Prospects of passive seismic for shallow subsurface characterization at EMR

- a candidate site for ET

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Additional credits: [Fugro](), [Sisprobe]()

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Scope of the talk

Where we start?
- Existing passive array
- Existing group/phase velocity maps
- Existing Vs-depth maps

Example Eigenfunction estimation
- Fundamental and overtones

Determination of frequency band of interest
- Spatial distribution of Rayleigh-wave depth of penetration

Minimum sensor separation
- Avoid non-uniqueness/Local control of phase velocity estimates
- Azimuthal averaging of cross-correlations

Future array design

How ambient seismic noise interferometry works?

Acquire seismic noise with an array

Iterate – new campaign

Learn and improve array

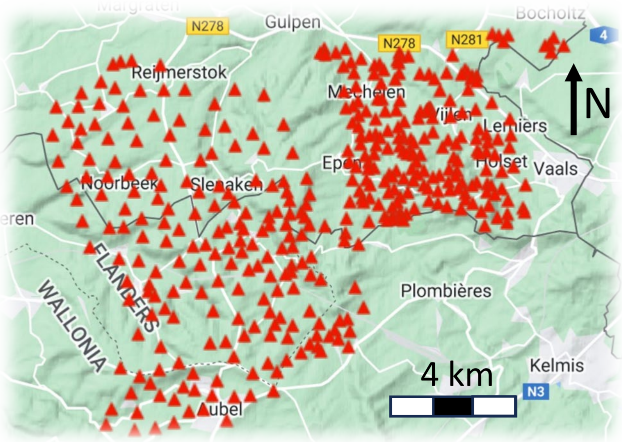
3-D subsurface model

Pre-processing before cross-correlations

Temporal normalization

Spectral whitening

Array analysis



Surface-wave tomography

Noise cross-correlation between station-pairs

Stacked cross-correlation between station-pairs

Linear, Robust, N^{th} root, phase-weighted etc.

Surface waves – Rayleigh/Love

Surface-wave dispersion

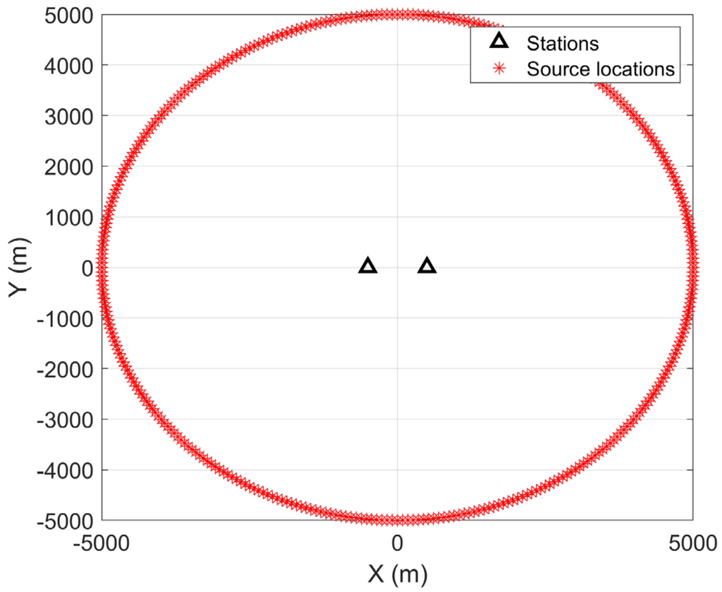
Body waves/leaky modes

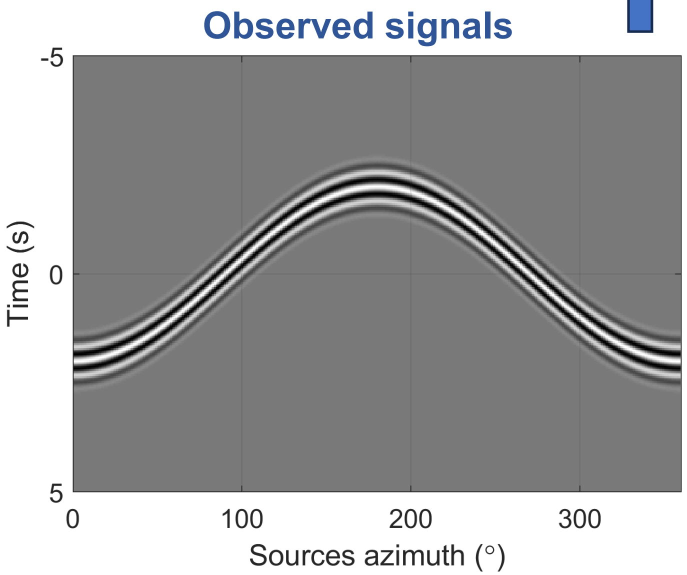
Body-wave tomography

Why and when ambient seismic noise interferometry works?

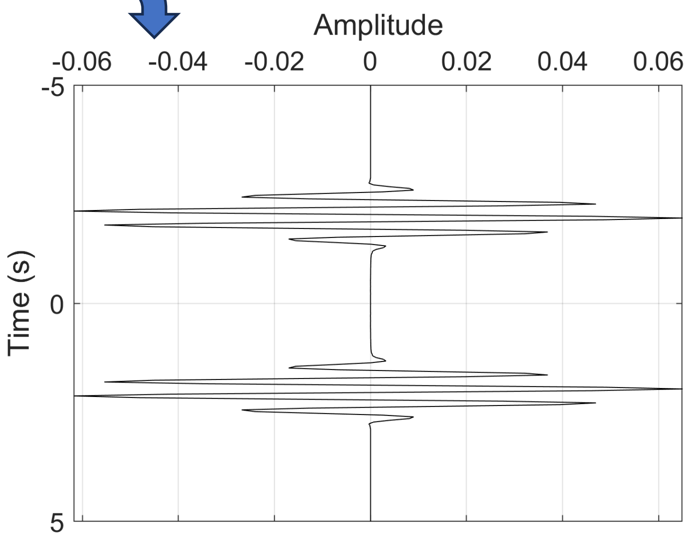
Ensemble average of seismic noise correlations (C_{AB}) **over a sufficiently long measurement period** approximates to the Green's function of the propagation medium (EGF)

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





azimuthal sum



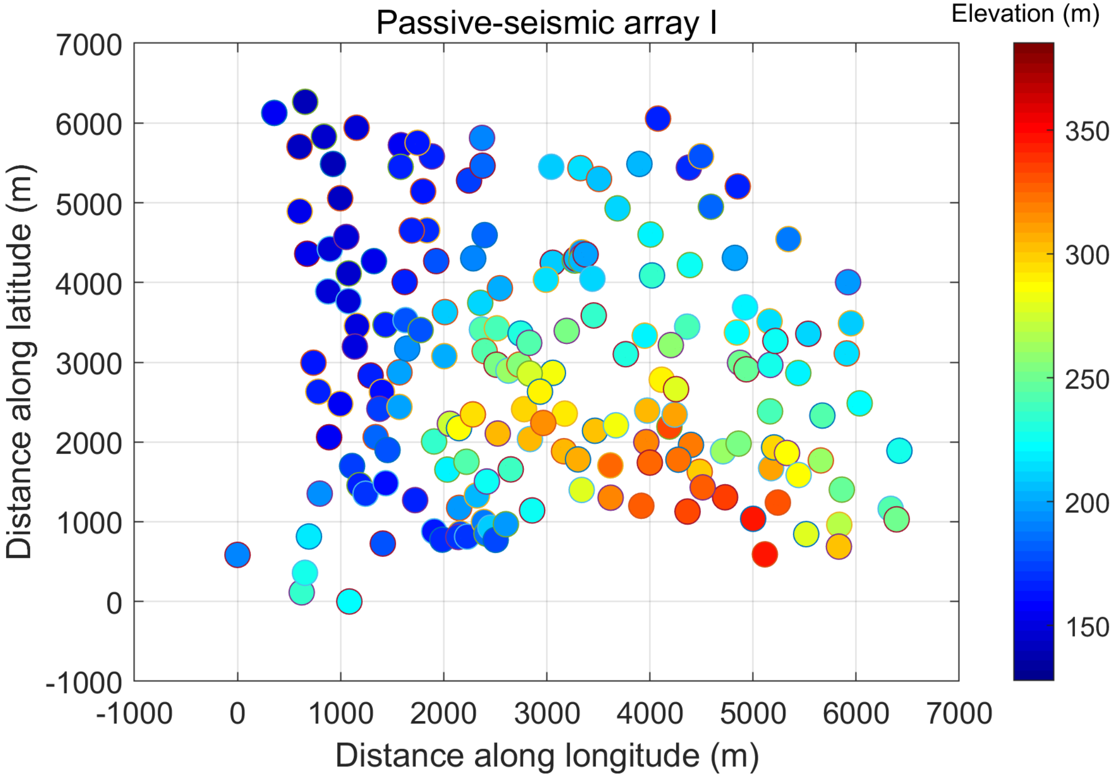
- **Isotropic distribution** of noise sources
- **Sufficiently long measurement time** might mimic isotropic distribution

