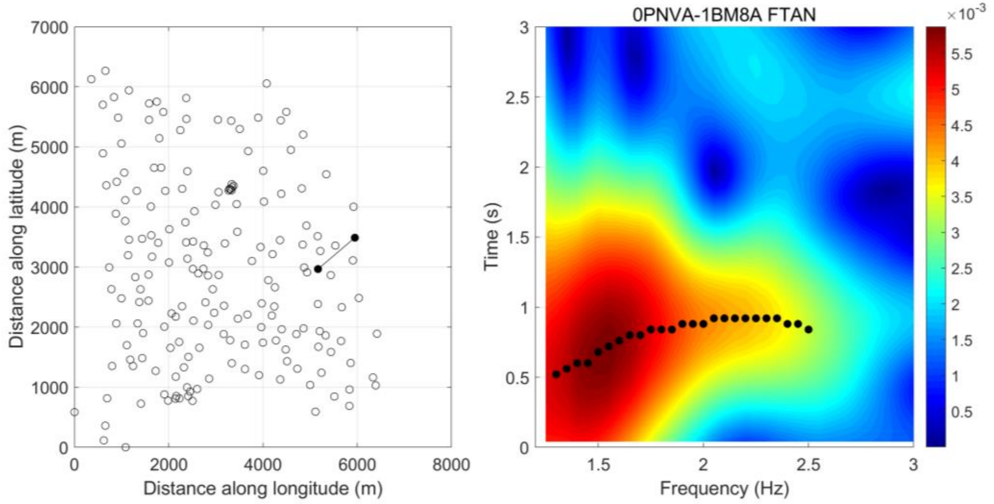
- Group velocity shows larger changes in velocity, since it is related to the gradient of phase velocity
- $v_{grp} = \frac{v_{phase}}{(1 - \frac{\omega}{v_{phase}} * \frac{dv_{phase}}{d\omega})}$, ω is angular frequency

Related Literature: Boschi et al 2013

Towards tomography – Frequency-time analysis (FTAN)

- FTAN theory – Group velocities estimated at frequency ω_0 by using travel time corresponding to the peak of the envelope obtained as $\mathrm{X}(\omega_0, t) = IFFT(S_\omega(1 + \mathrm{sgn}(\omega))G(\omega - \omega_0))$, where S_ω is the analytic CCF and $\mathrm{G}(\omega - \omega_0) = e^{-\alpha\left(\frac{\omega - \omega_0}{\omega_0}\right)^2}$ is a narrow-band gaussian filter.
- We chose α to linearly vary between 30 and 50 starting at 1.2 Hz and ending at 2.5 Hz at intervals of 0.1 Hz. Essentially, the filter widens as frequency increases



