6C Site Characterization

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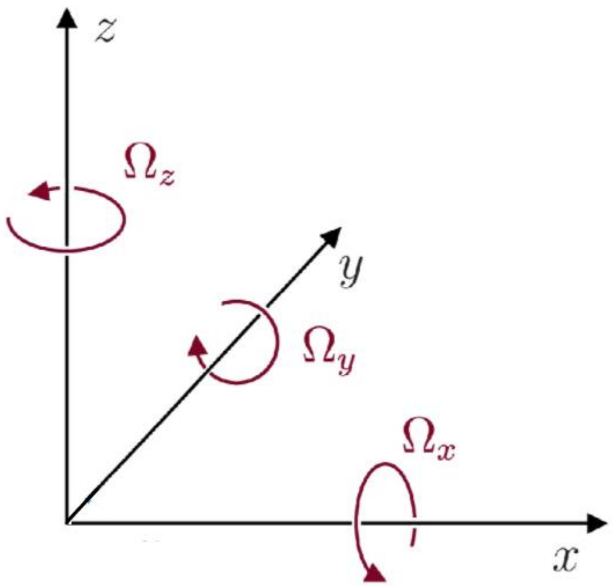
Skience 2025



Outline

1. What is 6C seismology and why is it useful in cities?

2. Methodology

3. Field studies

4. Exercises 6C dispersion curve computation

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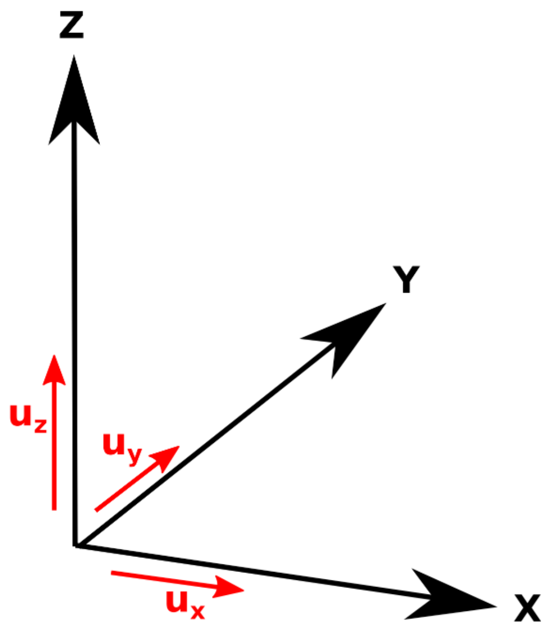
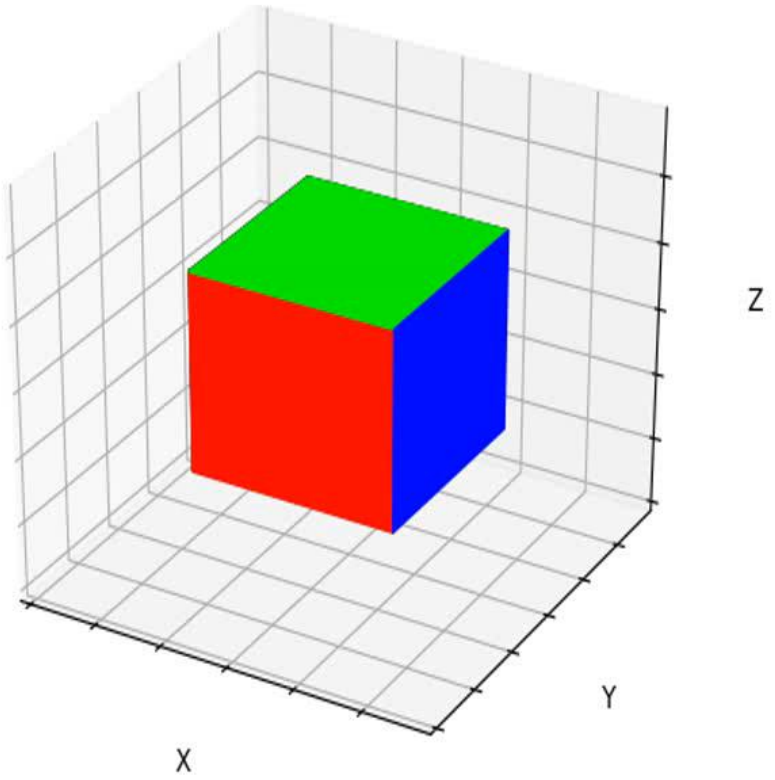
6C Seismology

