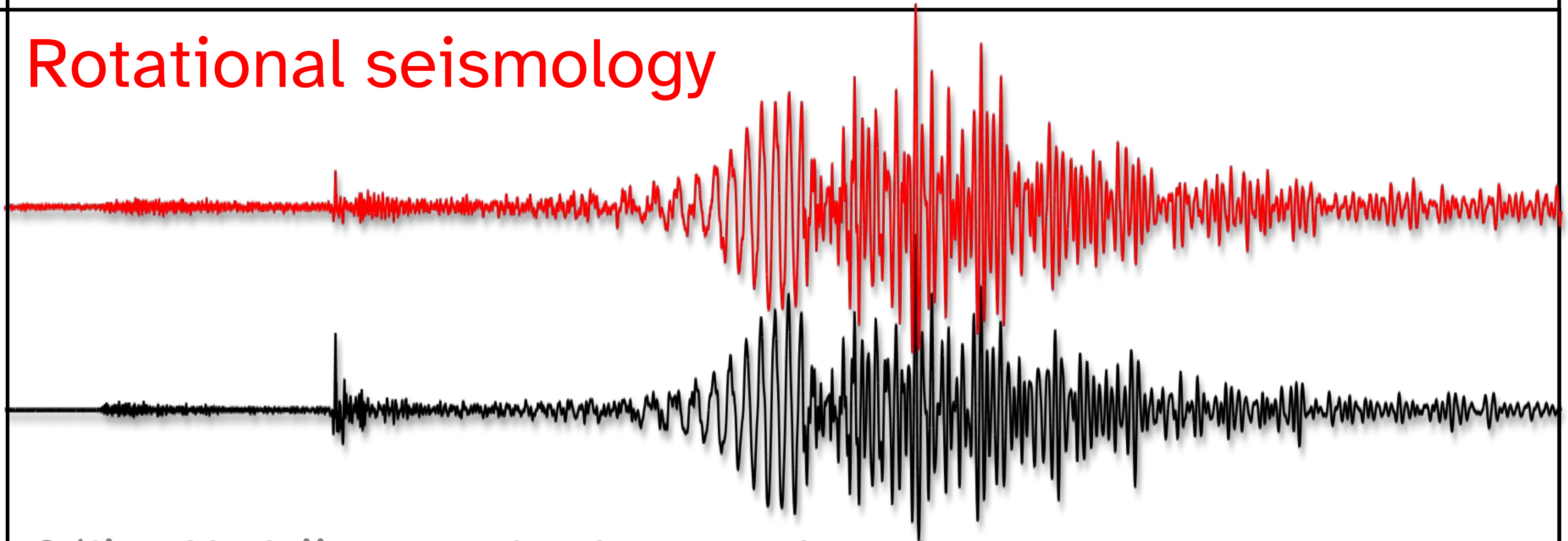
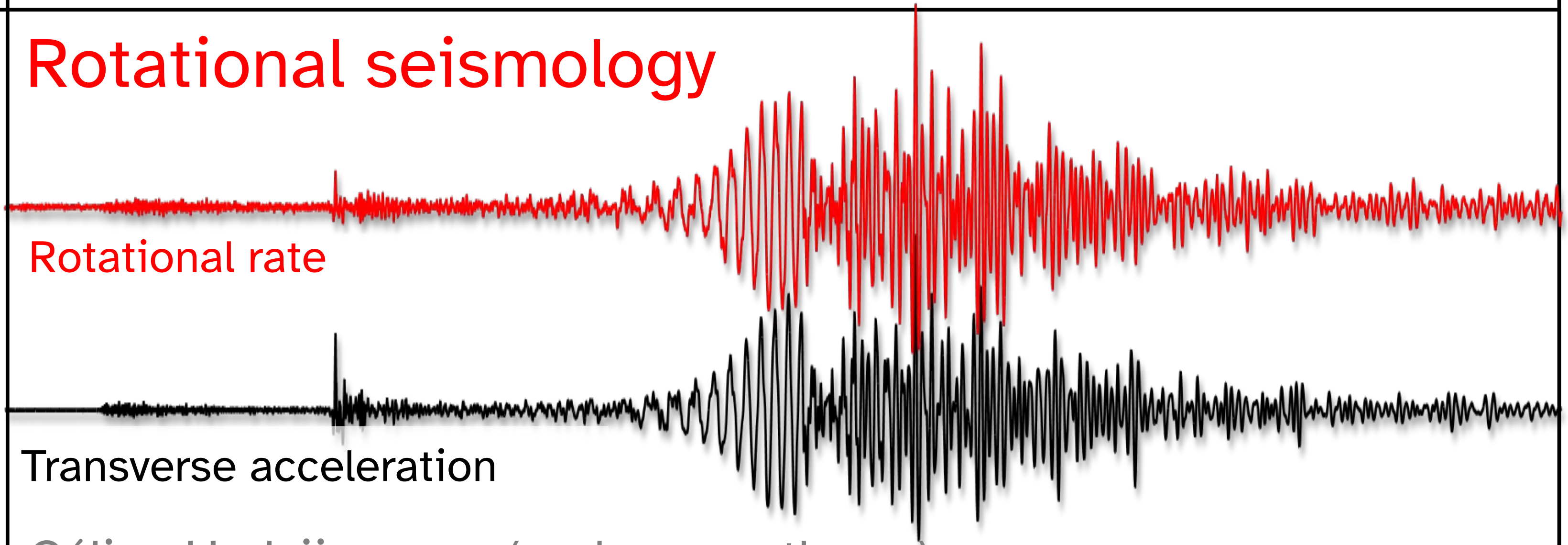
Rotational seismology



Céline Hadziioannou (and many others..)

University of Hamburg, Germany

Rotational seismology



Céline Hadziioannou (and many others..)

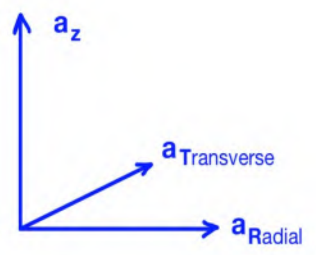
University of Hamburg, Germany

What are rotations?

Entire ground motion, all degrees of freedom

$$u(x+\delta x) = u(x) + \varepsilon\, \delta x + \omega \times \delta x$$

3C Translation



Ground acceleration

Seismometer

What are rotations?

Entire ground motion, all degrees of freedom

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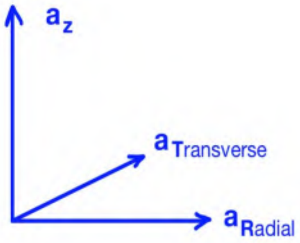
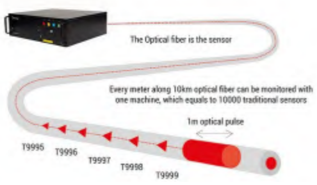
3C Translation + 6C Strain



Ground acceleration
Seismometer

Strain
Strainmeter, Distributed Acoustic Sensing (DAS)



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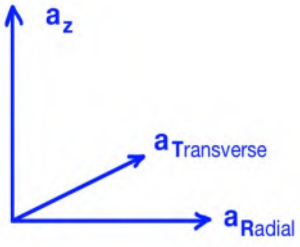

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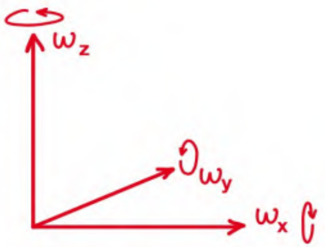
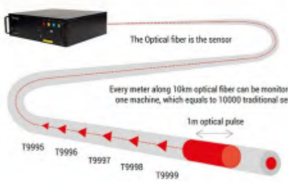


Rotation rate
Rotation sensor



Review: e.g. Cochard et al., 2006; Schmelzbach 2018

What are rotations?

Entire ground motion, all degrees of freedom

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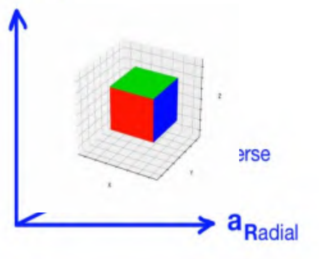

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Seismometer

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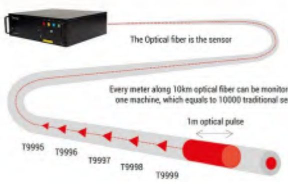
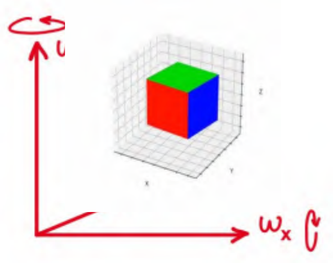




Rotation rate
Rotation sensor

Animation by Felix Bernauer
Review: e.g. Cochard et al., 2006; Schmelzbach 2018

Why?

Structural engineering

Why?

Source

Structure

Wavefield

Structural engineering

Why?

Source

Structure

Instrumentation

Wavefield

Structural engineering

Why?

