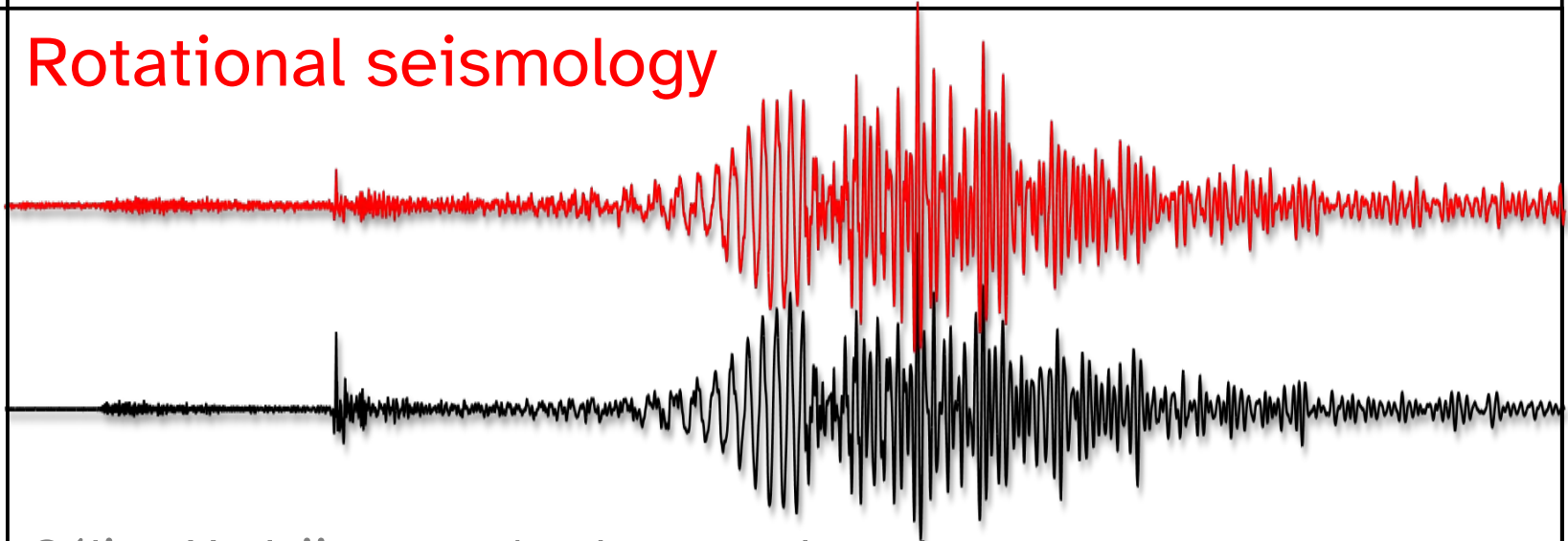


Rotational seismology



Céline Hadziioannou (and many others..)



University of Hamburg, Germany



Rotational seismology

Rotational rate

Transverse acceleration

Céline Hadziioannou (and many others..)



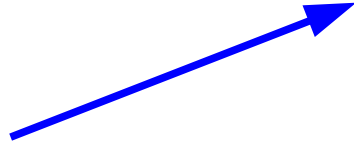
University of Hamburg, Germany



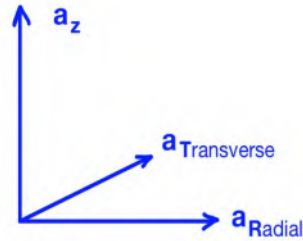
What are rotations?

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

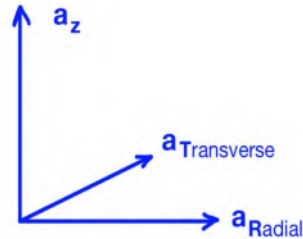


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3C Translation



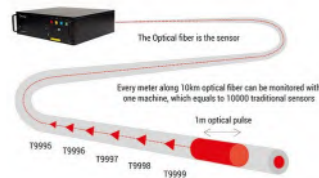
Ground acceleration
Seismometer



+ 6C Strain



Strain
**Strainmeter,
Distributed
Acoustic
Sensing (DAS)**

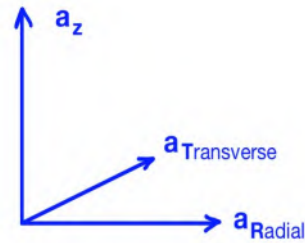


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Entire ground motion, all degrees of freedom

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

3C Translation



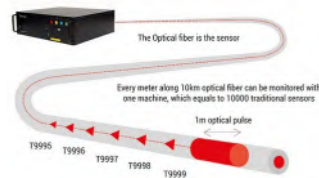
Ground acceleration
Seismometer



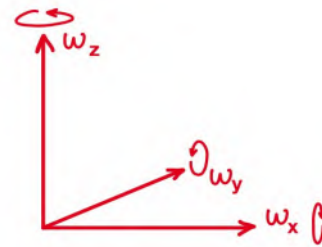
+ 6C Strain



Strain
**Strainmeter,
Distributed
Acoustic
Sensing (DAS)**



+ 3C Rotation



Rotation rate
Rotation sensor



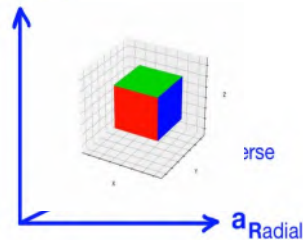
Review: e.g. Cochard et al., 2006; Schmelzbach 2018

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



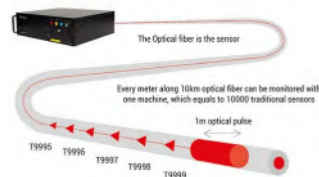
Ground acceleration
Seismometer



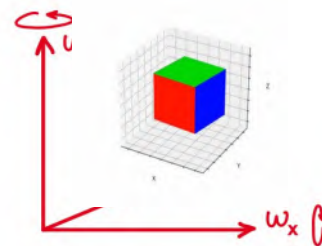
+ 6C Strain



Strain
**Strainmeter,
Distributed
Acoustic
Sensing (DAS)**



+ 3C Rotation



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

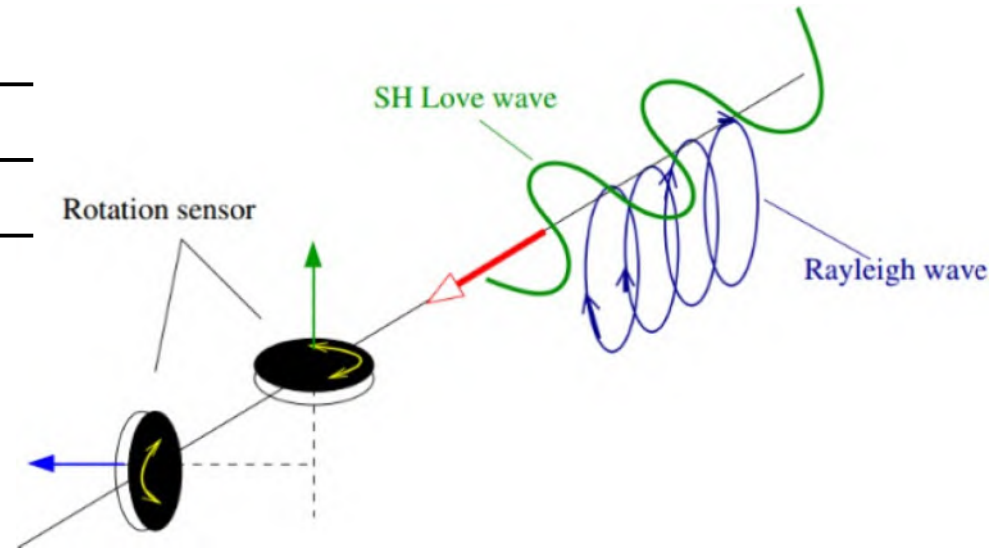
Structure

Instrumentation

Wavefield

Structural engineering

Rotations → wavetype filter

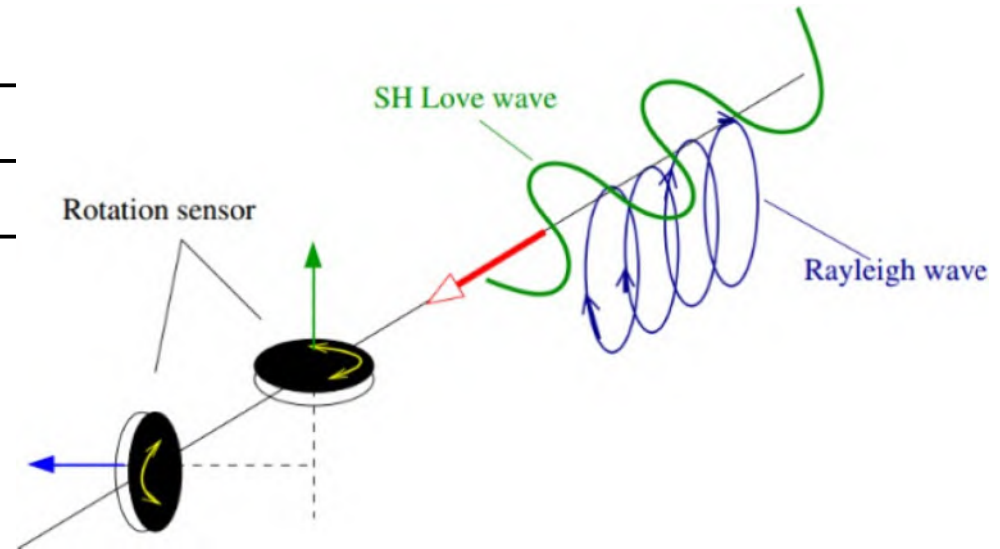
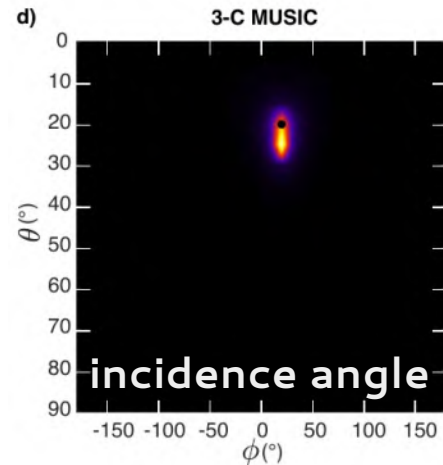
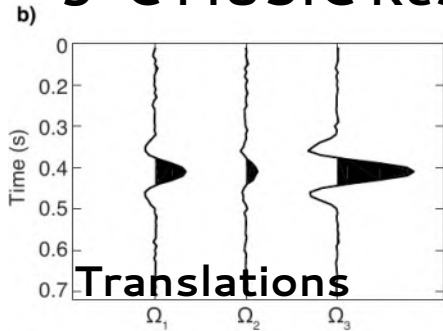


