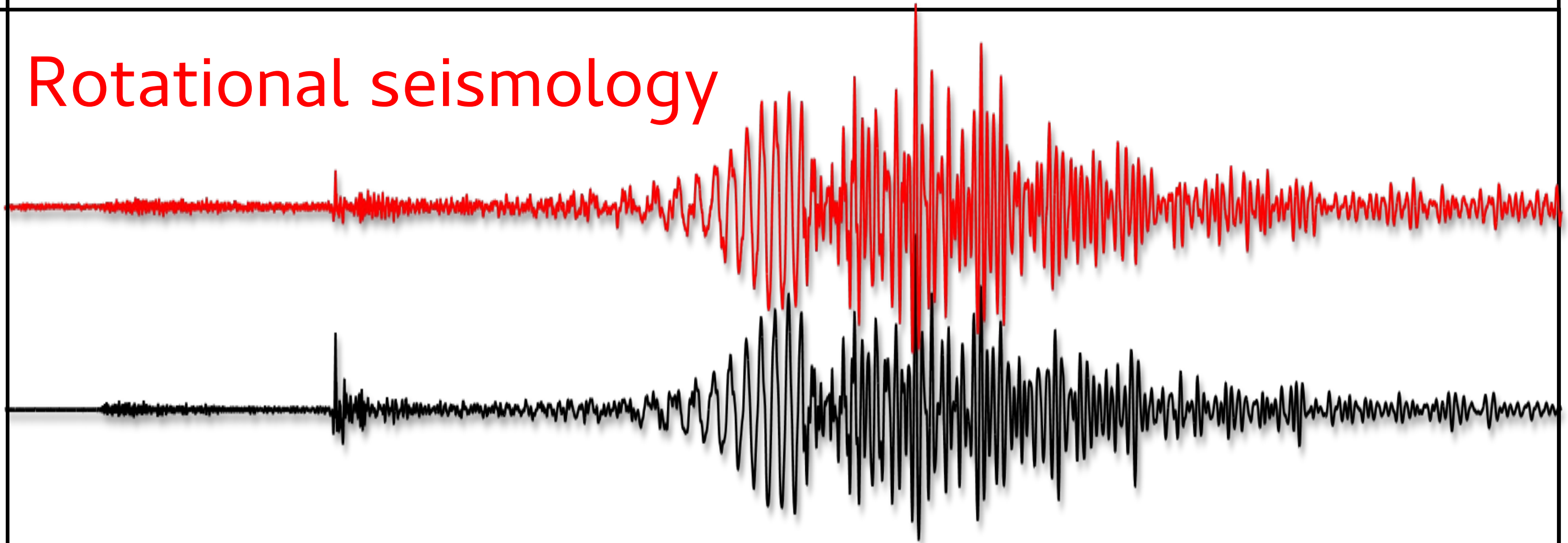
Rotational seismology

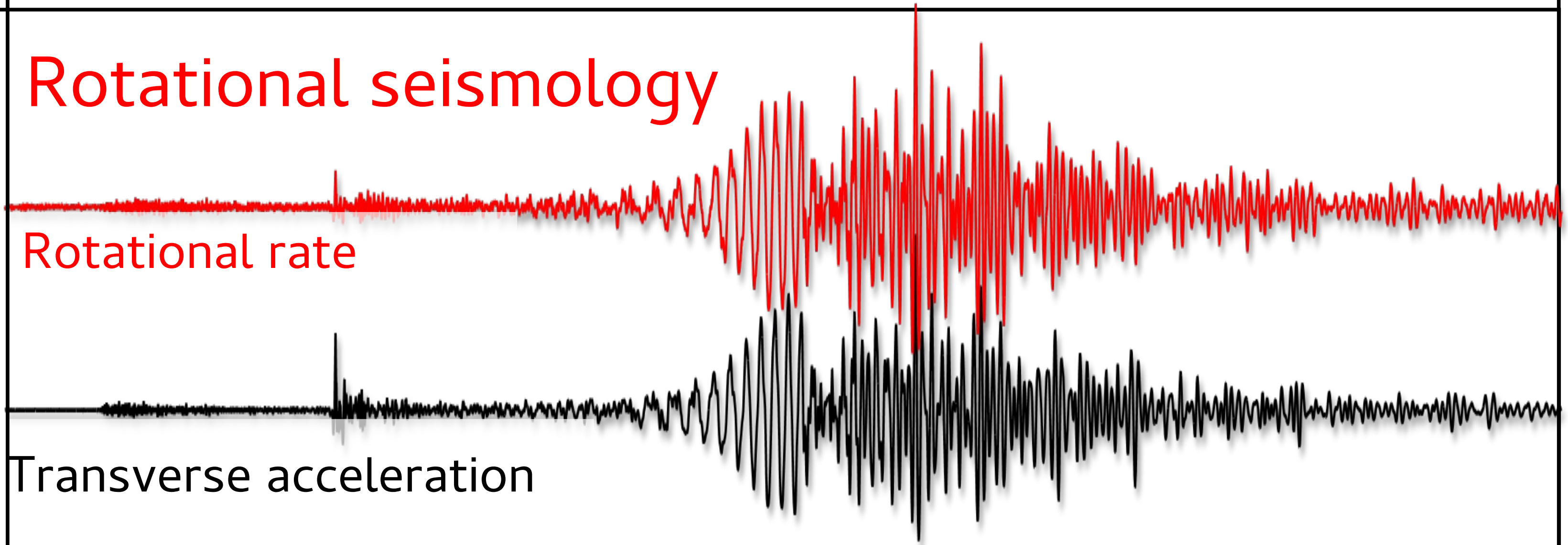


Céline Hadziioannou (and many others..)

Ludwig Maximilians University, Munich

University of Hamburg

Rotational seismology



Céline Hadziioannou (and many others..)

Ludwig Maximilians University, Munich

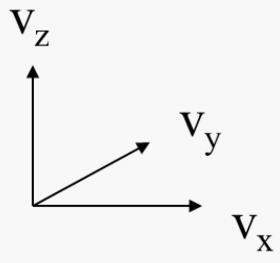
University of Hamburg

What are rotations?

Entire wave field:

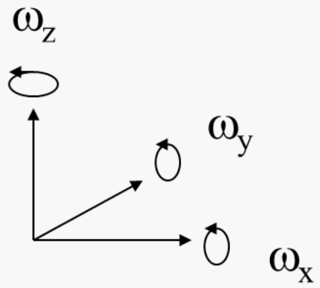
$$u(x+\delta x) = u(x) + \varepsilon\,\delta x + \omega \times \delta x$$

3C Translation + 6C Strain + 3C Rotation



Ground velocity

Seismometer



Rotation rate

Rotation sensor

$$\omega = 1/2\ \nabla \times u(x)$$

$$\omega_x = 1/2\ (\partial u_z/\partial y - \partial u_y/\partial z)$$
$$\omega_y = 1/2\ (\partial u_x/\partial z - \partial u_z/\partial x)$$
$$\omega_z = 1/2\ (\partial u_y/\partial x - \partial u_x/\partial y)$$

e.g. Cochard et al., 2006

Why?

Structural engineering

Why?

Source

Structure

Wavefield

Structural engineering

Why?