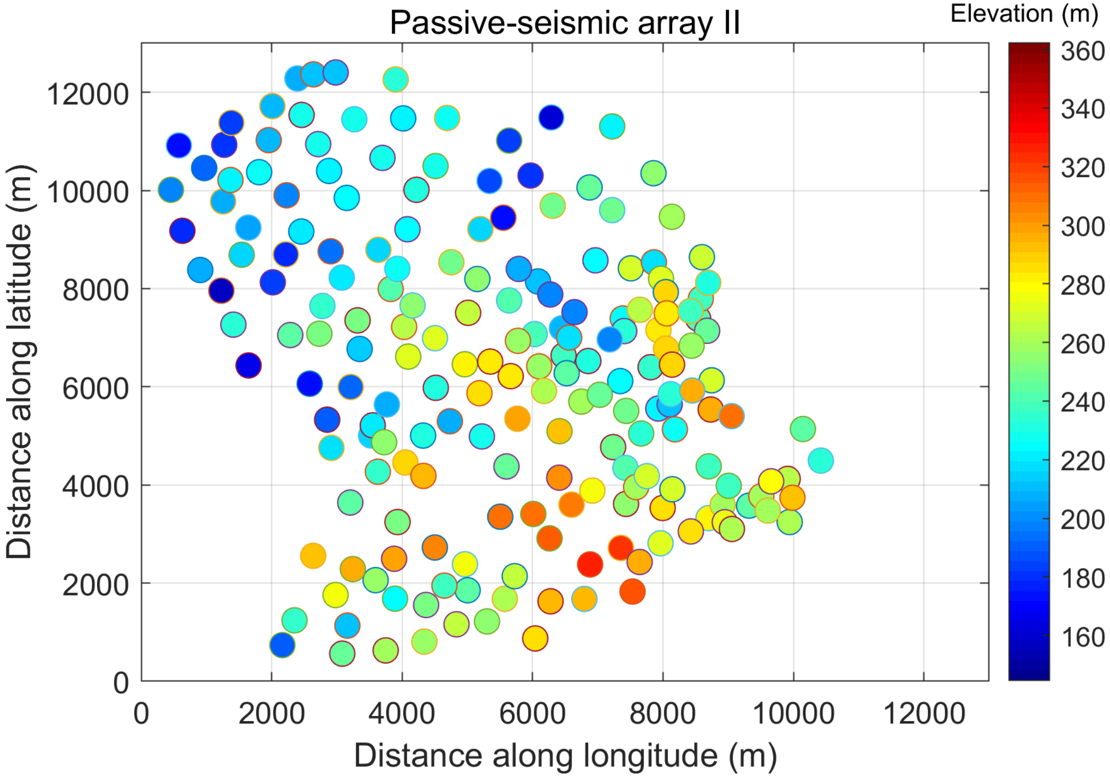
- Phases cancel for:
  - $180 - \theta_{\mathrm{FZ}} > \phi > 0 + \theta_{FZ}$, and
  - $360 - \theta_{\mathrm{FZ}} > \phi > 180 + \theta_{FZ}$
- θ_{FZ} is the Fresnel angle where constructive interference occurs

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

Where we stand at the EMR site – Two passive seismic arrays so far

Two reconnaissance passive-seismic arrays of 5 Hz vertical component geophones were deployed between 2020-2021- **understand noise wavefield and subsurface characteristics for targeted arrays**





Note that an elevation difference of 200 m might not matter for low-frequency (< 3 Hz) analysis

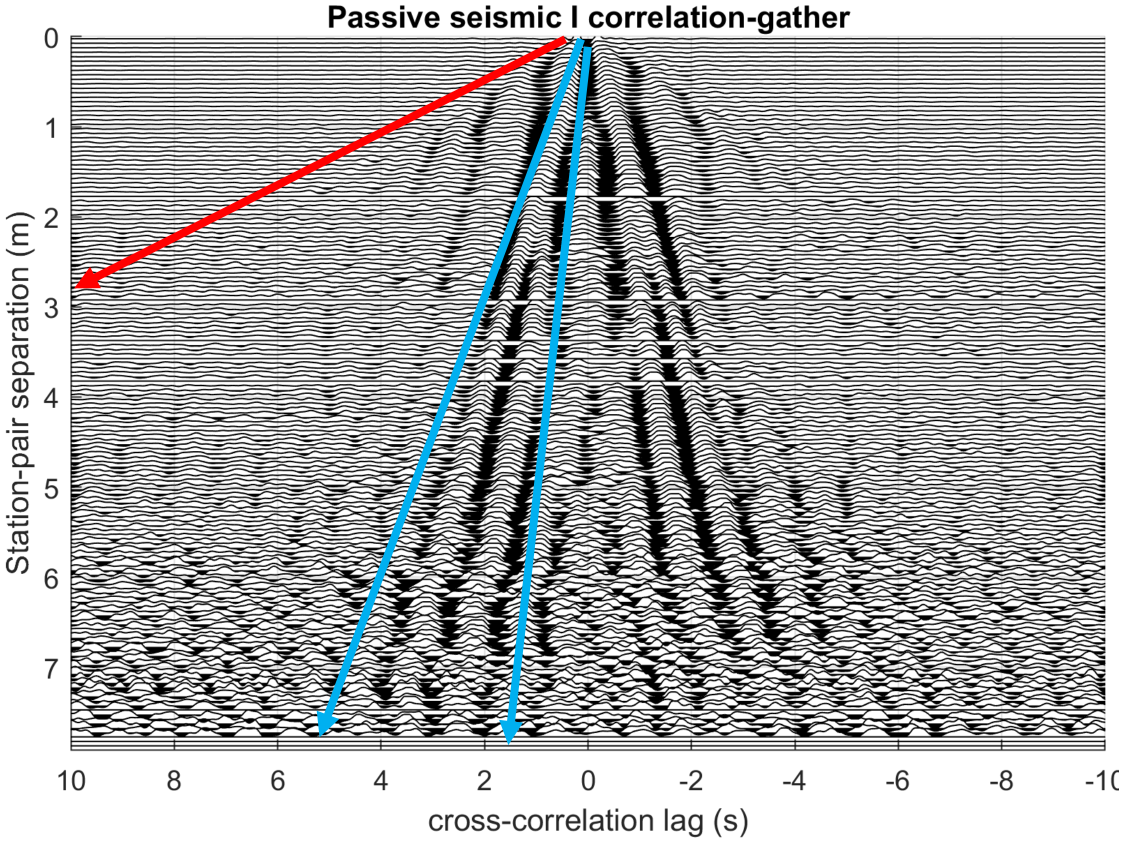
- **wavelengths >> elevation difference**