3C Translations

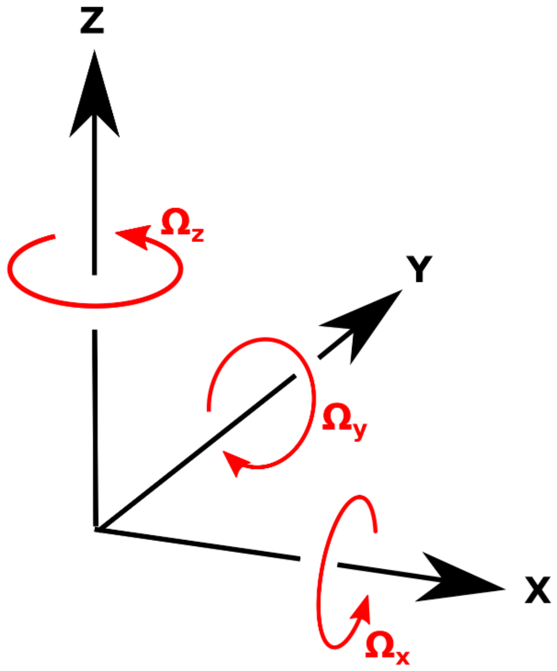


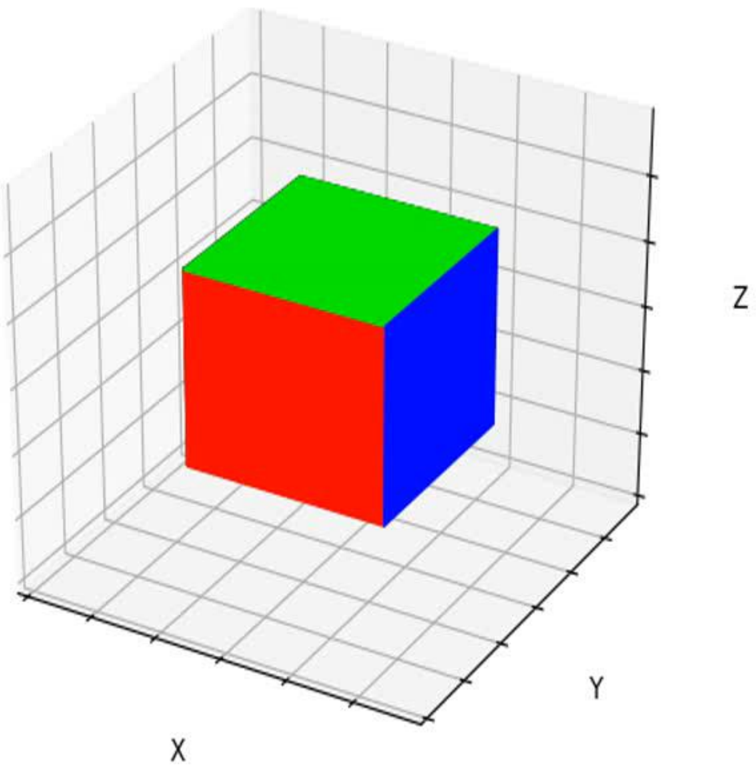


@Felix Bernauer

→ A regular seismometer measures 3 components of translational motion

3C Rotations



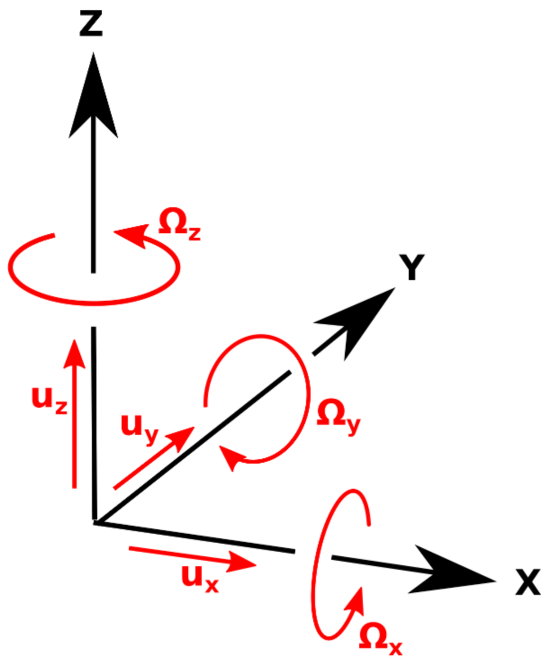


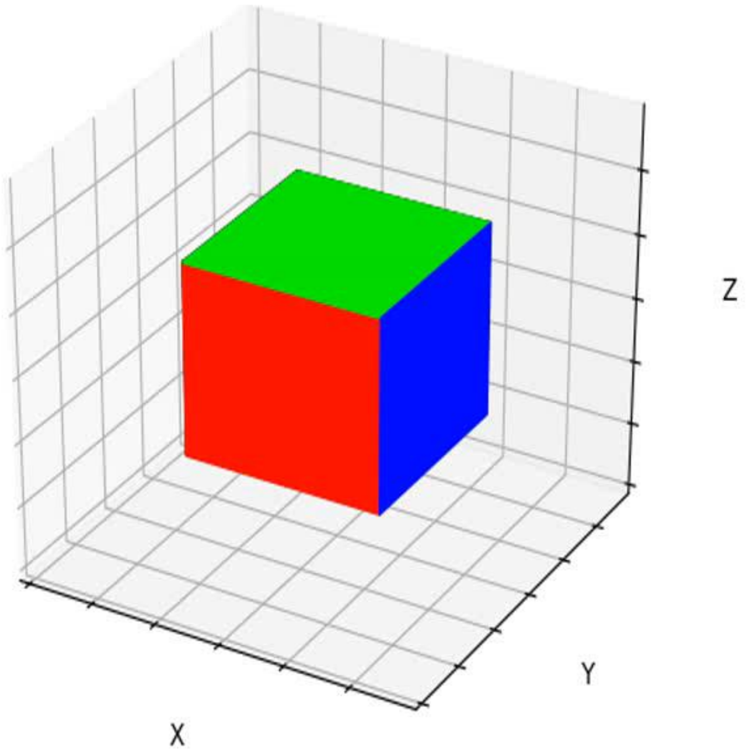
@Felix Bernauer

→ A seismic wavefield also contains rotational motions

6C Seismology

3C Translation + 3C Rotation = 6C



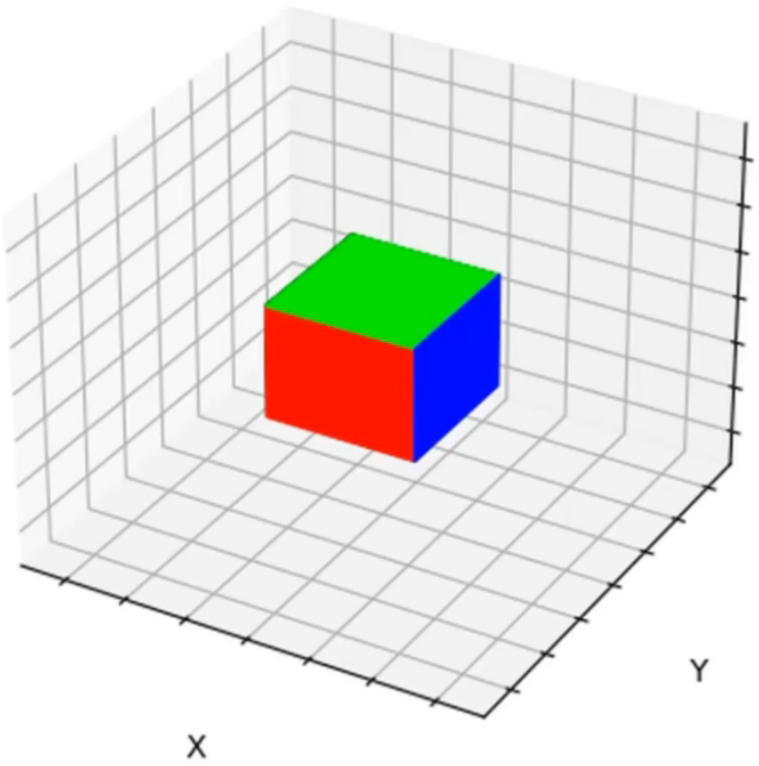


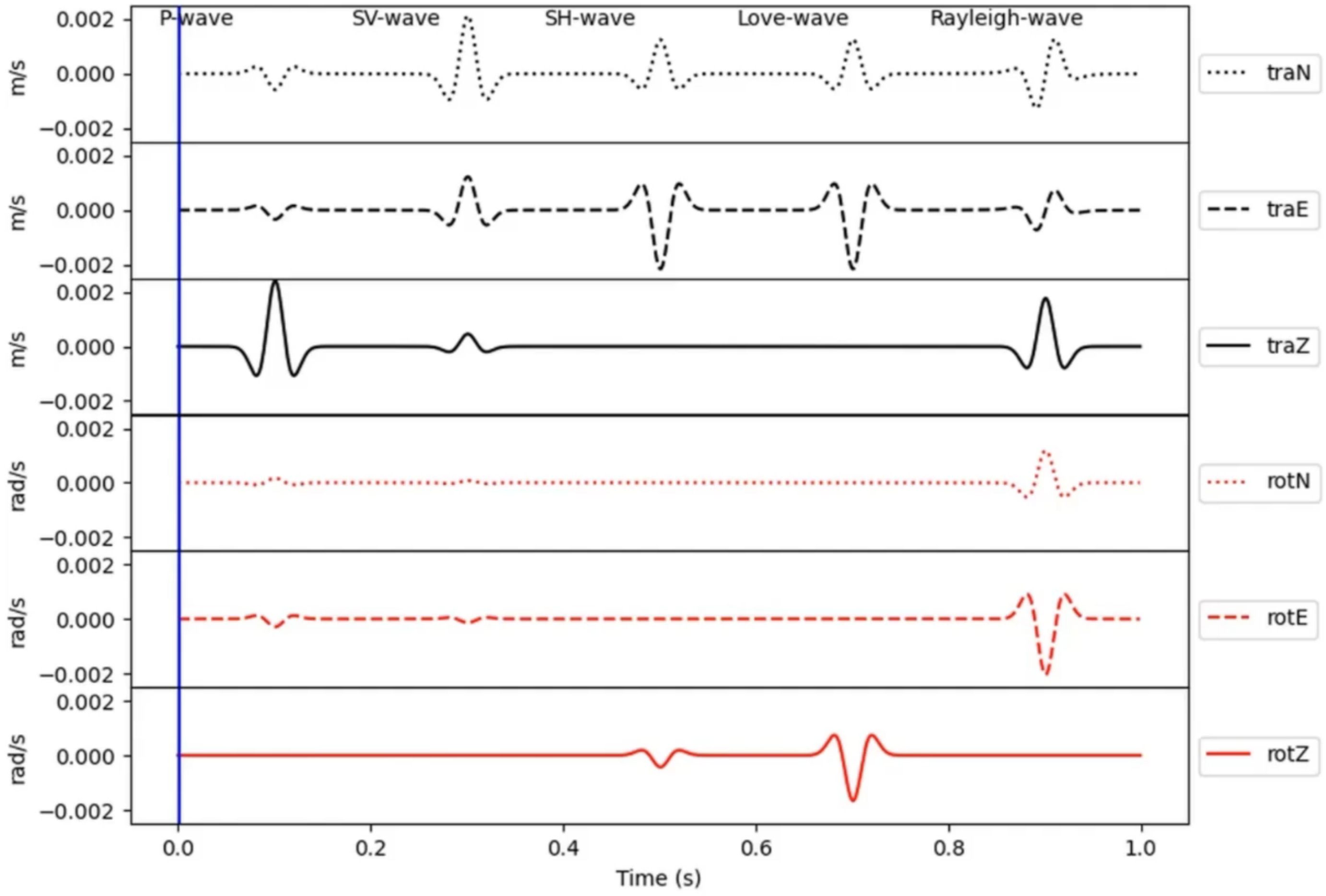
@Felix Bernauer

→ We need 6 components to describe the seismic wavefield in more detail

6C Seismology

→ Different wavetypes cause different motion on 6C recordings



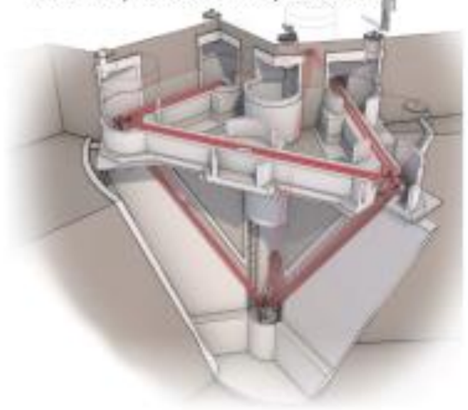


6C Seismology

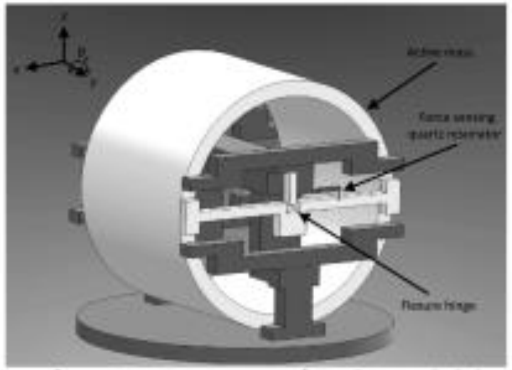
Instrumentation

ROMY

Hand, *Science*, 2017



QRS



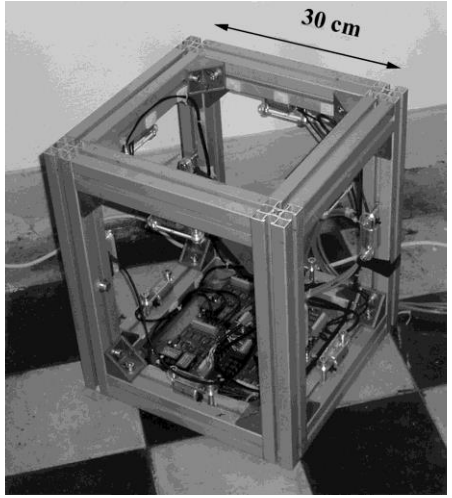
Venkateswara et al., *SRL*, 2021

blueSeis-3A

G-ring

Astrid Eckert / TUM

Rotaphone

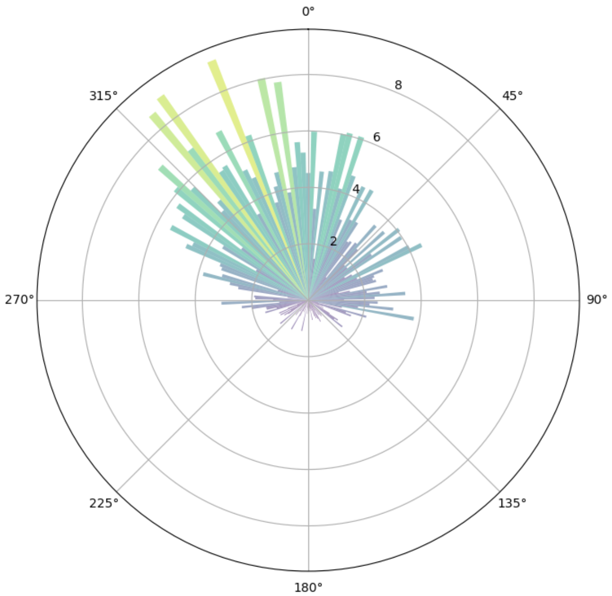


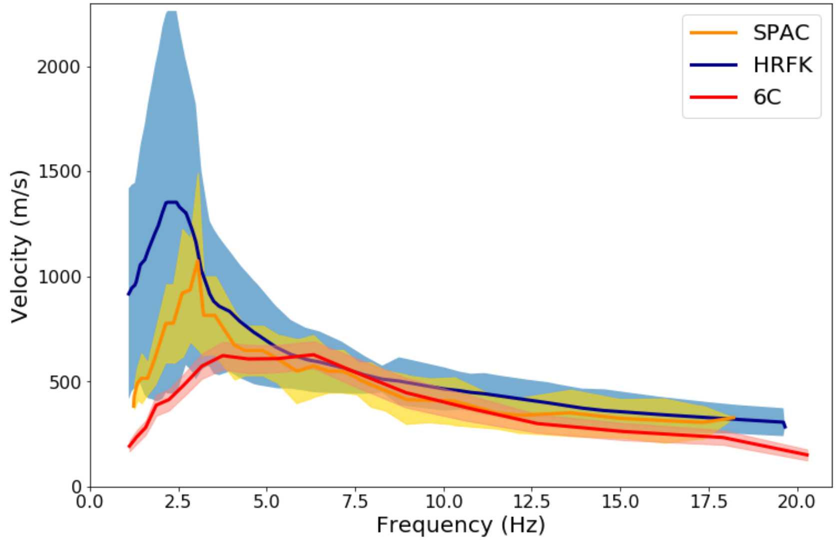
Brokesova end Malek, 2013

6C Seismology

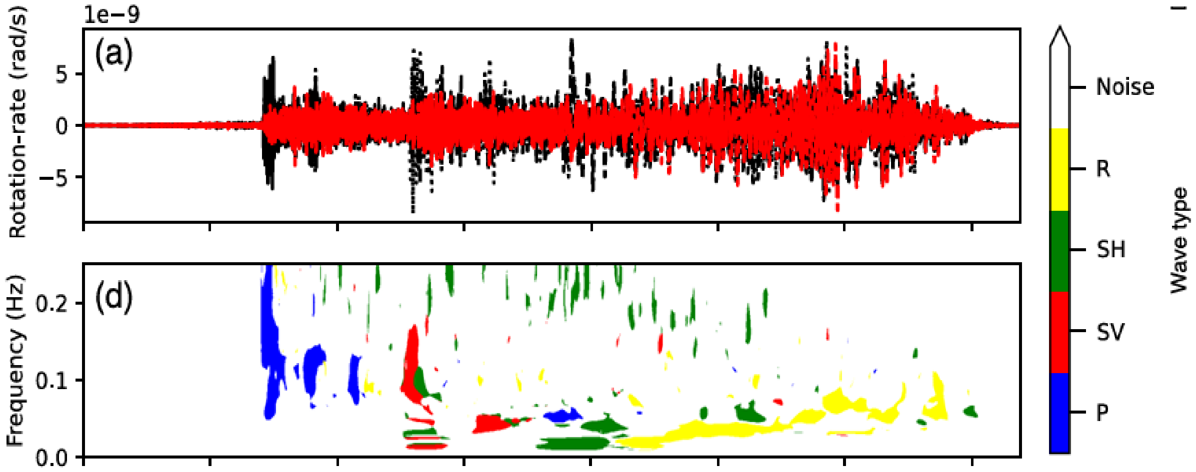
Why useful in cities?