Source

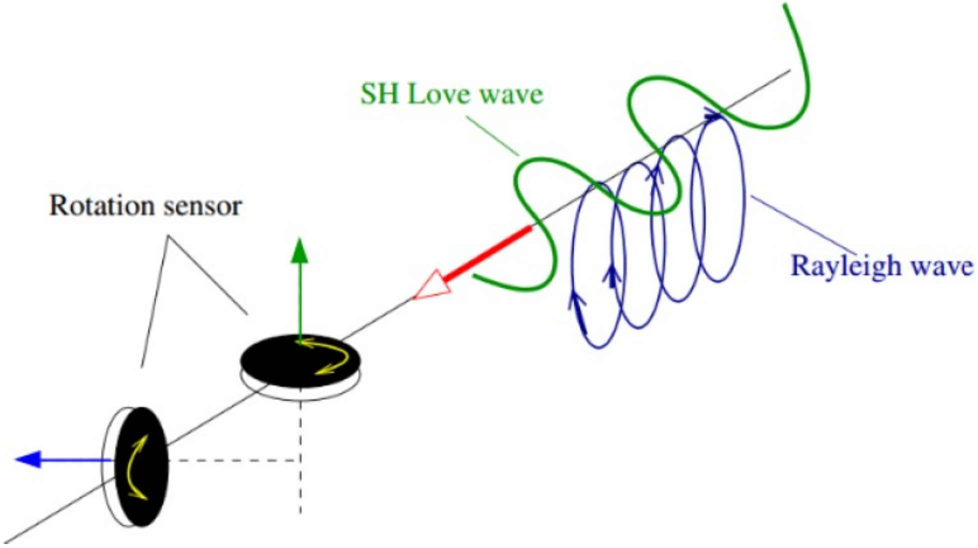
Structure

Instrumentation

Wavefield

Structural engineering

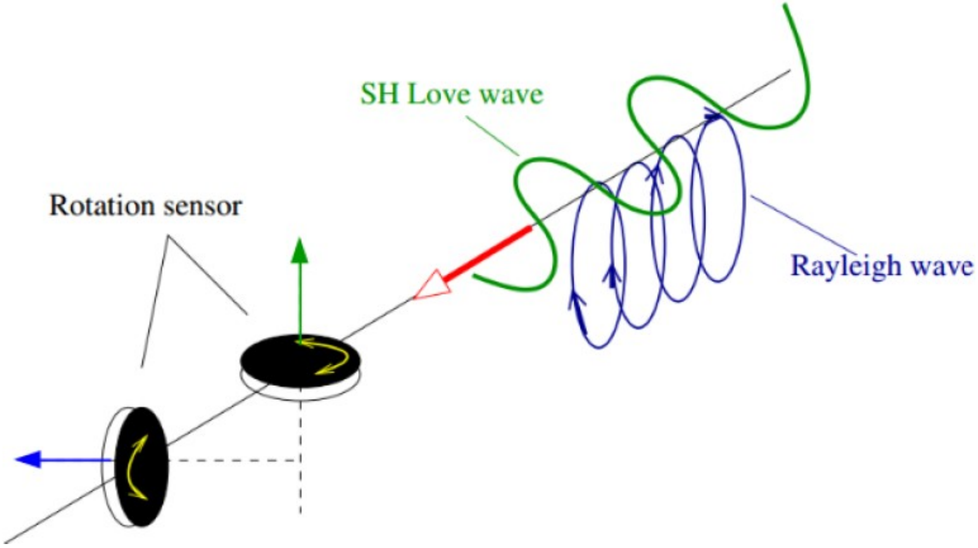
Rotations → wavetype filter



Love & SH motion → vertical rotation

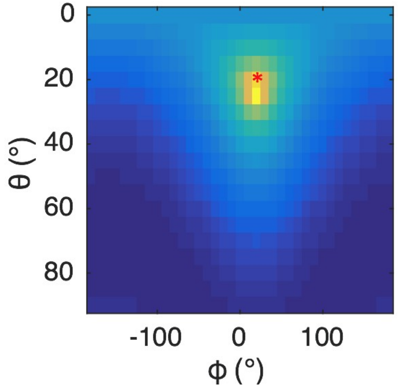
Rayleigh → horizontal rotation

Rotations → wavetype filter



Love & SH motion → vertical rotation

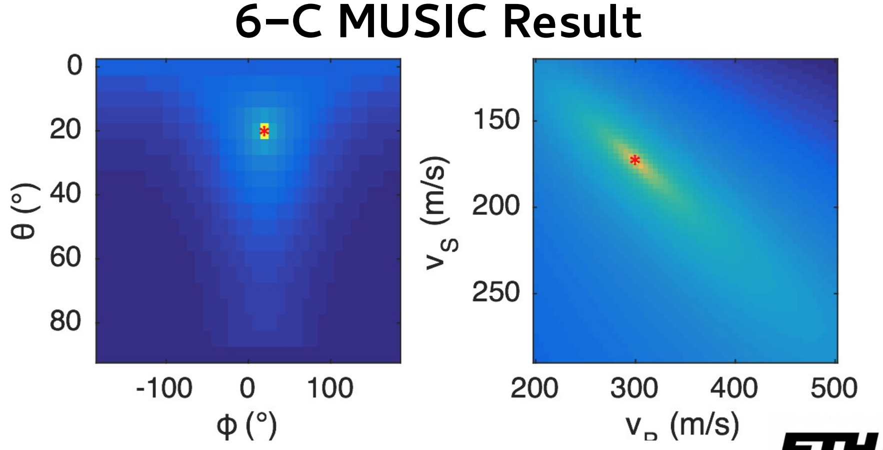
Rayleigh → horizontal rotation



David Sollberger *et al.*

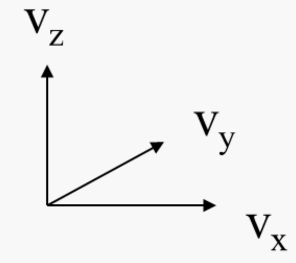
Polarization analysis

With 3 vs 6 components



Combining Rotation and Translation

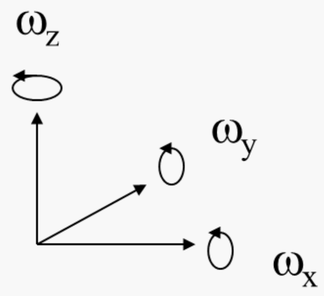
3C Translation



Ground velocity

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.**

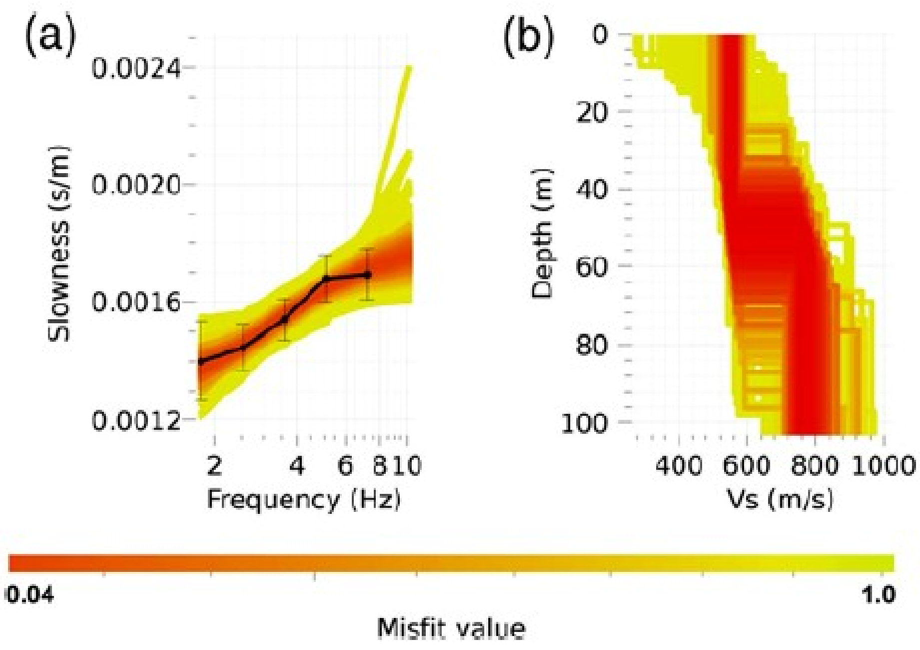
Phase velocity → using single measurement of 6C → **structure**

in phase → waveforms similar → can find source direction → **source**

Structure – determining it using 6C

Single 6C-station dispersion curves:

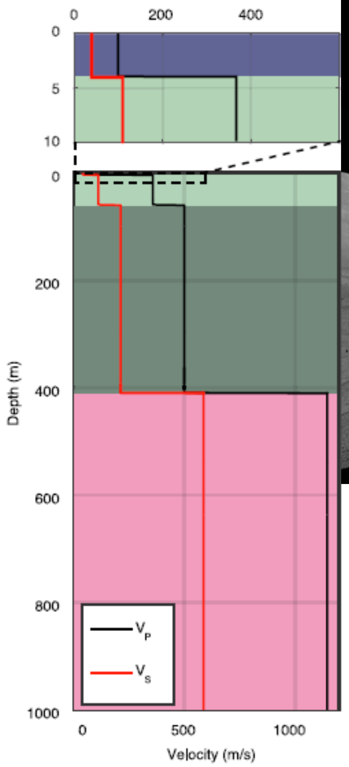
$$c(f) = -\frac{1}{2}\ddot{u}_T(f)/\dot{\omega}_3(f),$$