Source

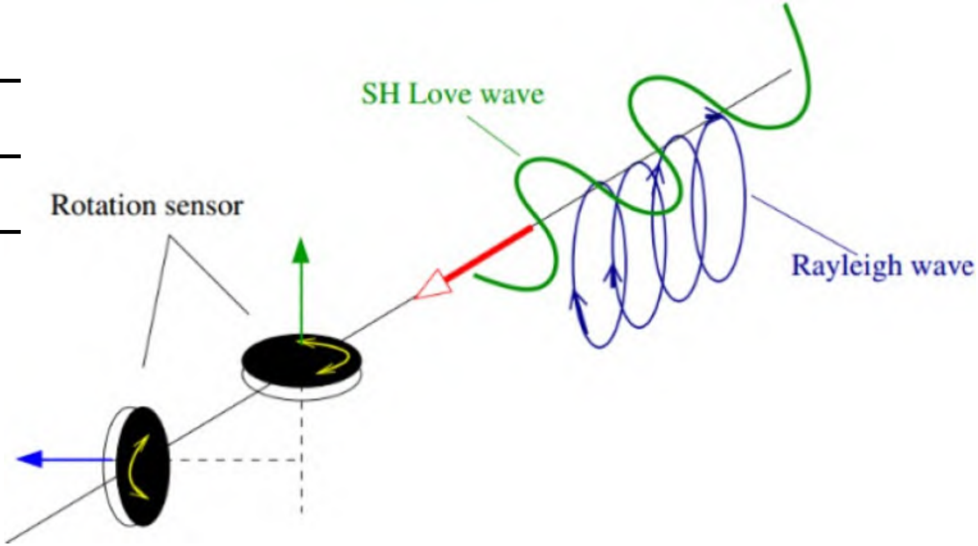
Structure

Instrumentation

Wavefield

Structural engineering

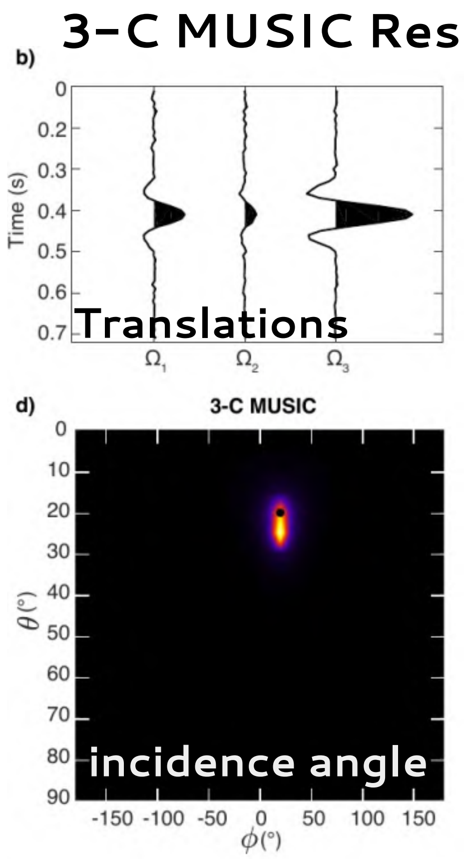
Rotations → wavetype filter

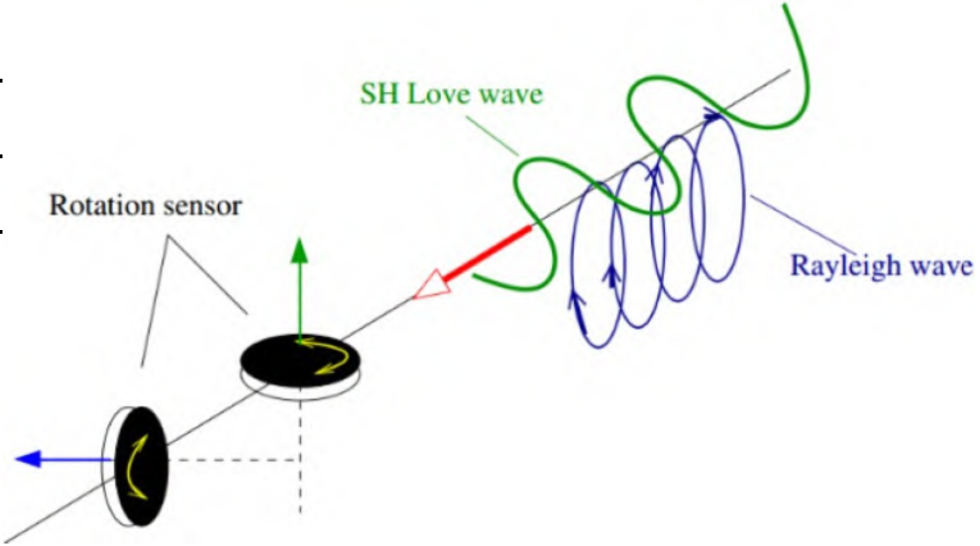


Love & SH motion → vertical rotation
Rayleigh → horizontal rotation

Rotations → wavetype filter

Polarization analysis: 3 vs 6 components

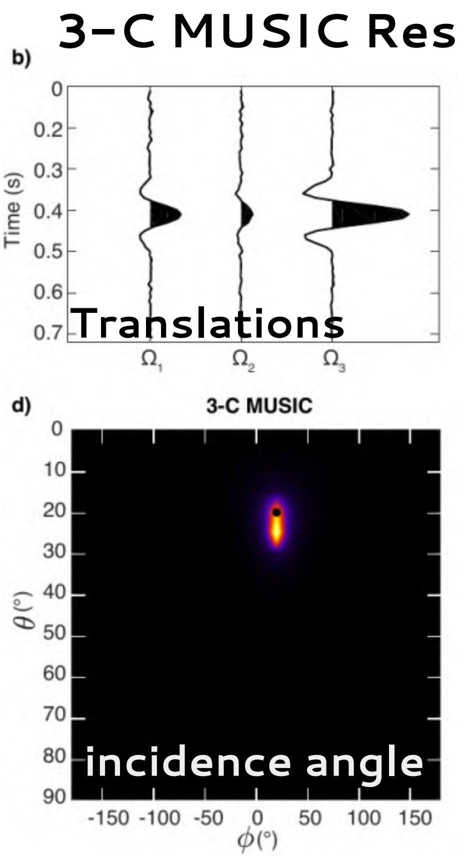


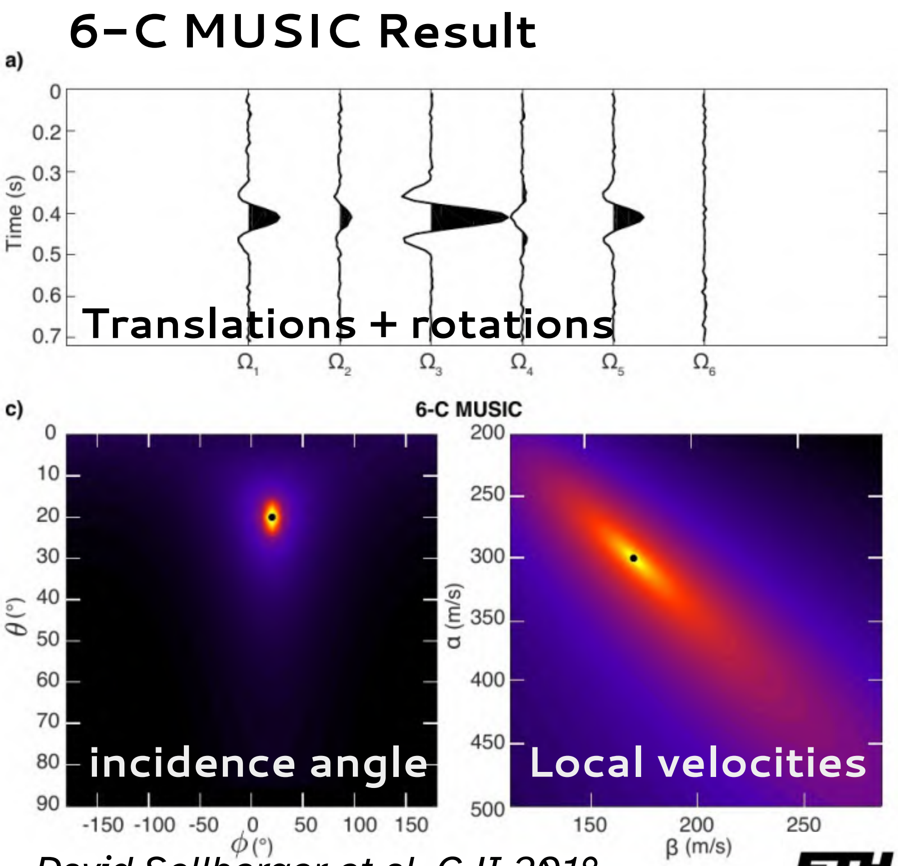


Love & SH motion → vertical rotation
Rayleigh → horizontal rotation

Rotations → wavetype filter

Polarization analysis: 3 vs 6 components





Sabrina Keil

David Sollberger et al. GJI 2018

Overview

Source

Structure

Instrumentation

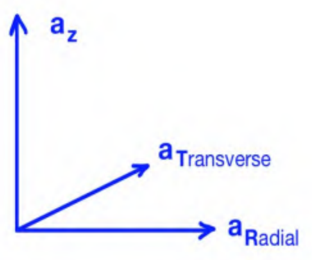
Wavefield

- Wavetype separation
- Wavetype ratios

Structural engineering

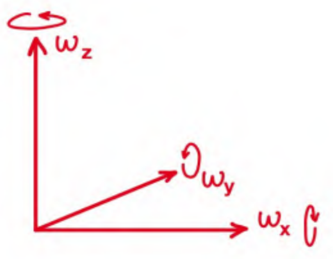
Combining Rotation and Translation

3C Translation



Ground acceleration
Seismometer

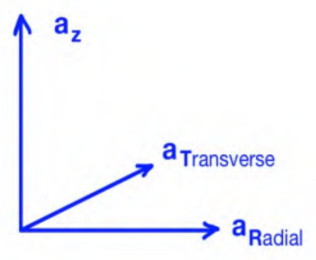
+ 3C Rotation



Rotation rate
Rotation sensor

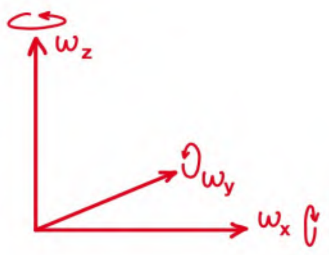
Combining Rotation and Translation

3C Translation



Ground acceleration
Seismometer

+ 3C Rotation

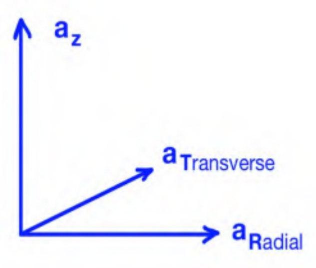


Rotation rate
Rotation sensor

$$\frac{a_T}{\dot{\omega}_z}$$

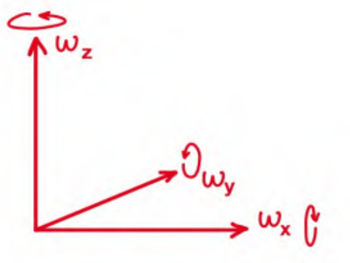
Combining Rotation and Translation

3C Translation



Ground acceleration
Seismometer

+ 3C Rotation

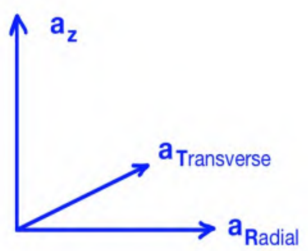


Rotation rate
Rotation sensor

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

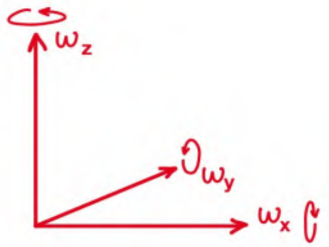
Combining Rotation and Translation

3C Translation



Ground acceleration
Seismometer

+ 3C Rotation

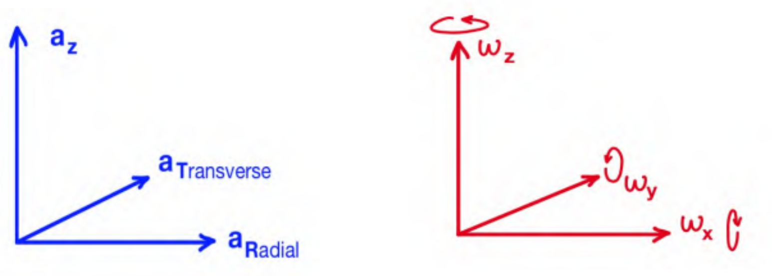


Rotation rate
Rotation sensor

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

Combining Rotation and Translation

3C Translation + 3C Rotation



Ground acceleration
Seismometer

Rotation rate
Rotation sensor

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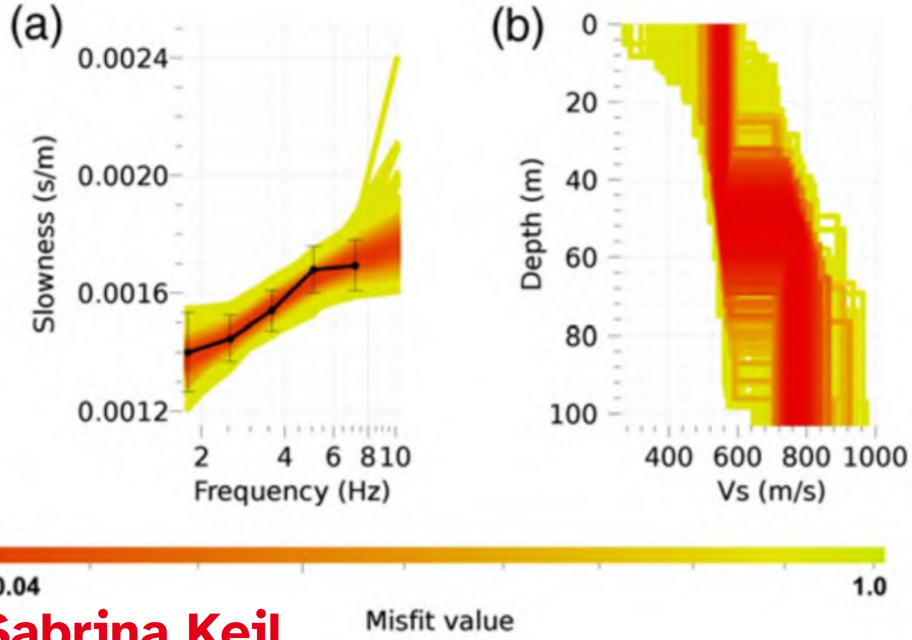
+ Rotation rate and acceleration should be **in phase**
+ amplitudes scaled by **two times the horizontal phase velocity.**

phase velocity → using single measurement of 6C → **structure**
in phase → waveforms similar → can find source direction → **source**