Love & SH motion → vertical rotation
Rayleigh → horizontal rotation

Rotations → wavetype filter

Polarization analysis: 3 vs 6 components

3-C MUSIC Result

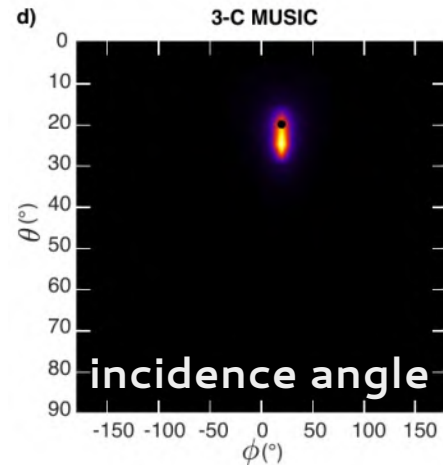
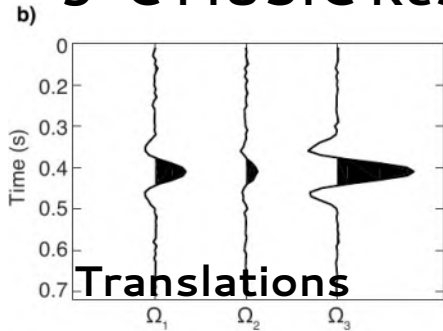


Love & SH motion → vertical rotation
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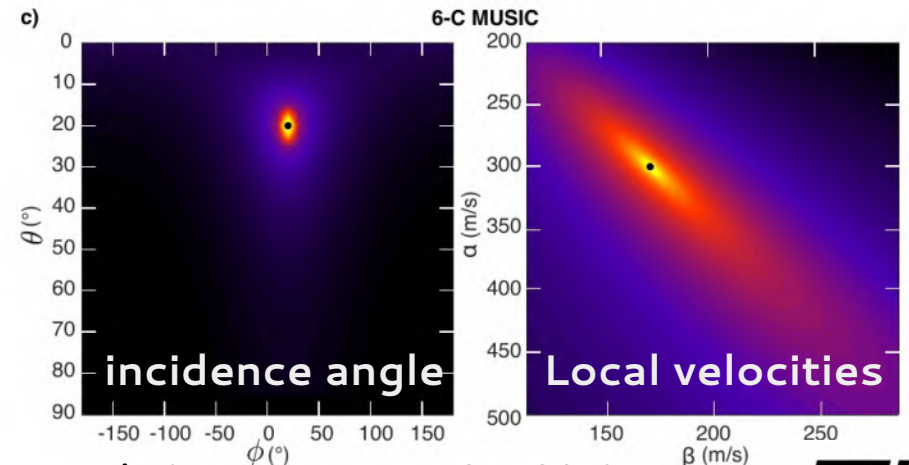
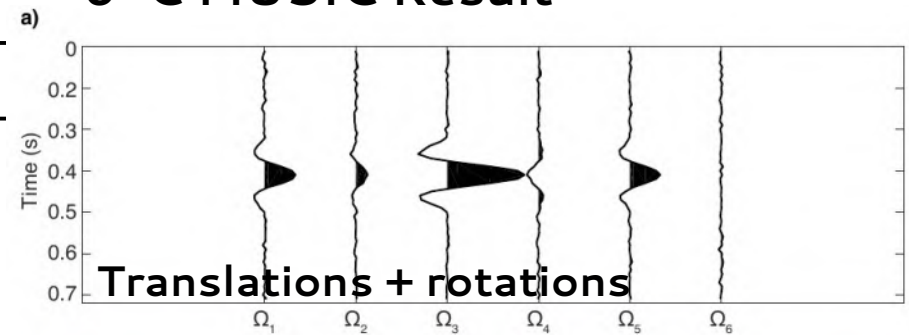
Rotations → wavetype filter

Polarization analysis: 3 vs 6 components

3-C MUSIC Result



6-C MUSIC Result



Sabrina Keil

David Sollberger et al. GJI 2018

Source

Structure

Instrumentation

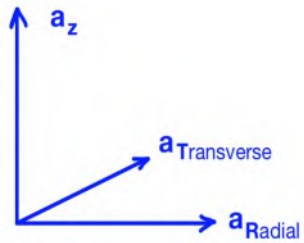
Wavefield

- Wavetype separation
- Wavetype ratios

Structural engineering

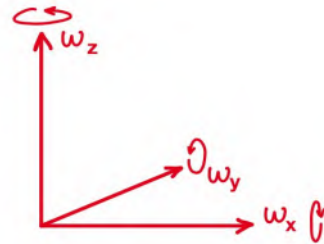
Combining Rotation and Translation

3C Translation



Ground acceleration
Seismometer

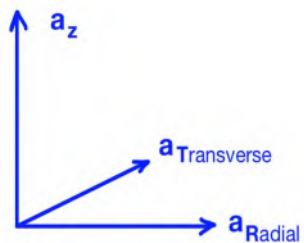
+ 3C Rotation



Rotation rate
Rotation sensor

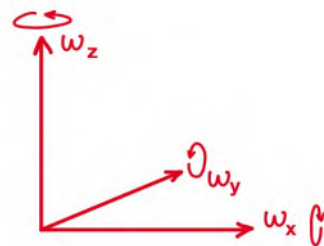
Combining Rotation and Translation

3C Translation



Ground acceleration
Seismometer

+ 3C Rotation

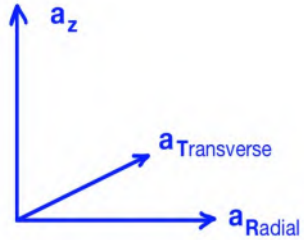


Rotation rate
Rotation sensor

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

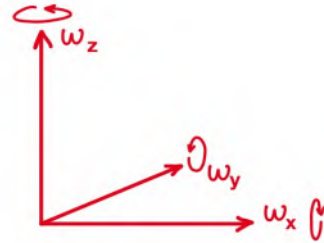
Combining Rotation and Translation

3C Translation



Ground acceleration
Seismometer

+ 3C Rotation

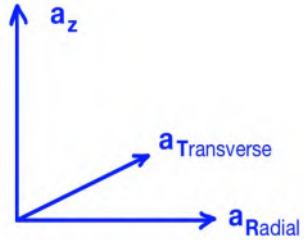


Rotation rate
Rotation sensor

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

Combining Rotation and Translation

3C Translation



Ground acceleration
Seismometer

+ 3C Rotation

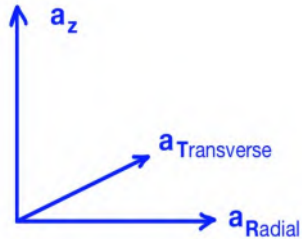


Rotation rate
Rotation sensor

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

Combining Rotation and Translation

3C Translation



Ground acceleration
Seismometer

+ 3C Rotation



Rotation rate
Rotation sensor

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

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

phase velocity
in phase

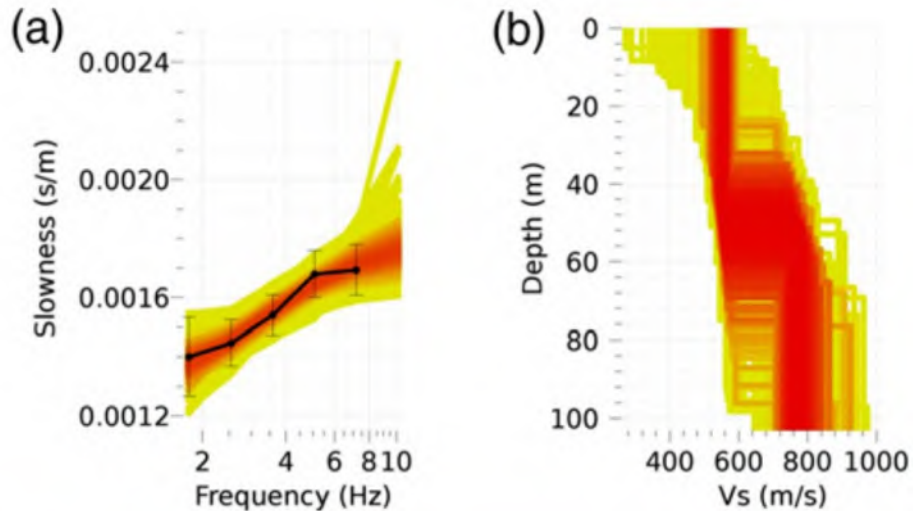
→ using single measurement of 6C
→ waveforms similar → can find source direction

→ **structure**
→ **source**

Structure - determining it using 6C

Single 6C-station dispersion curves:

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



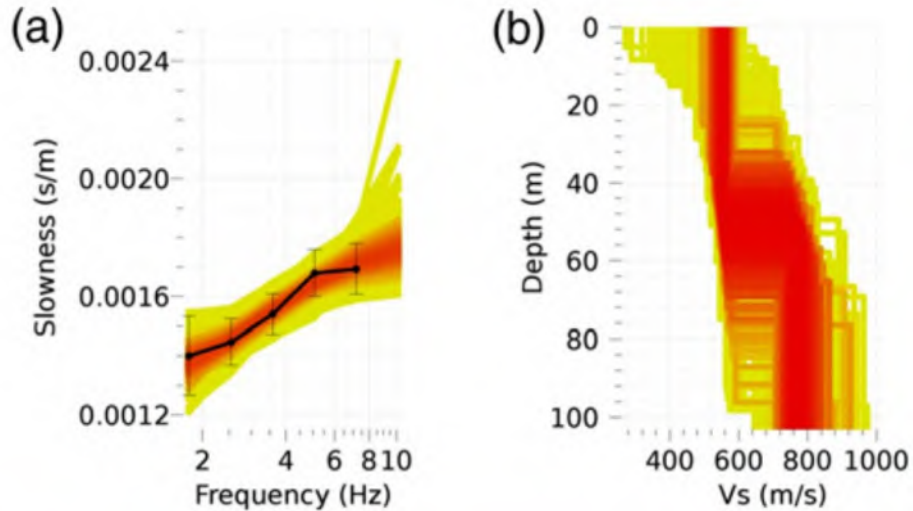
Sabrina Keil

Wassermann et al., BSSA 2016

Structure - determining it using 6C

Single 6C-station dispersion curves:

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



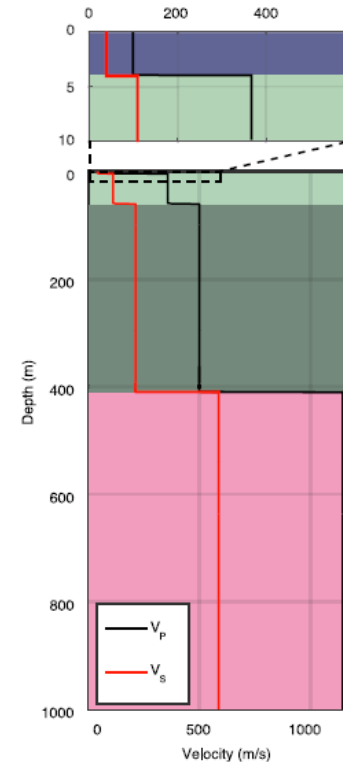
0.04 Misfit value 1.0

Sabrina Keil

Wassermann et al., BSSA 2016



Lunar Vp & Vs structure
"Point" 6C measurement



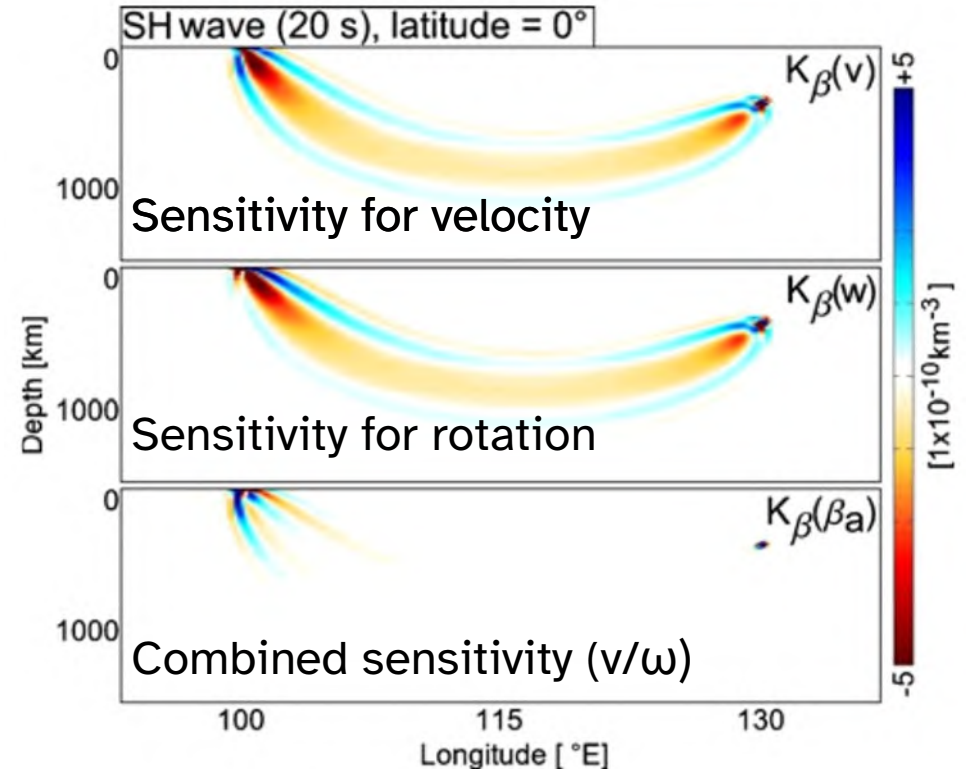
Sollberger et al.,
GRL 2016

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

Source

Wavefield

- Wavetype separation
- Wavetype ratios

Instrumentation

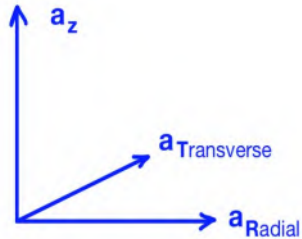
Structure

- Phase velocity
- Dispersion
- Sensitivity kernels

Structural engineering

Combining Rotation and Translation

3C Translation



Ground acceleration
Seismometer

+ 3C Rotation



Rotation rate
Rotation sensor

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

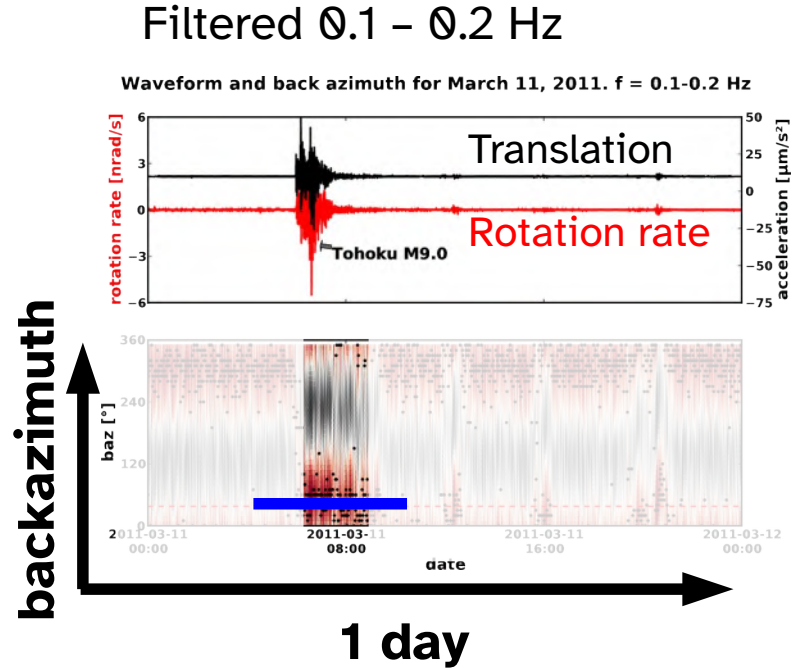
- + Rotation rate and acceleration should be **in phase**
- + amplitudes scaled by **two times the horizontal phase velocity**.

phase velocity
in phase

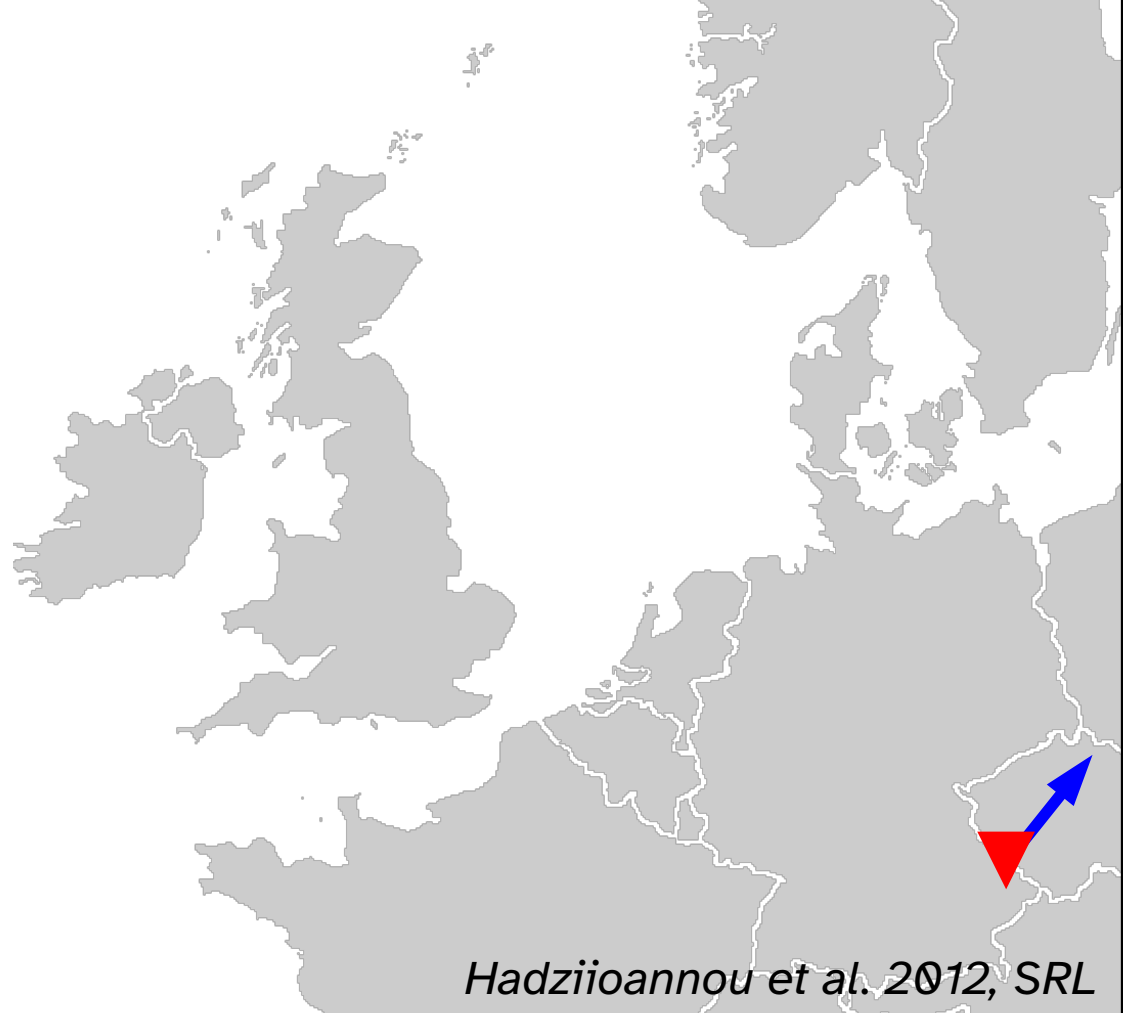
→ using single measurement of 6C
→ waveforms similar → can find source direction