→ Single-station 6C measurement acts as seismic array





- Backazimuth estimation
- Dispersion curve extraction
- Wavetype analysis
- .
- .
- .

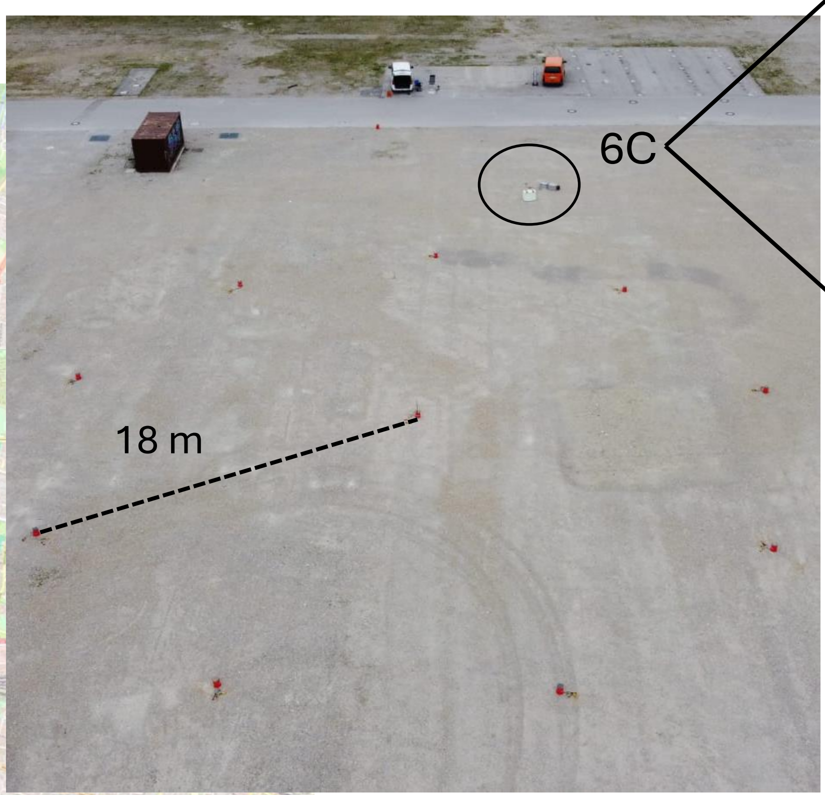


Sollberger et al. 2023

6C Seismology

Why useful in cities?

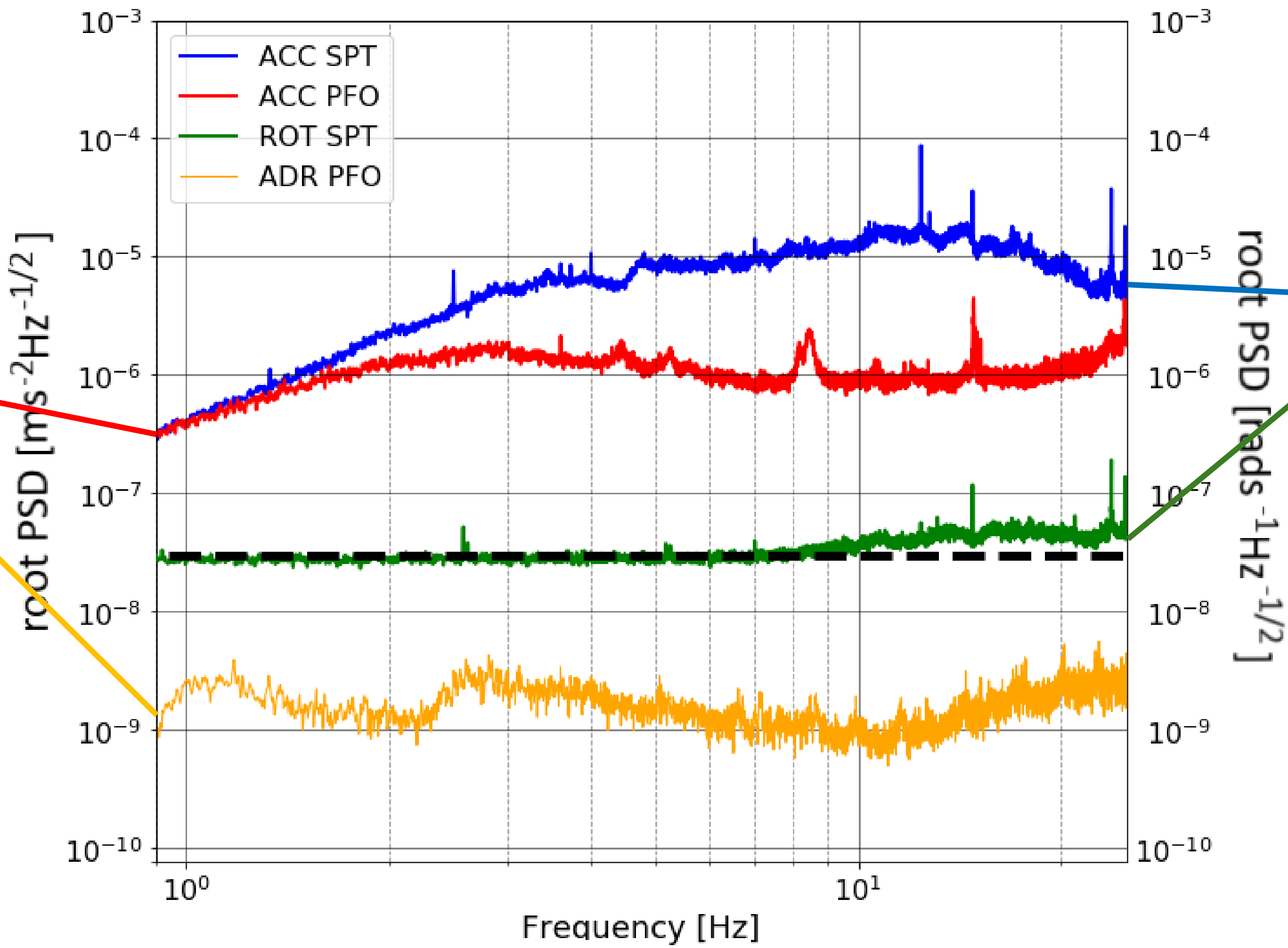
Less space required !!



6C Seismology

Why useful in cities?

High ambient noise levels!!



Outline

1. What is 6C seismology and why is it useful in cities?

2. Methodology

3. Field studies

4. Exercises 6C dispersion curve computation

Methodology

The rotational motions of a wavefield are related to the curl of the translational motions according to:

$$\begin{pmatrix} \omega_x \\ \omega_y \\ \omega_z \end{pmatrix} = \frac{1}{2}\begin{pmatrix} \partial_x \\ \partial_y \\ \partial_z \end{pmatrix} \times \begin{pmatrix} u_x \\ u_y \\ u_z \end{pmatrix} = \frac{1}{2}\begin{pmatrix} \partial_y u_z - \partial_z u_y \\ \partial_z u_x - \partial_x u_z \\ \partial_x u_y - \partial_y u_x \end{pmatrix} \qquad (1)$$

Assume a transversely polarized plane wave propagating in x-direction:

$$u = (0, A\sin(kx - kct), 0)^T \qquad (2)$$

Apply equation (1) to equation (2) and differentiate:

$$\dot{\omega}_z = \frac{1}{2} k^2 c A \sin(kx - kct) \qquad (3)$$

ω Rotation
u Displacement

A Amplitude
k Wavenumber
c Phase velocity
$\dot{\omega}$ rotation rate

Methodology

$$\dot{\omega}_z = \frac{1}{2} k^2 c A \sin(kx - kct) \qquad (3)$$

The transverse acceleration is further defined as:

$$a_T = \ddot{u}T = -k^2 c^2 A \sin(kx - kct) \qquad (4)$$

Dividing equation (4) by (3):

$$\boxed{-\frac{1}{2} \frac{a_T}{\dot{\omega}_z} = c} \qquad (5)$$

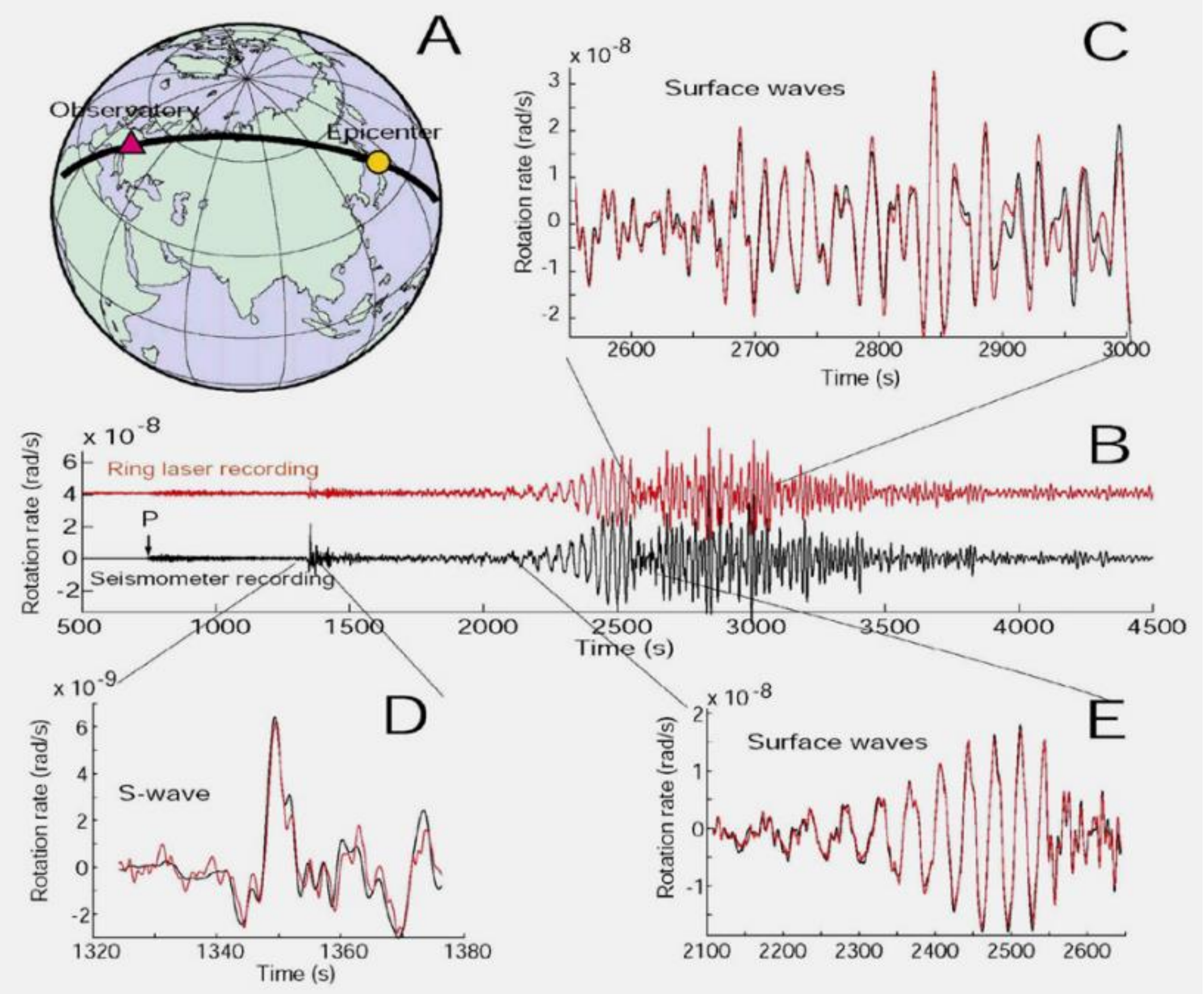
→ Simple relation for the phase velocity of Love waves