Structure – determining it using 6C

Single 6C-station dispersion curves:

$$c(f) = -\frac{1}{2}\ddot{u}_T(f)/\dot{\omega}_3(f)$$



Sabrina Keil

Wassermann et al., BSSA 2016

Structure – determining it using 6C

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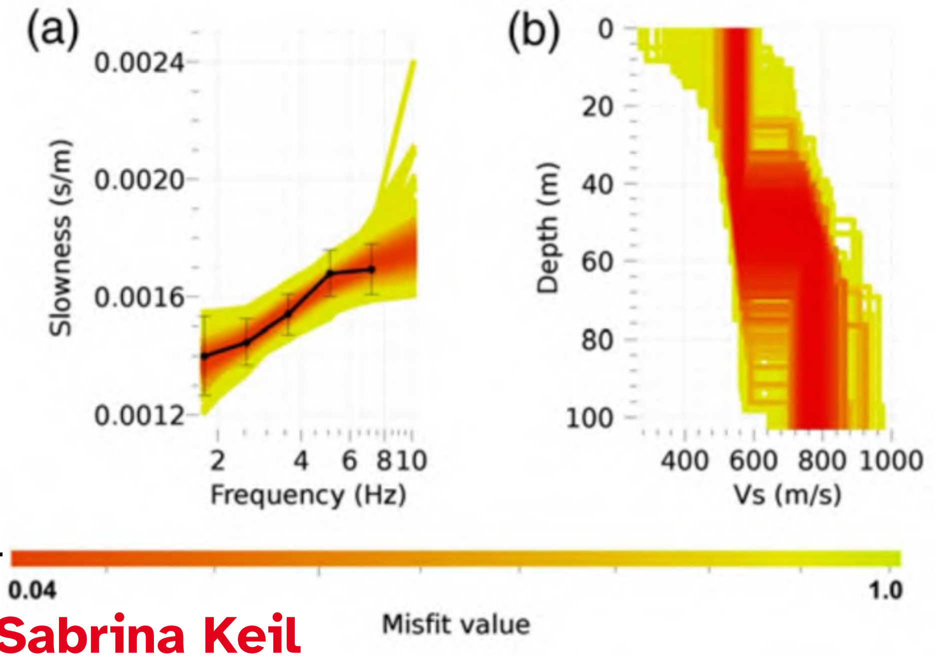
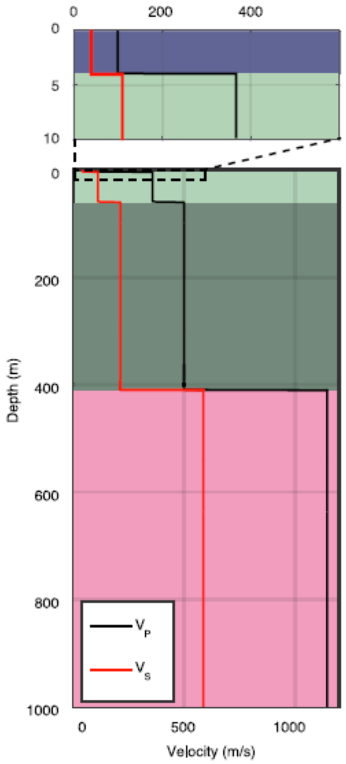


Sabrina Keil

Wassermann et al., BSSA 2016

Lunar Vp & Vs structure
"Point" 6C measurement



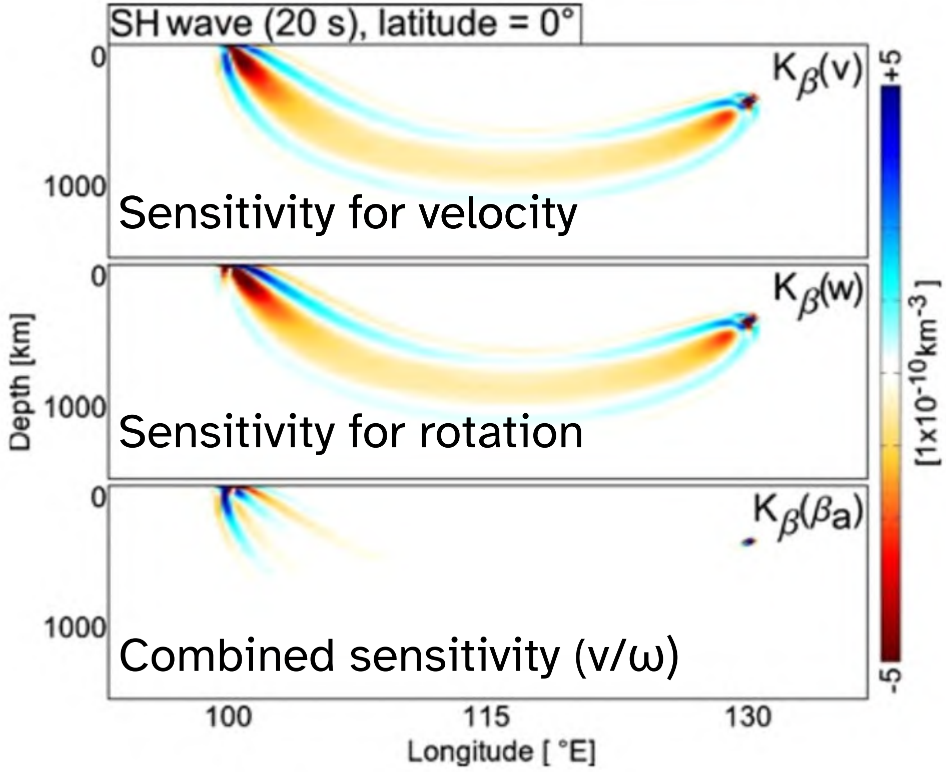
Sollberger et al., GRL 2016

Structure – sensitivity kernels

Sensitivity kernels for:

$$\frac{\dot{v}_T(x,t)}{\omega(x,t)} = -2c(x)$$

+ Local near surface structure
+ Without source info
- accurate amplitudes needed



Bernauer et al., Geophysics 2009
Fichtner & Igel, BSSA 2009
Bernauer et al., J. Seismol. 2012

Overview

Source

Instrumentation

Structure

- Phase velocity
- Dispersion
- Sensitivity kernels

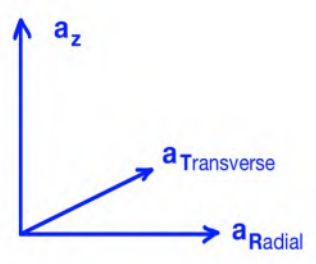
Wavefield

- Wavetype separation
- Wavetype ratios

Structural engineering

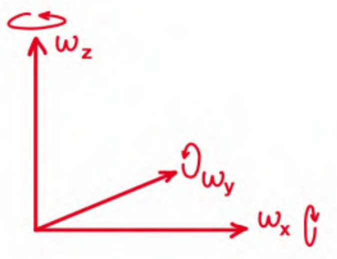
Combining Rotation and Translation

3C Translation



Ground acceleration
Seismometer

+ 3C Rotation



Rotation rate
Rotation sensor

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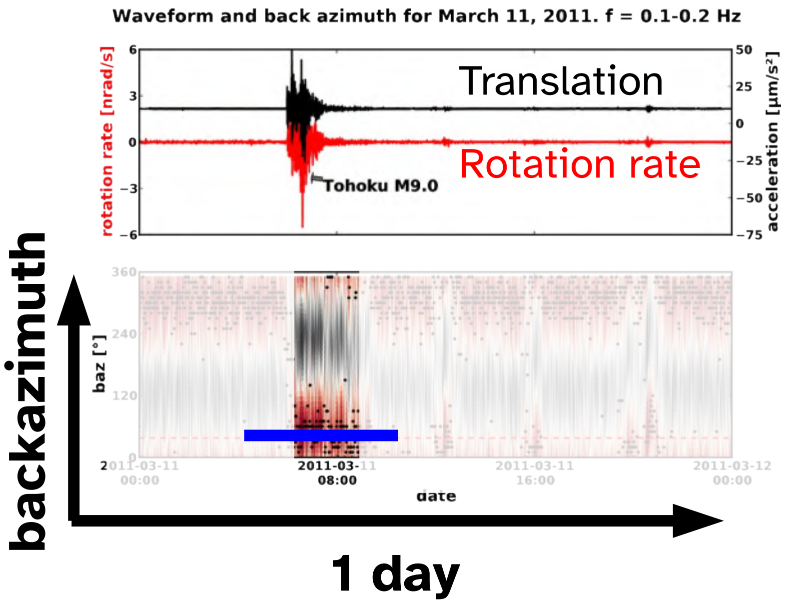
Source – source direction