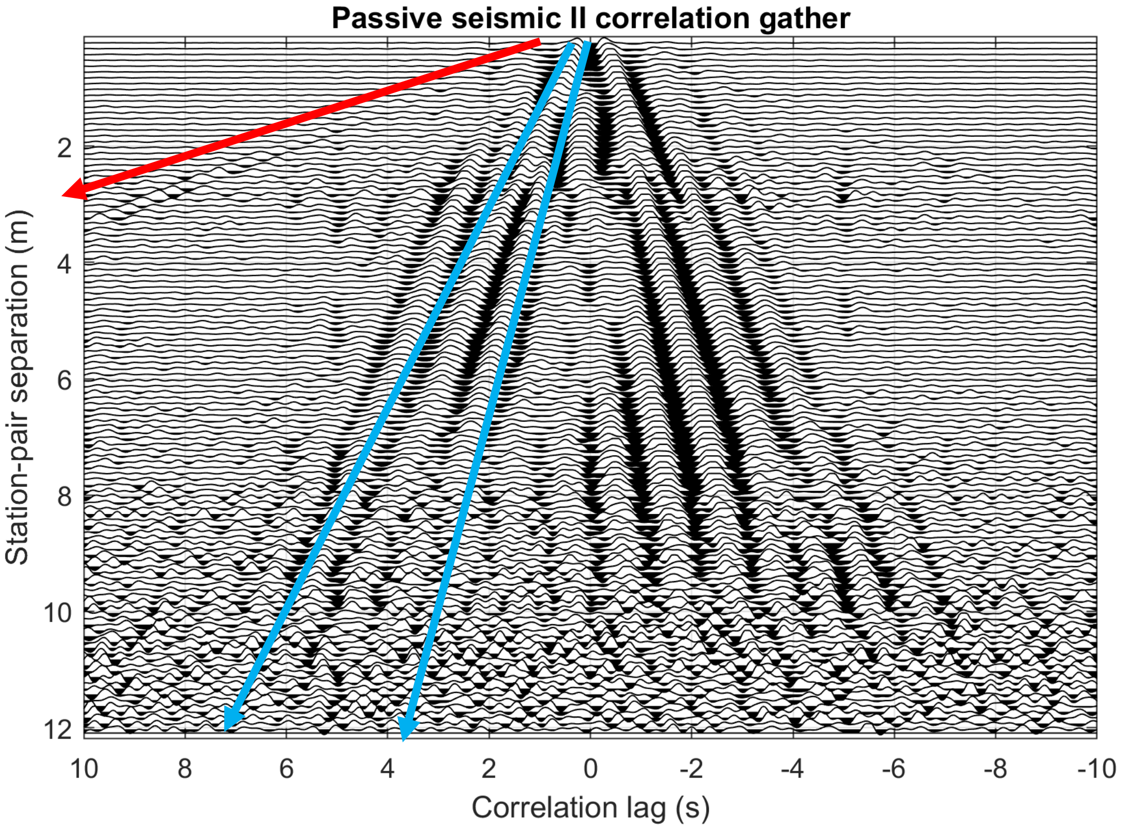
Data quality for the two arrays – correlation gathers

Both passive correlation gathers show dominant ballistic surface waves in the frequency band 0.5 – 3 Hz

- **Propagating approximately between1.5 – 3.5 km/s – dispersion**
- **Azimuthal averaging makes the correlations time-symmetric – not symmetric for one pair**

Summed azimuthally in 50 m distance bins





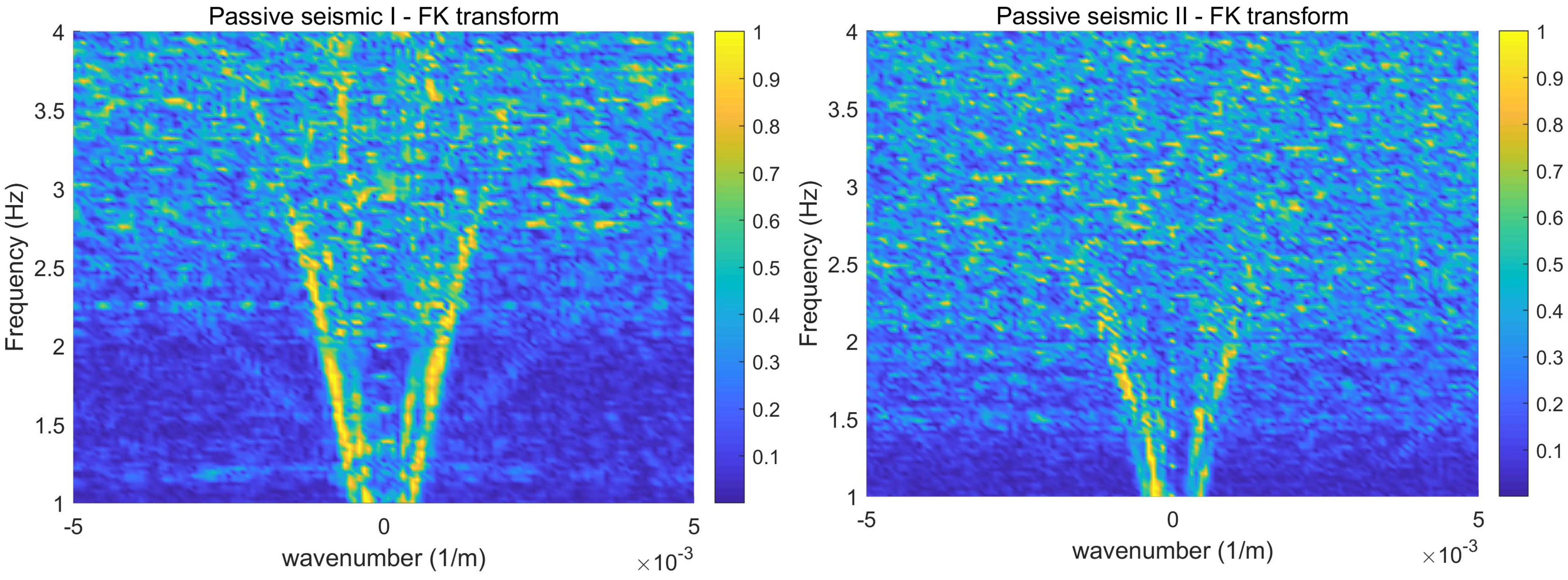
Note a strange acoustic like arrival propagating approximately at 330 m/s – To be understood (low-velocity zone)

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

Data quality for the two arrays – frequency-wavenumber characteristics

Phase dispersion (ω/k) can be understood from frequency-wavenumber transform

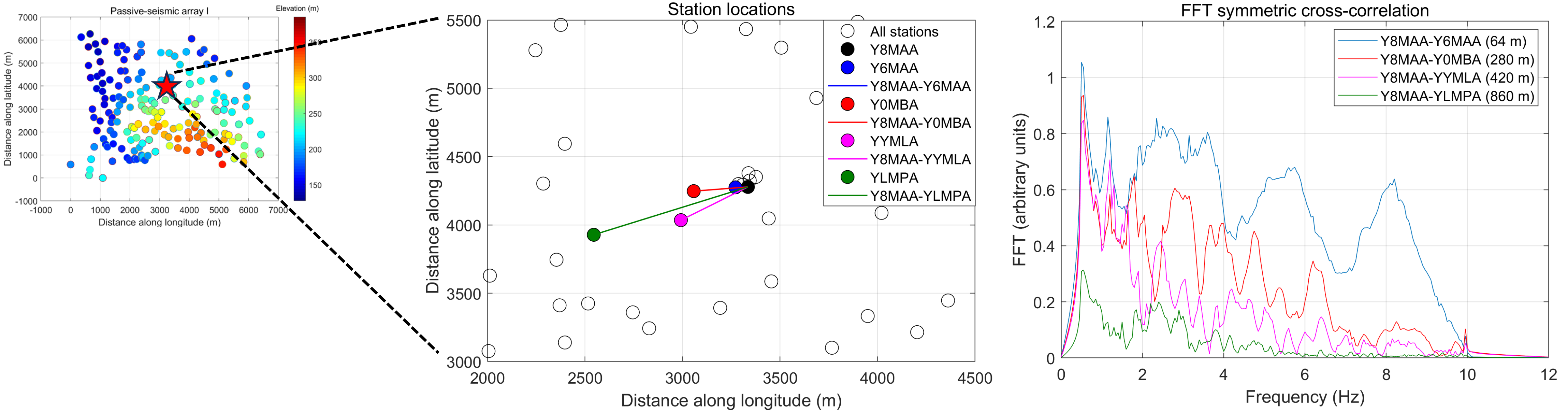
- Both arrays show similar dispersion
- Passive I which has maximum station-separation of 7 kms show much stronger coherence (up to 3 Hz) than Passive II (~2.5 Hz) which is about 12 kms in aperture



Learning I – correlation vs distance attenuation

Current analysis uses noise up to 3 Hz due to lack of significant correlation between distant stations at greater frequencies: however, we need to move to higher frequencies (why?)