Methodology

M8.1 Tokachi-oki earthquake, 25 September 2003

Data recorded at the G-ring in Wettzell, Germany

→ the vertical rotation rate and transverse acceleration are in phase and the amplitudes are related by the phase velocity



Igel et al. 2005

Methodology

Love waves

$$-\frac{1}{2}\frac{a_T}{\dot{\omega}_z} = c_L(f) \qquad (5)$$

φ Backazimuth

Where:

$$a_T = \sin(\varphi)\, a_N - \cos(\varphi)\, a_E \qquad (6)$$

→ Vertical rotation rate and transverse acceleration should be in phase

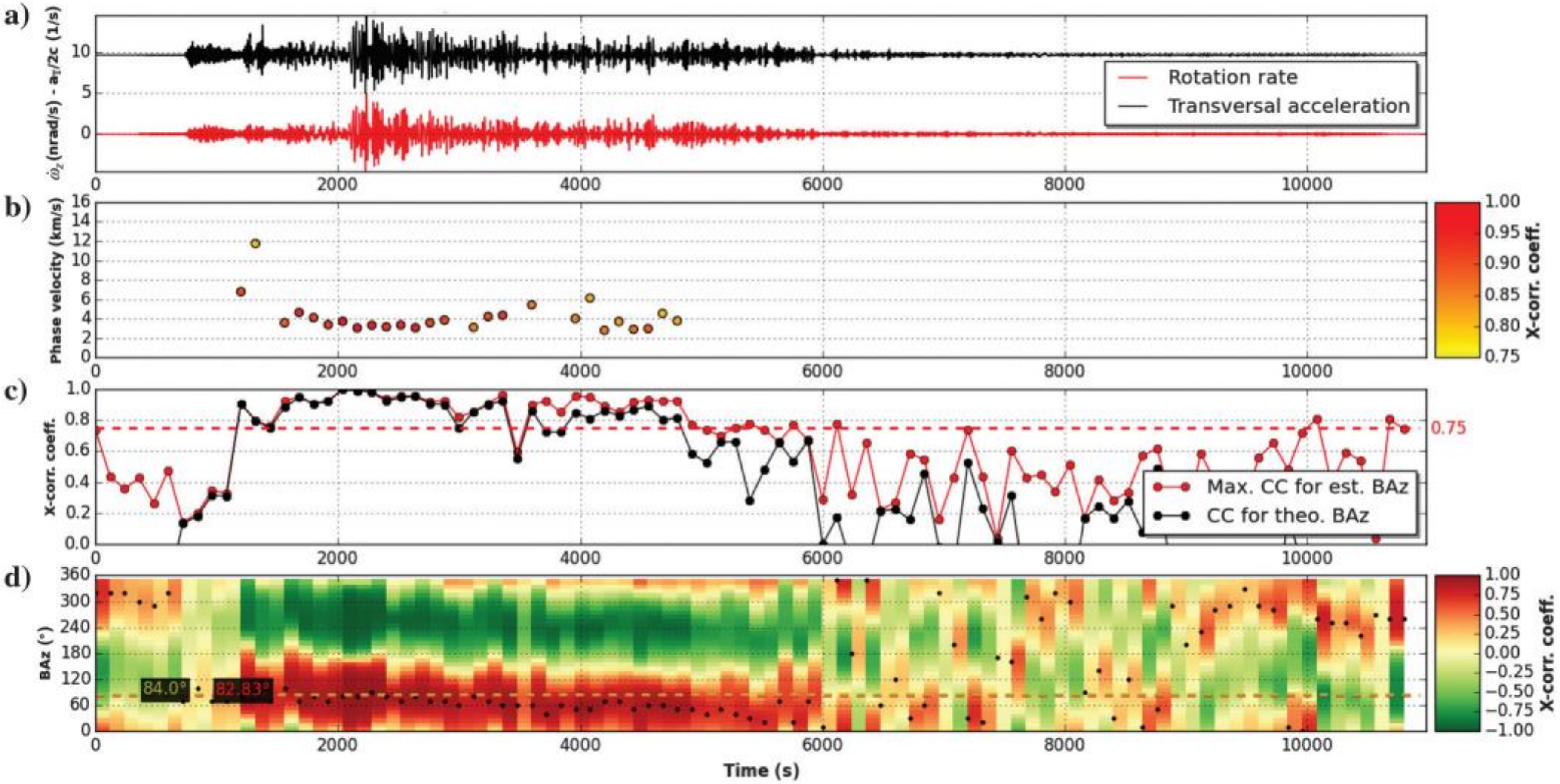
→ Estimate the source direction of SH-type motions by rotating the horizontal components of the seismometer record along different angles, until their resemblance with the rotational measurements is maximal

Methodology

Earthquake location

Mw 7.9 earthquake in Nepal on 25 April 2015

Data recorded at Wettzell, Germany



Schmelzbach et al. 2018

→ cross-correlation between translational and rotational data allow the estimation of the BAZ

Methodology

Rayleigh waves

→Only contain rotational motions on horizontal compontents

→Based on the plane wave assumption, the ratio between the two horizontal rotational components is directly related to the BAz according to:

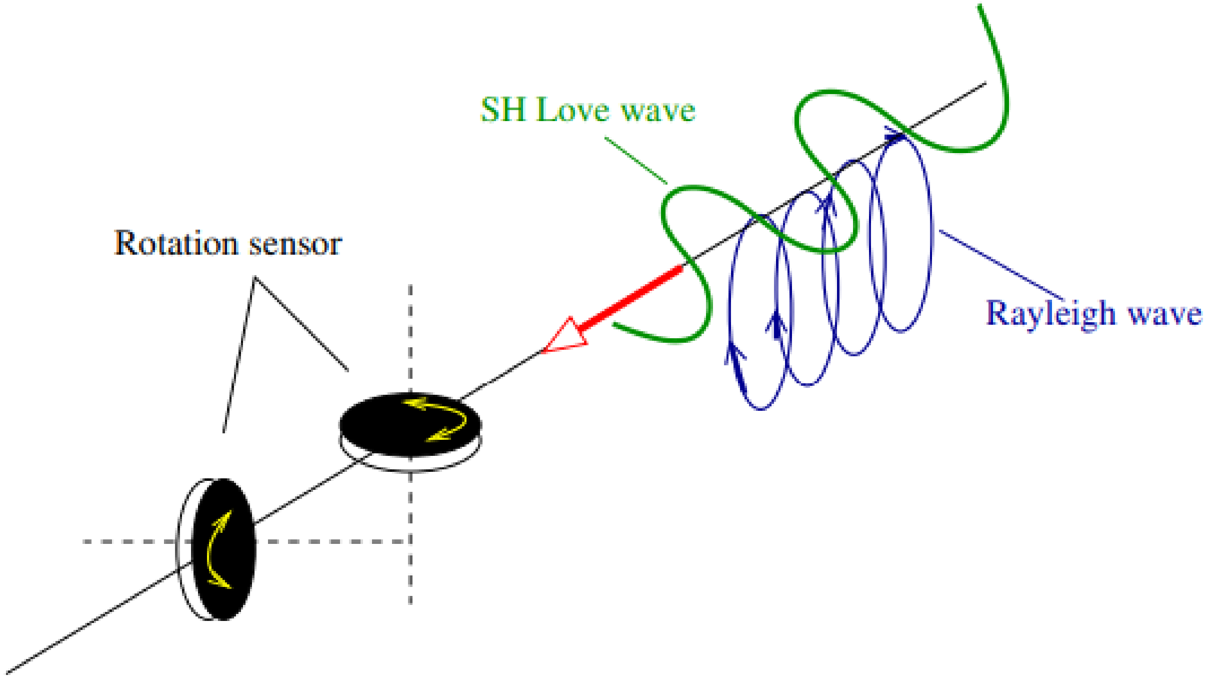
$$\theta_{BAz} = -\arctan\left(\frac{\dot{\omega}_N}{\dot{\omega}_E}\right) \qquad (7)$$

→negative θ_{BAz} value is converted to the value within 0 and 180° by adding 180°.

→remove the 180° ambiguity:

compare the rotated transverse component of rotational rate based on θ_{BAz} to the vertical component of acceleration (a_z). If they are positively correlated, 180° should be added to θ_{BAz}.

Methodology



Suryanto 2007

Love waves:

$$-\frac{1}{2}\frac{a_T}{\dot{\omega}_Z} = \mathrm{c_L(f)} \qquad (5)$$

Rayleigh waves:

$$\frac{a_z}{\dot{\omega}_T} = \mathrm{c_R(f)} \qquad (8)$$

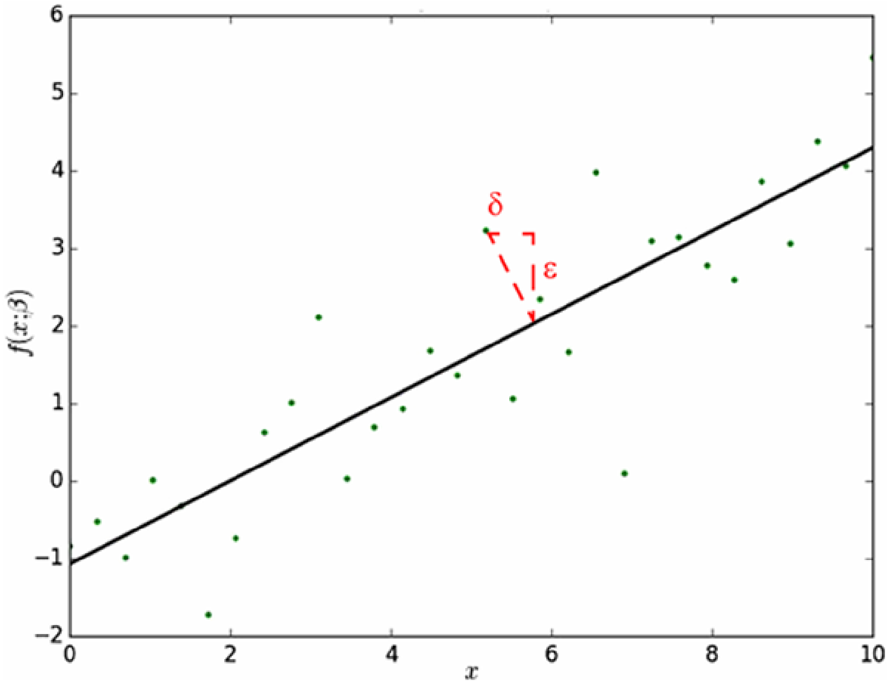
Surface waves are dispersive → Computation of dispersion curves

Methodology

1.) ROLODE (Rotational Love wave Dispersion Estimation; Wassermann et al. 2016)

Orthogonal distance regression

- Simultaneous estimation of direction and velocity using the principle of the orthogonal distance regression (ODR)
- The regression line minimizes the vertical distance be tween the different data points