Filtered 0.1 – 0.2 Hz

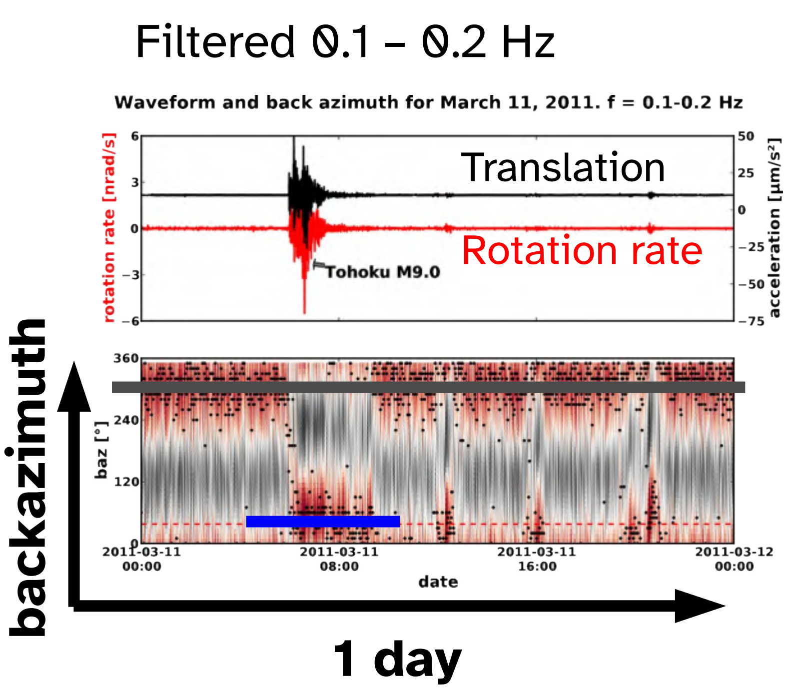


Corrcoef = 1
Corrcoef =-1

Hadziioannou et al. 2012, SRL

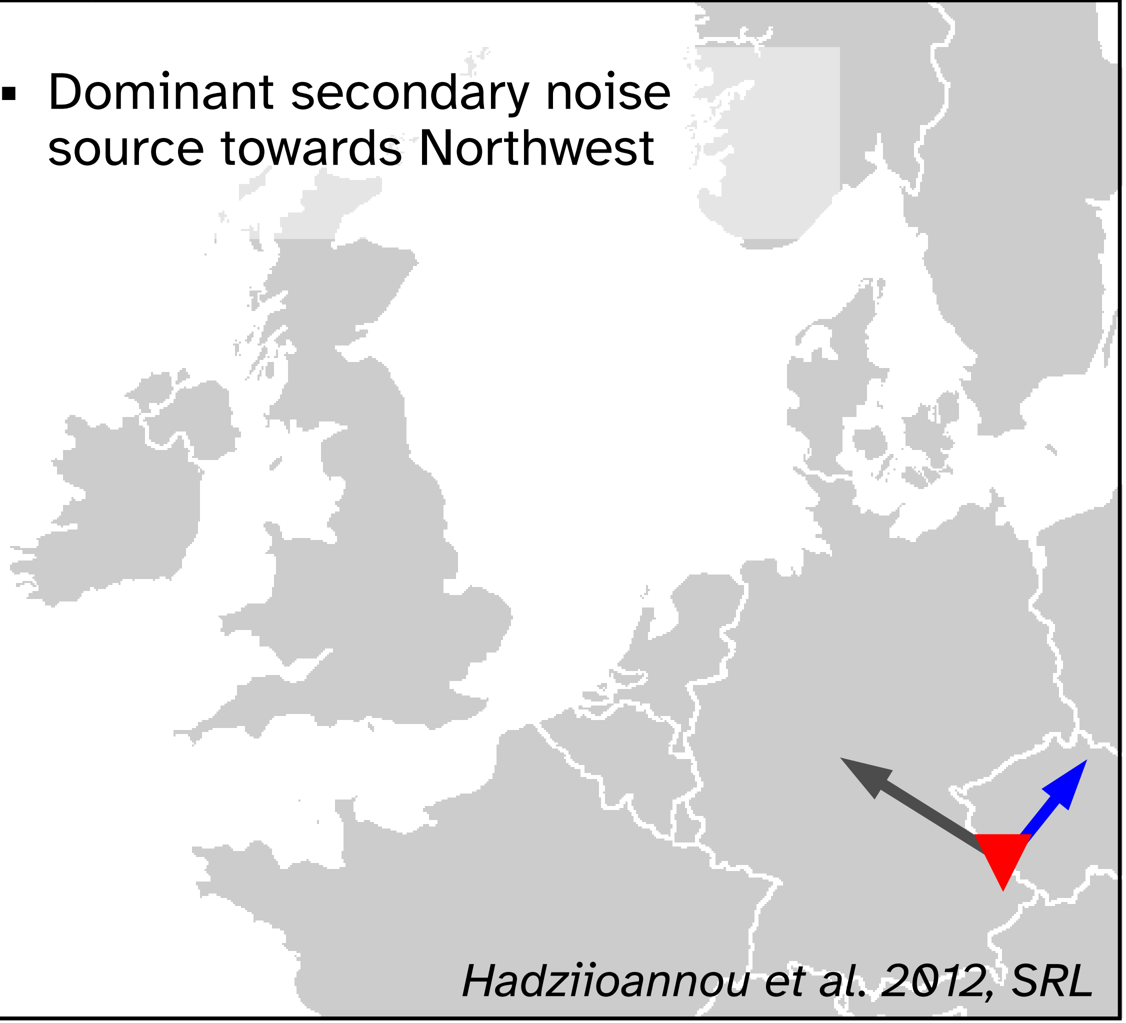
Source – source direction

Filtered 0.1 – 0.2 Hz



Corrcoef = 1
Corrcoef =-1

- Dominant secondary noise source towards Northwest



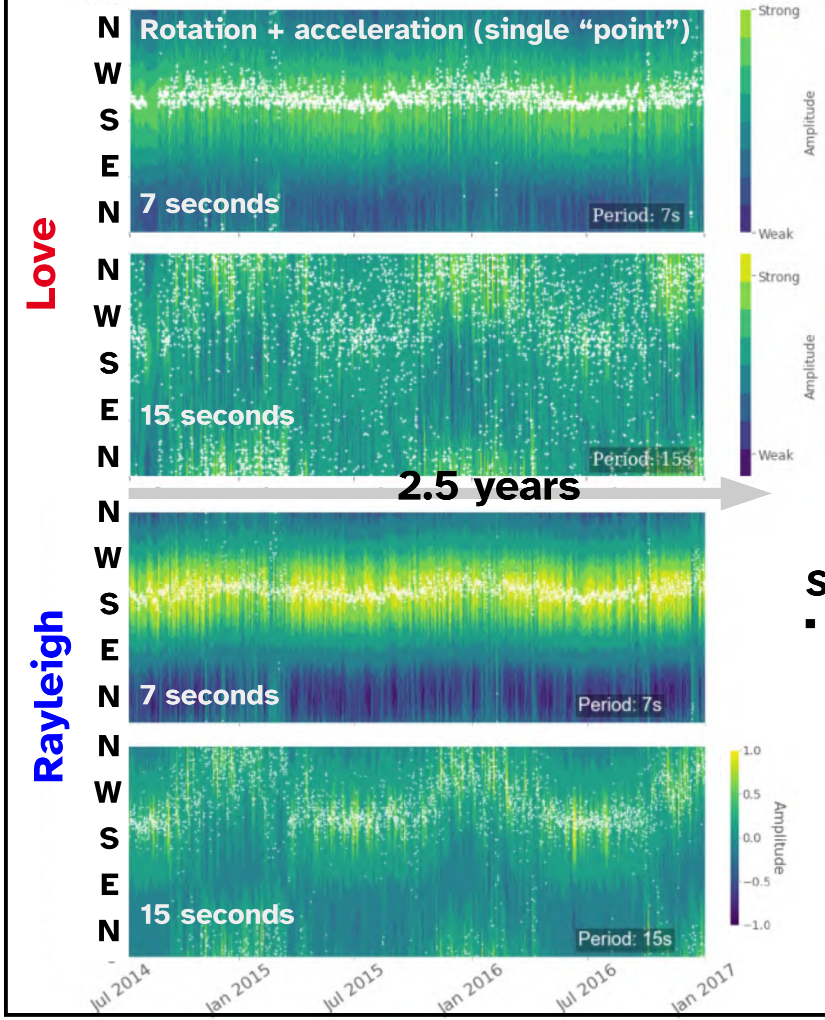
Hadziioannou et al. 2012, SRL

Source – source direction

***Single-point* backazimuth determination**
- Direction of secondary and primary microseism

Christoph Schroeer (UHH)

Source – source direction

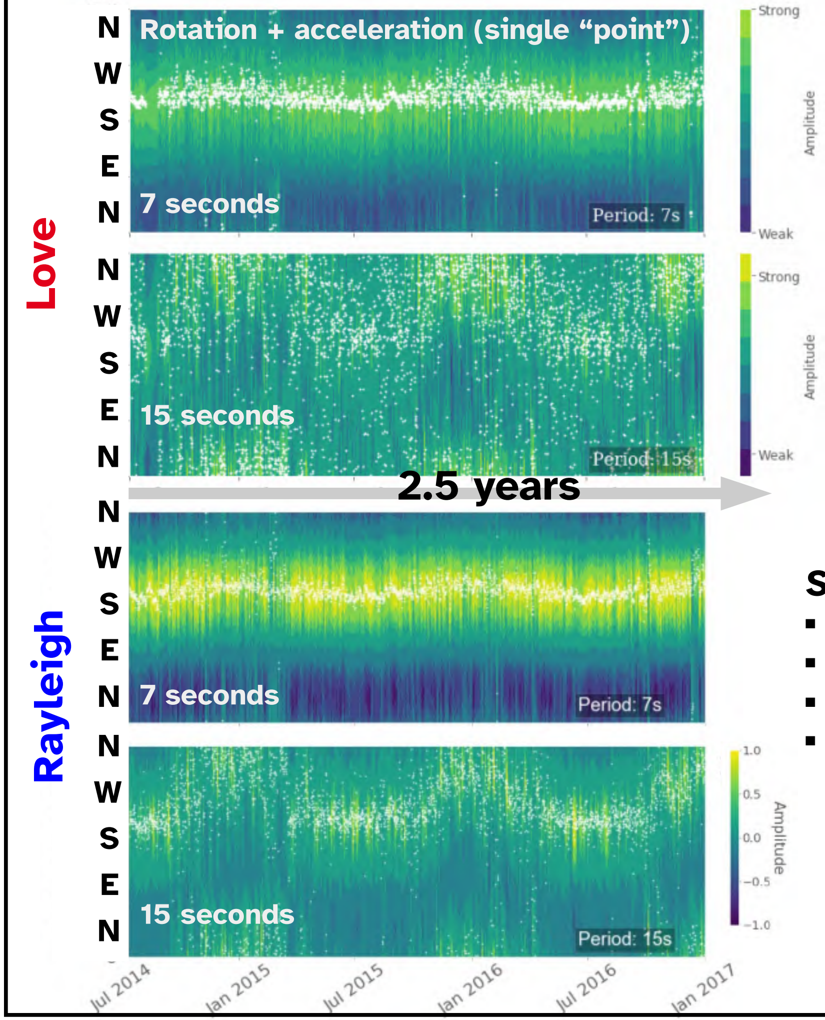


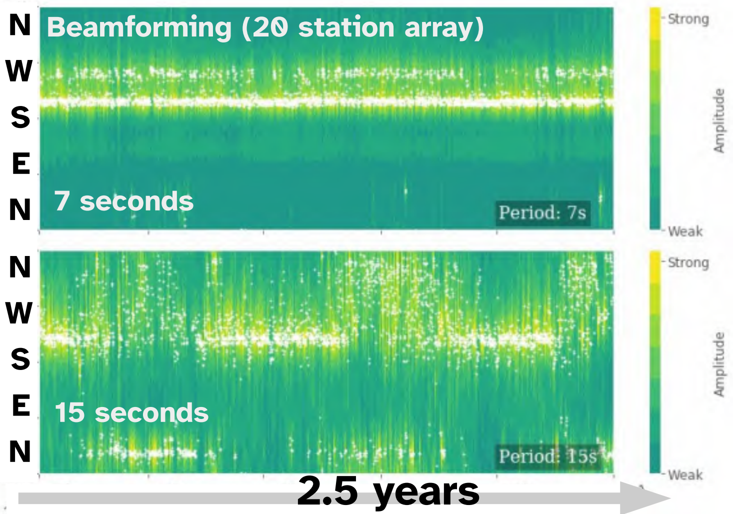
***Single-point* backazimuth determination**

- Direction of secondary and primary microseism

Christoph Schroeer (UHH)

Source – source direction





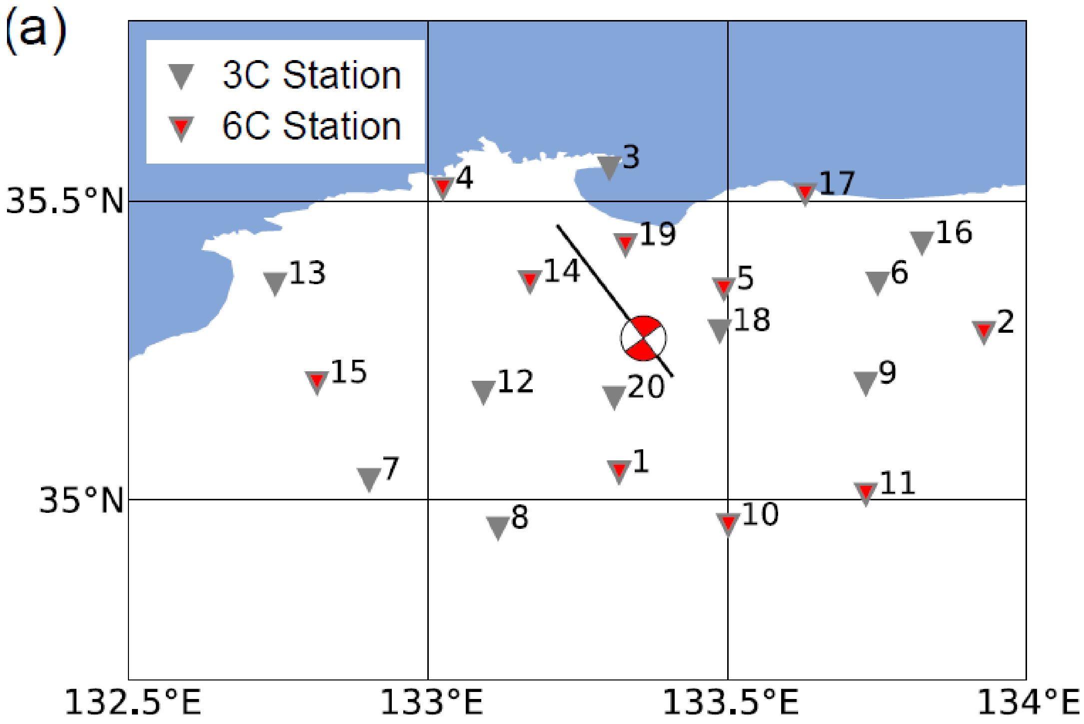
Single-point **backazimuth determination**

- Direction of secondary and primary microseism
- Compare **rotation** measurements to **beamforming**
- Dominant source retrieved, fits with beamforming
- *Separation of simultaneous sources needs work*

Christoph Schroeer (UHH)

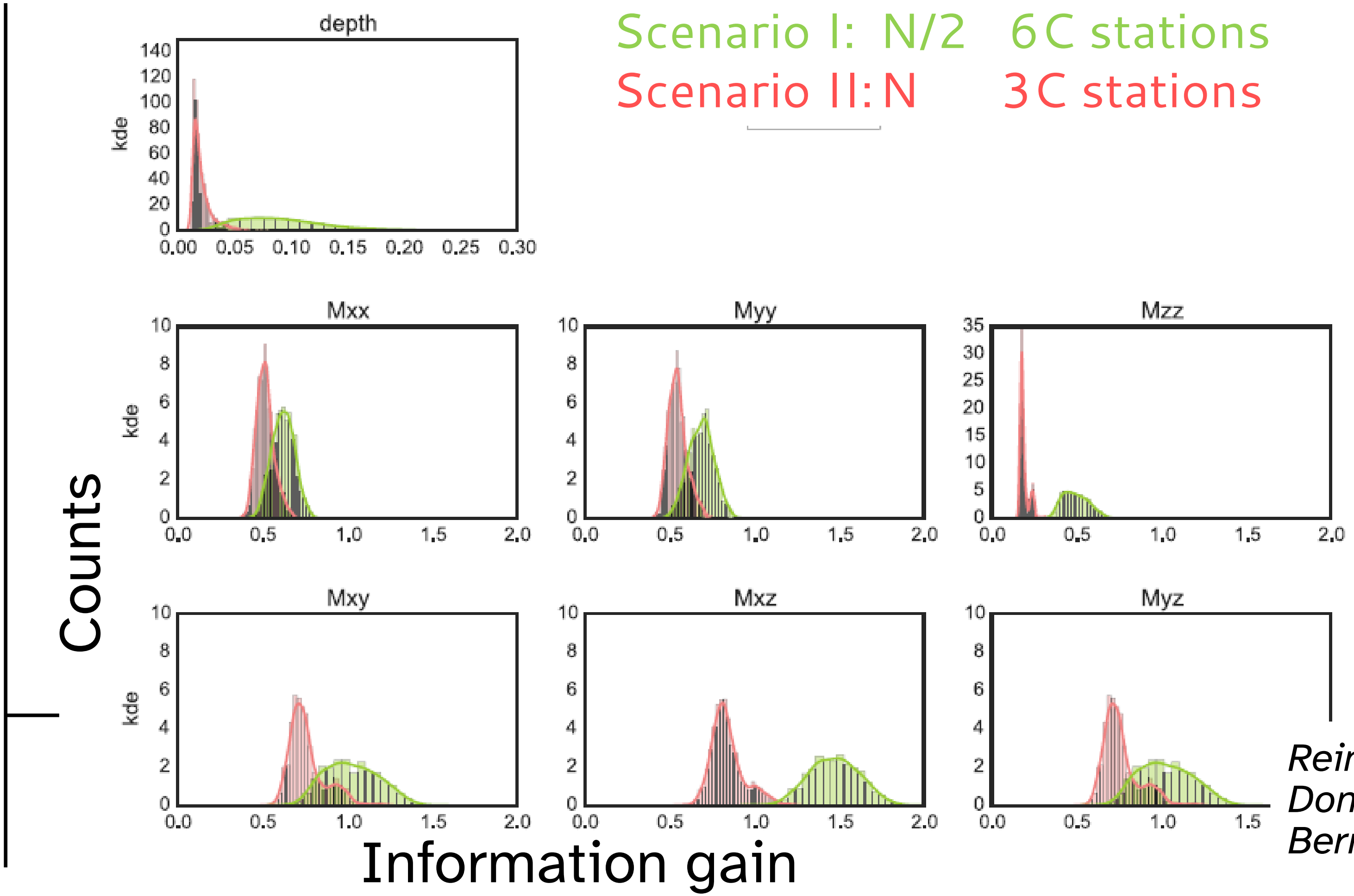
Earthquake Source inversion

improved constraints on kinematic and point source parameters with ½ the stations
+ Scenario I: N receivers with 3C observations (translations)
+ Scenario II: N/2 receivers with 6C observations (translations and rotations)