→ **structure**
→ **source**

Source – source direction



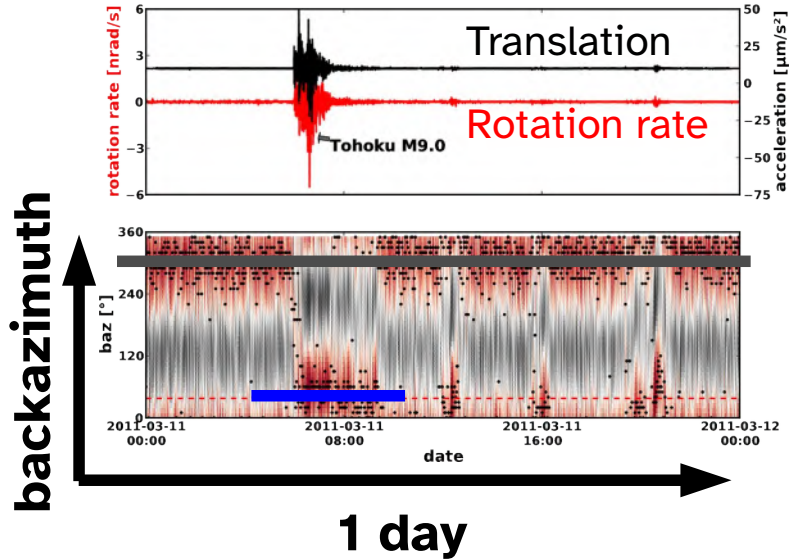
Corrcoef = 1
Corrcoef = -1



Source – source direction

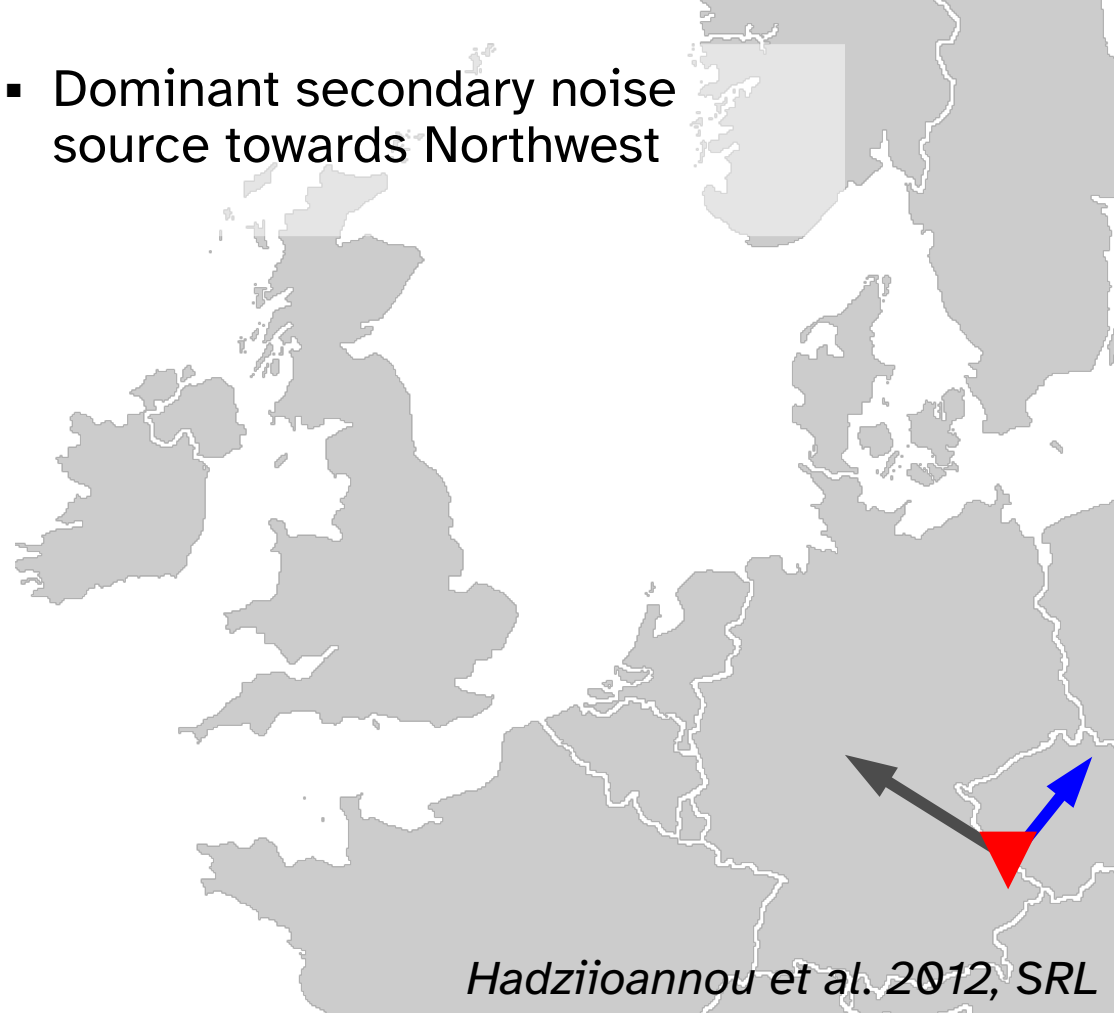
Filtered 0.1 – 0.2 Hz

Waveform and back azimuth for March 11, 2011. $f = 0.1-0.2$ Hz



Corrcoef = 1
Corrcoef = -1

- Dominant secondary noise source towards Northwest

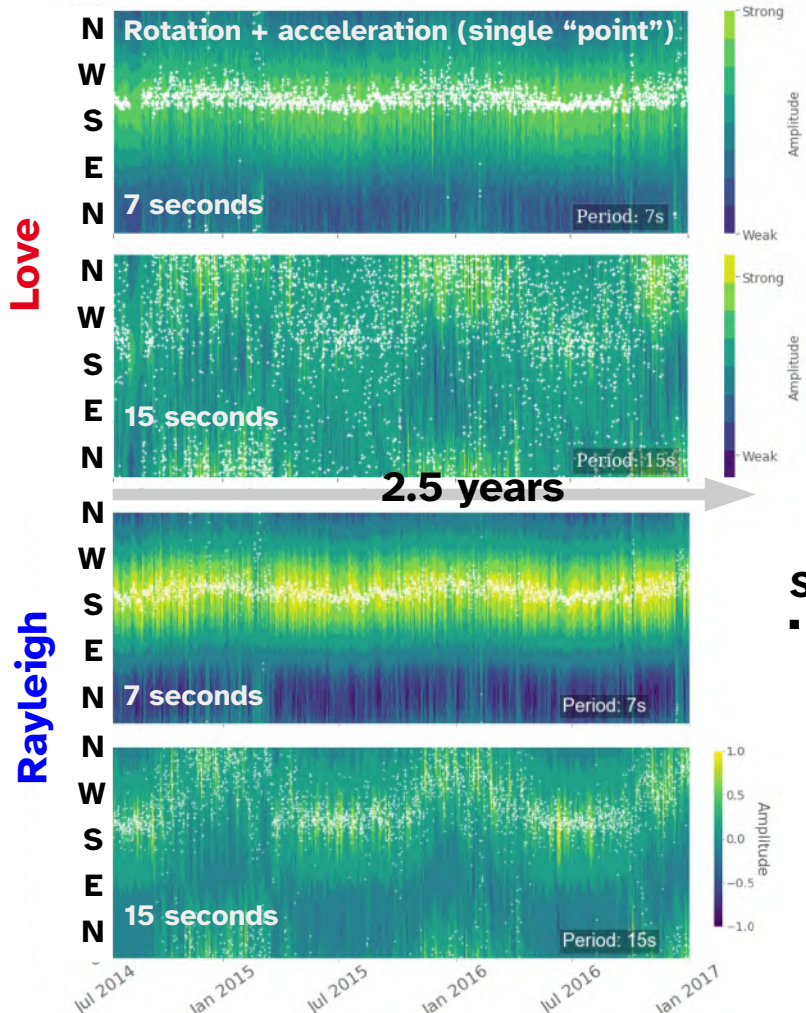


Source – source direction

***Single-point* backazimuth determination**

- Direction of secondary and primary microseism

Source – source direction



Single-point backazimuth determination

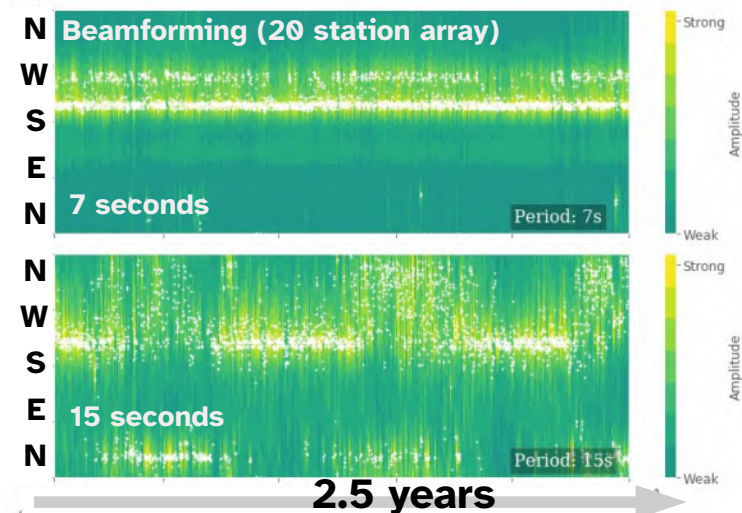
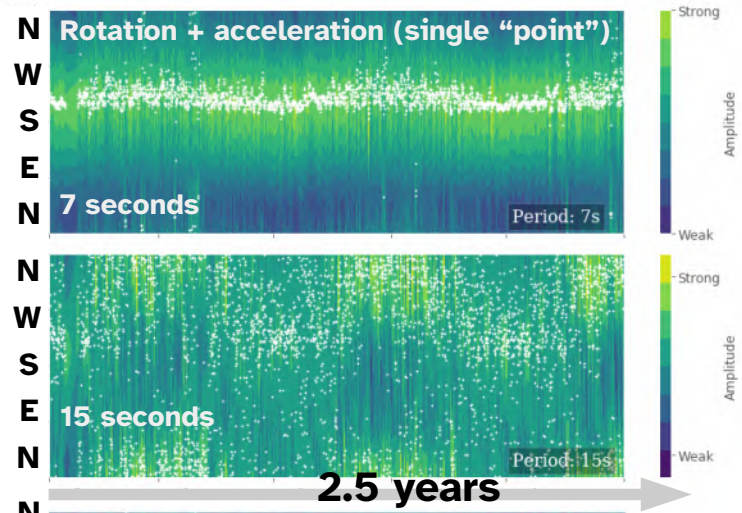
- Direction of secondary and primary microseism



Christoph Schroeer (UHH)

Source – source direction

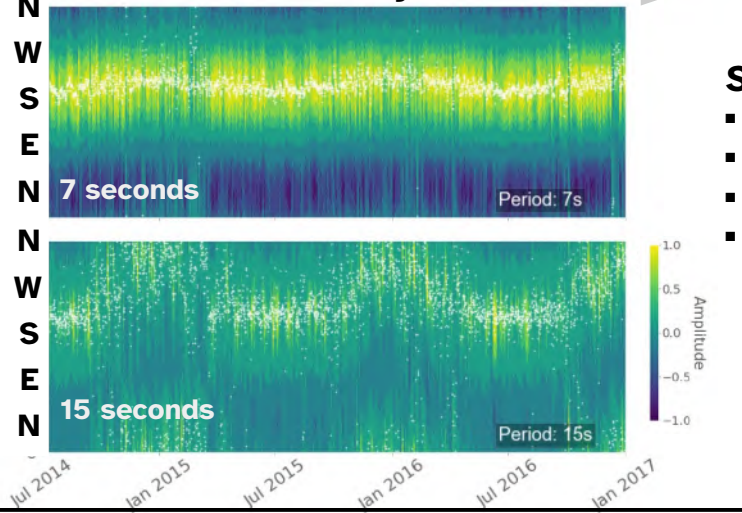
Love



2.5 years

2.5 years

Rayleigh



Single-point backazimuth determination

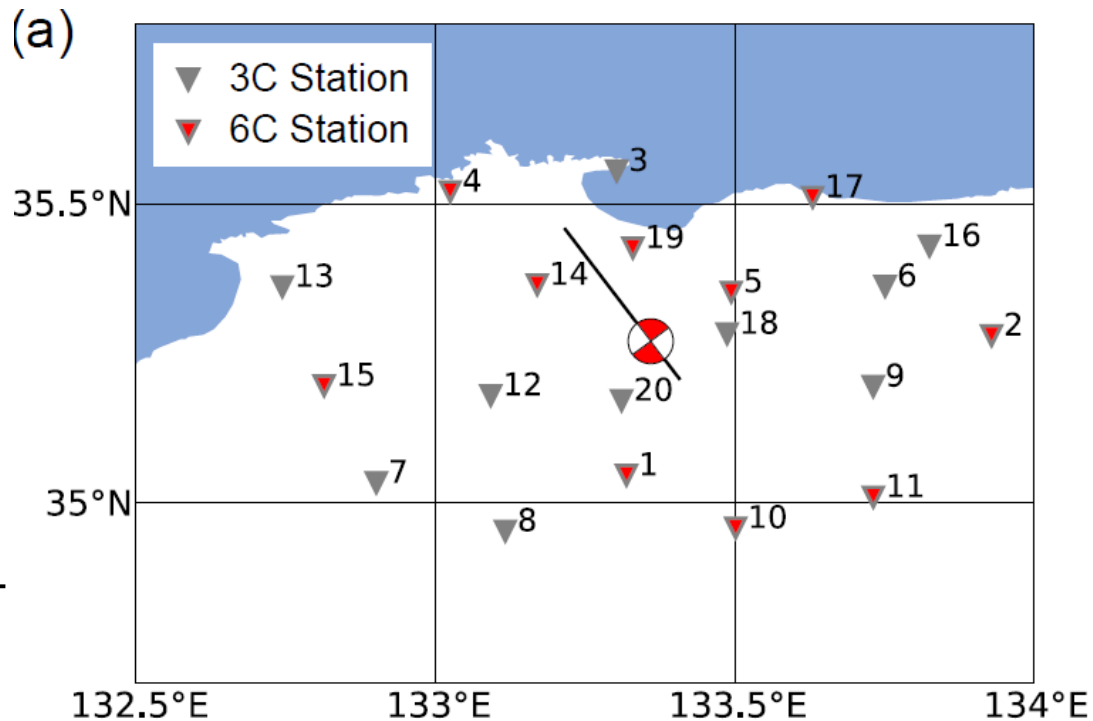
- Direction of secondary and primary microseism
- Compare **rotation** measurements to **beamforming**
- Dominant source retrieved, fits with beamforming
- *Separation of simultaneous sources needs work*