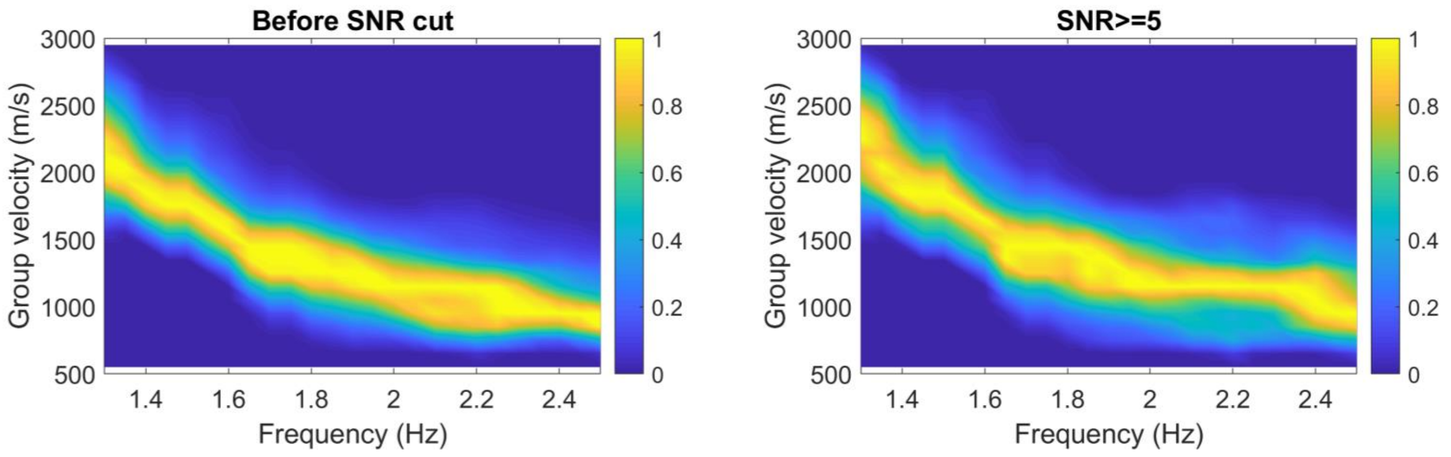


- FTAN above corresponds to the symmetric component of the CCF pertaining to different station-pairs, the locations of which are shown in the figures
- In principle, the FTAN travel times are derived separately for the causal and anti-causal part and only those frequency bins with deviations less than 20% travel time are considered
- The causal and anti-causal travel time differences are also used to construct the time-travel covariance matrix used during tomography

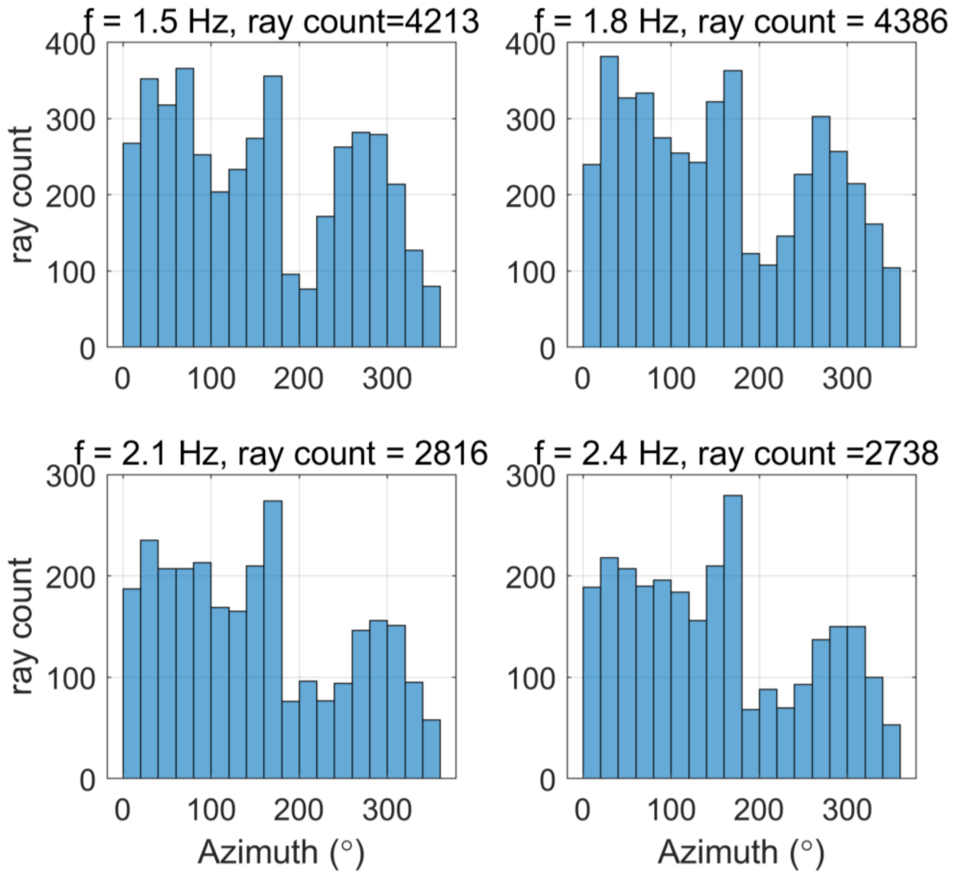
Related Literature: Dziewonski et al, 1969, Levshin & Ritzwoller, 2001

Towards tomography – Station pair selection

- Based on anti-causal and causal travel time difference of 20% and a spectral SNR of greater than 5 we select station pairs suitable for tomography
- Starting at 16,653 cross-correlation pairs
- We end up with about 4500 station pairs at 1.5 Hz and 2500 pairs at 2.5 Hz