Reinwald et al,. Solid Earth 2016
Donner et al., GJI 2016
Bernauer et al, JGR: SE 2014

Earthquake Source inversion



Reinwald et al,. Solid Earth 2016
Donner et al., GJI 2016
Bernauer et al, JGR: SE 2014

Earthquake Source inversion

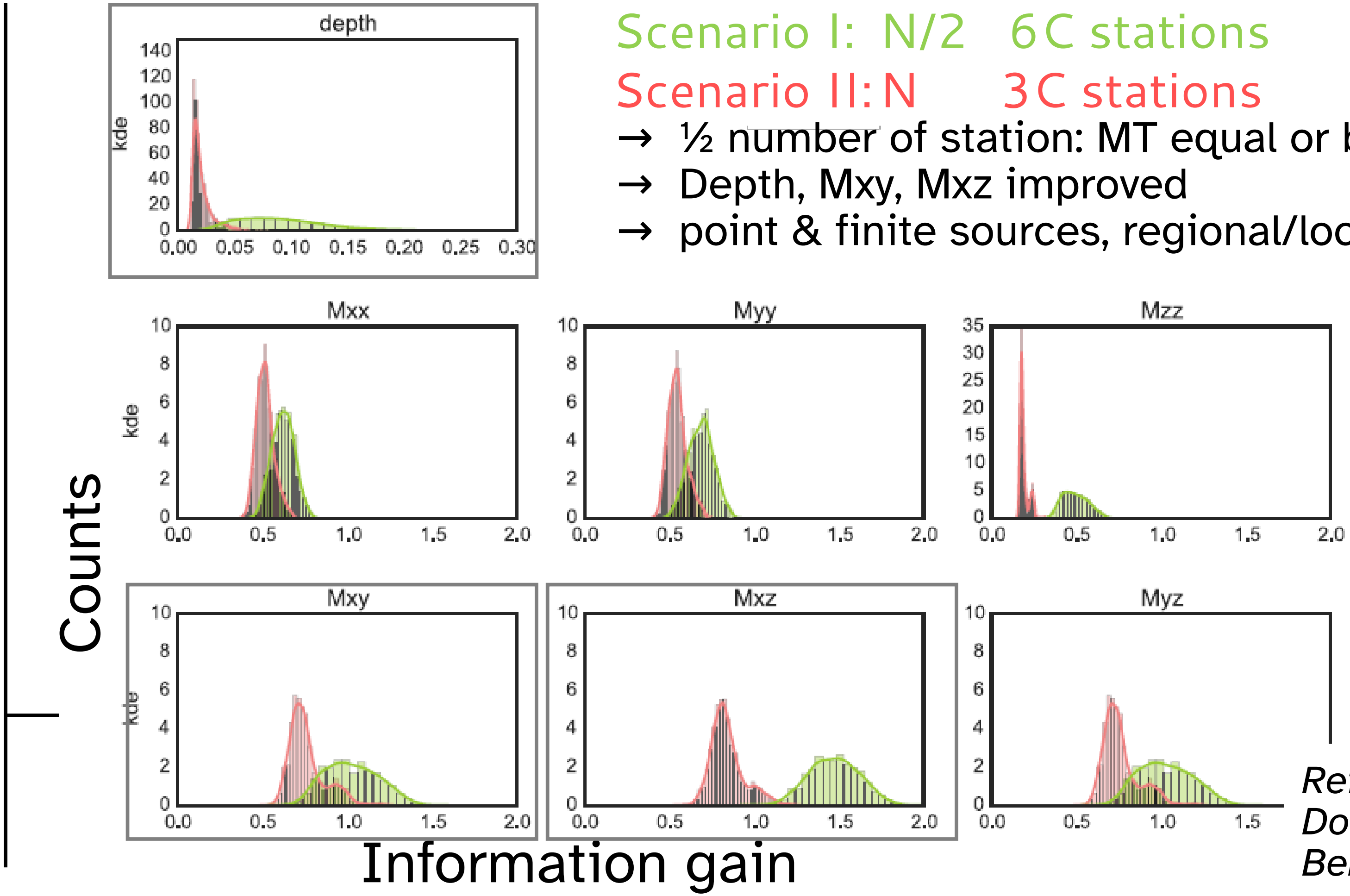
Scenario I: N/2 6C stations

Scenario II: N 3C stations

→ ½ number of station: MT equal or better retrieved

→ Depth, Mxy, Mxz improved

→ point & finite sources, regional/local



Reinwald et al,. Solid Earth 2016

Donner et al., GJI 2016

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Overview

Source
- MT inversion
- Microseisms

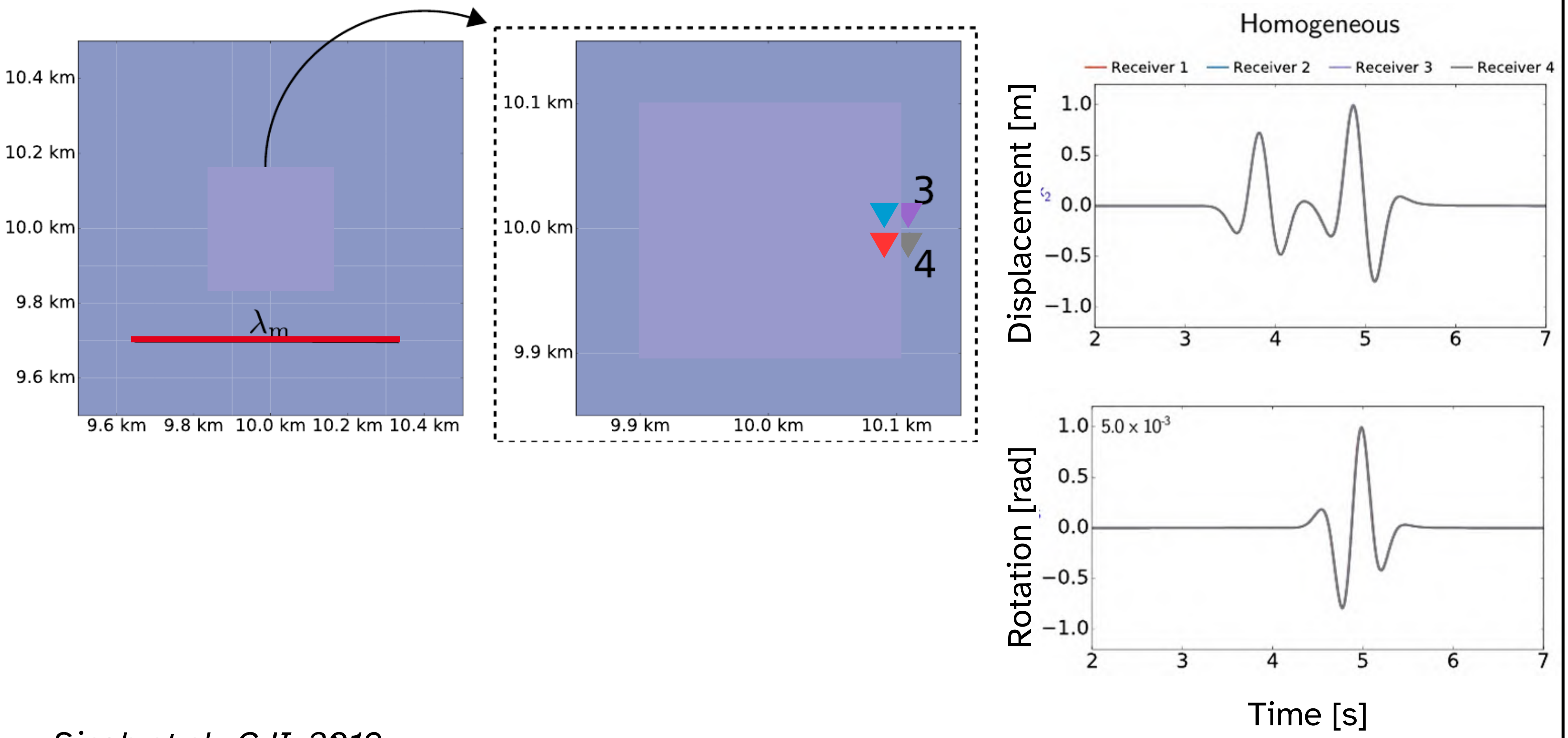
Instrumentation

Structure
- Phase velocity
- Dispersion
- Sensitivity kernels

Wavefield
- Wavetype separation
- Wavetype ratios

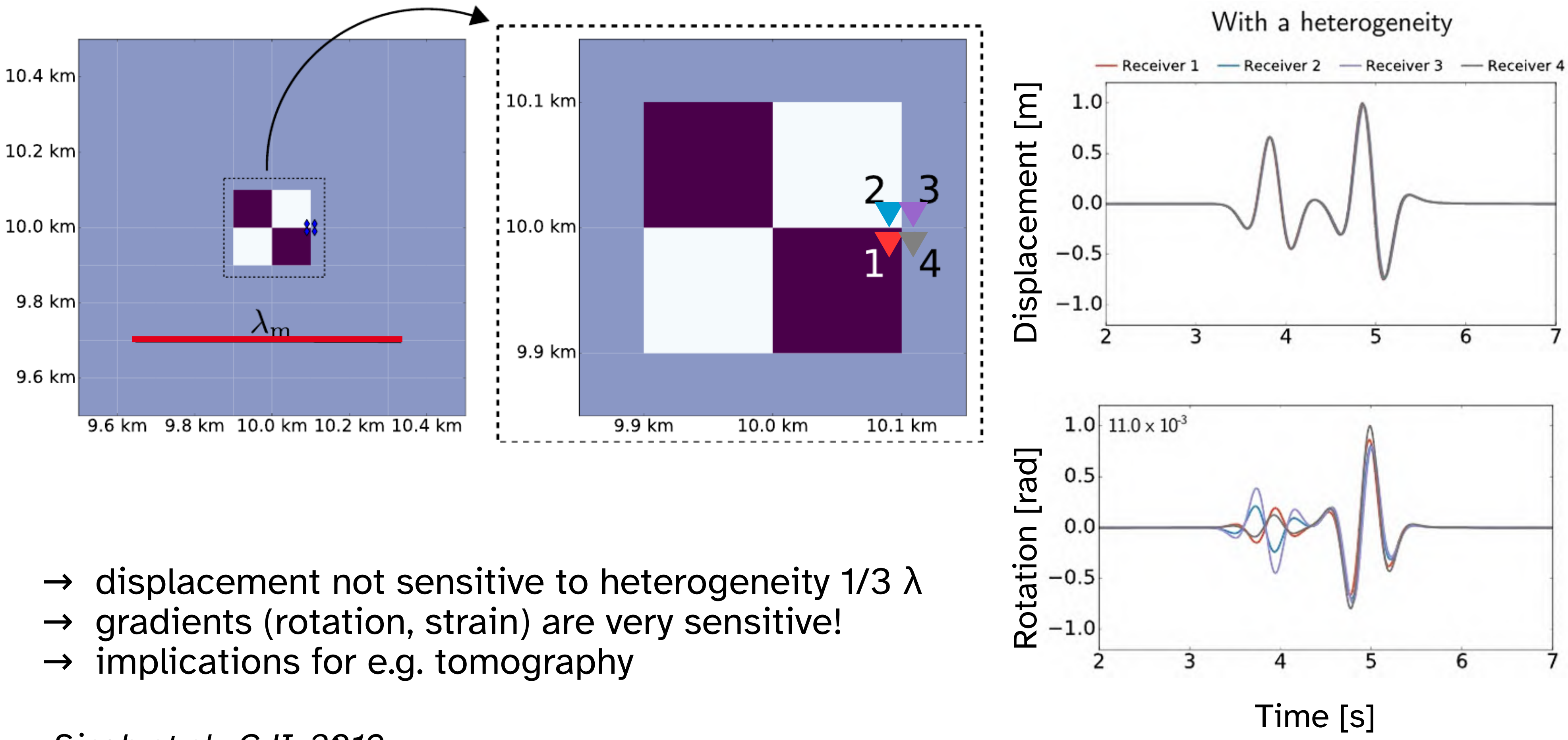
Structural engineering

Structure – sensitivity to heterogeneity



Singh et al., GJI, 2019

Structure – sensitivity to heterogeneity

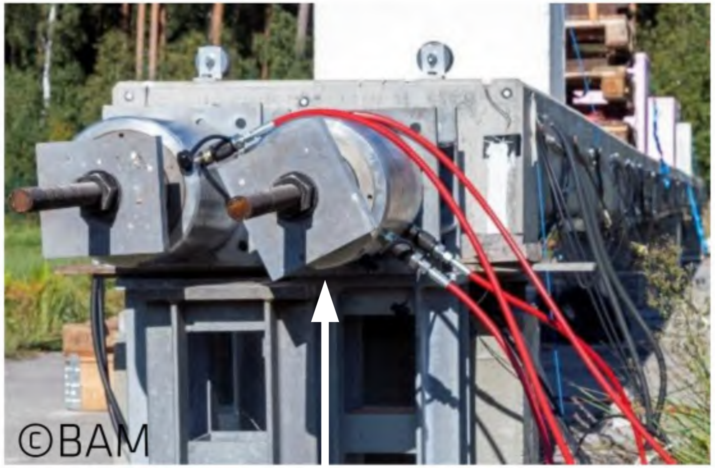


→ displacement not sensitive to heterogeneity 1/3 λ
→ gradients (rotation, strain) are very sensitive!
→ implications for e.g. tomography

Singh et al., GJI, 2019

Structure – civil engineering → structural health monitoring