Wassermann et al. 2016

Methodology

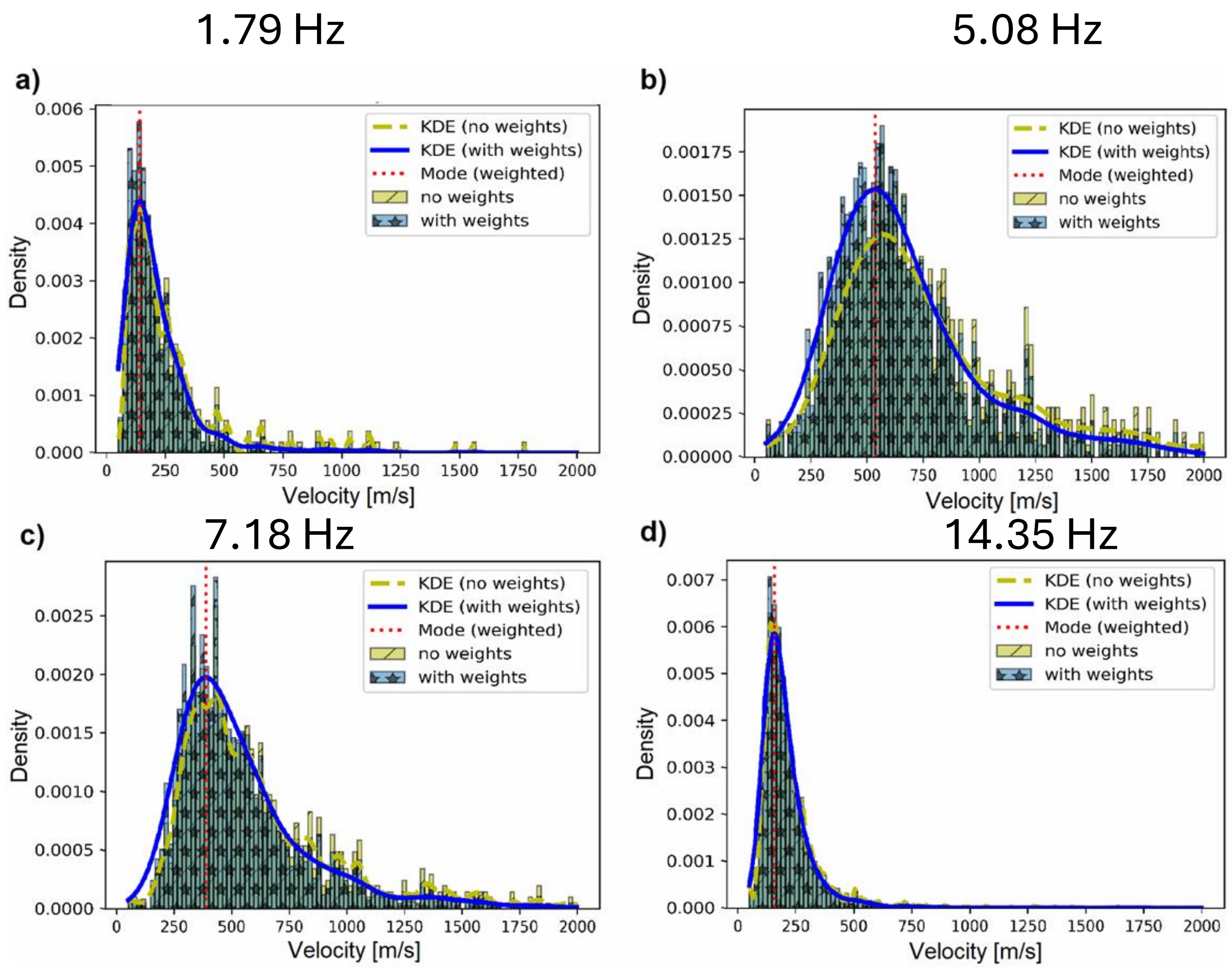
1.) ROLODE (Rotational Love wave Dispersion Estimation; Wassermann et al. 2016)

1.) Filter data in small frequency bands

2.) Apply phase velocity estimation to small time windows

3.) Sum up phase velocity estimates in histogram

4.) Pick the mode as the velocity estimation at the particular frequency

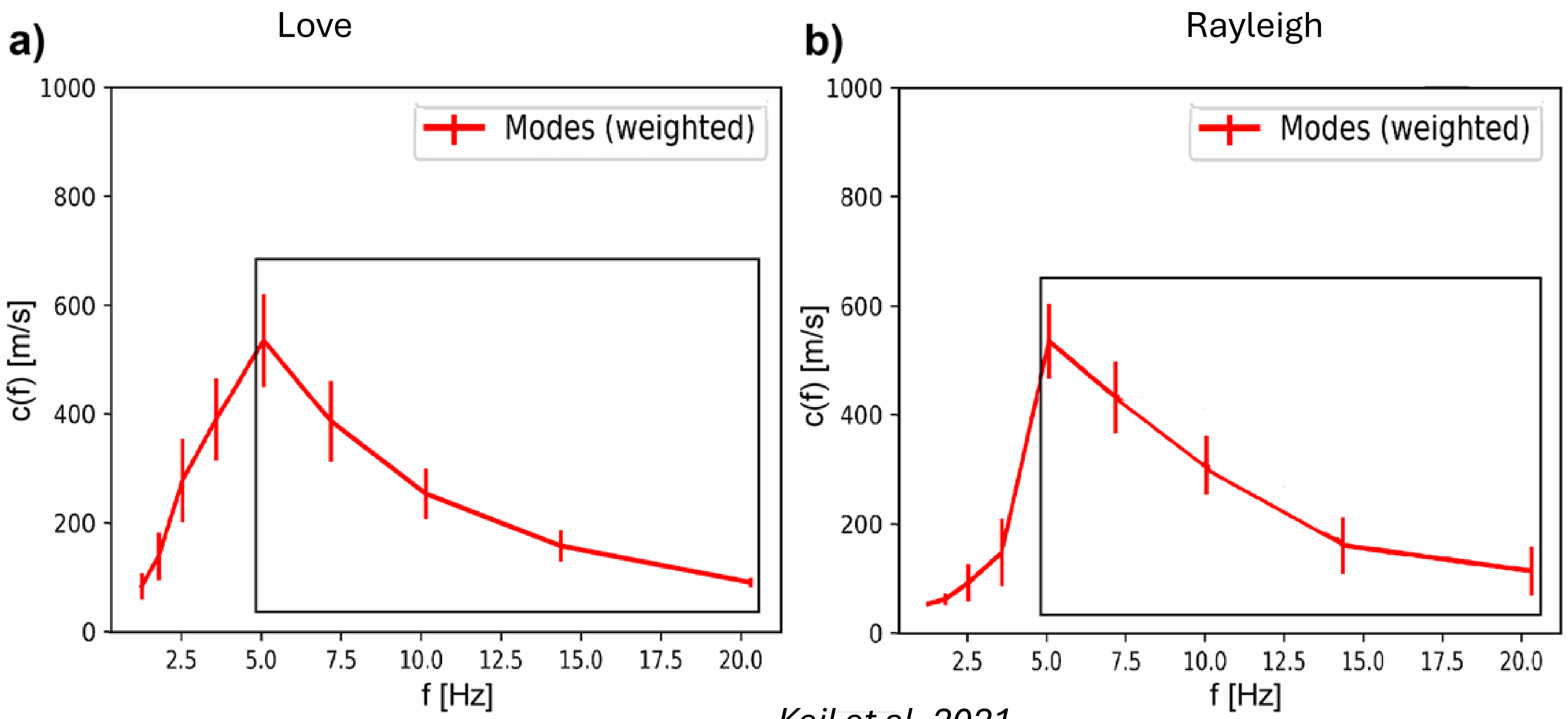


Keil et al. 2021

Methodology

1.) ROLODE

Dispersion curves



Keil et al. 2021

Methodology

2.) TWISTPY (Sollberger et al. 2023)

TwistPy

Toolbox for Wavefield Inertial Sensing Techniques

TwistPy is a small open-source Python package for seismic data processing. It includes routines for single-station polarization analysis and filtering, as well as array processing tools.

Methodology

2.) TWISTPY

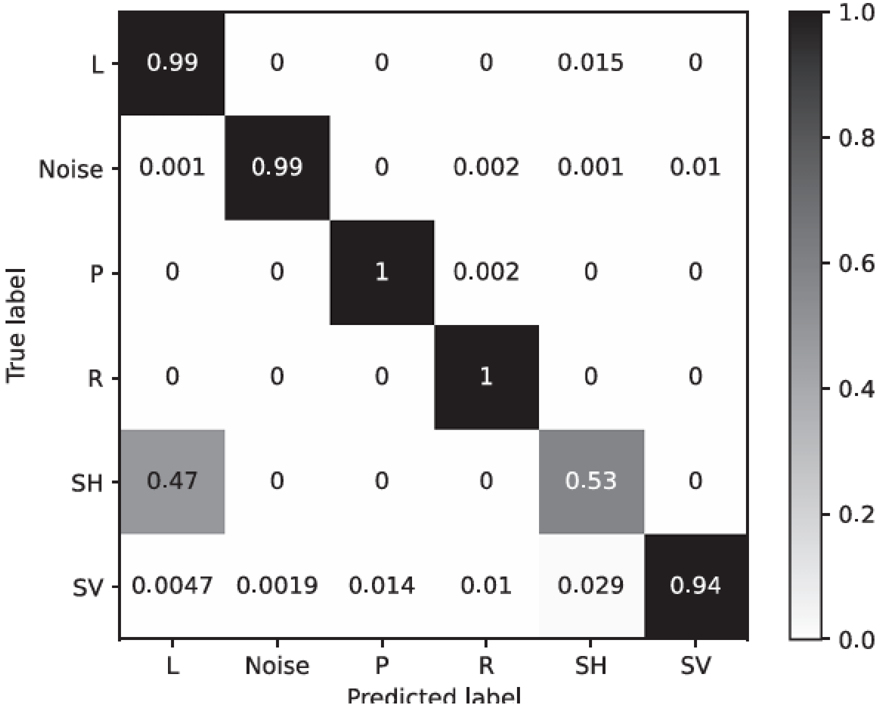
Six-component dispersion analysis

In this tutorial, you will learn how to extract dispersion curves and frequency-dependent Rayleigh wave ellipticity angles from single-station six-component recordings of ambient noise.