Christoph Schroerer (UHH)

Earthquake Source inversion

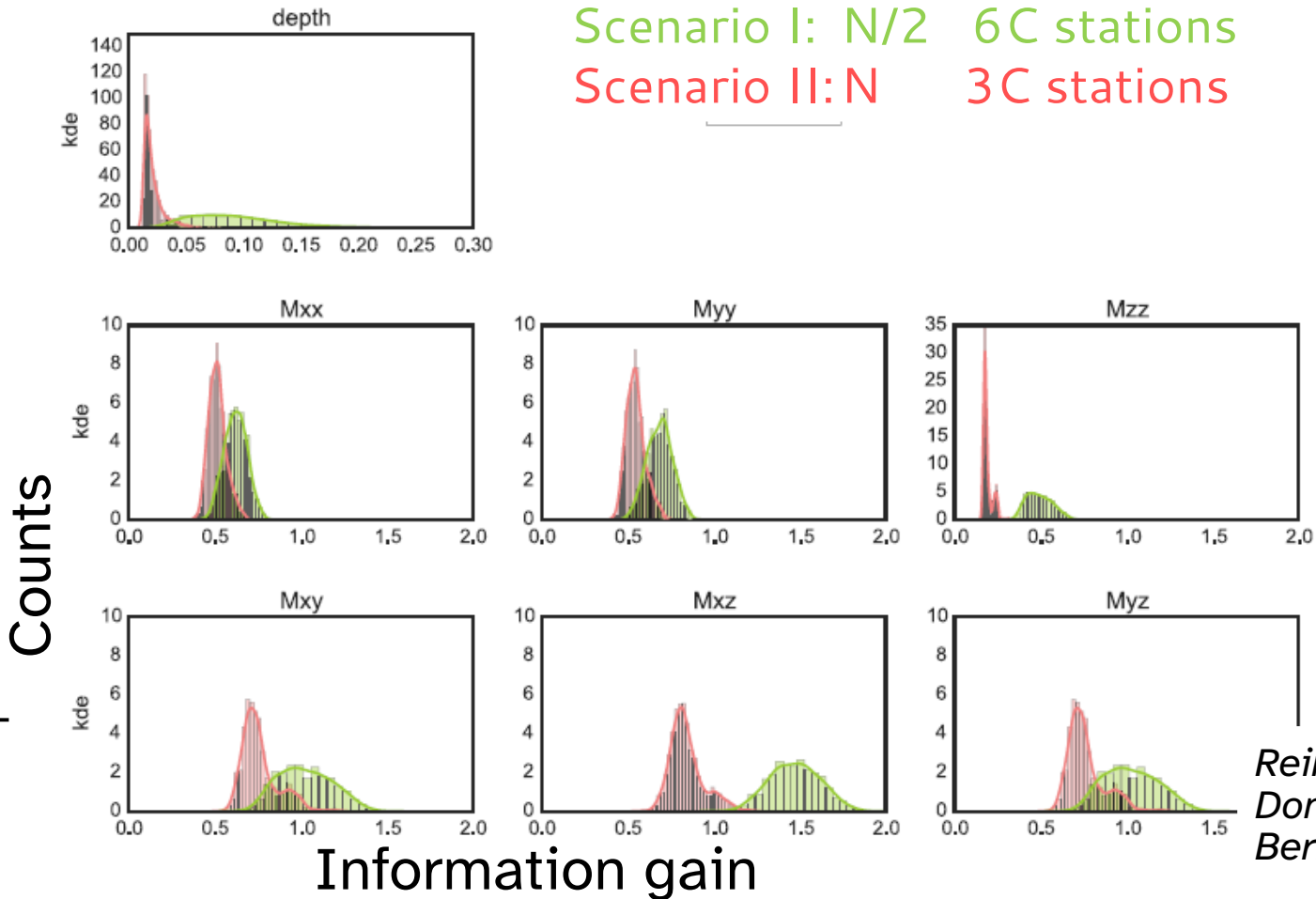
- improved constraints on kinematic and point source parameters with $\frac{1}{2}$ the stations
- + Scenario I: N receivers with 3C observations (translations)
- + Scenario II: N/2 receivers with 6C observations (translations and rotations)



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

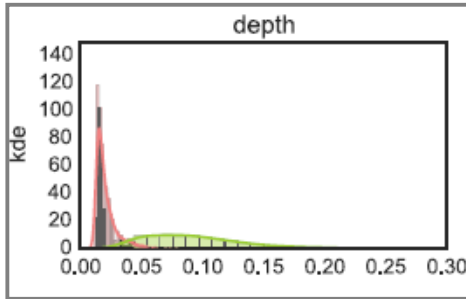
Earthquake Source inversion

Scenario I: N/2 6C stations
Scenario II: N 3C stations



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

Earthquake Source inversion

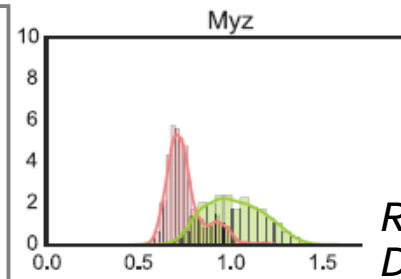
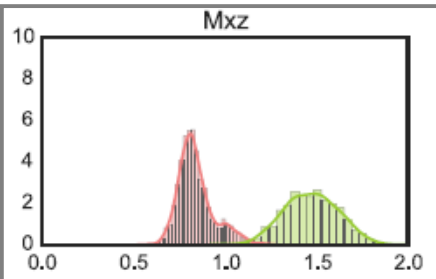
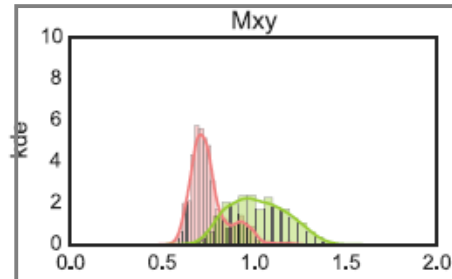
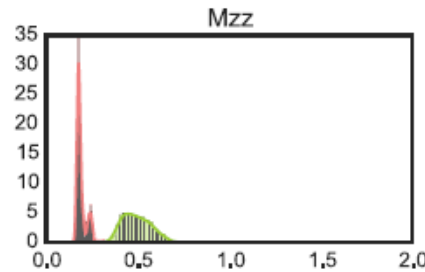
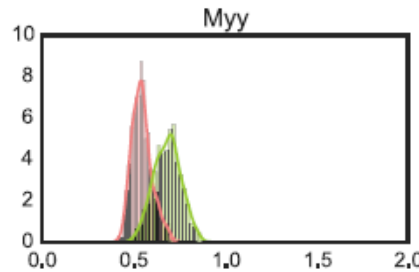
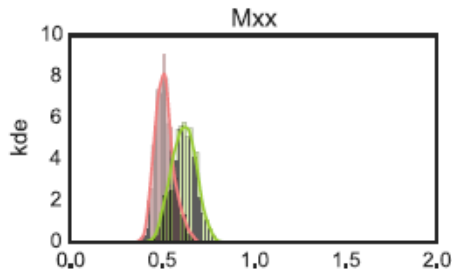


Scenario I: N/2 6C stations

Scenario II: N 3C stations

- ½ number of station: MT equal or better retrieved
- Depth, Mxy, Mxz improved
- point & finite sources, regional/local

Counts



Information gain

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

Overview



Source

- MT inversion
- Microseisms

Wavefield

- Wavetype separation
- Wavetype ratios

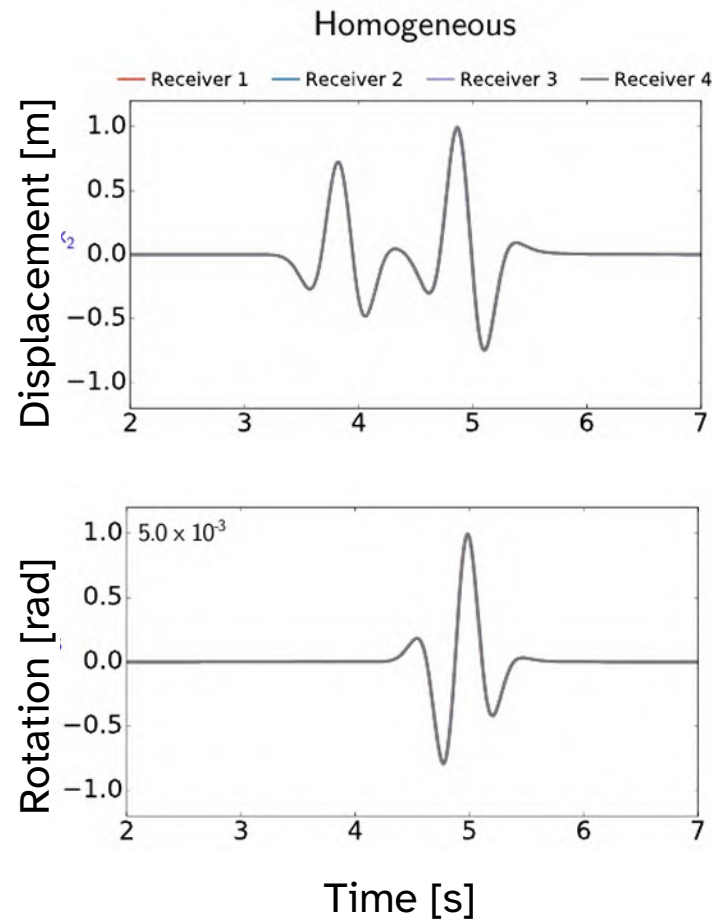
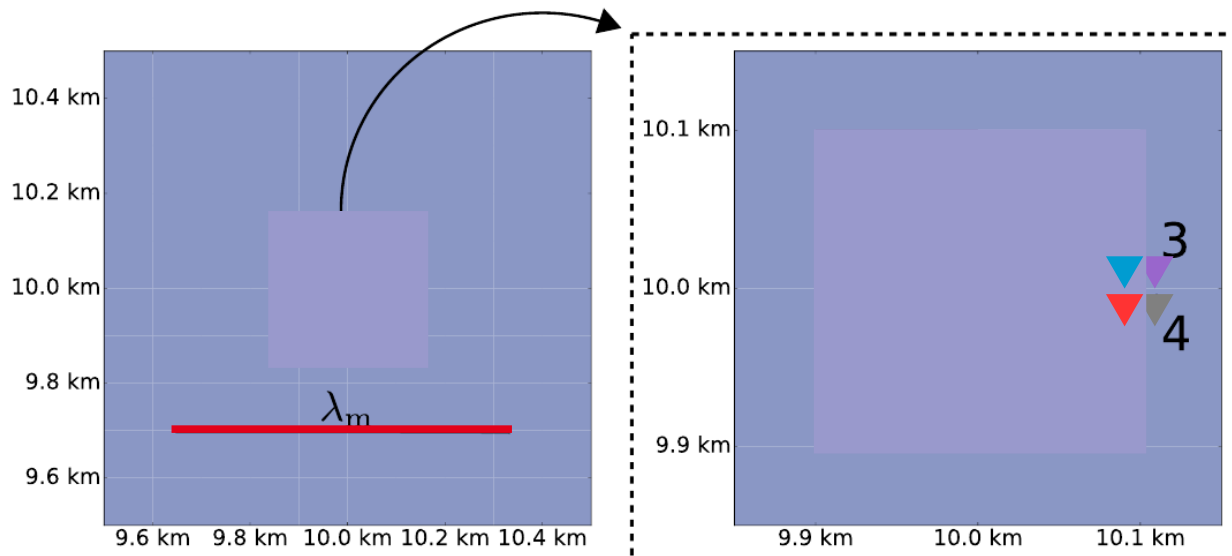
Instrumentation