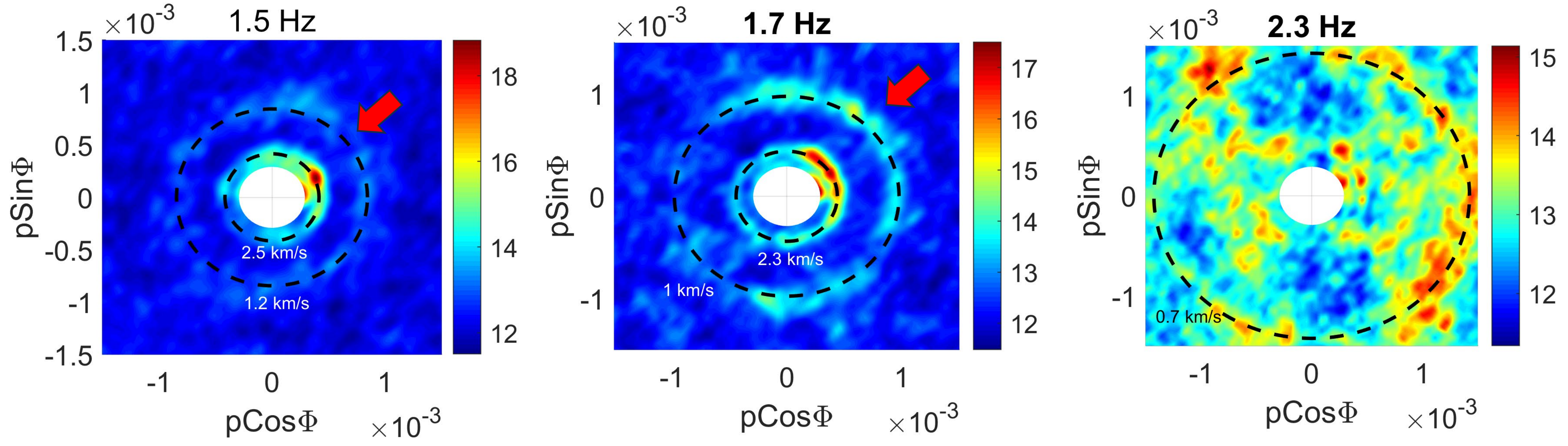
- **A station spacing of about 150 m would ensure good correlation between stations (Passive 1 – nominal separation 250 m, passive II – nominal separation 450 m)**
- **A denser station spacing will also enable double beamforming or traditional beamforming – a fall back in case tomography fails**



Learning II – Distribution of noise sources is anisotropic

We use a Bartlett Beamformer to determine velocity and direction of propagation of the coherent part of noise

- Dominant propagation is North-Eastern, existence of modes
- Decrease of coherent noise at frequencies > 2 Hz
- Accurate EGF construction still possible: If noise direction along the Fresnel zone of the line joining station pairs: $\pi/4$ phase error (Yao & van der Hilst, 2009)

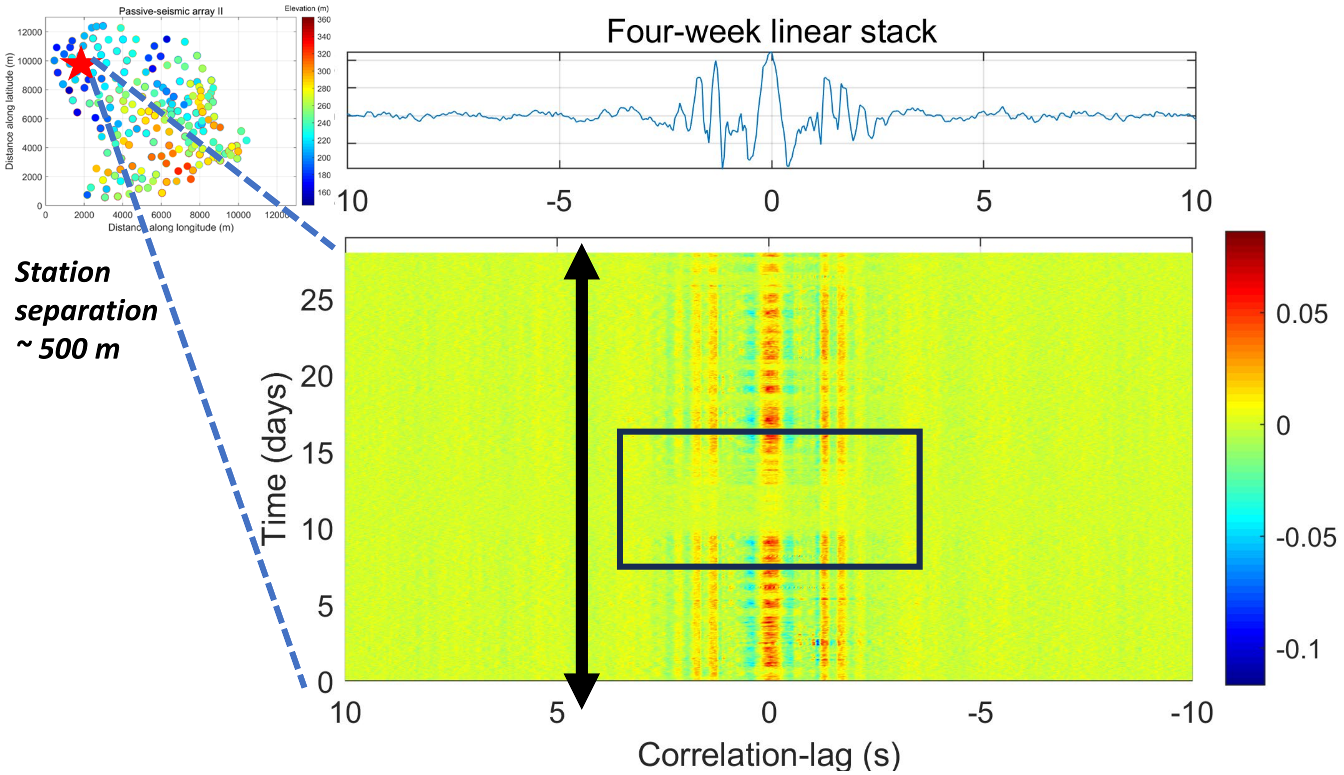


Related Literature: ***Koley et al 2022***

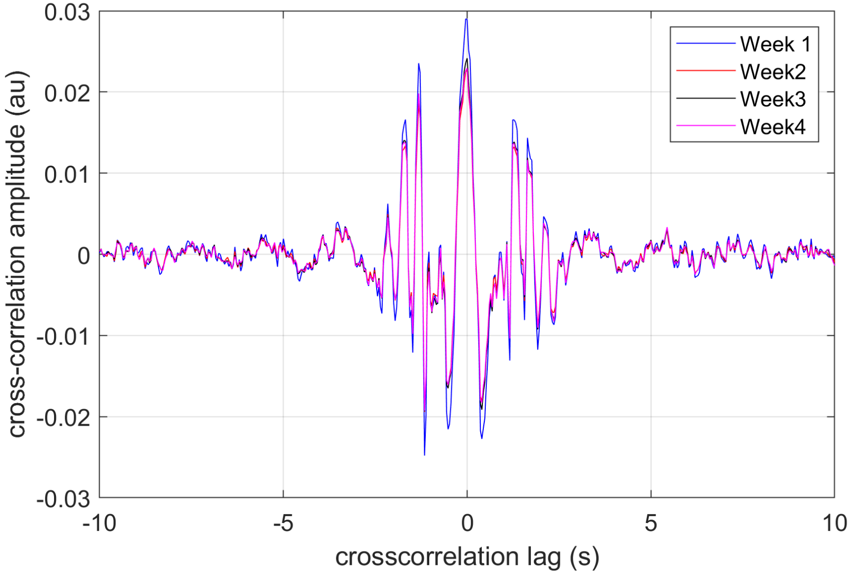
Learning III – How long we need to measure?