Wassermann et al., BSSA 2016

Lunar Vp & Vs structure

"Point" 6C measurement



Sollberger et al., GRL 2016

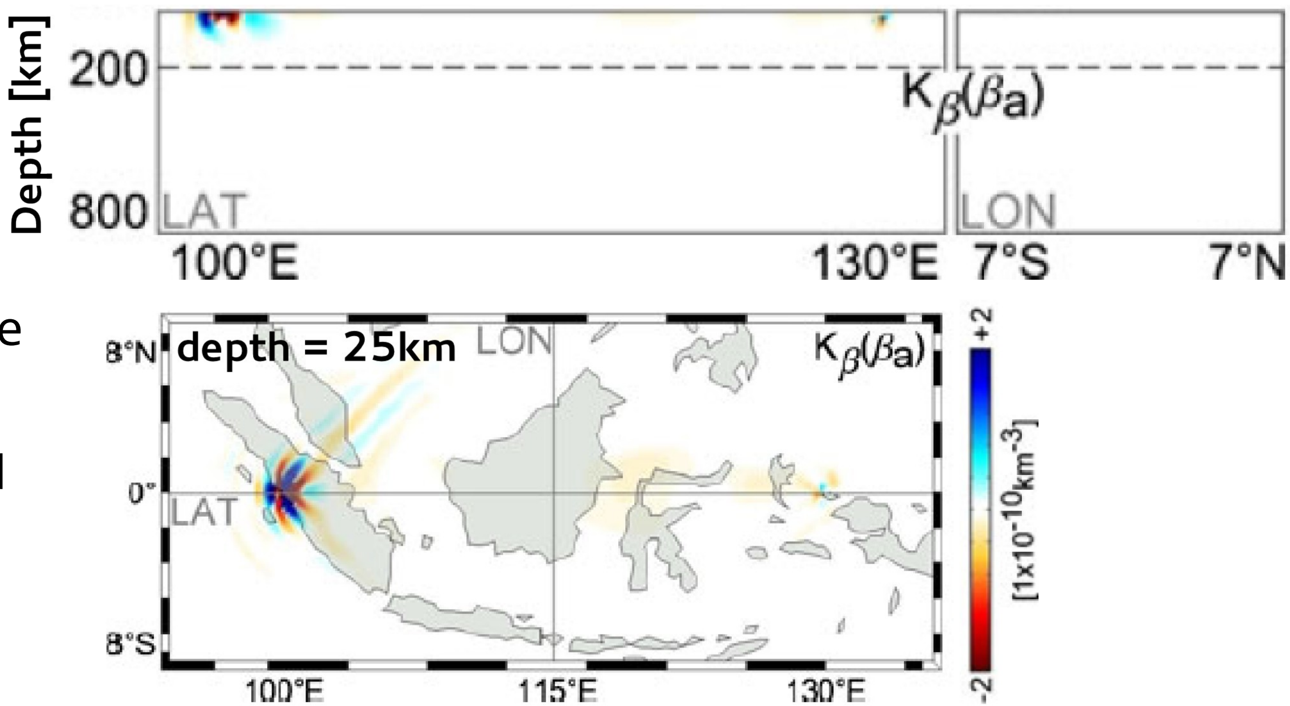
Structure – sensitivity kernels

Sensitivity kernels for:

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

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

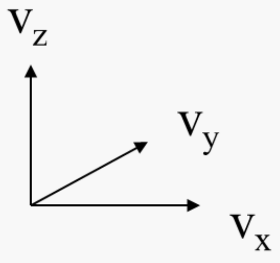
Love wave (50s)



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

Combining Rotation and Translation

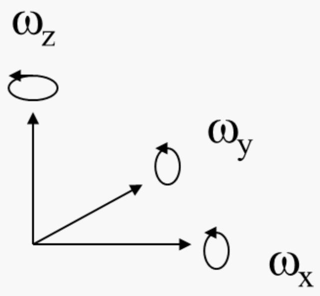
3C Translation



Ground velocity

Seismometer

\+ 3C Rotation



Rotation rate

Rotation sensor

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\+ Rotation rate and acceleration should be **in phase**

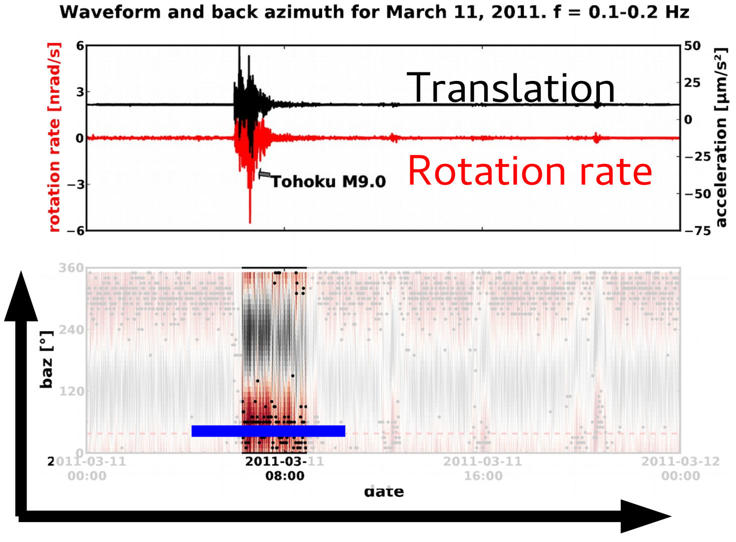
\+ amplitudes scaled by **two times the horizontal phase velocity.**