Structure

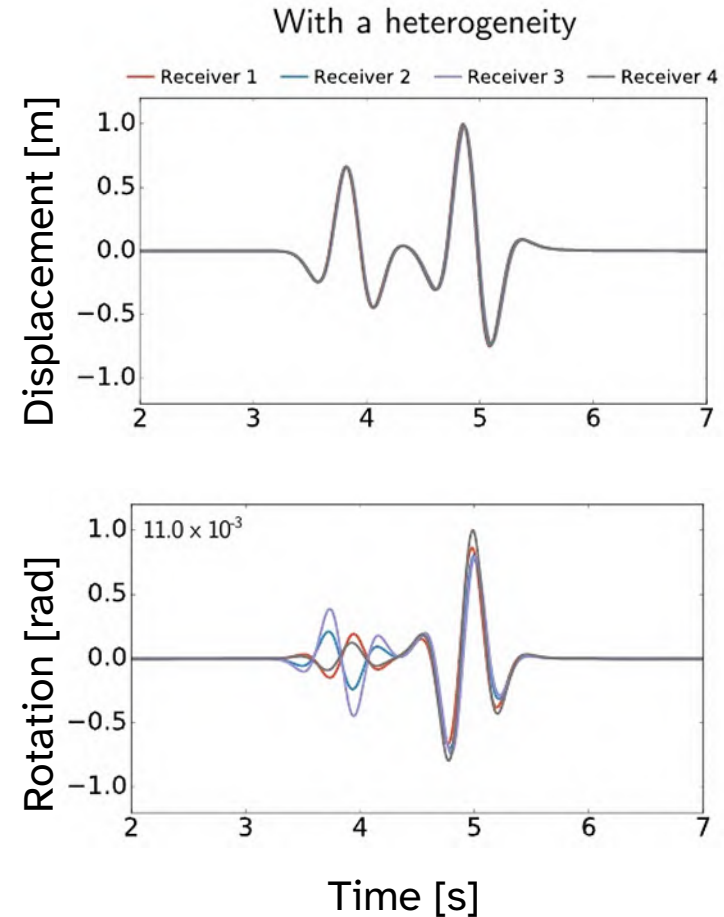
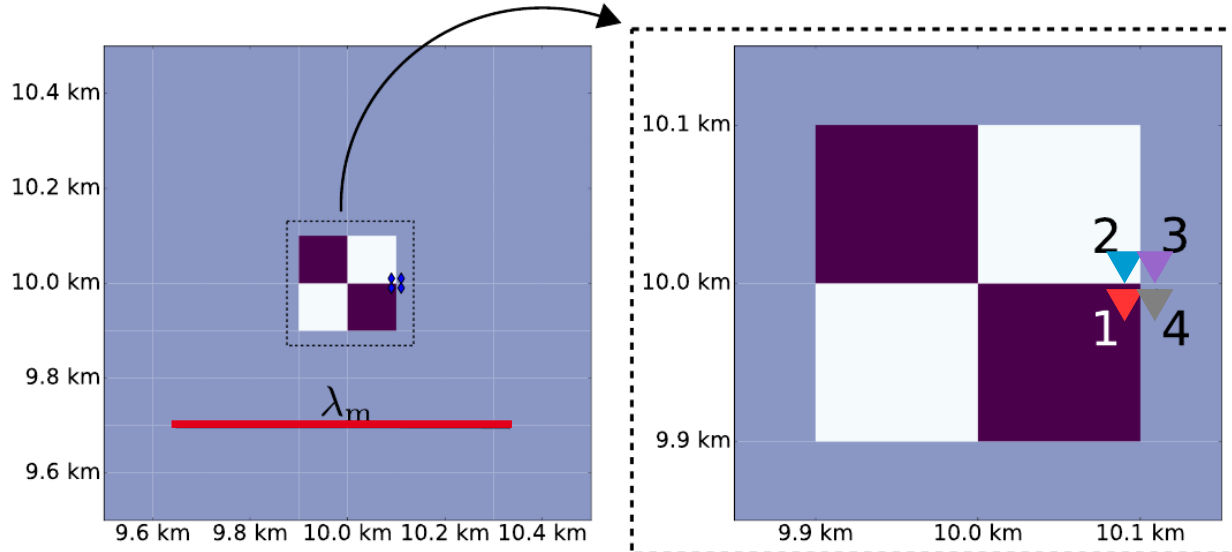
- Phase velocity
- Dispersion
- Sensitivity kernels

Structural engineering

Structure - sensitivity to heterogeneity



Structure – sensitivity to heterogeneity



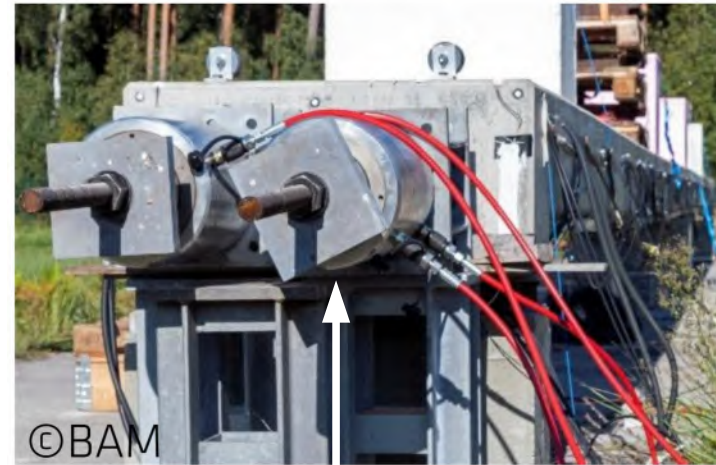
- displacement not sensitive to heterogeneity $1/3 \lambda$
- gradients (rotation, strain) are very sensitive!
- implications for e.g. tomography

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

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

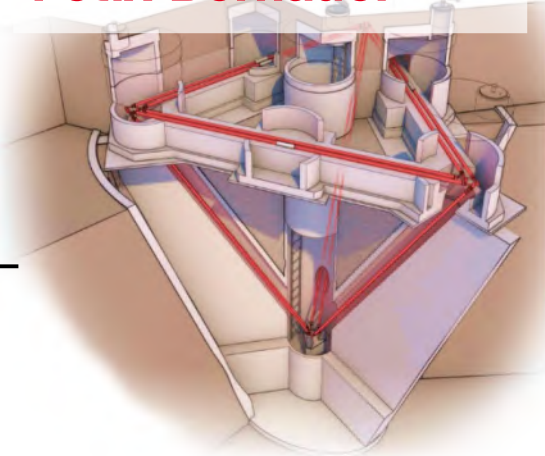
Instrumentation – How to observe rotations?

Observatory instruments

Ring lasers



**Andreas Brotzer &
Felix Bernauer**



Field instruments

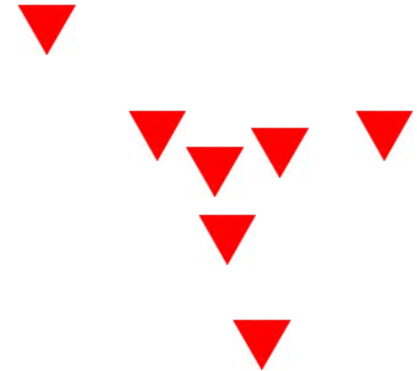
e.g. Fiber optic gyros



Laurent Mattio

Dense arrays

Seismometers



$$L < \frac{1}{4} \lambda$$

Instrumentation – Ring Lasers

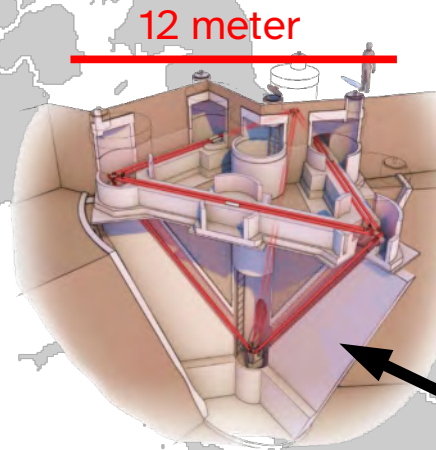
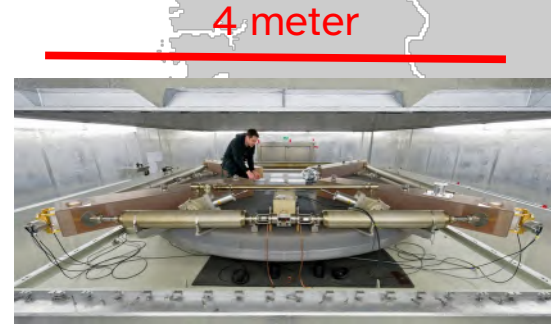
Observatory instruments

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

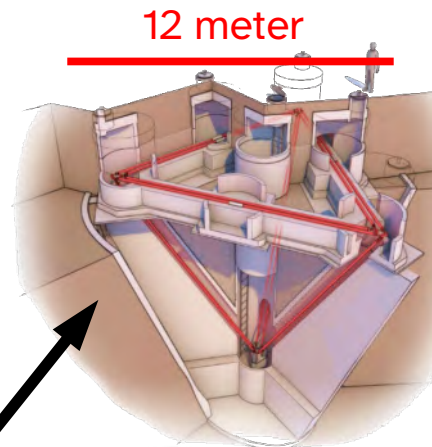
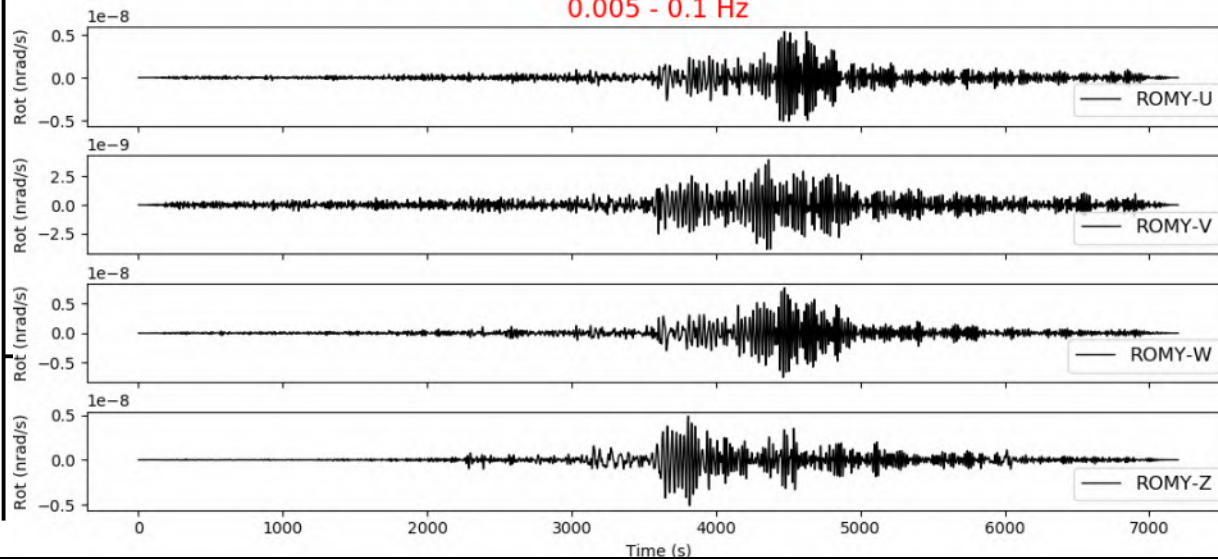
Ring lasers