We propose a measurement time of at least 3 weeks – hourly or bihourly correlation evaluation

- Unlike theoretical works where noise sources move-around with time – reality is that the cross-correlations are stationary (hourly)
  - Implies that the noise is already mixed or diffused
- There can be time windows in which noise amplitudes are low, example for Passive II campaign (Feb 26 – March 31, 2021)



- Tomography with weekly stacks improves the error estimates (similar approach for low frequencies in Goutorbe et al., 2015)



Related Literature: ***Seats 2012***

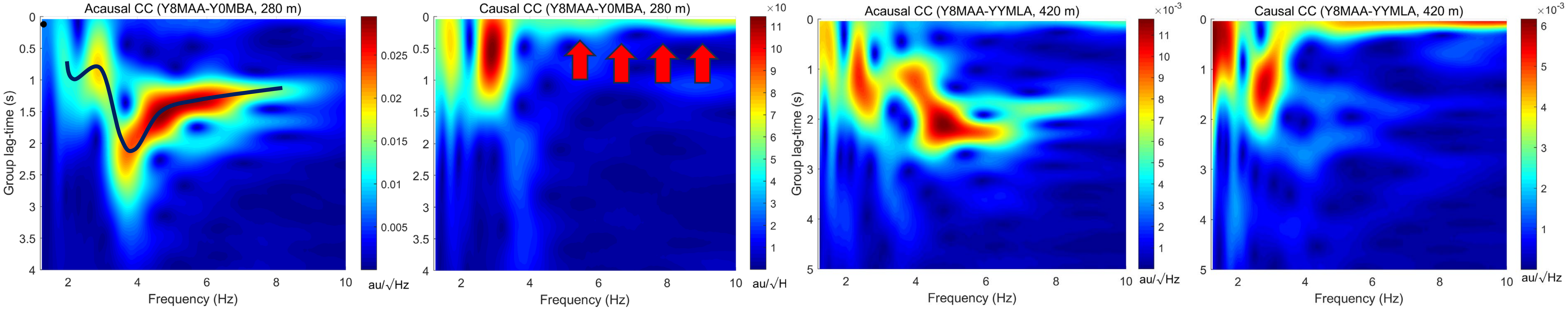
Learning IV – Noise correlations are seldom symmetric!

Traditional straight ray tomography approaches rely on accurate selection of frequency dependent travel-times between station pairs – problematic for anisotropic noise distribution

- Two example Frequency-Time Analysis (Bensen et al 2007) for a station pair from Passive I Array are shown

- Group travel-time for the causal and the acausal times are not the same
- Clear observation of body-waves at higher frequencies for the causal part of cross-correlation (almost zero travel-time)
  - **Outcome – wrong travel-time selection**

- At a station-pair separation of more than 400 m, mode mixing and poor convergence of cross-correlation to the Empirical Green's function is highly probable
- Reduce station-spacing
  - As proposed earlier ~ 150 m

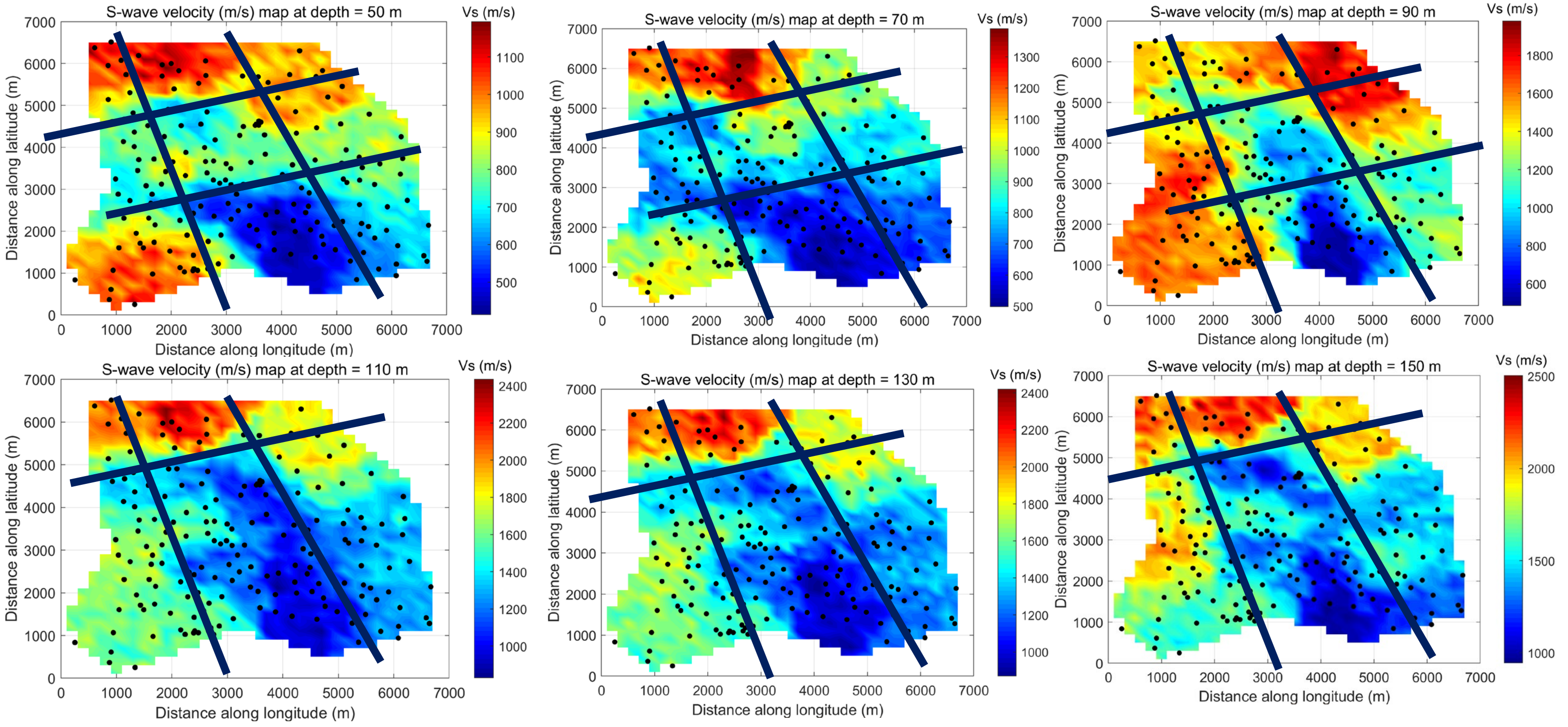


Related Literature: Dziewonski et al, 1969, Levshin & Ritzwoller, 2001

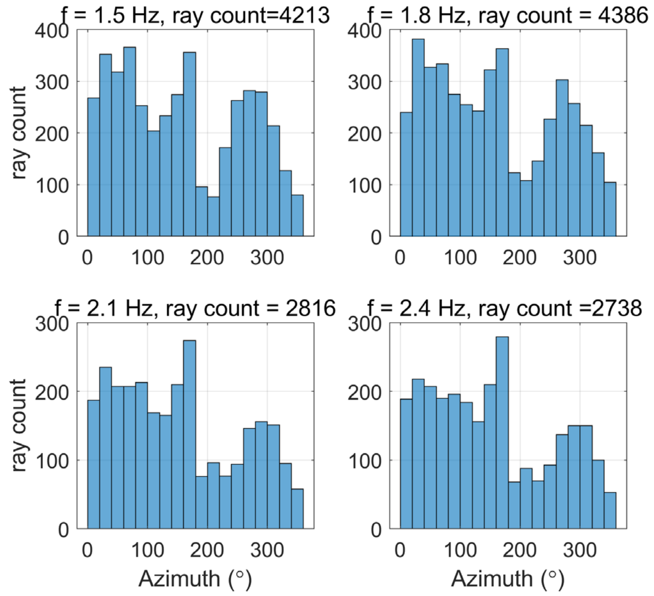
Straight-ray tomography results from Passive Array I