Can we use *gradient measurements* to detect material changes? (Can we locate **damage**?)
Goal: more sensitive 6C measurements on buildings



Rotation + translation sensors

increased load 300 → 600 → 900 kg

Change pre-tension of bridge

See Marco Dominguez Bureos' poster next week!

Chun-Man Liao et al., 2022

GIOTTO = UHH + LMU + BAM

Summary

Source
- MT inversion
- Microseisms

Wavefield
- Wavetype separation
- Wavetype ratios

Instrumentation

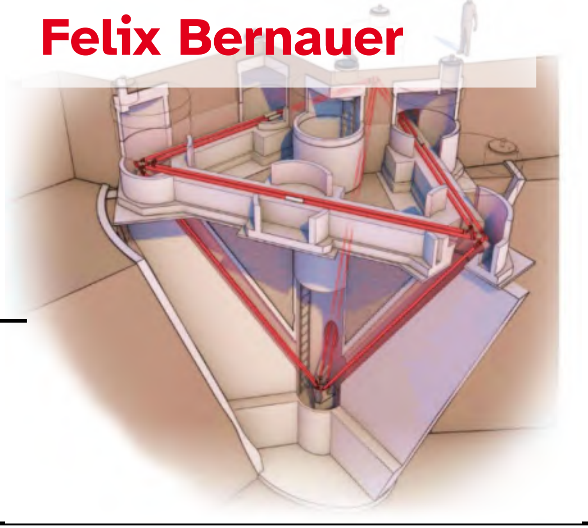
Structure
- Phase velocity
- Dispersion
- Sensitivity kernels
- Heterogeneity

Structural engineering
- Structural changes
- Torsional modes
- Interstory drift

Instrumentation – How to observe rotations?

Observatory instruments
Ring lasers

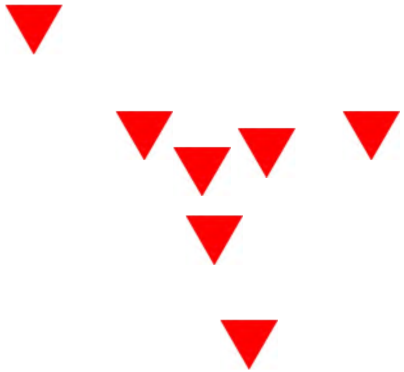
Andreas Brotzer &
Felix Bernauer



Field instruments
e.g. Fiber optic gyros

Laurent Mattio

Dense arrays
Seismometers



L < ¼ λ

Instrumentation – Ring Lasers

Observatory instruments

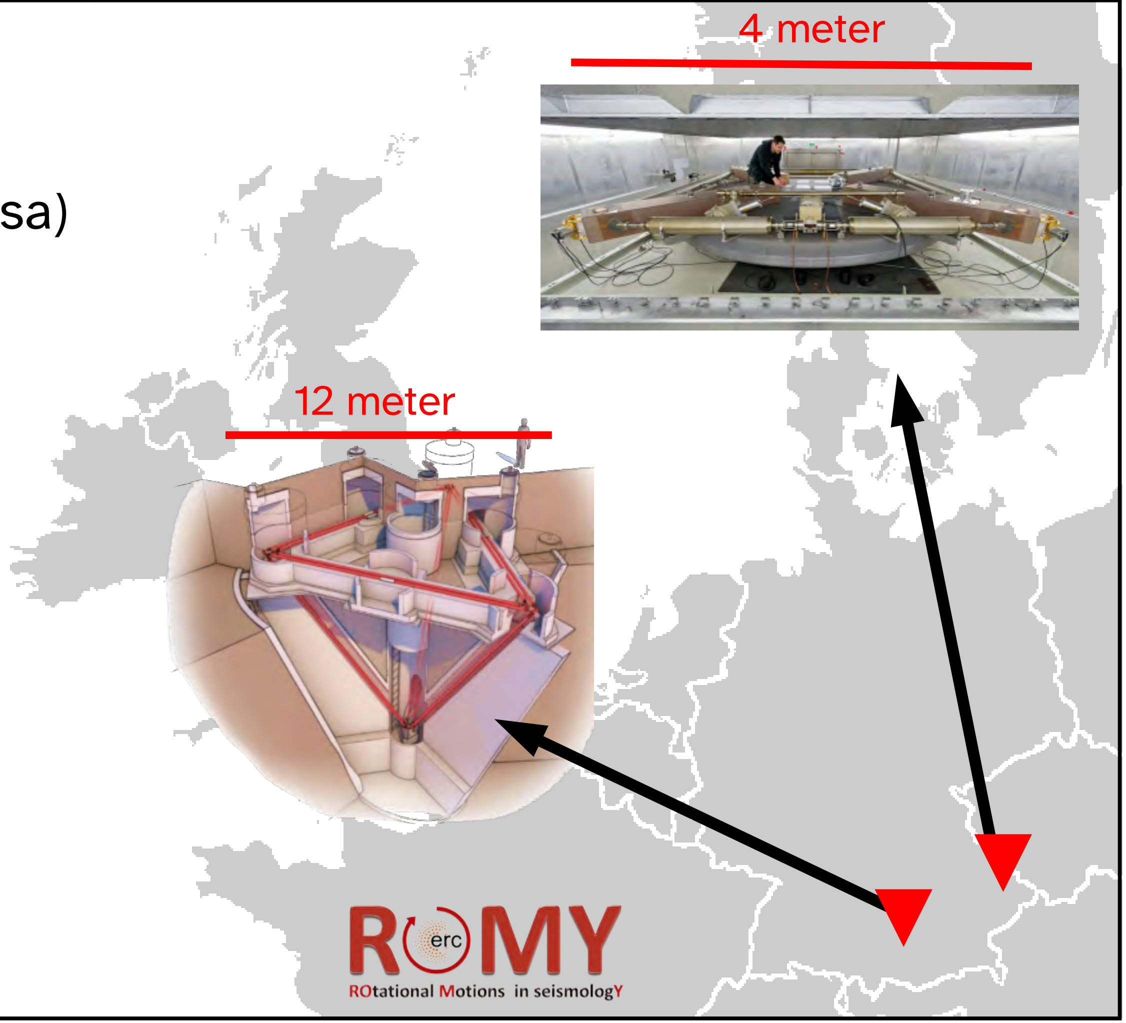
Ring lasers

+ 6 worldwide (PFO, Christchurch, Pisa)

+ G-ring in Wettzell, Germany:
  most sensitive

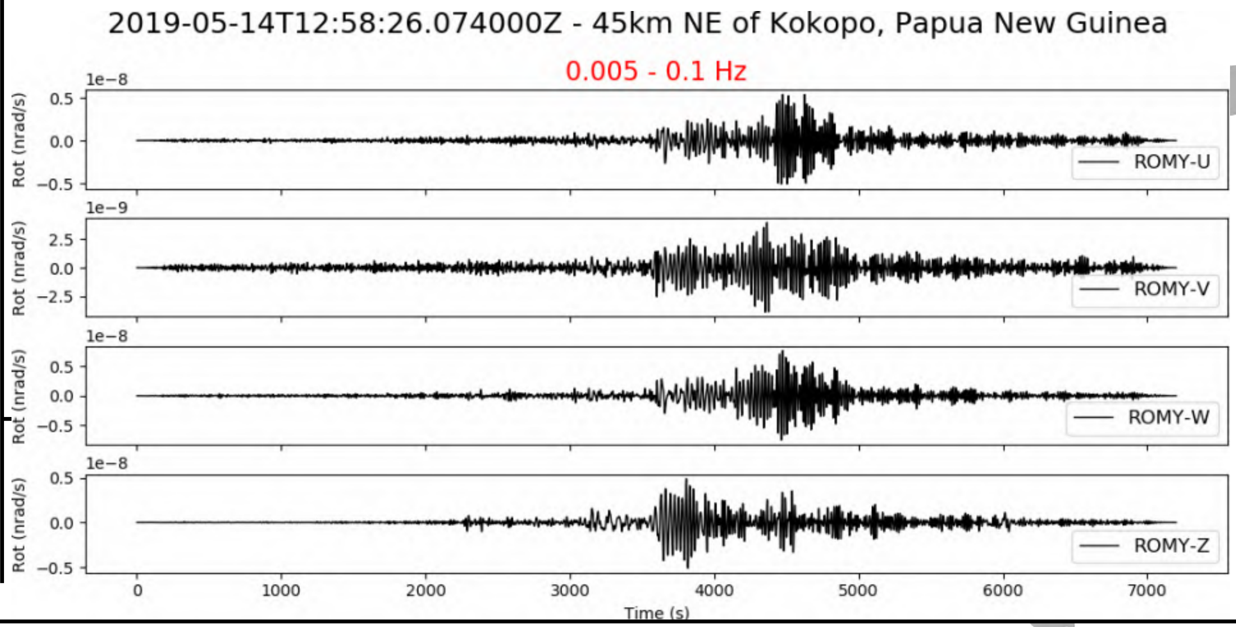
+ ROMY near Munich, Germany:
  first 3-component rotation