+ ROMY: first 3-component rotation

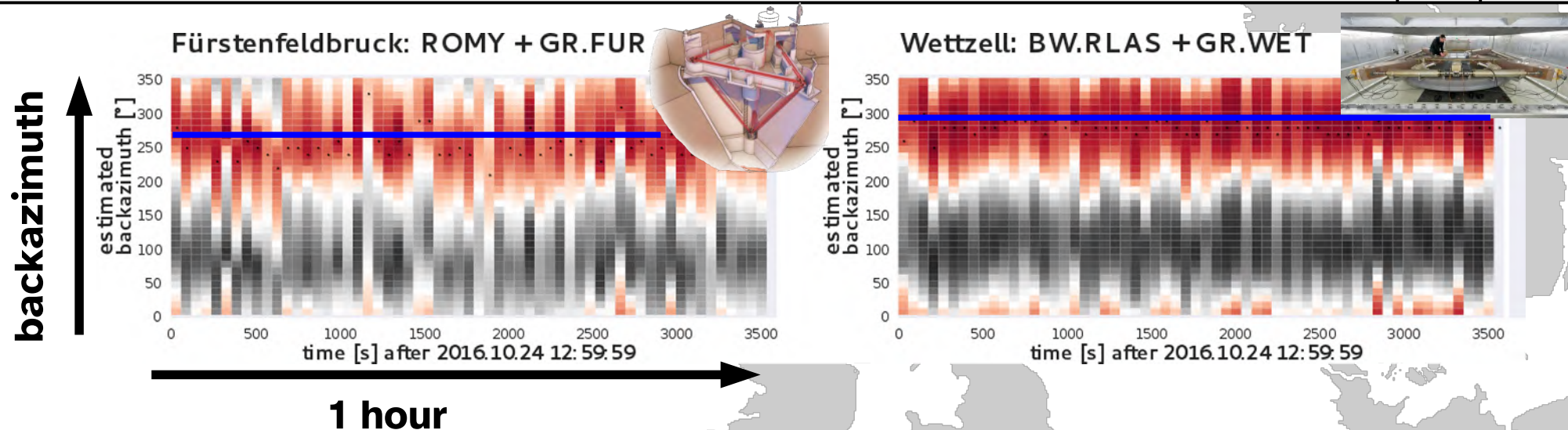
+ first observation on all 4 rings:

2019-05-14T12:58:26.074000Z - 45km NE of Kokopo, Papua New Guinea

0.005 - 0.1 Hz



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](https://youtu.be/nRi-XfK_F7Y)



Summary

Source

- MT inversion
- Microseisms

Wavefield

- Wavetype separation
- Wavetype ratios

Instrumentation

- Observatory
- Field instruments
- Dense arrays

Structure

- Phase velocity
- Dispersion
- Sensitivity kernels
- Heterogeneity

Structural engineering

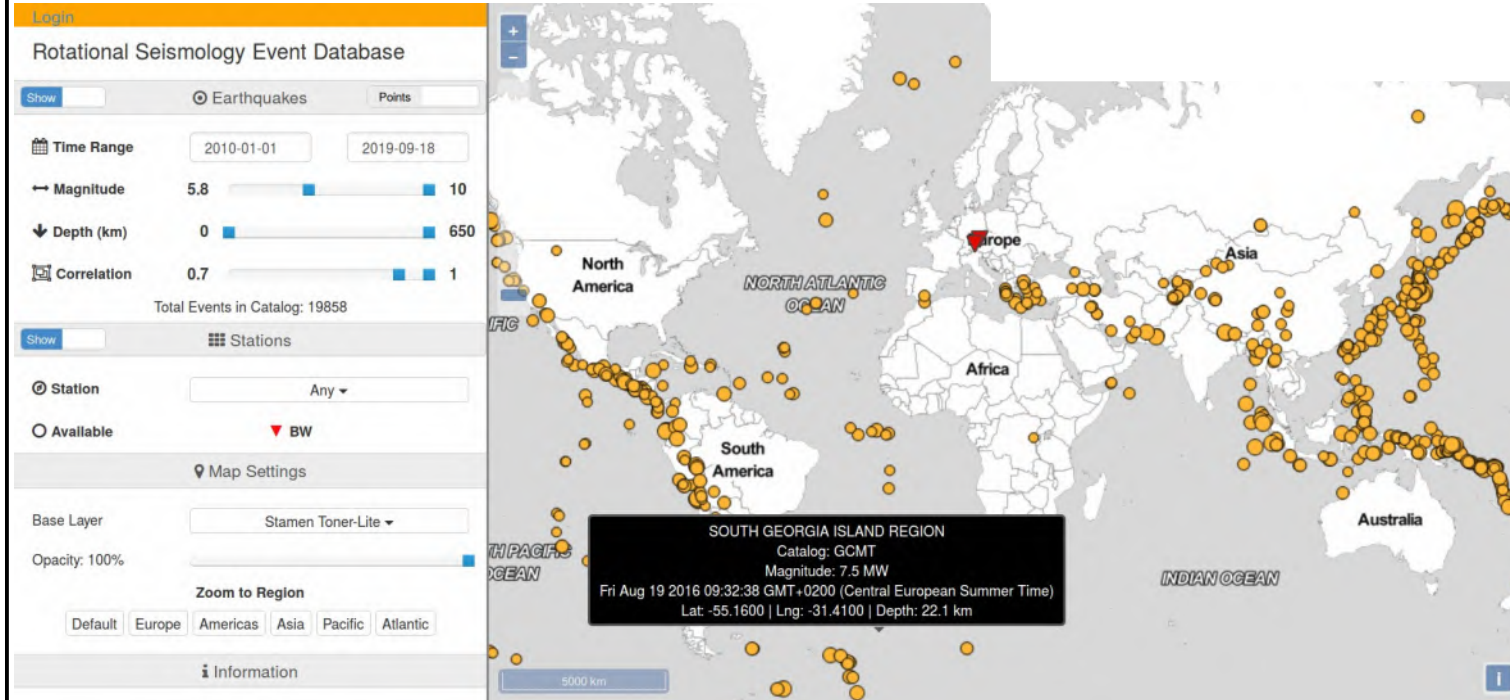
- Structural changes
- Torsional modes
- Interstory drift

Awesome, where do I start?

Rotational seismology database

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

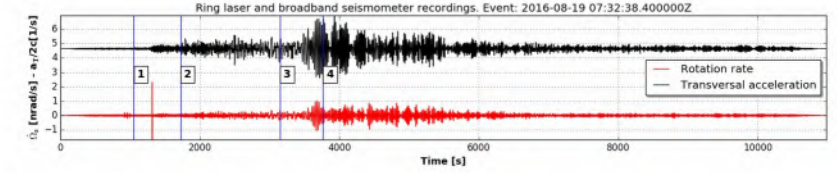
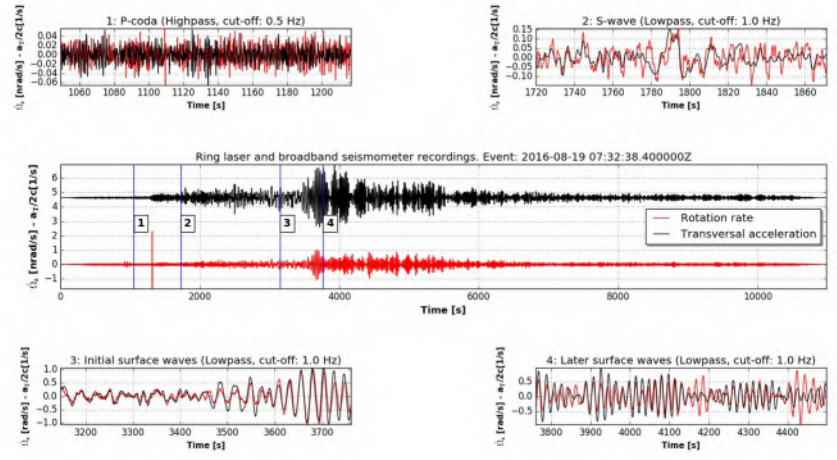
- Waveform download
- Example analysis
- Python code to start
- *Salvermoser et al., SRL 2017*



Rotational seismology database

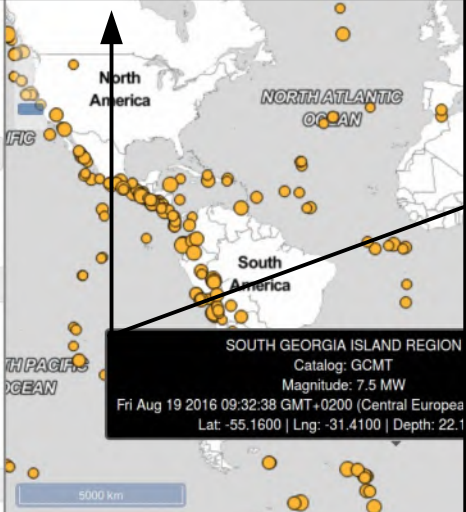
Access via rotational-seismology.org → “Data”
 Or rotations-database.geophysik.uni-muenchen.de

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

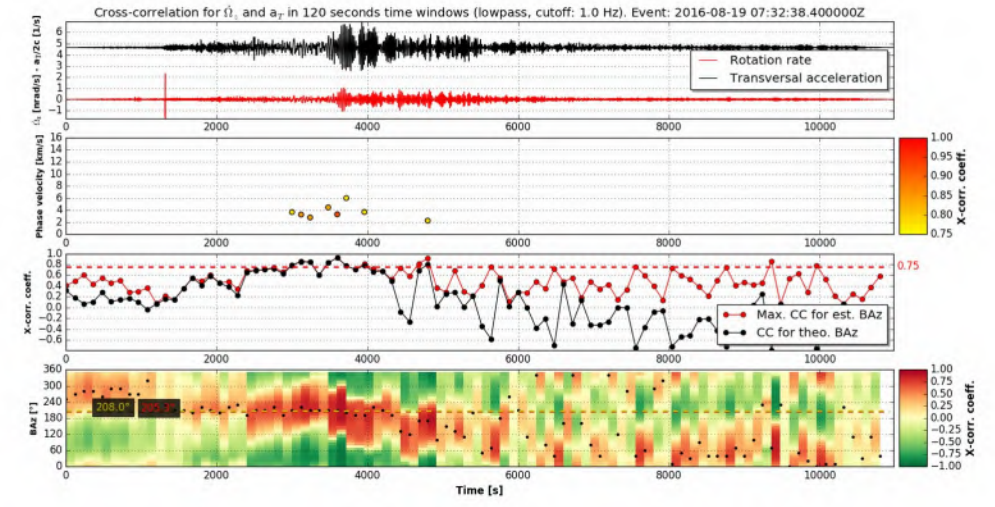


Magnitude 5.8 10
 Depth (km) 0 650
 Correlation 0.7 1
 Total Events in Catalog: 19858

 Station Any ▾
 Available BW
 Map Settings
 Base Layer Stamen Toner-Lite ▾
 Opacity: 100%
 Zoom to Region



SOUTH GEORGIA ISLAND REGION
 Catalog: GCMT
 Magnitude: 7.5 MW
 Fri Aug 19 2016 09:32:38 GMT+0200 (Central Europe)
 Lat: -55.1600 | Lng: -31.4100 | Depth: 22.1



How to get started

Activities • Chromium Web Browser - Mi Sep 18, 11:30
http://seismo-live.org/ - Chromium
http://seismo-live.org/ x download+preprocess... x +
Not secure | seismo-live.org

Seismo-Live
Live Jupyter Notebooks
for Seismology

47 of 50
Seismo-Live containers are
currently available
Not persistent. Will be deleted after being idle
for 30 minutes.