Straight ray tomography was performed using Rayleigh wave dispersion in the frequency band 1.0 – 2.5 Hz

- Two faults were identified and each on dominant at different depths
- Geul valley fault
- Another West-East trending fault



- Some limitations of the study
  - A spatial resolution of between 200 – 300 m
  - Low Ray Count (<20 %)
  - Shallow vertical resolution of 50 m
  - Need to probe higher frequencies

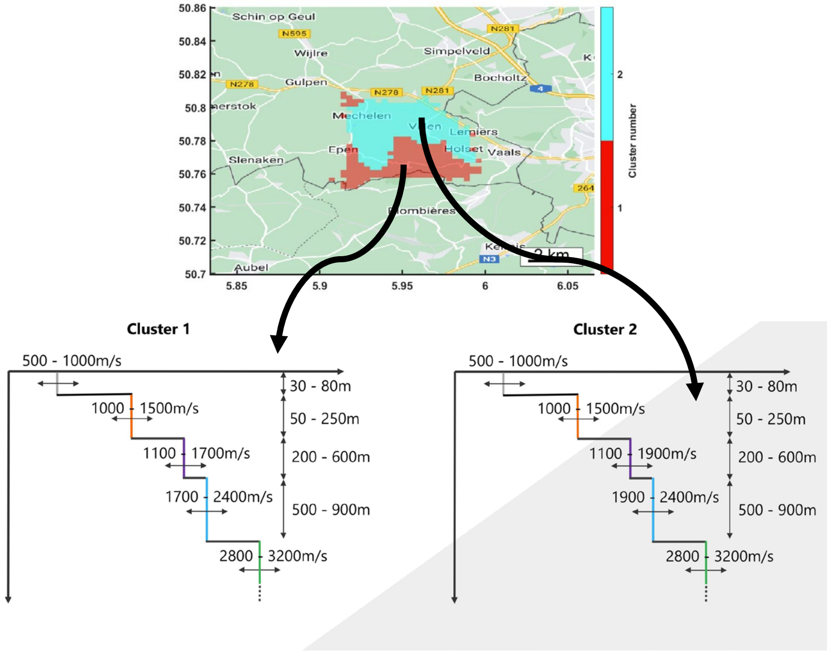


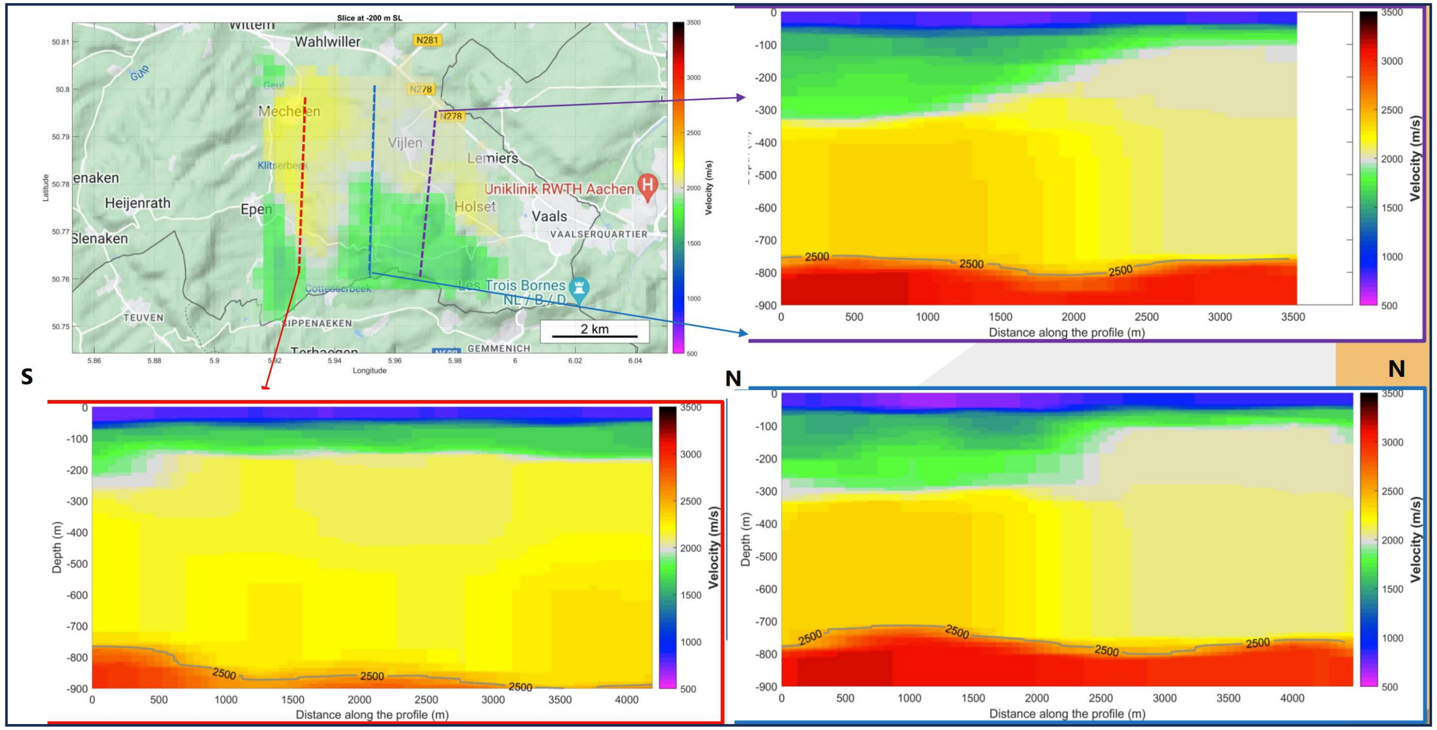
Related Literature: ***Chmiel et al 2018*** ***Mordret et al 2013***

Straight-ray tomography results from Passive Array I (Sisprobe)

Frequency domain group-velocity to velocity-depth conversion using stochastic search approach

- Inversion performed using local group velocity at the cell and the global phase velocity
- A 5-layer model used as the starting point shown in the figure below
- Sisprobe uses a stochastic search algorithm (e.g, NA)



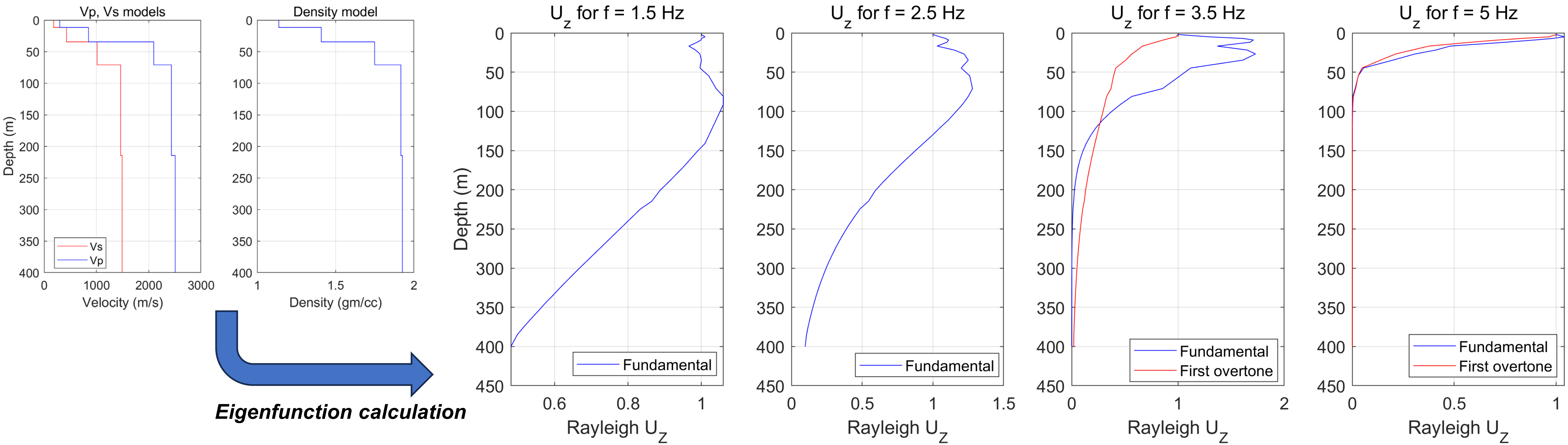


Related Literature: ***Sambridge, 1999***

Learning V – Rayleigh wave Eigenfunction and frequency band of interest

Based on Vs depth models from Passive I array, we calculate the Rayleigh wave Eigenfunctions at different frequencies – shows the sensitivity of Rayleigh waves to different depth of penetration