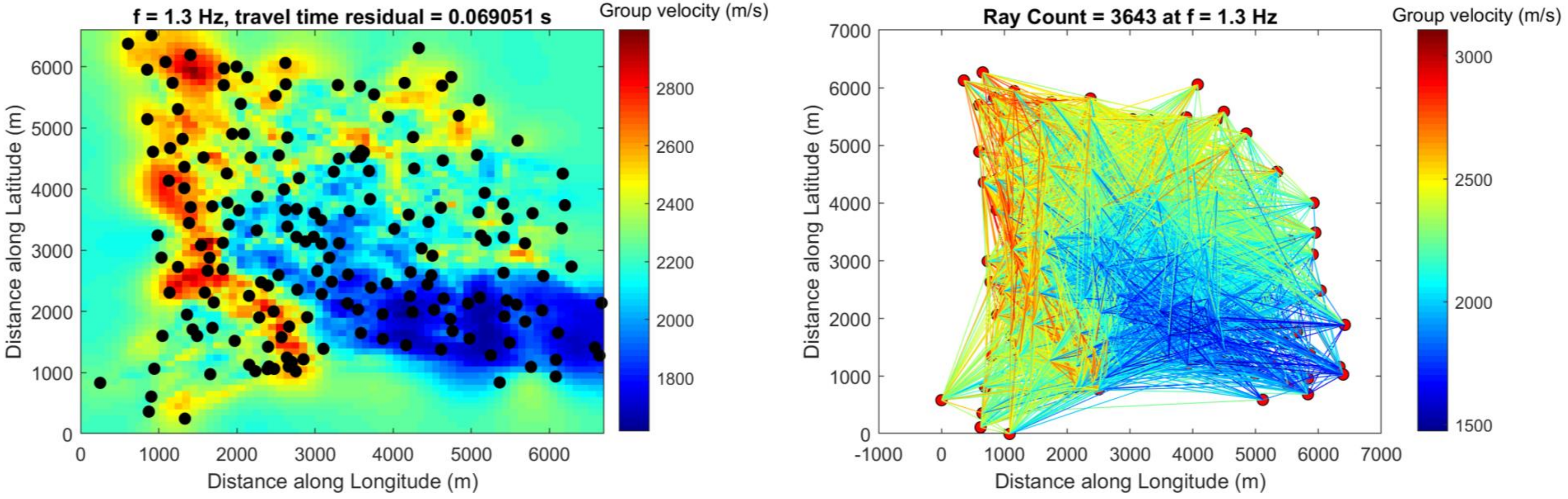
- A sufficient azimuthal distribution of station-pairs is achieved in the frequency band 1.3 – 2.5 Hz, which is necessary for tomography
- Criss-crossing rays per-cell are necessary for tomography in order to avoid directional bias in velocity estimates