Launch Seismo-Live

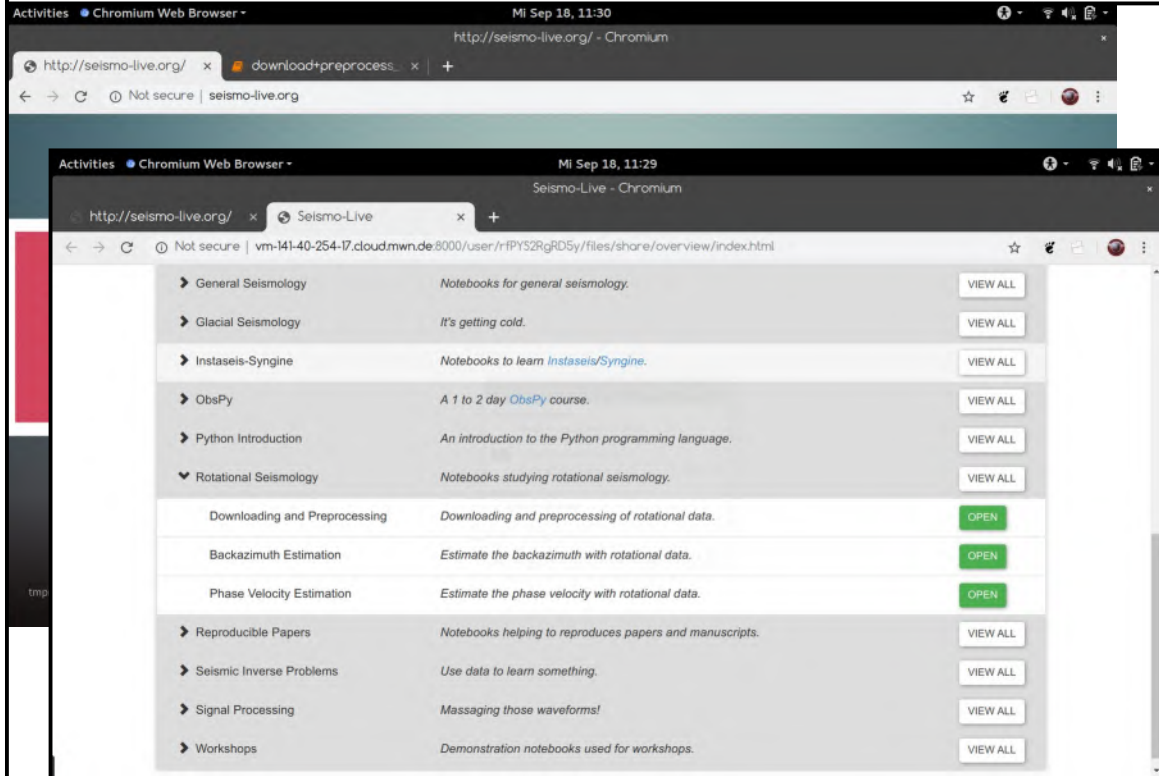
Help - What is Seismo-Live?

More Information

tmpnb server: http://vm-141-40-254-17.cloud.mwn.de:8000
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Go to seismo-live.org
→ click green square to launch

How to get started



Activities • Chromium Web Browser - MI Sep 18, 11:30

http://seismo-live.org/ - Chromium

http://seismo-live.org/ x download+preprocess... x +

← → ↻ Not secure | seismo-live.org

Activities • Chromium Web Browser - MI Sep 18, 11:29

Seismo-Live - Chromium

http://seismo-live.org/ x Seismo-Live x +

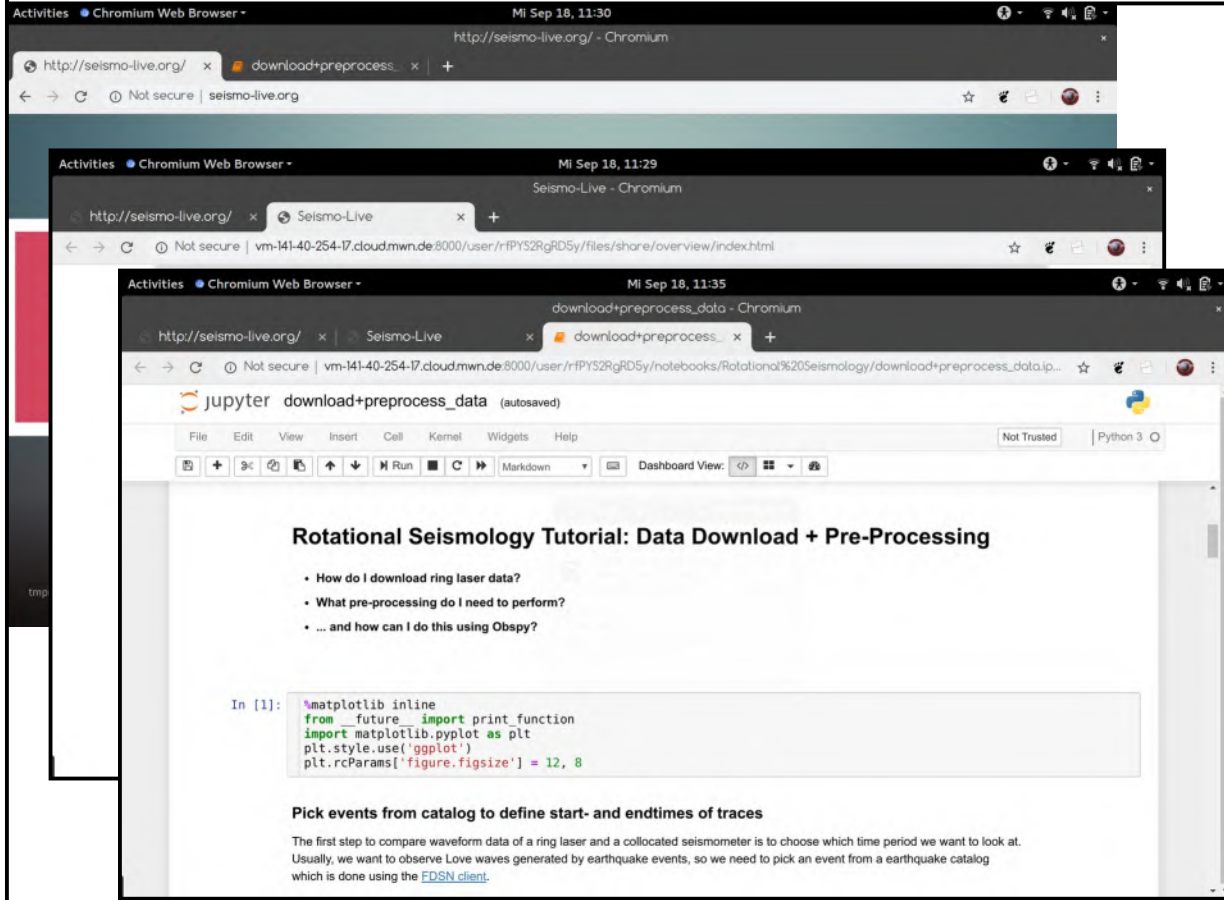
← → ↻ Not secure | vm-141-40-254-17.cloud.mwn.de:8000/user/rfPY52RgRDSy/files/share/overview/index.html

▶ General Seismology	<i>Notebooks for general seismology.</i>	VIEW ALL
▶ Glacial Seismology	<i>It's getting cold.</i>	VIEW ALL
▶ Instaseis-Syngine	<i>Notebooks to learn Instaseis/Syngine.</i>	VIEW ALL
▶ ObsPy	<i>A 1 to 2 day ObsPy course.</i>	VIEW ALL
▶ Python Introduction	<i>An introduction to the Python programming language.</i>	VIEW ALL
▼ Rotational Seismology	<i>Notebooks studying rotational seismology.</i>	VIEW ALL
Downloading and Preprocessing	<i>Downloading and preprocessing of rotational data.</i>	OPEN
Backazimuth Estimation	<i>Estimate the backazimuth with rotational data.</i>	OPEN
Phase Velocity Estimation	<i>Estimate the phase velocity with rotational data.</i>	OPEN
▶ Reproducible Papers	<i>Notebooks helping to reproduce papers and manuscripts.</i>	VIEW ALL
▶ Seismic Inverse Problems	<i>Use data to learn something.</i>	VIEW ALL
▶ Signal Processing	<i>Massaging those waveforms!</i>	VIEW ALL
▶ Workshops	<i>Demonstration notebooks used for workshops.</i>	VIEW ALL

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



Activities • Chromium Web Browser - Mi Sep 18, 11:30
http://seismo-live.org/ - Chromium

Activities • Chromium Web Browser - Mi Sep 18, 11:29
Seismo-Live - Chromium

Activities • Chromium Web Browser - Mi Sep 18, 11:35
download+preprocess_data - Chromium

jupyter download+preprocess_data (autosaved)

Rotational Seismology Tutorial: Data Download + Pre-Processing

- How do I download ring laser data?
- What pre-processing do I need to perform?
- ... and how can I do this using Obspy?

```
In [1]: %matplotlib inline
from _future_ import print function
import matplotlib.pyplot as plt
plt.style.use('ggplot')
plt.rcParams['figure.figsize'] = 12, 8
```

Pick events from catalog to define start- and endtimes of traces

The first step to compare waveform data of a ring laser and a collocated seismometer is to choose which time period we want to look at. Usually, we want to observe Love waves generated by earthquake events, so we need to pick an event from a earthquake catalog which is done using the [FDSN client](#).

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

Wavefield

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

Instrumentation

- Observatory
- Field instruments
- Dense arrays

Structure

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

Structural engineering

- Structural changes
- Torsional modes
- Interstory drift

Summary

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- **Structural changes**
- Torsional modes
- Interstory drift

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](http://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!)