→ Based on wave type fingerprinting

→ Compare to analytically derived six-component polarization models

→ Supervised machine learning method of support vector machines



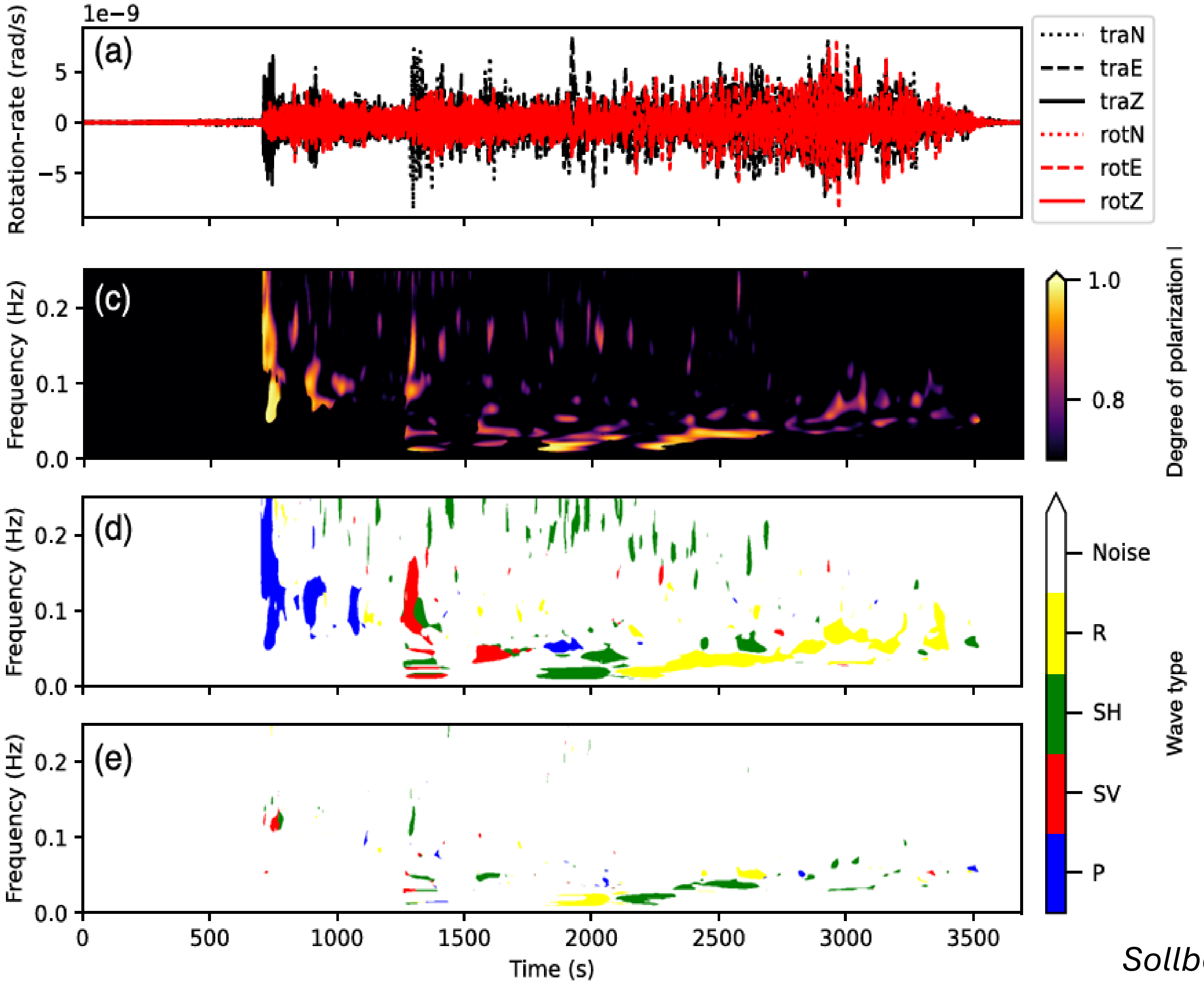
Sollberger et al. 2023

Methodology

2.) TWISTPY

Wavetype separation

2018 Gulf of Alaska earthquake

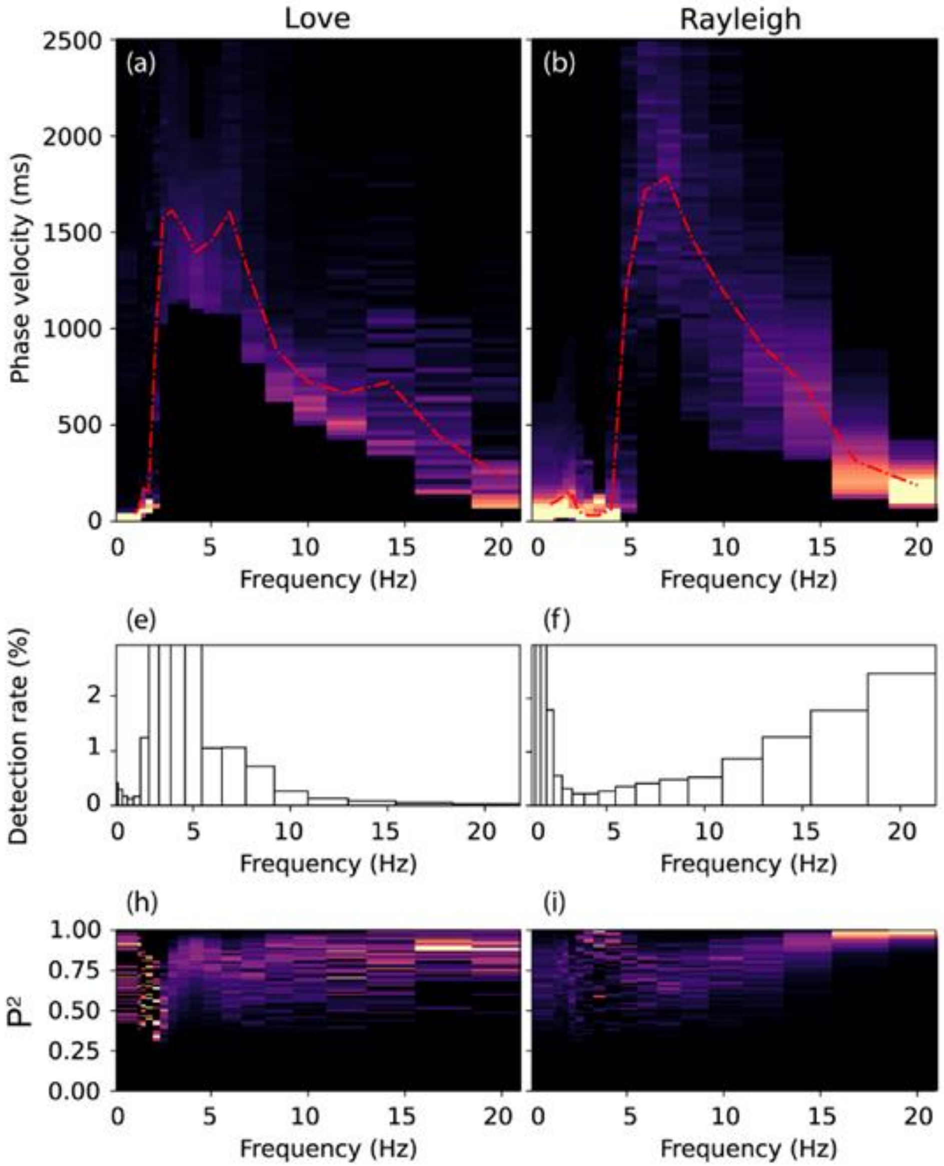


Sollberger et al. 2023

Methodology

2.) TWISTPY

Dispersion curve analysis



Sollberger et al. 2023

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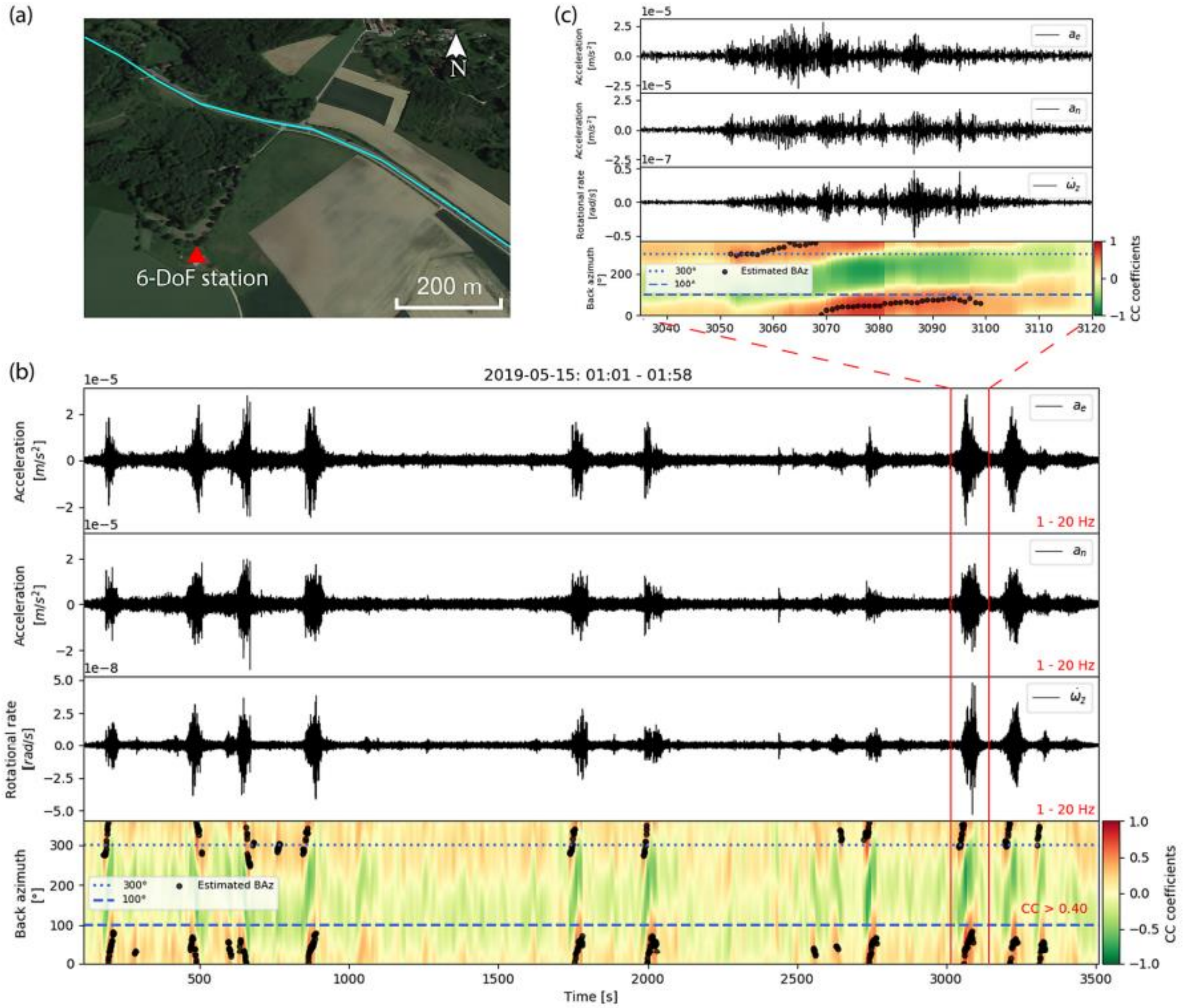
Field Studies

Source tracking:

Traffic monitoring at the geophysical observatory in Fürstenfeldbruck, Germany

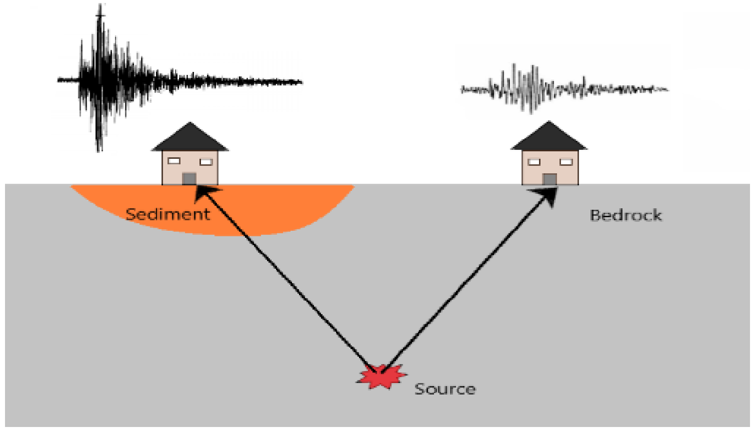
(ROMY Data)