Phase velocity → using single measurement of 6C → **structure**

in phase → waveforms similar → can find source direction → **source**

Source – source direction

Filtered 0.1 – 0.2 Hz

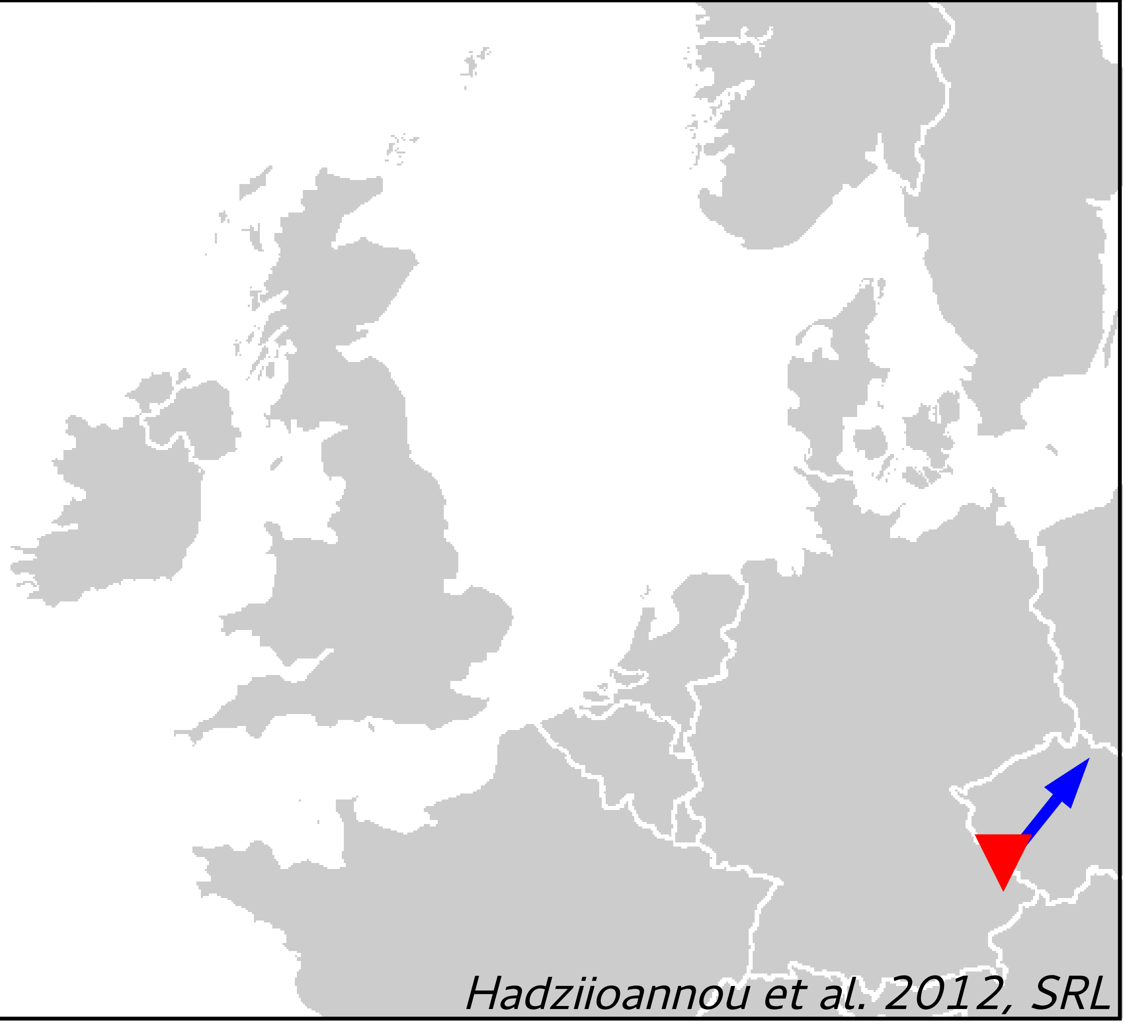


backazimuth

1 day

Corrcoef = 1

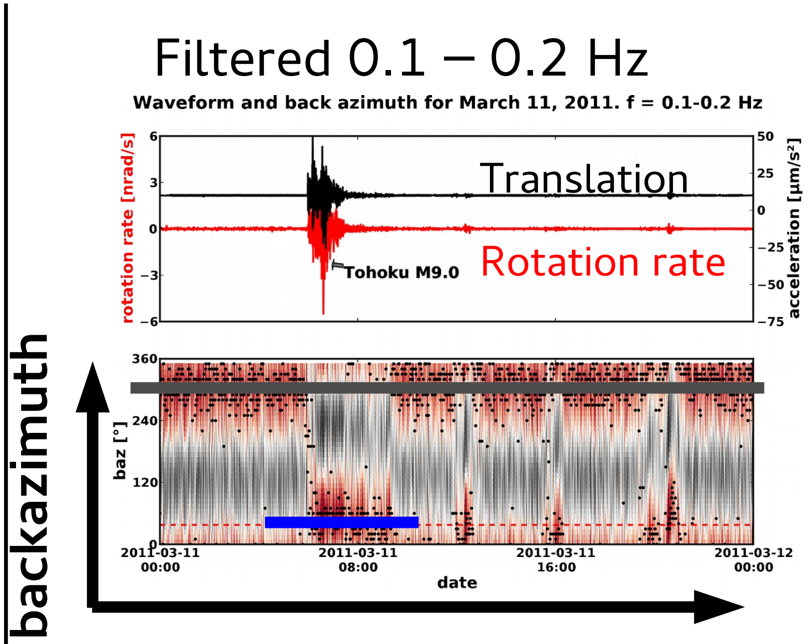
Corrcoef =-1



Hadziioannou et al. 2012, SRL

Source – source direction

Filtered 0.1 – 0.2 Hz

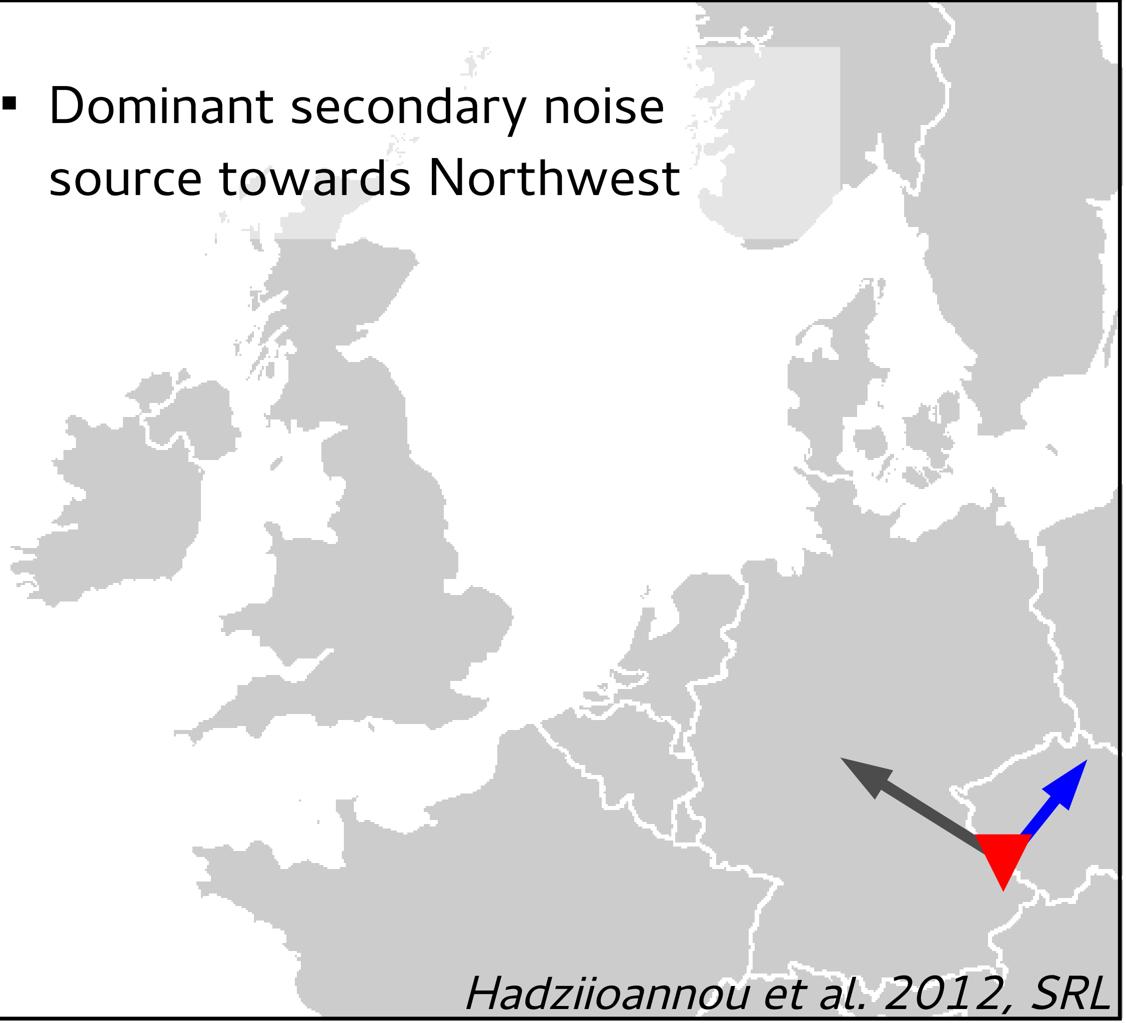


1 day

Corrcoef = 1

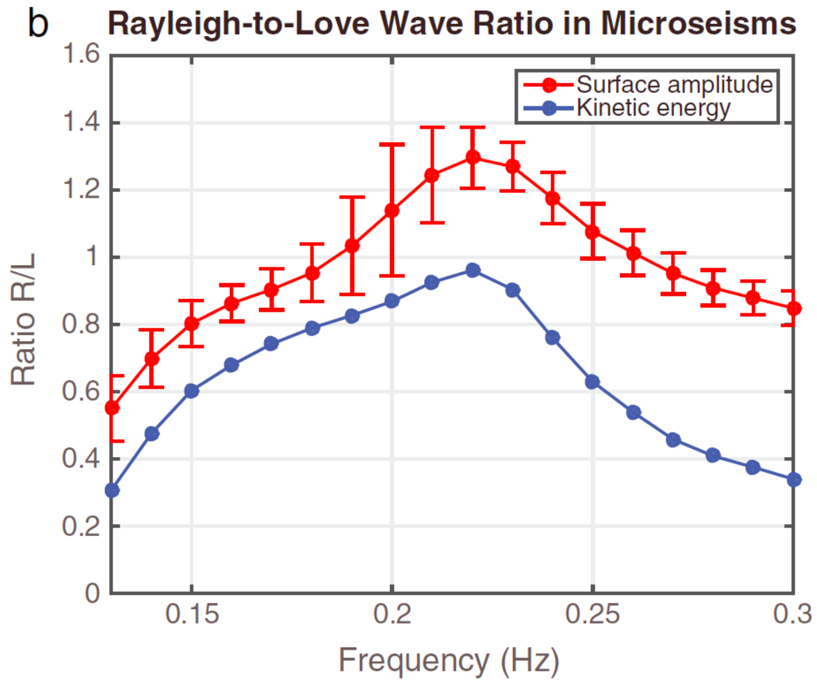
Corrcoef =-1

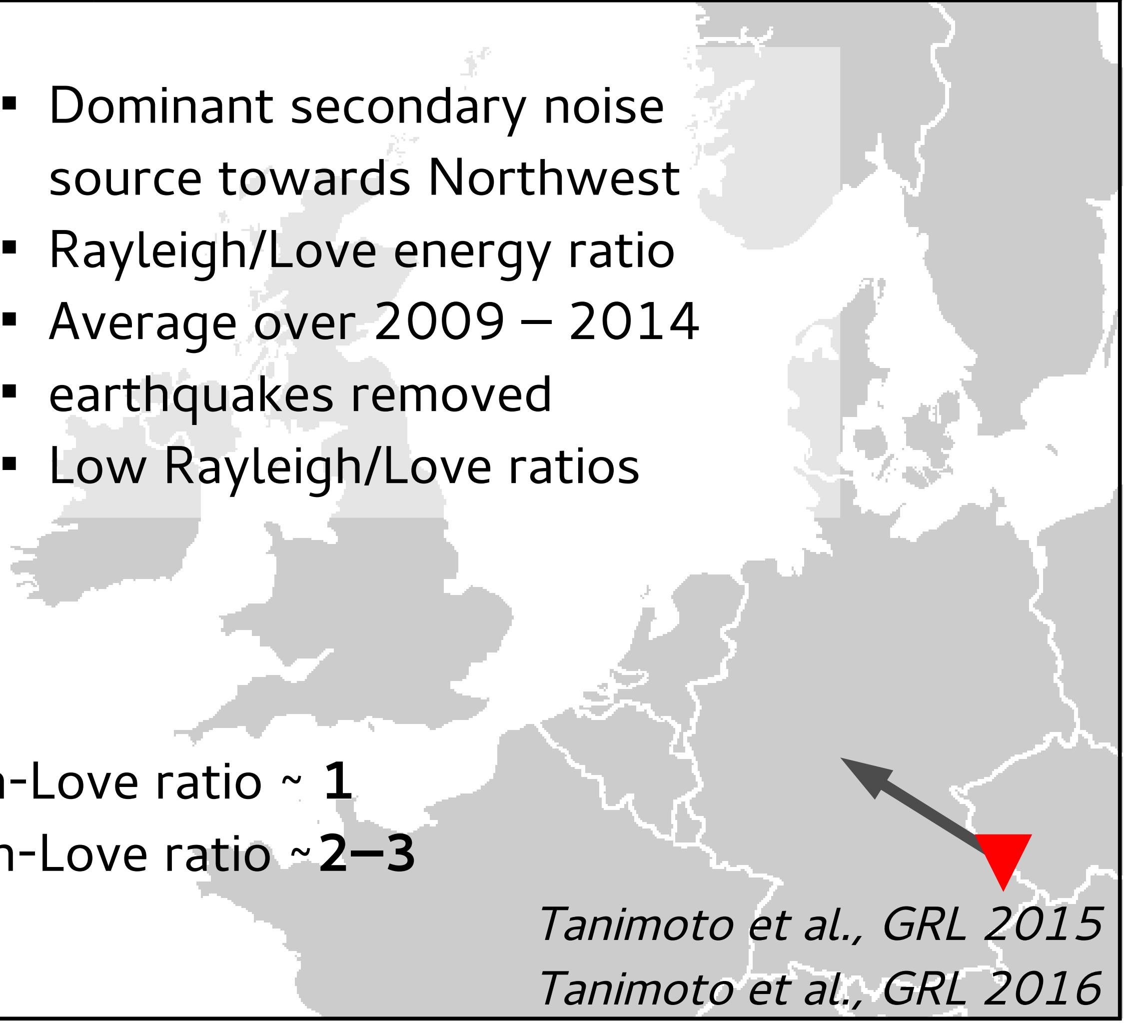
- Dominant secondary noise source towards Northwest



Hadziioannou et al. 2012, SRL