Related Literature: Chmiel et al 2018

Straight ray tomography

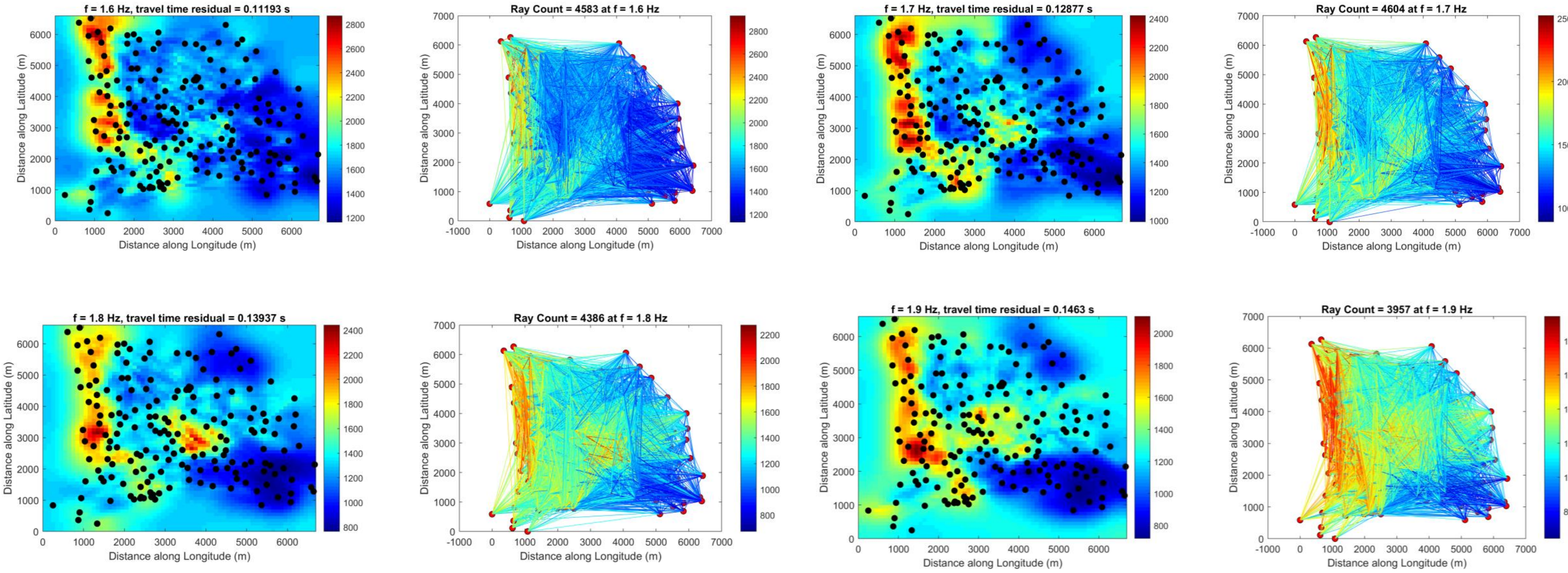
- Given the travel time t between a station pair at a frequency f, the theoretical travel time can be modeled as $t = Gm$, where G is a sparse matrix comprising the distance traveled by a ray in a cell. It is sparse, because only a few cells are traversed by a ray
- This problem is reformulated as $\Delta t = G\Delta m$, where Δm is a perturbation in model around the mean slowness m_0
- Solution to this problem can be obtained by minimizing the penalty function
- $(Gm_0 - t)^T C^{-1}(Gm_0 - t) + \Sigma_k^N \alpha_k^2 \left|\left|F_k(m_0)\right|\right|^2 + \Sigma_k^N \beta_k^2 \left|\left|H_k(m_0)\right|\right|^2$
- $\Delta m = (\Delta t - Gm_0)^T C^{-1}(\Delta t - Gm_0) + m_0^T Q m_0$, where $Q = F^T F + H^T H$
- A detailed expansion of matrices F and H can be found in *Barmin et al 2001*
- We use smoothing parameters $\alpha = 4000, \beta = 300,$ and $\sigma = 200$ *Goutorbe et al 2015* (open to debate, but should not change results considerably)
- Grid size = 200 × 200 sq. m, Approximate ray-count per cell ≈ 100



Related Literature: Picozzi et al 2009

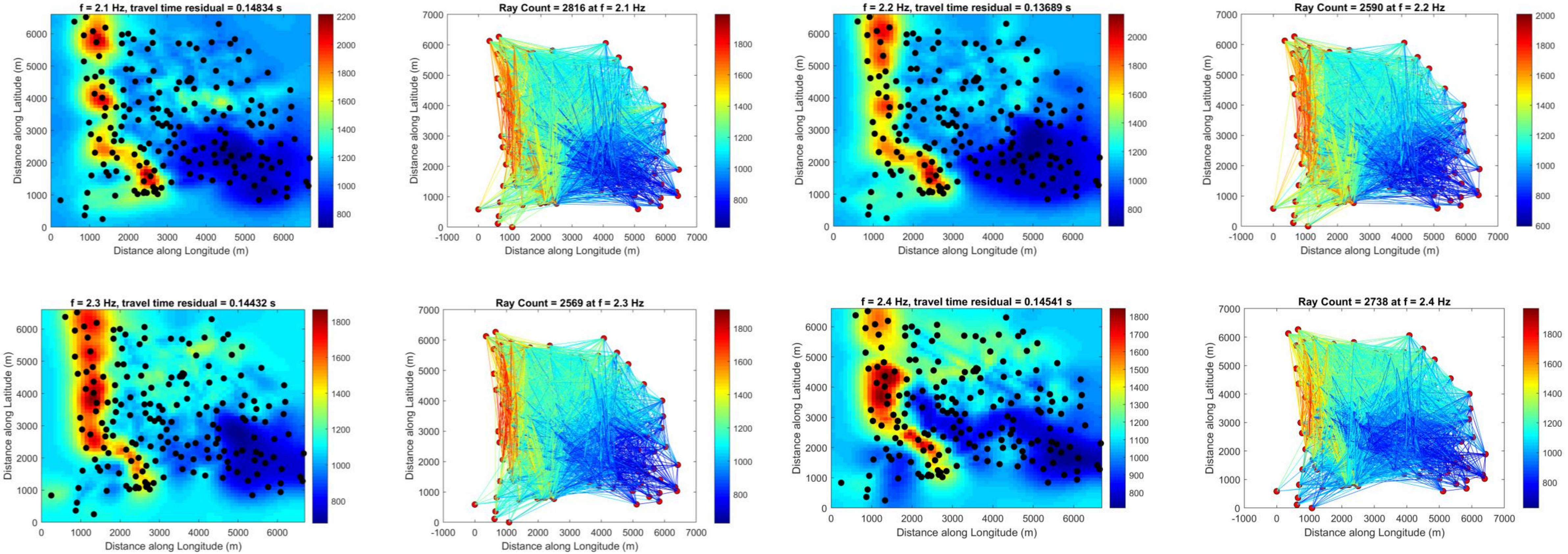
Straight ray tomography (1.6-1.9 Hz)