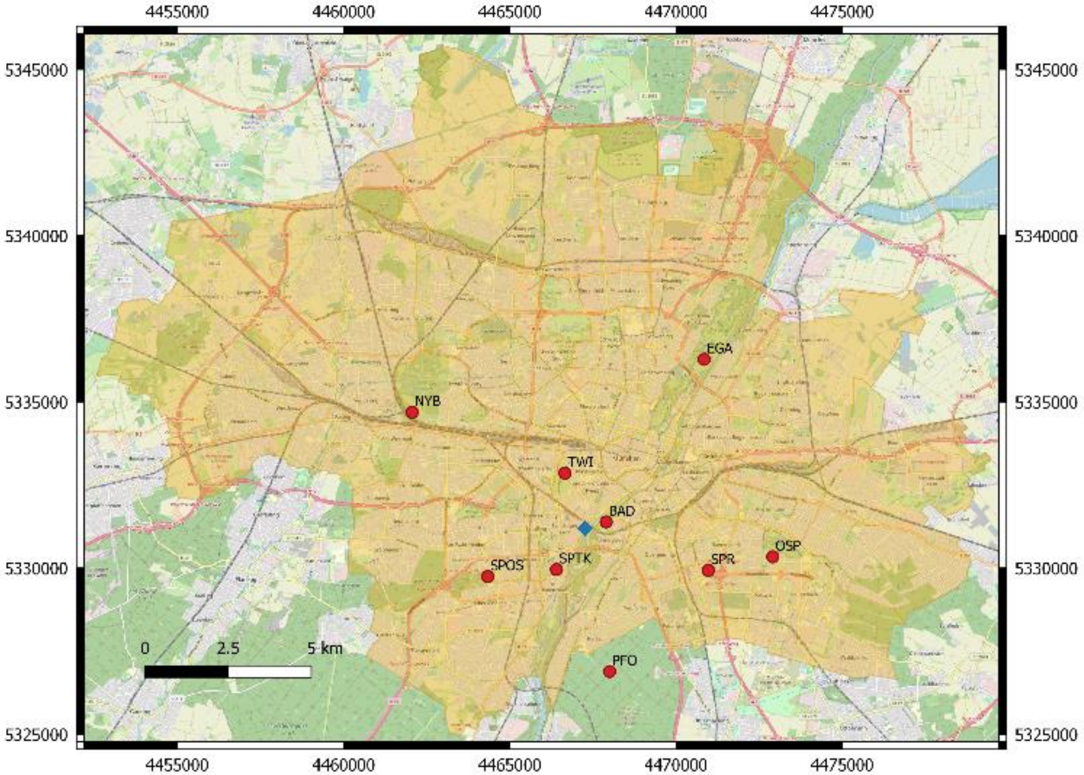
Yuan et al. 2021



Field Studies

Site Characterization

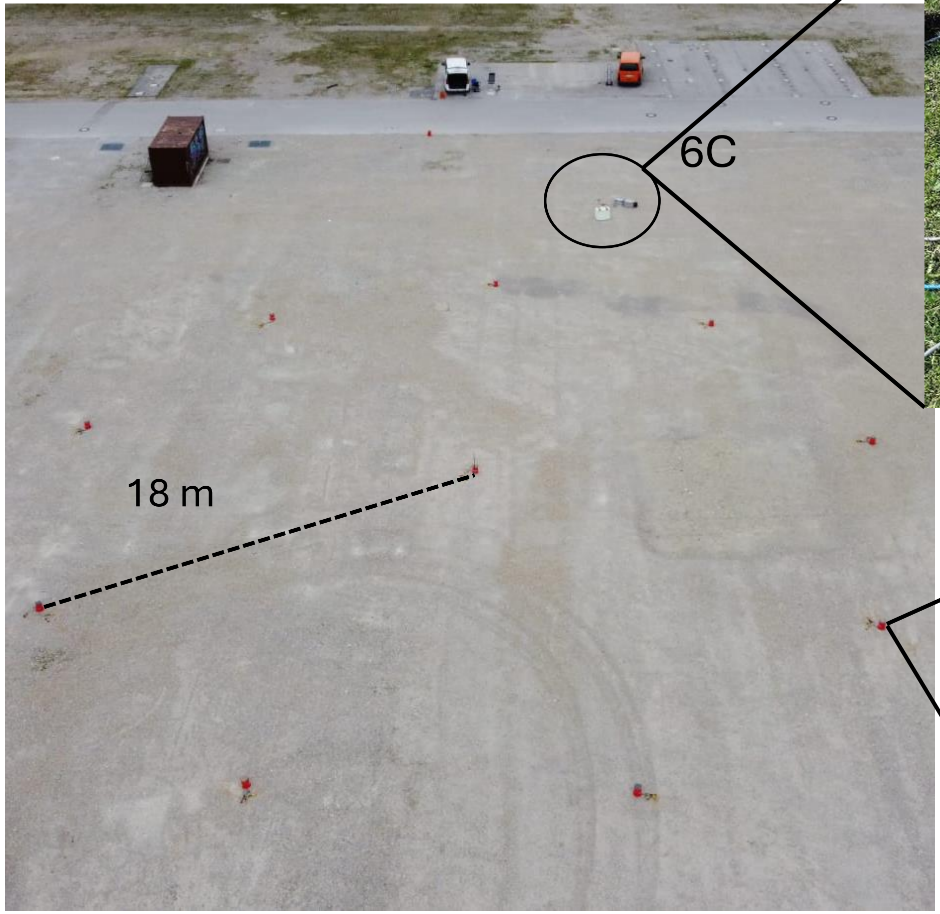




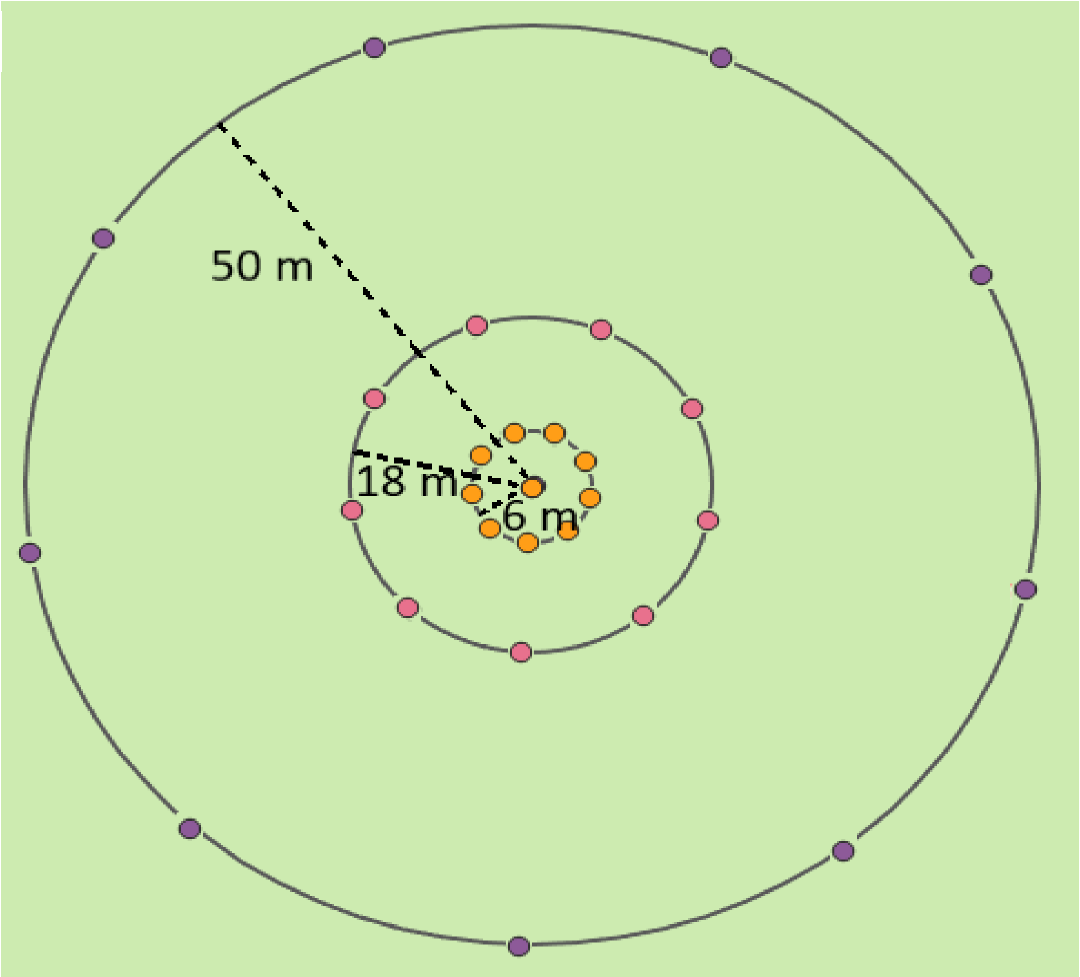
- Ambient noise measurements
- Frequency content: 1-20 Hz (urban noise)
- Trillium Compact 120s + iXblue blueSeis-3A
- ~ 2h acquisition