Source – Microseism Rayleigh/Love ratios





- Dominant secondary noise source towards Northwest
- Rayleigh/Love energy ratio
- Average over 2009 – 2014
- earthquakes removed
- Low Rayleigh/Love ratios

Wettzell, Germany: Rayleigh-Love ratio ~ **1**

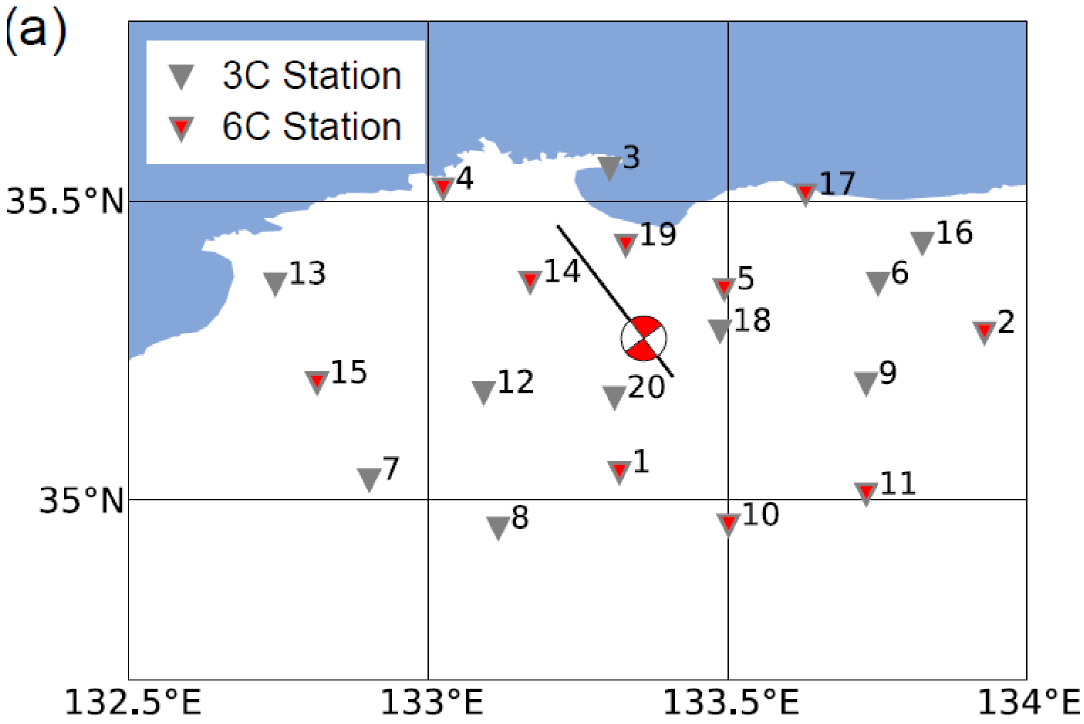
Pinion Flat Observatory: Rayleigh-Love ratio ~**2–3**

Tanimoto et al., GRL 2015

Tanimoto et al., GRL 2016

Earthquake Source – Moment tensor inversion

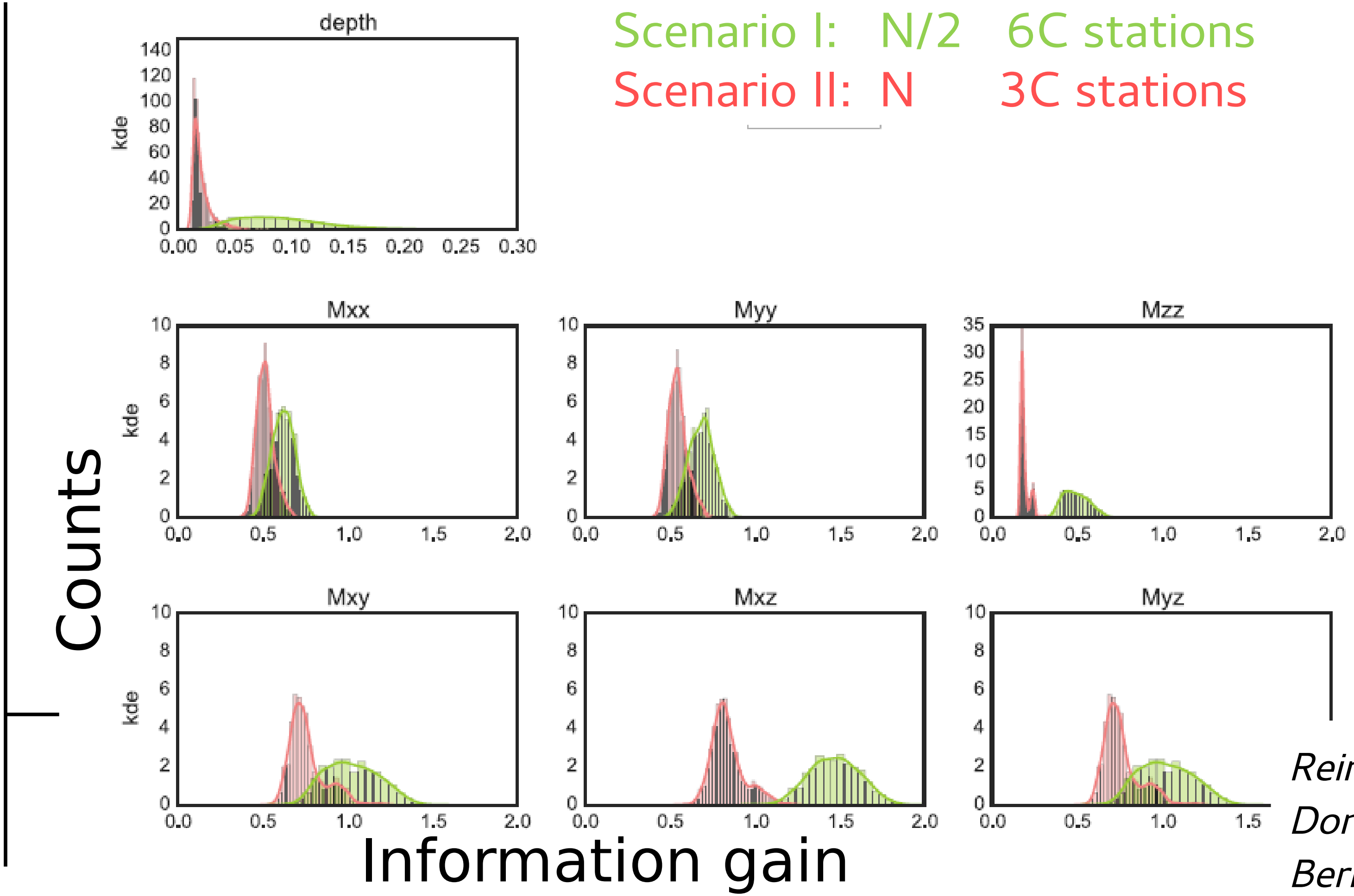
+ Scenario I: N receivers with 3C observations (translations)
+ Scenario II: N/2 receivers with 6C observations (translations and rotations)