- *A high velocity anomaly observed at western part of the array*
- *Low velocities observed in south-eastern part of the array*
- *Velocity perturbations of about 30% around the mean value – slightly high considering the philosophy behind the approach*
- *Spatial resolution of about 400 m is achieved*



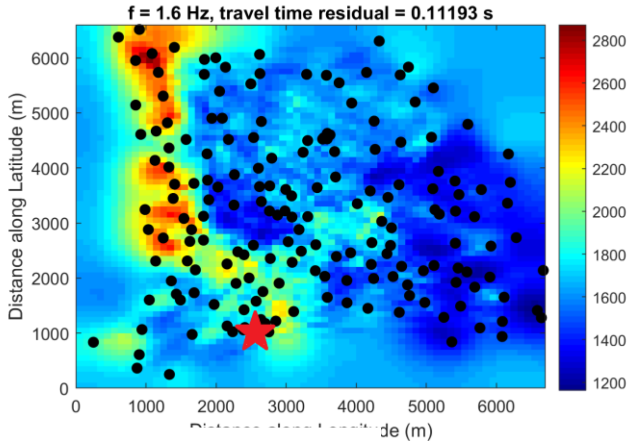
Related Literature: [Helmholtz tomography, Mordret et al 2013]

Straight ray tomography (2.1-2.5 Hz)



Related Literature: Mordret et al 2013

Preliminary inversion to depth at Cottessen



- A 1D depth inversion of the observed dispersion at Cottessen is performed
- Since the frequency band of dispersion is limited to about 2.5 Hz, we don't achieve a good shallow resolution
- For depth between 100-250 m, veloicties from inversion are in agreement with those observed from logging