Field Studies

Theresienwiese



Array set-up

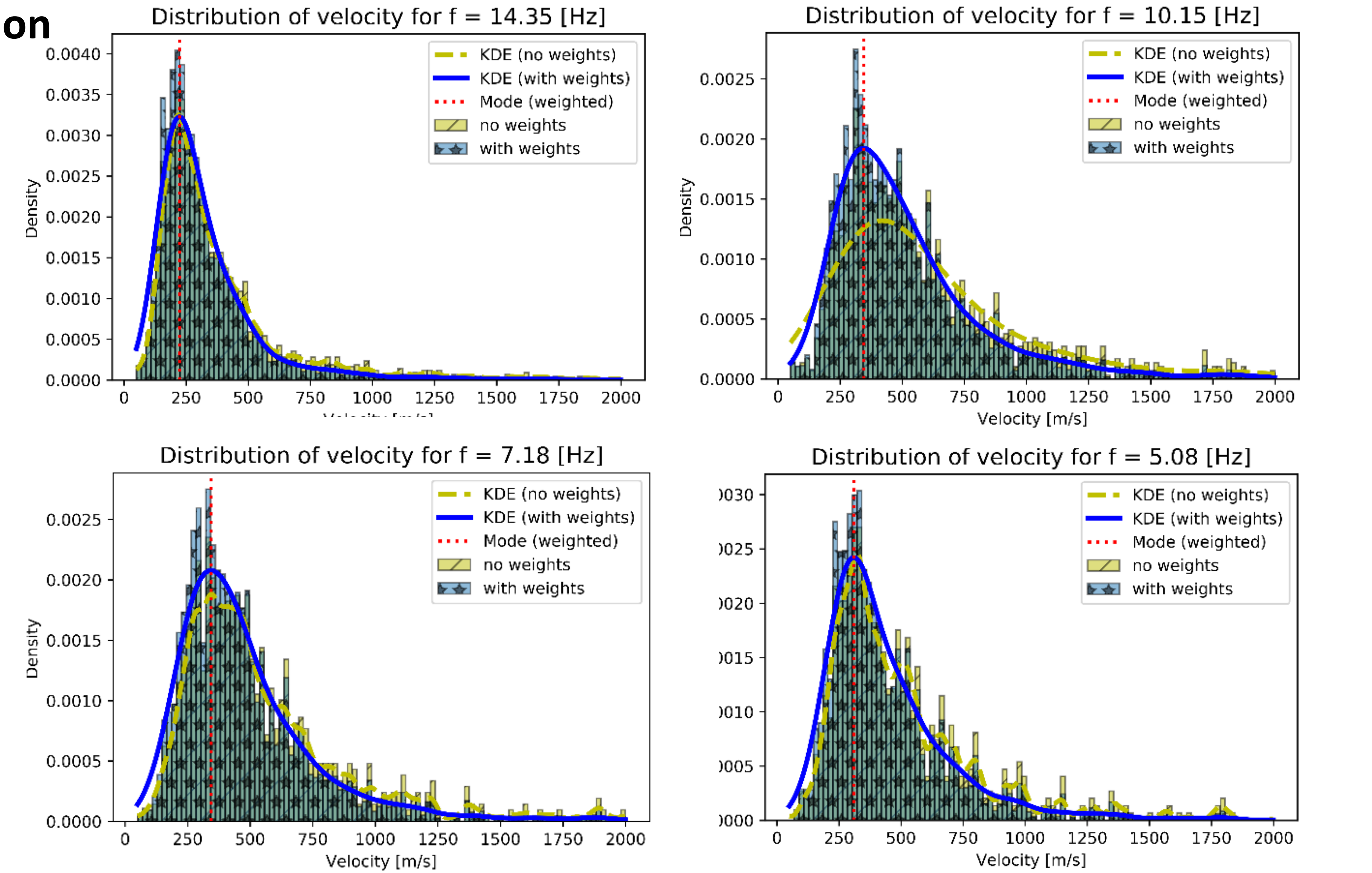


Keil et al. 2022

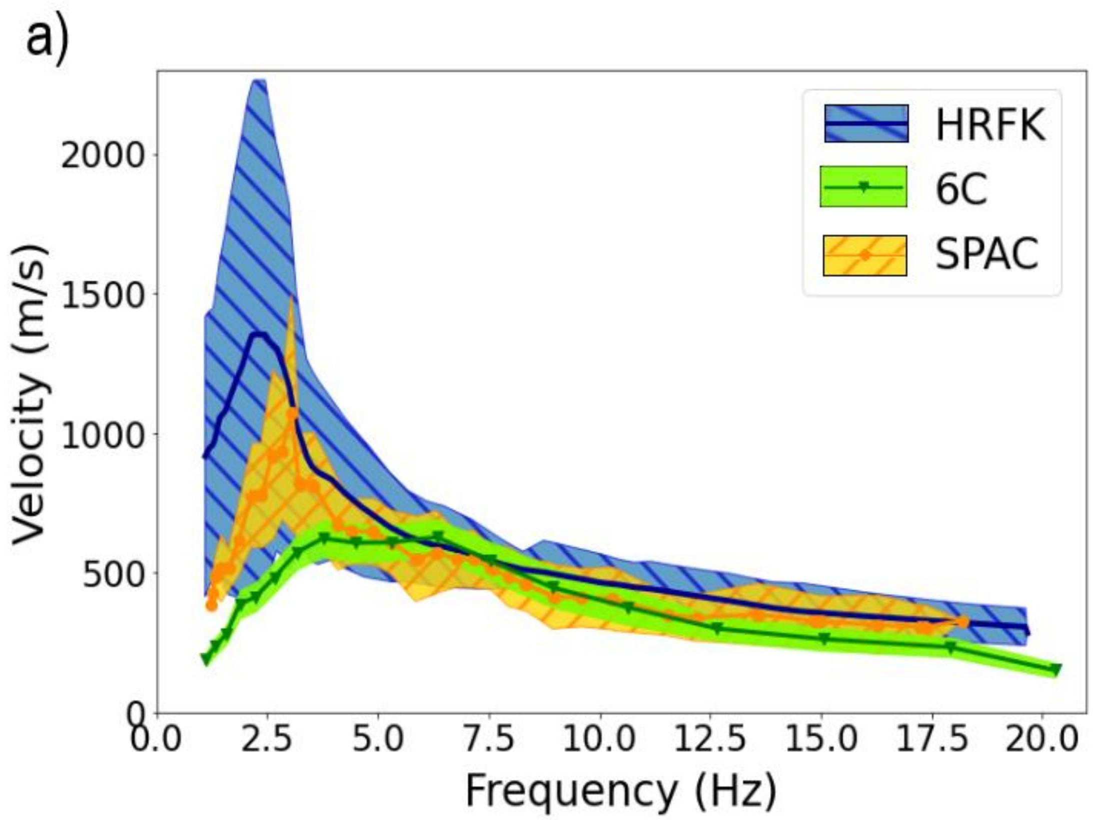
Field Studies

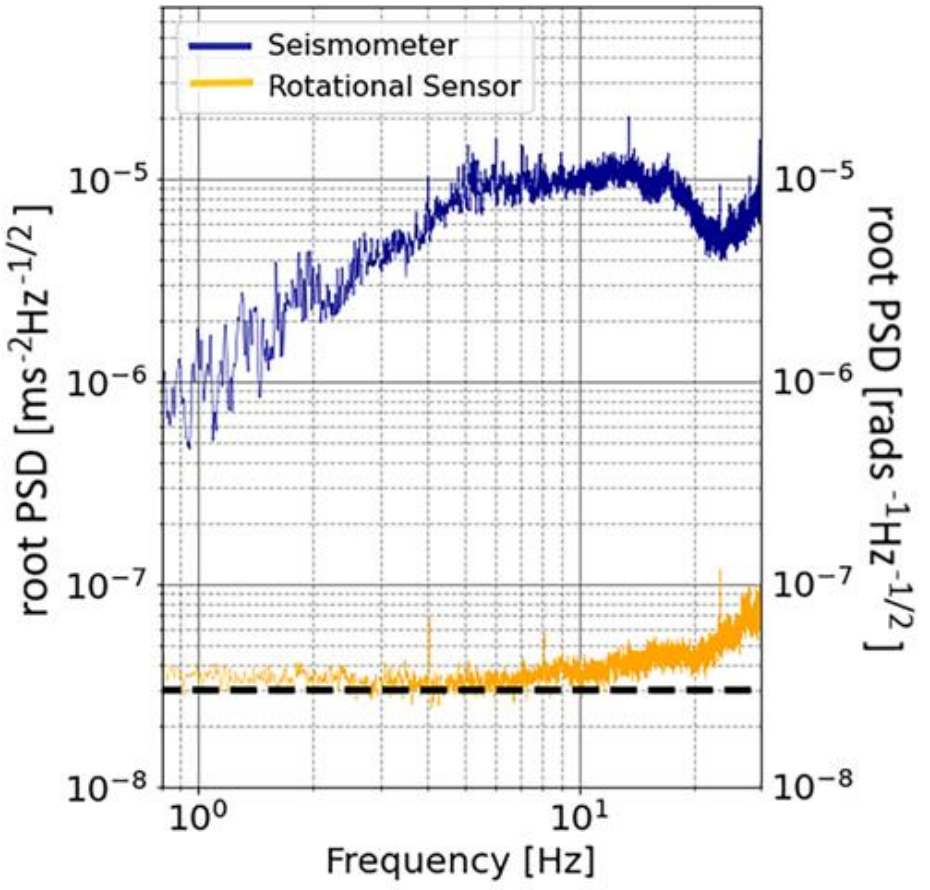
Site Characterization

$$-\frac{1}{2}\frac{a_T}{\dot{\omega}_z} = c_L(f)$$



Site Characterization

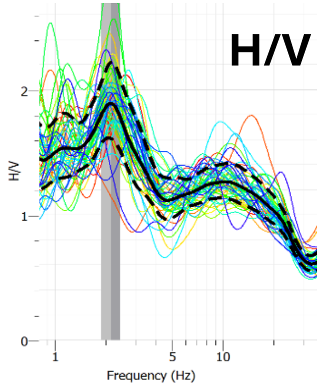


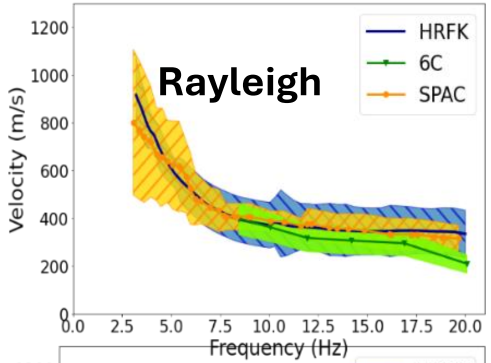


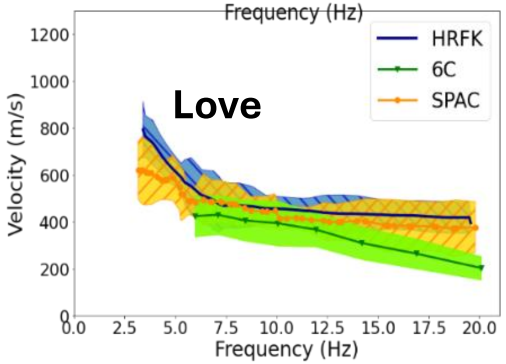
Keil et al. 2022

Field Studies

Site Characterization

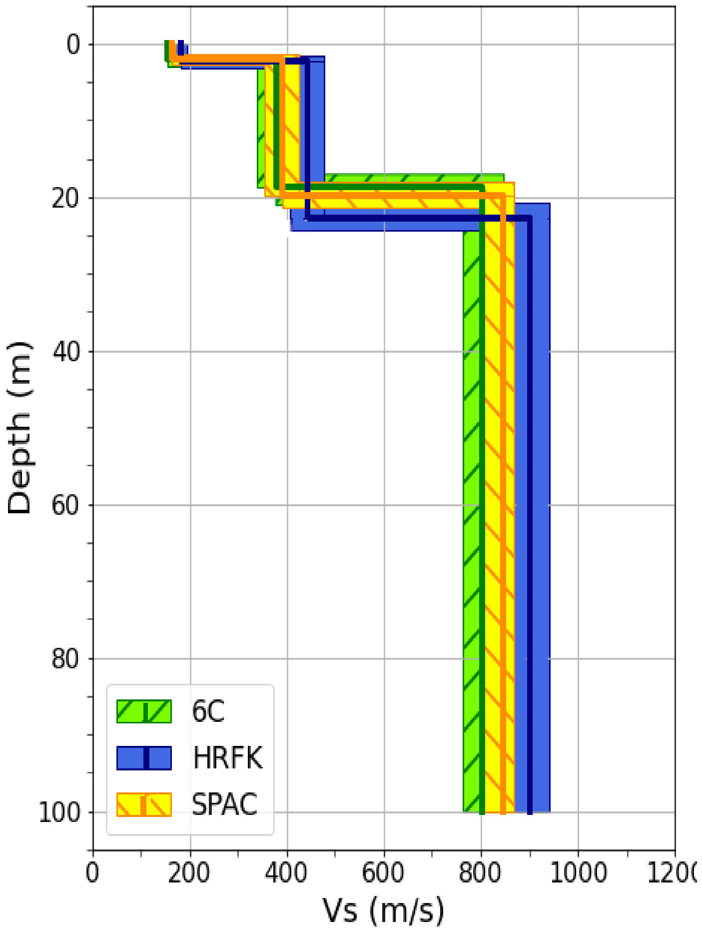






Inversion

Inversion



→ 6C method gives comparable results to array measurements

Outline

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2. Methodology

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4. Exercises 6C dispersion curve computation

Excercises

Dispersion curve extraction using simplified ROLODE and Twistpy

1.) Synthetic Data

2.) Munich ambient noise data

Literature

Igel, H., Schreiber, U., Flaws, A., Schuberth, B., Velikoseltsev, A., & Cochard, A. (2005). Rotational motions induced by the M8. 1 Tokachi-oki earthquake, September 25, 2003. *Geophysical research letters*, *32*(8).

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