- Frequencies below 2.5 Hz are mostly sensitive to depths greater than 50 m
- Need to probe at least to 4 Hz or 5 Hz to have a strong constraint on shallower structure
  - Note that frequencies below 2.5 Hz depend on shallower structures but to a lesser extent

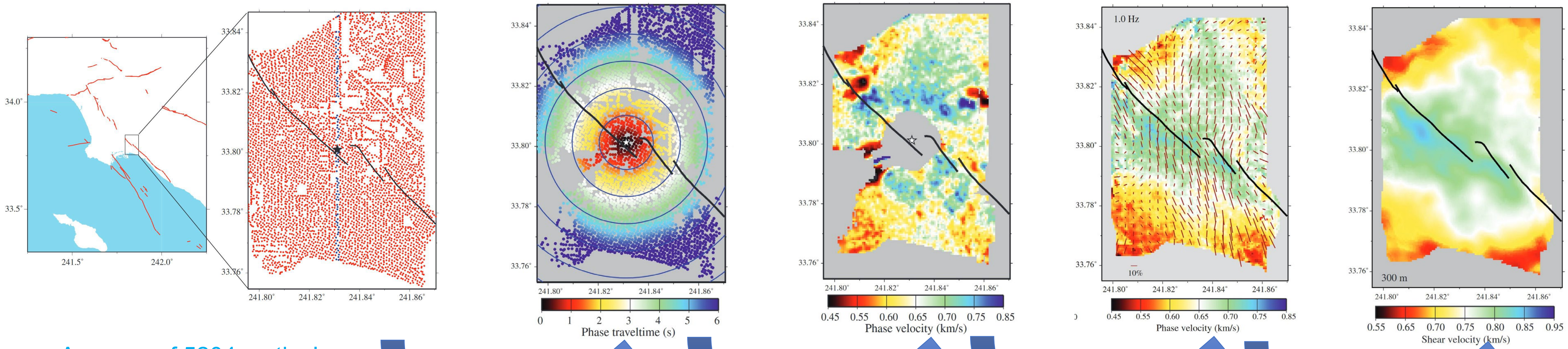


Related Literature: Cercato, 2007 CPS 330

Improvements: Moving towards Eikonal phase-traveltime tomography

Eikonal tomography works on virtual source-receiver gather and evaluates the traveltime gradient at each grid-point: gives local estimate of velocity and direction of propagation of the wavefront (*Lin et al., 2013*)

- Can handle anisotropic noise illumination
- Gives an estimate of local anisotropy



- An array of 5204 vertical component stations covering an area of 7 × 10 sq. km
- Recording time – 3 months

- Pick travel times from virtual gather
- Ignore bad picks

Phase travel time – phase velocity

Repeat for many virtual gathers

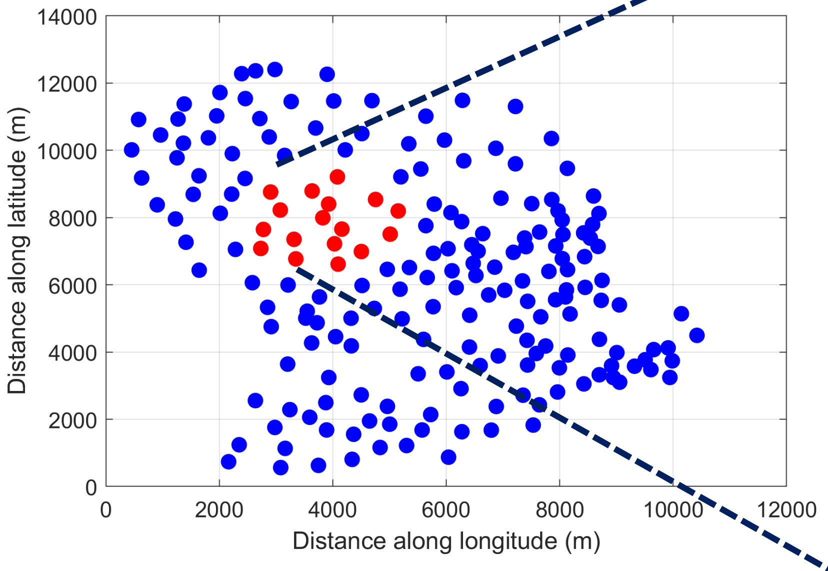
Phase velocity – Vs depth inversion

Related Literature: ***Lin et al 2009, Fu et al, 2022***

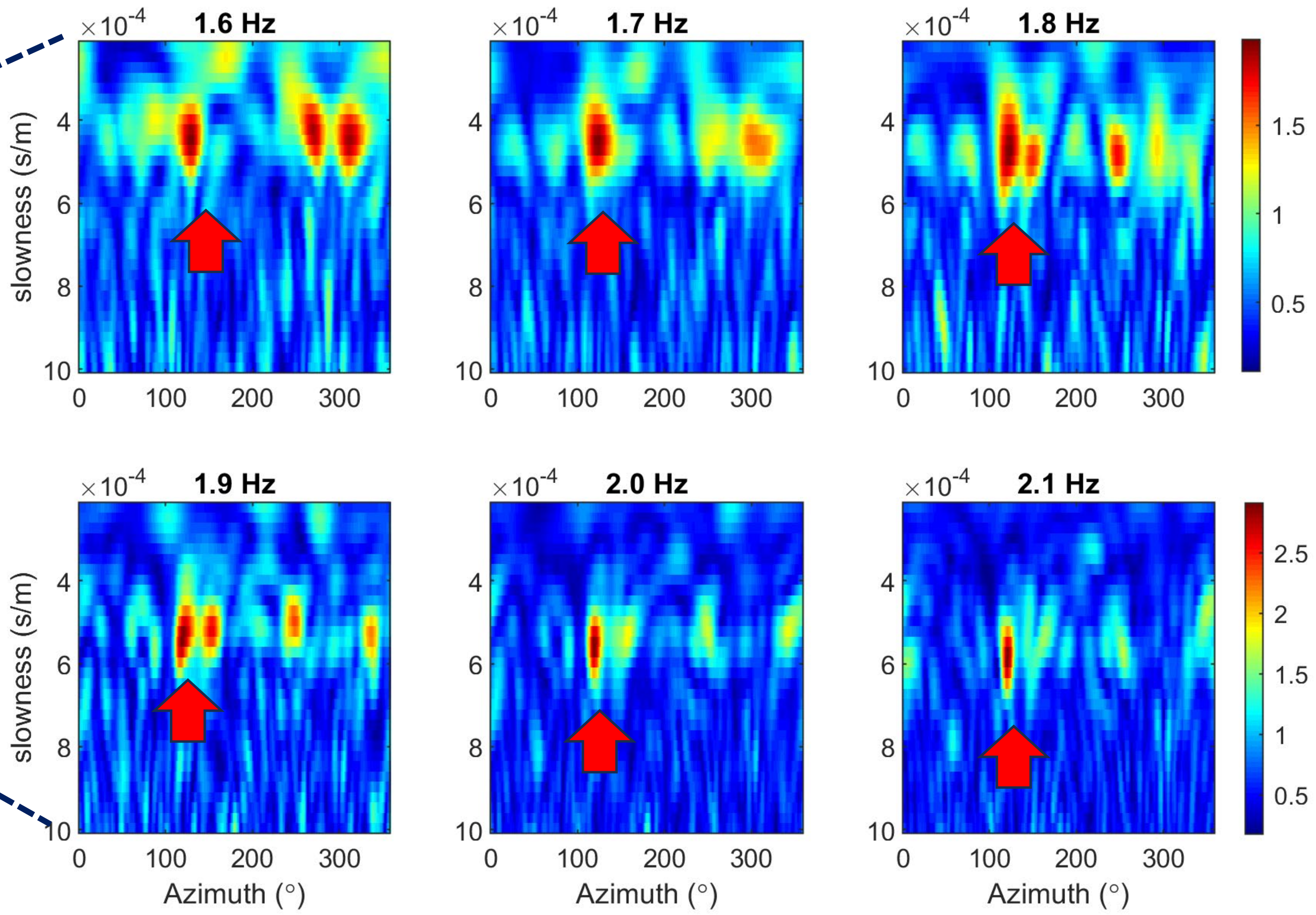
Improvements: A double-beamforming based subarray approach