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

Earthquake Source – Moment tensor 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 – Moment tensor inversion

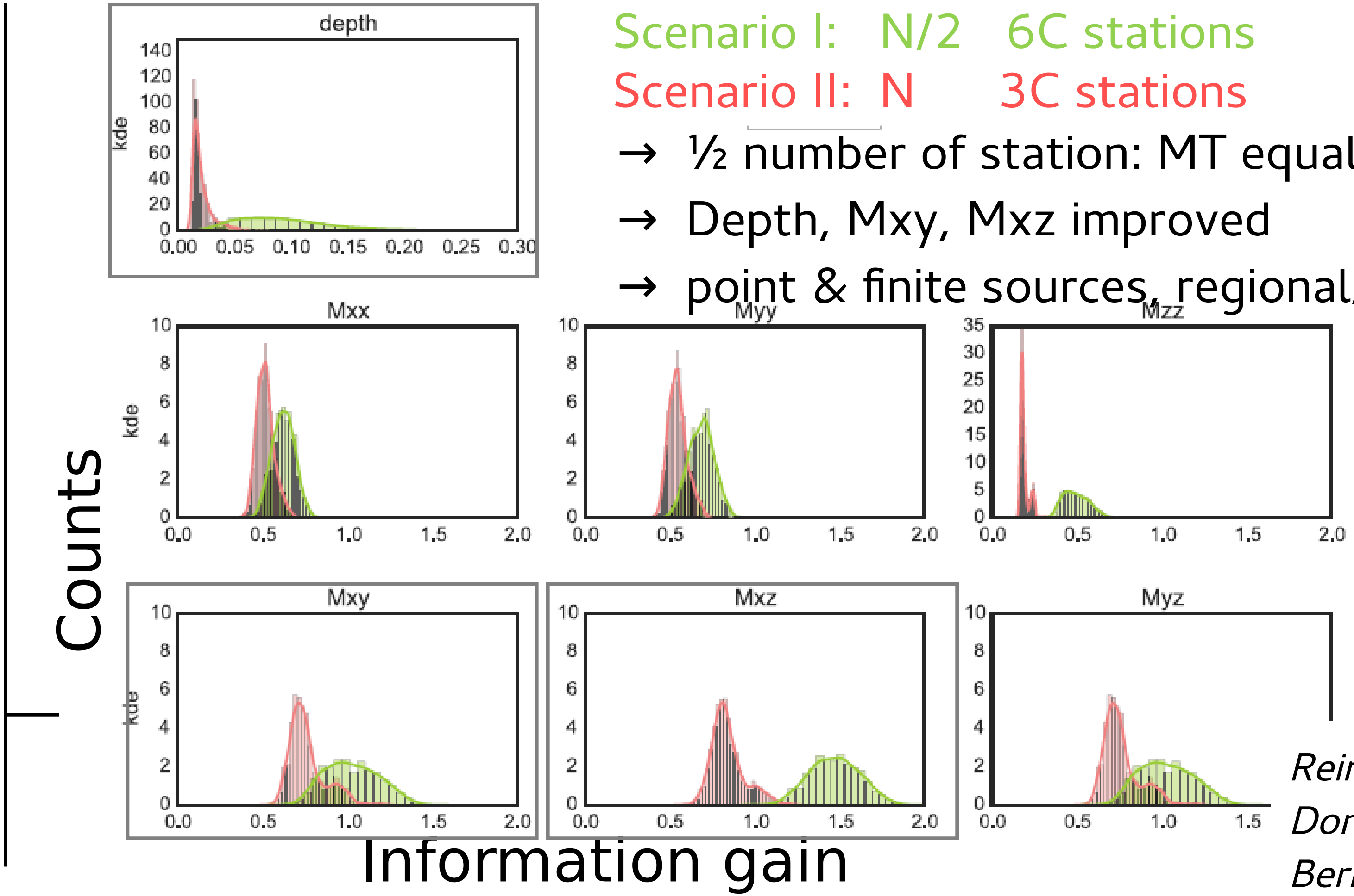
Scenario I: N/2 6C stations

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

Bernauer et al, JGR: SE 2014

Summary

Source
- MT inversion
- Microseisms

Instrumentation

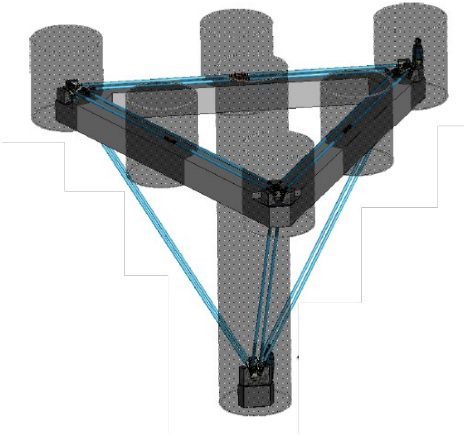
Structure
- Phase velocity
- Dispersion
- Sensitivity kernels

Wavefield
- Wavetype separation
- Wavetype ratios

Structural engineering

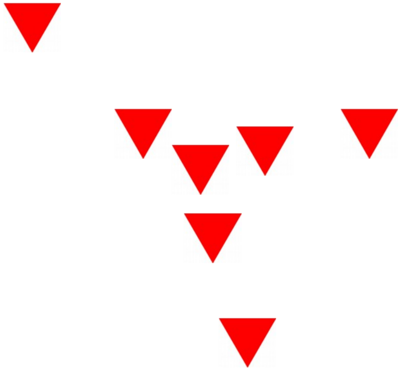
Instrumentation – How to observe rotations?

Observatory instruments
Ring lasers



Field instruments
e.g. Fiber optic gyros

Dense arrays
Seismometers



L < ¼ λ

Instrumentation – How to observe rotations?

Observatory instruments

Ring lasers

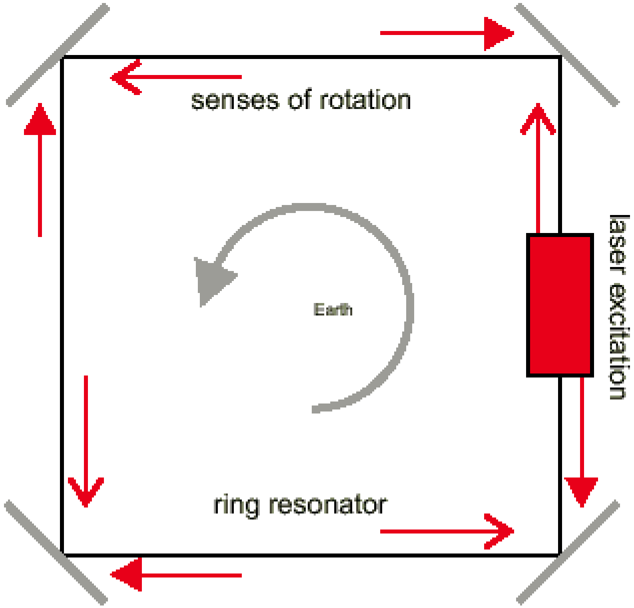
Sagnac interferometry

+ counterpropagating laser beams

→ beat frequency

+ system moved transversally: no effect

+ system rotated: beat frequency changes



Schreiber et al., Rev. Scientific Instr., 2013

Instrumentation – How to observe rotations?