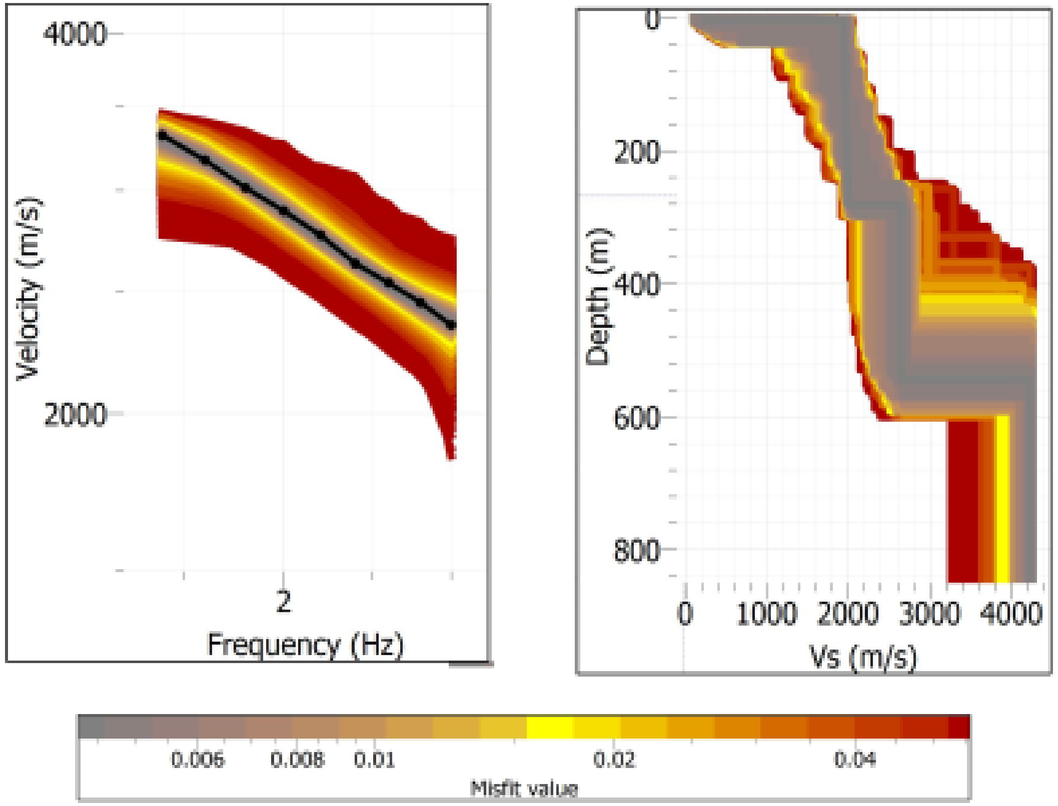
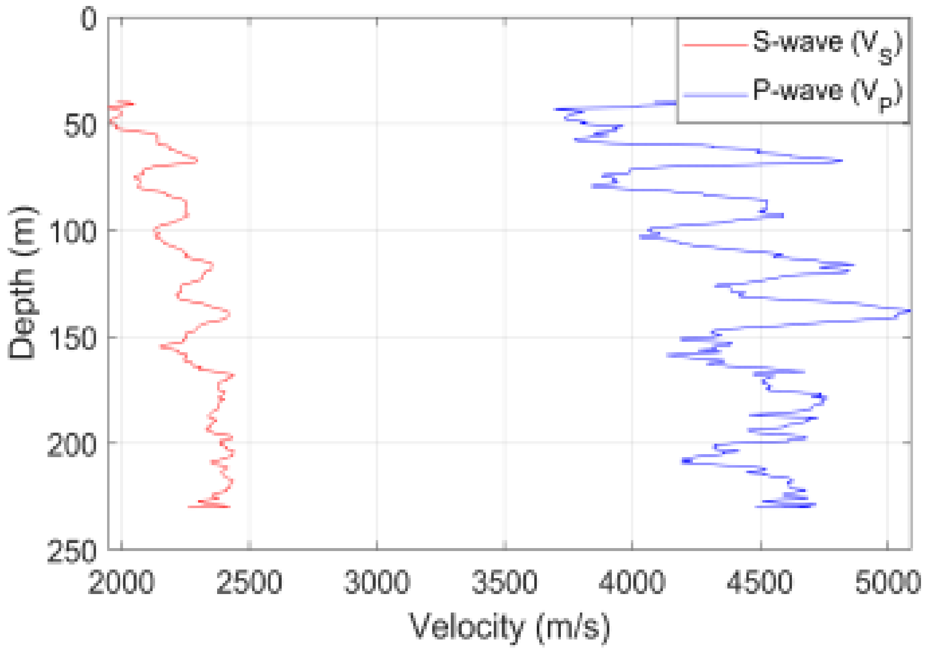


Figure: observed and fitted dispersion curve (left), explored S-wave velocity models (Geopsy)



Measured S-wave and P-wave velocity at Cottessen smoothed every 5 m (RWTH Aachen)

Related Literature: Wathelet et al 2004, Sambridge, 1999 (I) , Koley et al 2022

Research questions to be addressed

- *Shallow subsurface geology information necessary to facilitate transformation from frequency to depth*
  - *Especially P-wave velocity and density (RWTH Aachen)*

- *Realization of an optimal array configuration that would ensure analysis of a wider frequency band of interest and ability to perform tomography*
  - *Handling of overtones, body waves, anisotropic illumination etc – Work ongoing*
  - *Necessity to be able to analyze frequencies as high as 5 Hz, need for denser sampling*

- *Development of an MCMC (Metropolis-Hastings) code to perform the inversion – done!*

- *Check on the usage of Eikonal tomography, phase-front tracking*

- ***Acquisition improvements***
  - ***Ensure stations have better data – current installations had poor low-frequency sensitivity***
  - ***Ensure better coupling of sensors to the ground***
  - ***Field tests with software running is necessary before actual deployment***

Questions