The subarray based approach gives a local control on the phase velocity estimate, alleviating problems with cycle skipping, source phase ambiguity, local understanding of wave propagation before tomography

- A strong dispersion is observed for the source along azimuth 90 – 130 degrees



Passive Seismic II Array

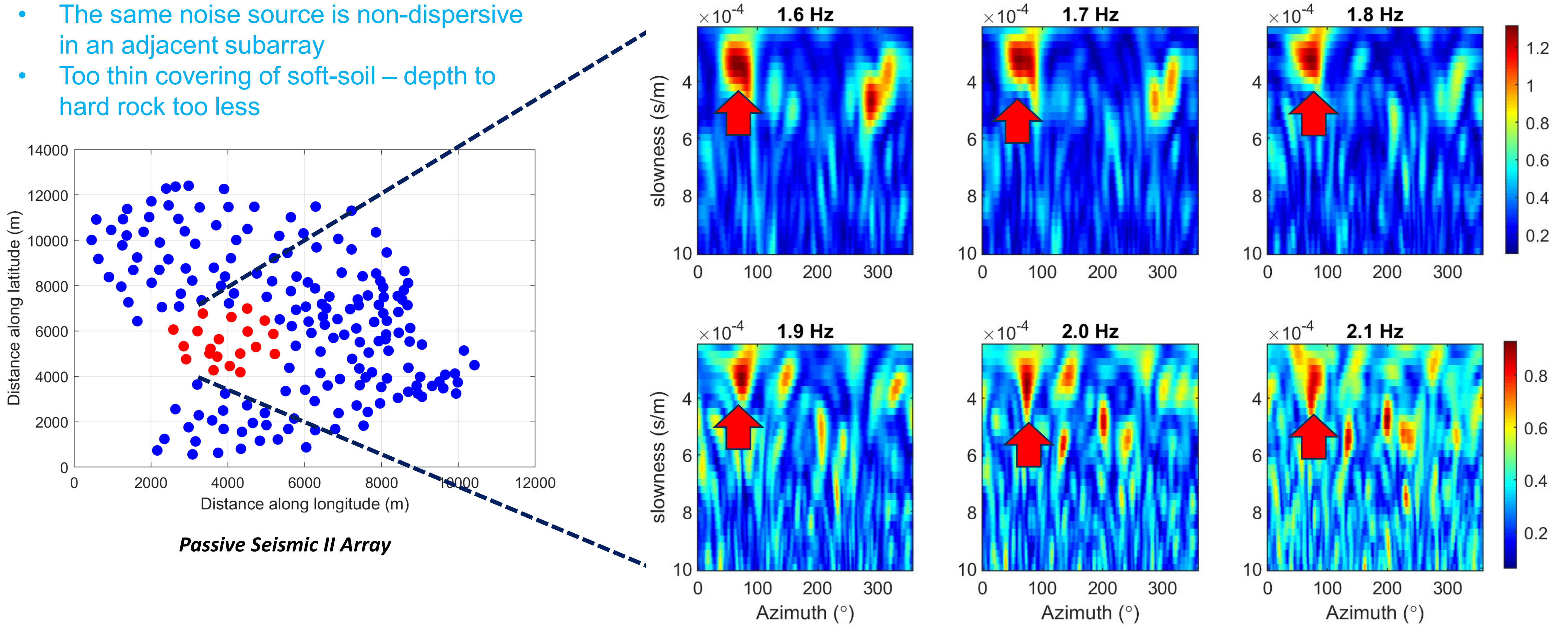


Related Literature: Fu et al., 2022, Ruigrok et al., 2017, Boue et al., 2013

Improvements: subarray approach and body-wave tomography

The subarray based approach gives a local control on the phase velocity estimate, alleviating problems with cycle skipping, source phase ambiguity, local understanding of wave propagation before tomography

- The same noise source is non-dispersive in an adjacent subarray
- Too thin covering of soft-soil – depth to hard rock too less

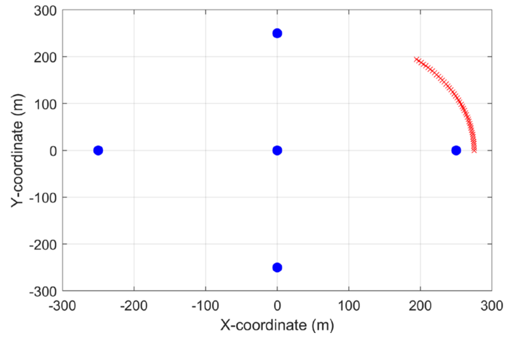


Passive Seismic II Array

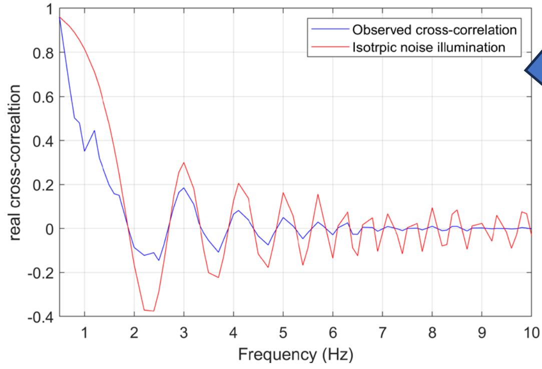
Related Literature: ***[Nakata et al, 2015](), [Ruigrok et al 2017]()***

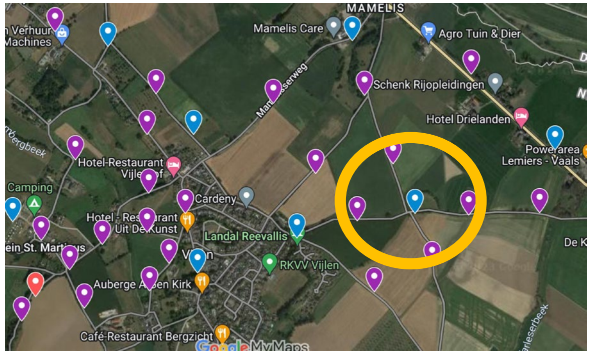
What's Next?

- Future arrays with 400 3-component stations and nominal separation of 150 m – tomographic resolution below 50 m, depth resolution – 10 m
- Try to have a variable node separation in areas like forests to ensure that beamforming can be done up to high frequencies (Fail-safe)
    - Rings of increasing radii
    - Increasing squares
- Use frequencies in the band 1.5 – 6 Hz, even if we can go to 5 Hz, we will have the shallowest layer at depths between 20-30 m
- Use several overlapping arrays for ET
- Deploy 3-component stations strategically and use the Rayleigh-ellipticity, Love wave and Rayleigh wave tomography
- Try to have a symmetrical azimuthal coverage of stations at fixed distances around a central station
    - Will enhance local velocity control while doing tomography
    - Eikonal tomography while computing the local traveltime gradient



Aki's principle





Related Literature: Aki 1957, Ohori et al., 2001

Thank you !

Questions?