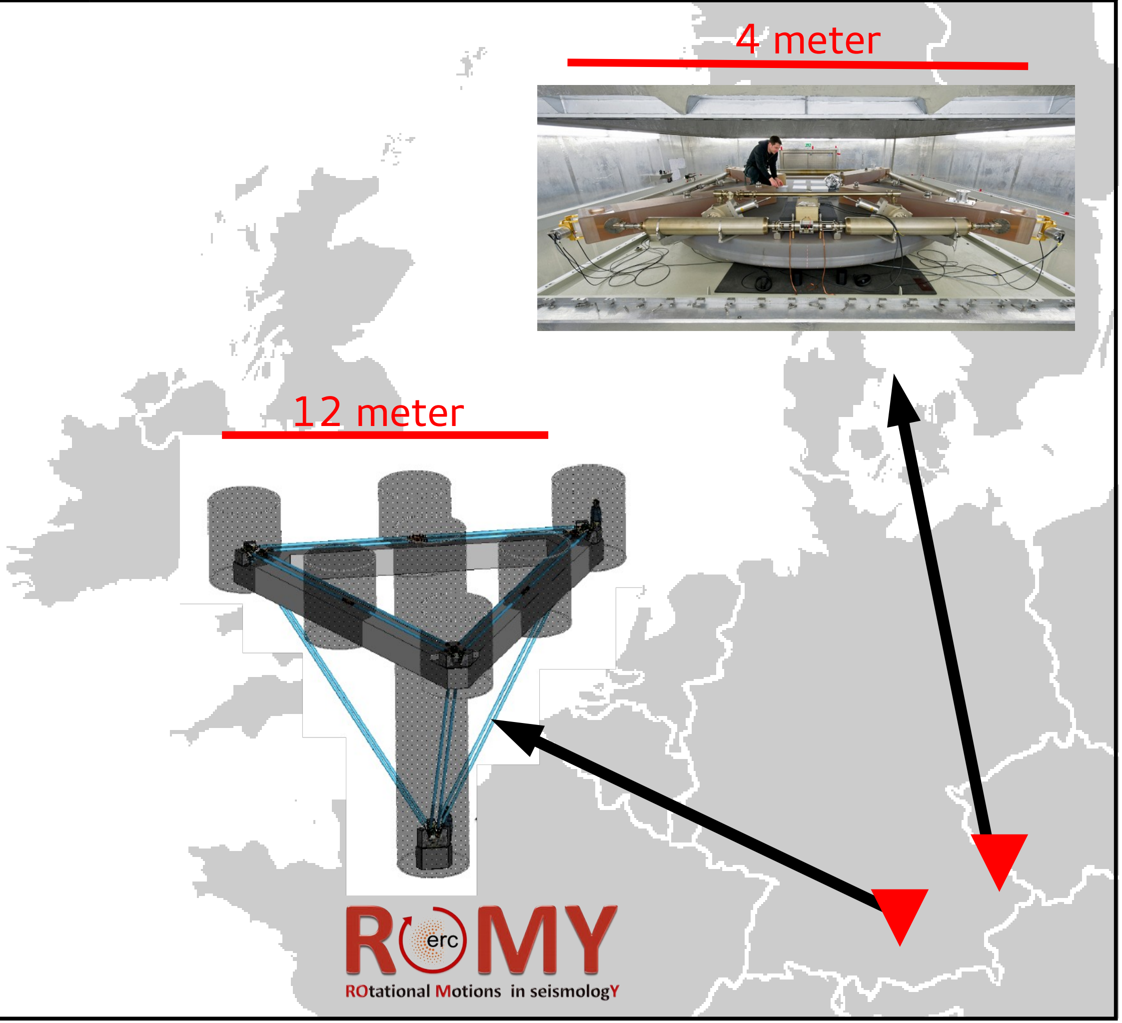
Observatory instruments

Ring lasers

+ 5 worldwide

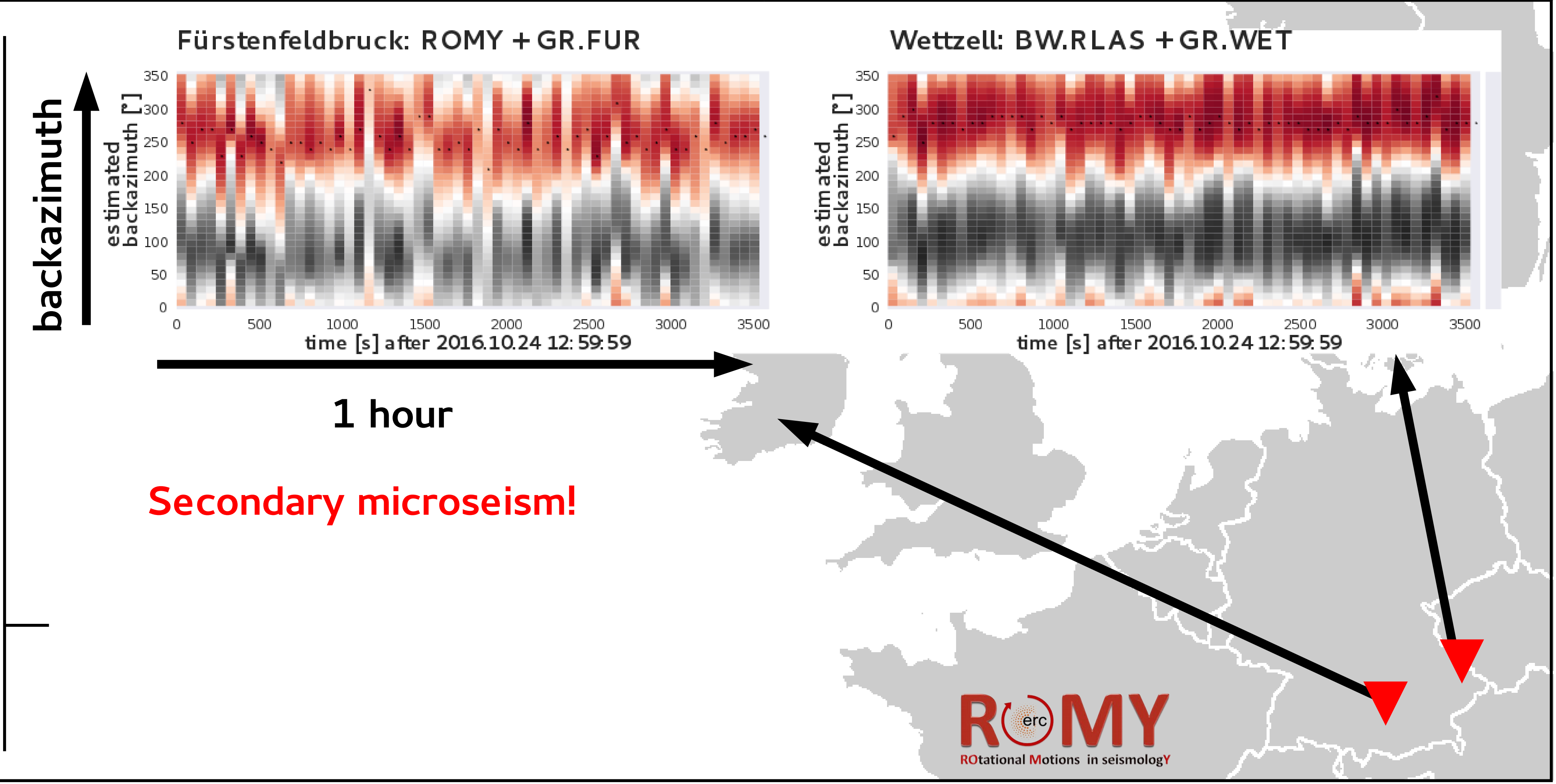
+ Wettzell, Germany most sensitive

+ ROMY: first 3-component rotation



"Lord of the Rings", Science, 2017

Instrumentation – How to observe rotations?