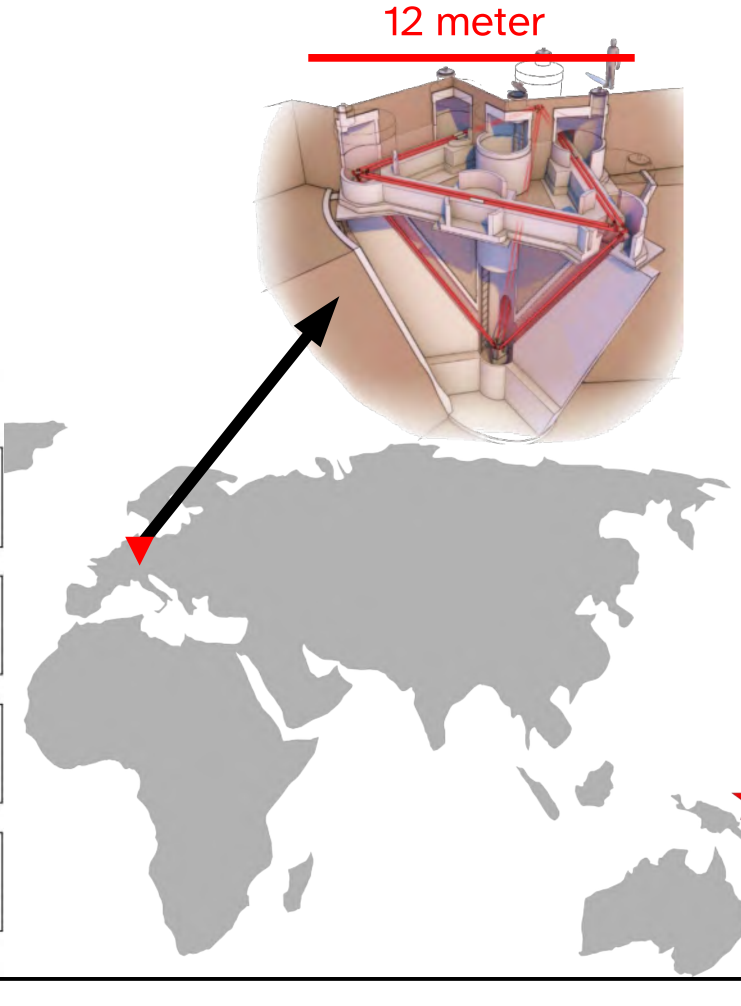
“Lord of the Rings”, Science, 2017



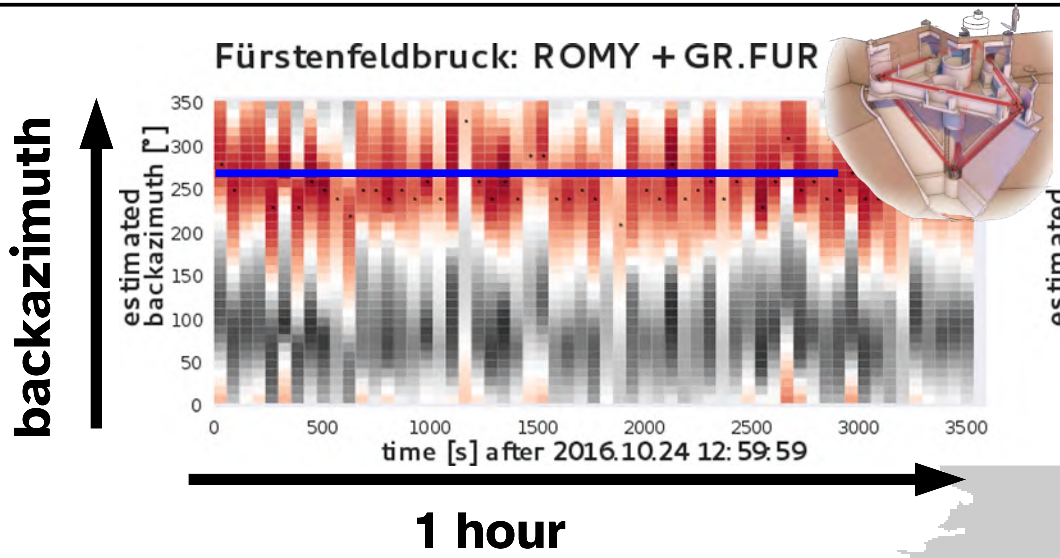
Instrumentation – Ring Lasers

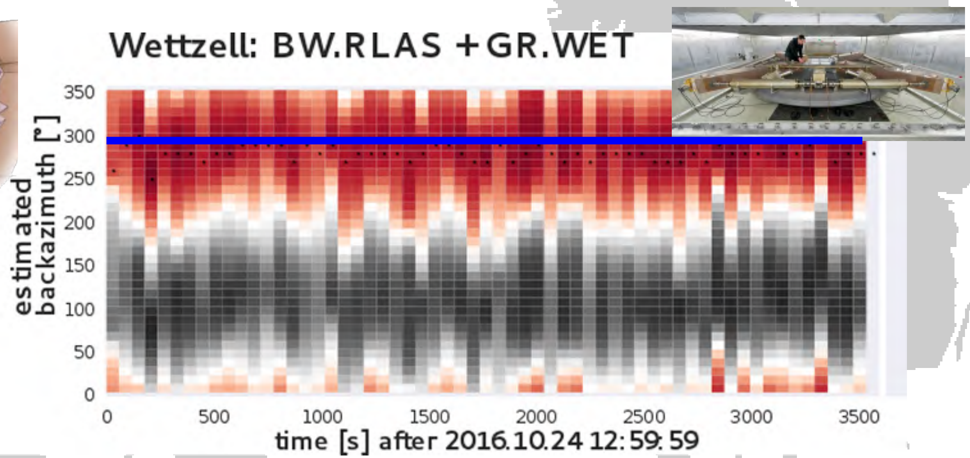
Observatory instruments
Ring lasers
+ ROMY: first 3-component rotation
+ first observation on all 4 rings:





Instrumentation – Ring Lasers





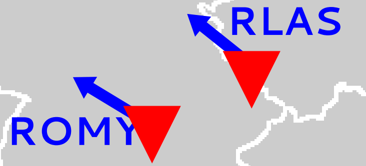
0.1 – 0.2 Hz

Secondary microseism available on both sensors

Dominant source toward **NW** consistent with beamforming

Microseism on two sensors → **seismic interferometry!**

Youtu.be/nRi-XfK_F7Y



ROMY ROtational Motions in seismologY

Summary

Source
- MT inversion
- Microseisms

Instrumentation
- Observatory
- Field instruments
- Dense arrays

Structure
- Phase velocity
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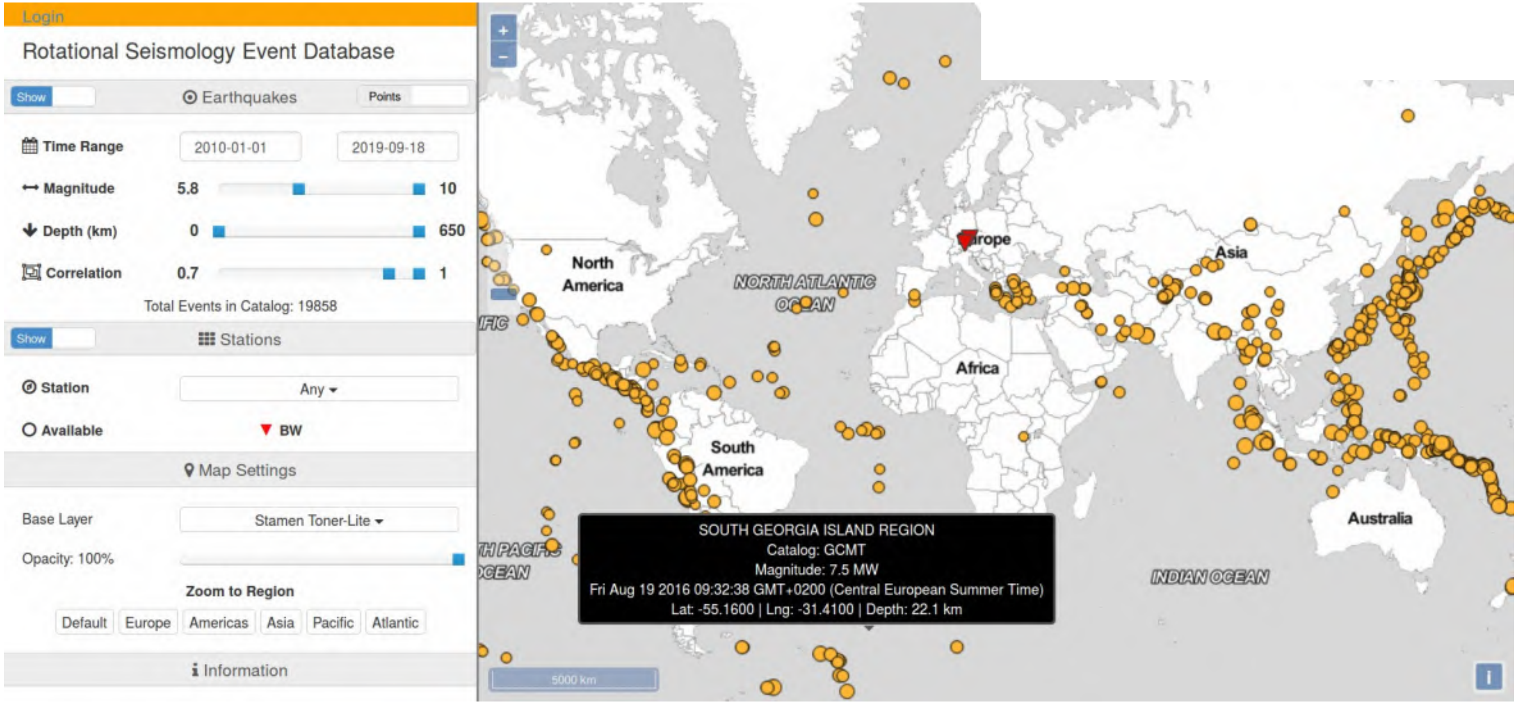
Awesome, where do I start?

Rotational seismology database

Access via rotational-seismology.org → “Data”
Or rotations-database.geophysik.uni-muenchen.de

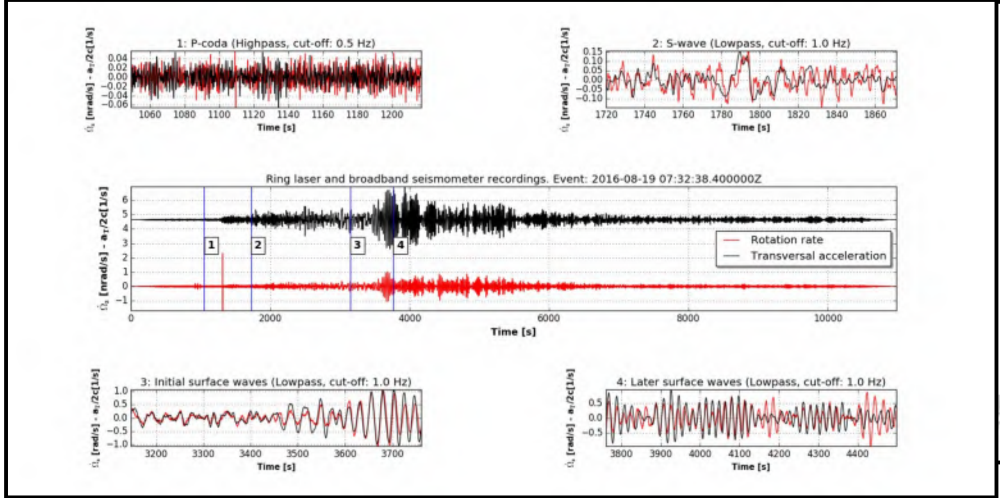
- Waveform download
- Example analysis
- Python code to start
- *Salvermoser et al., SRL 2017*

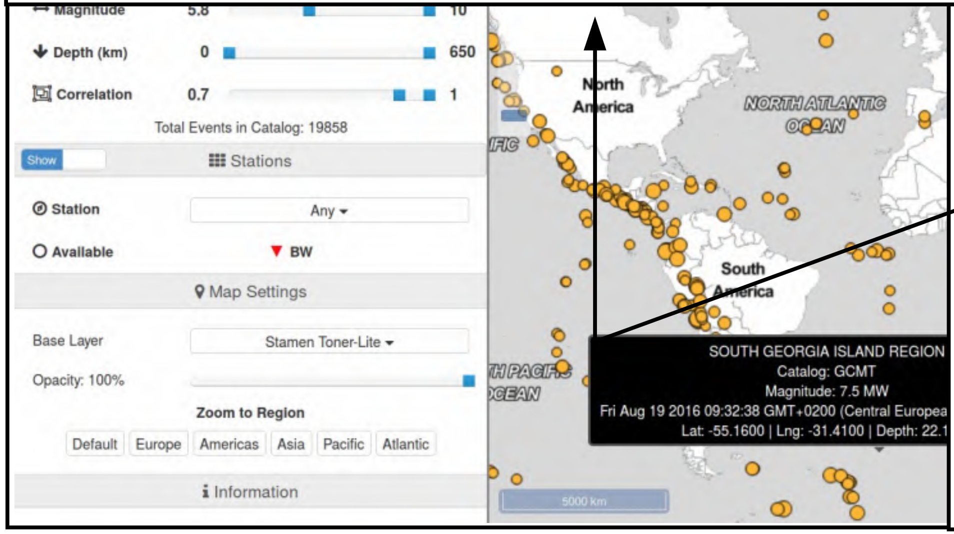


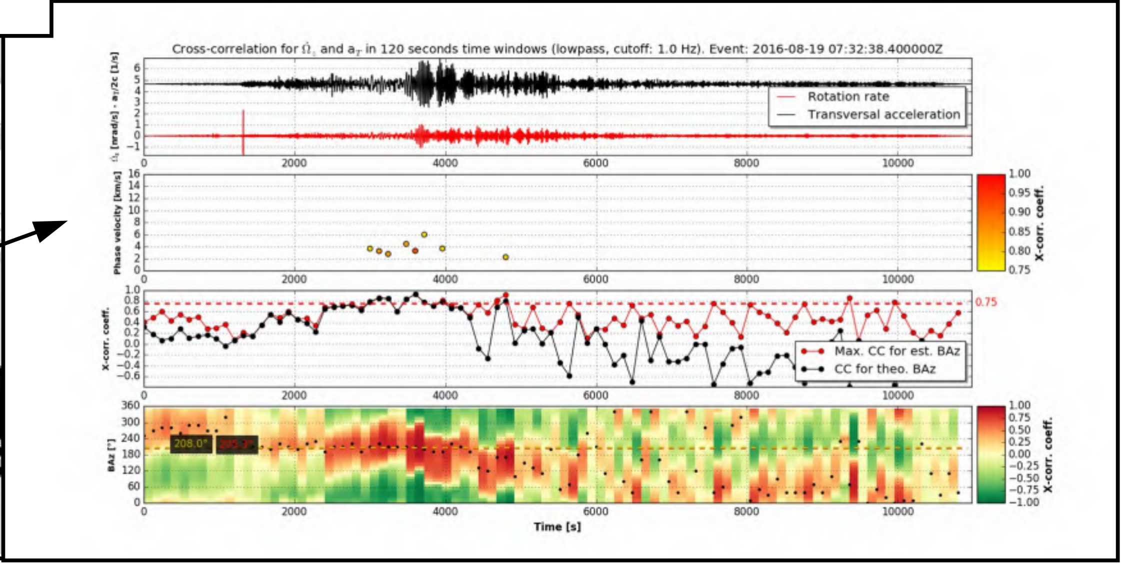
Rotational seismology database

Access via rotational-seismology.org → “Data”
Or rotations-database.geophysik.uni-muenchen.de

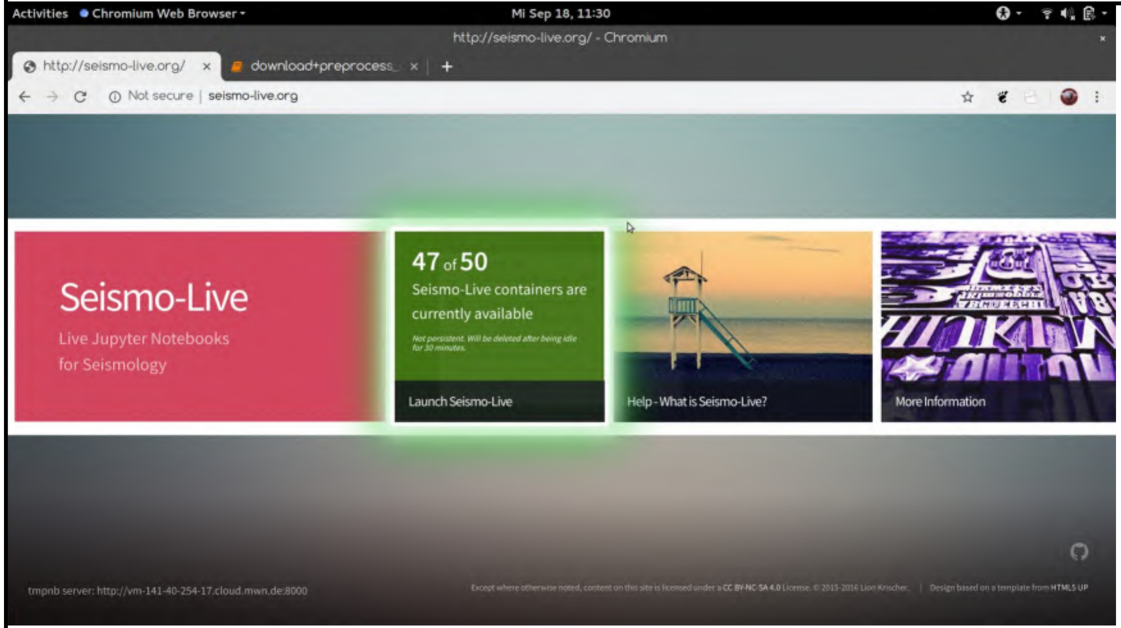
- Waveform download
- **Example analysis**
- Python code to start
- *Salvermoser et al., SRL 2017*





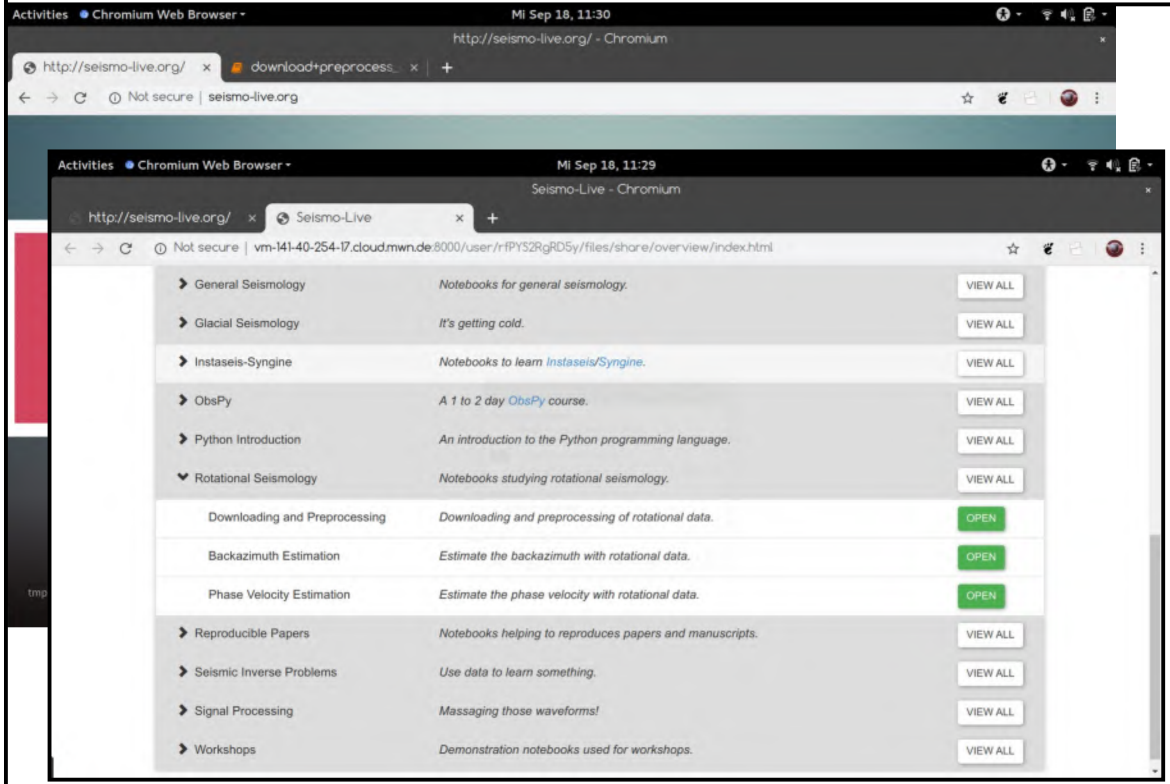


How to get started



Go to seismo-live.org
→ click green square to launch

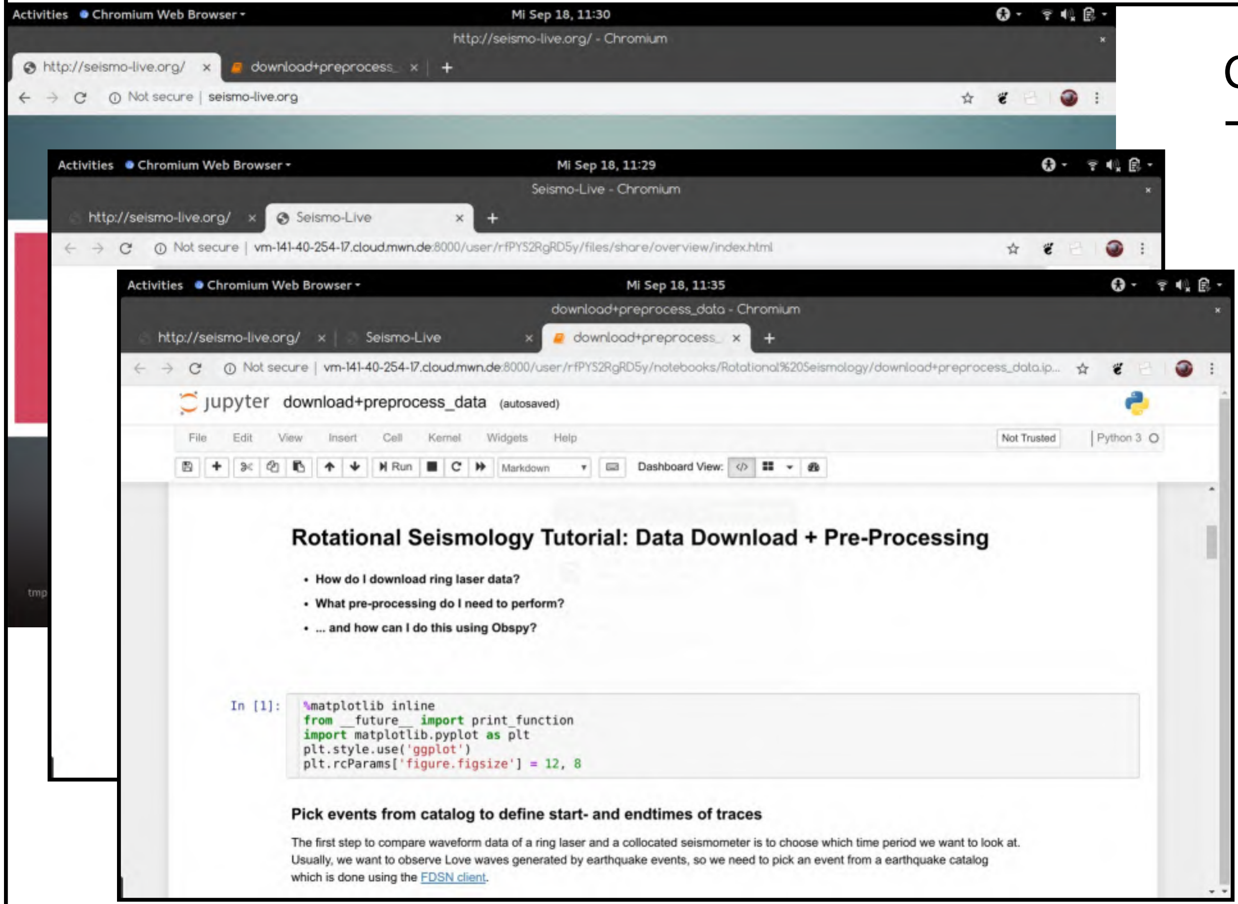
How to get started



Go to seismo-live.org
→ click green square to launch
→ select "Rotational Seismology" Notebooks for:

- Getting ringlaser data
- Backazimuth estimation
- Phase velocity estimation

How to get started



Go to seismo-live.org
→ click green square to launch
→ select "Rotational Seismology" Notebooks for:

- Getting ringlaser data
- Backazimuth estimation
- Phase velocity estimation

→ launch one of the notebooks
... and start playing with data!

.. a citation of Salvermoser et al., SRL 2017 is appreciated..

Summary

Source
- MT inversion
- Microseism

Structure
- Phase velocity
- Dispersion
- Sensitivity kernels
- Heterogeneity
- Toroidal modes

Instrumentation
- Observatory
- Field instruments
- Dense arrays

Wavefield
- Wavetype separation
- Scattering
- Wavetype ratios
- Tilt (OBS?)

Structural engineering
- Structural changes
- Torsional modes
- Interstory drift

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With 6C we have:

New observables

… to do more with fewer stations

… or with **single station**!

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- Access through www.romy-erc.eu → links

Get started with rotational data

- Seismo-live.org → rotational seismology → 3 introductory notebooks to reproduce some figures from the rotational database
- www.romy-erc.eu
- www.rotational-seismology.org (with mailing list!)