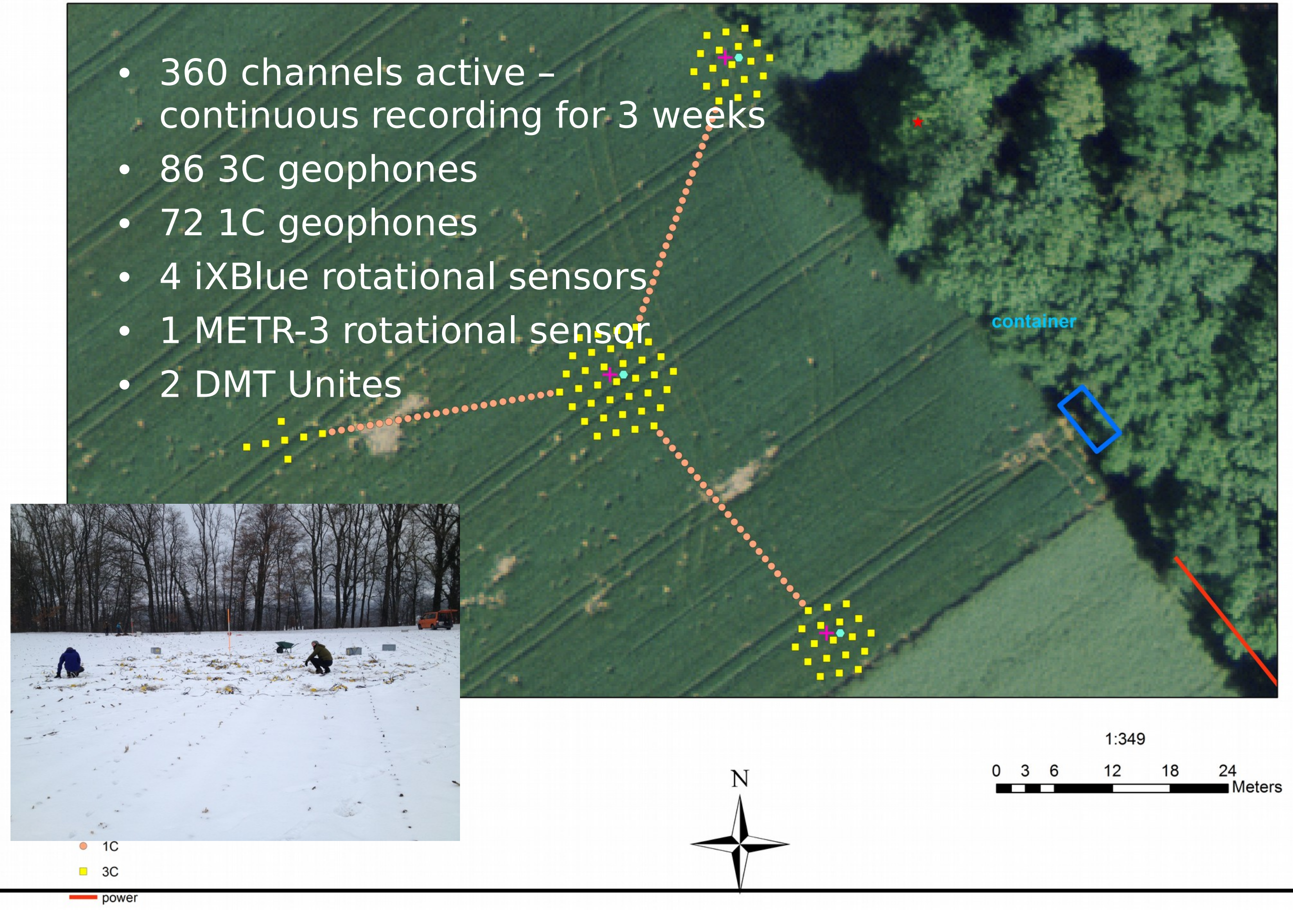


Secondary microseism!

Instrumentation – How to observe rotations?

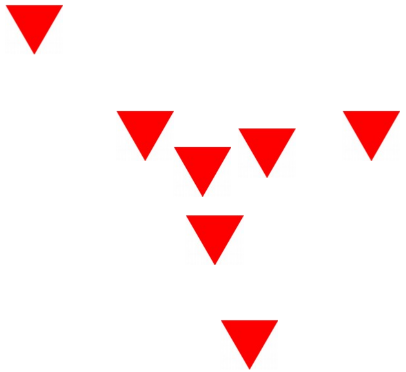
rot3D - setup

- 360 channels active – continuous recording for 3 weeks
- 86 3C geophones
- 72 1C geophones
- 4 iXBlue rotational sensors
- 1 METR-3 rotational sensor
- 2 DMT Unites



Dense arrays

Seismometers



L < ¼ λ

CARNEVAL project

Instrumentation – How to observe rotations?

Observatory instruments

Ring lasers

Field instruments

e.g. Fiber optic gyros

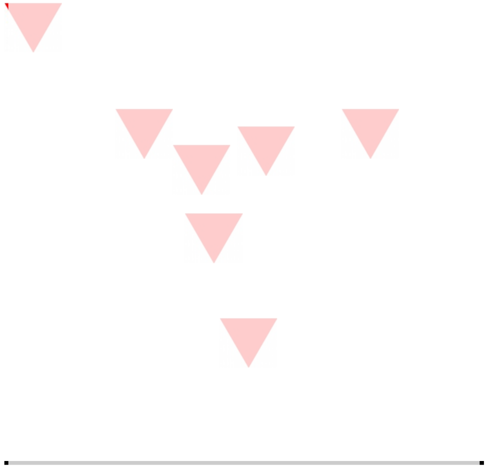
blueSeis

an iXblue product line

- 30-50 nrads^{-1} Hz$^{-1/2}$ PSD
- flat PSD over a wide frequency range (0.01 - 10 Hz)

Dense arrays

Seismometers



L < ¼ λ

Instrumentation – How to observe rotations?

LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

UH

Observatory instruments

Ring lasers

Field instruments

e.g. Fiber optic gyros

Available now!

blueSeis

an iXblue product line

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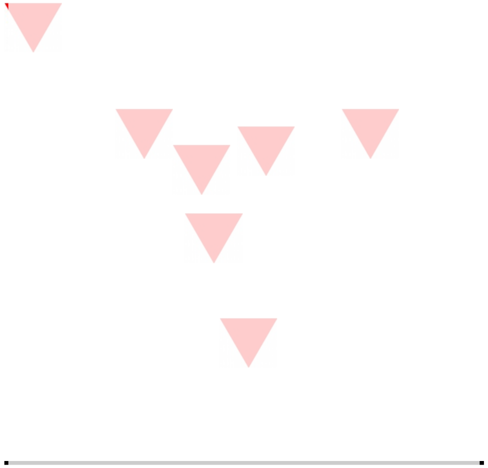
- flat PSD over a wide frequency range (0.01 - 10 Hz)

Dense arrays

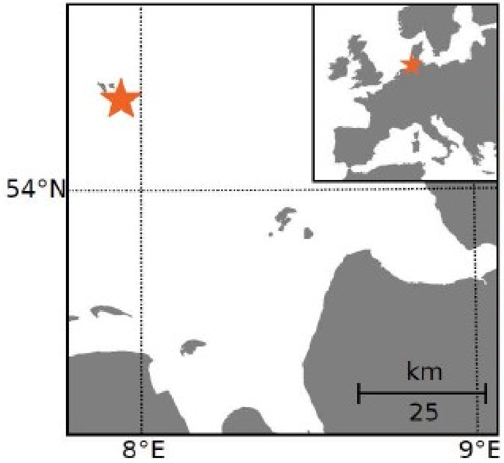
Seismometers

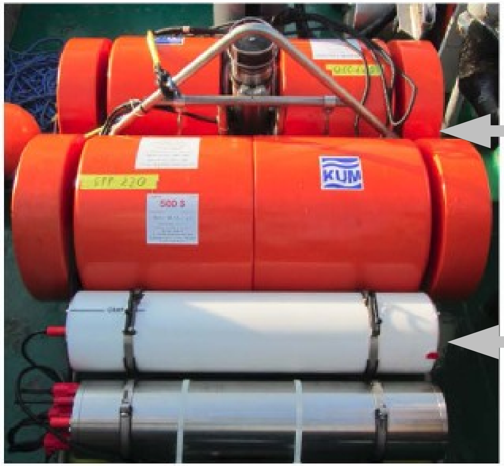


L < ¼ λ

www.blueseis.com

Instrumentation – What about tilt?





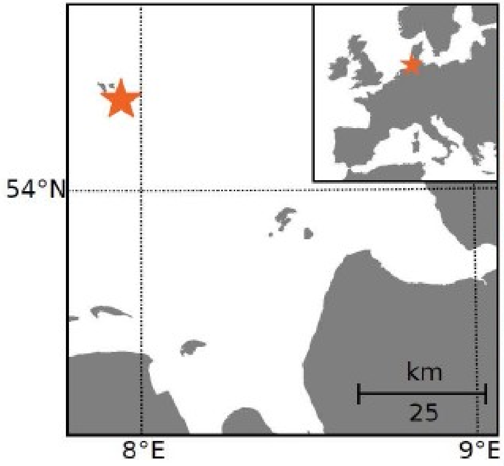
Seismometer (sensitive to tilt)

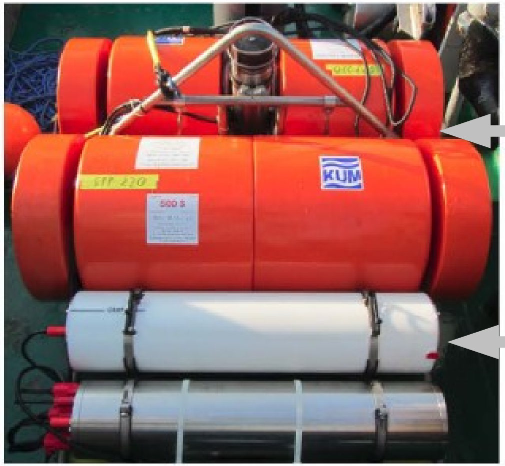
Fiber optic gyro (only tilt)

Ocean bottom seismometer

Lindner et al., SRL 2016

Instrumentation – What about tilt?

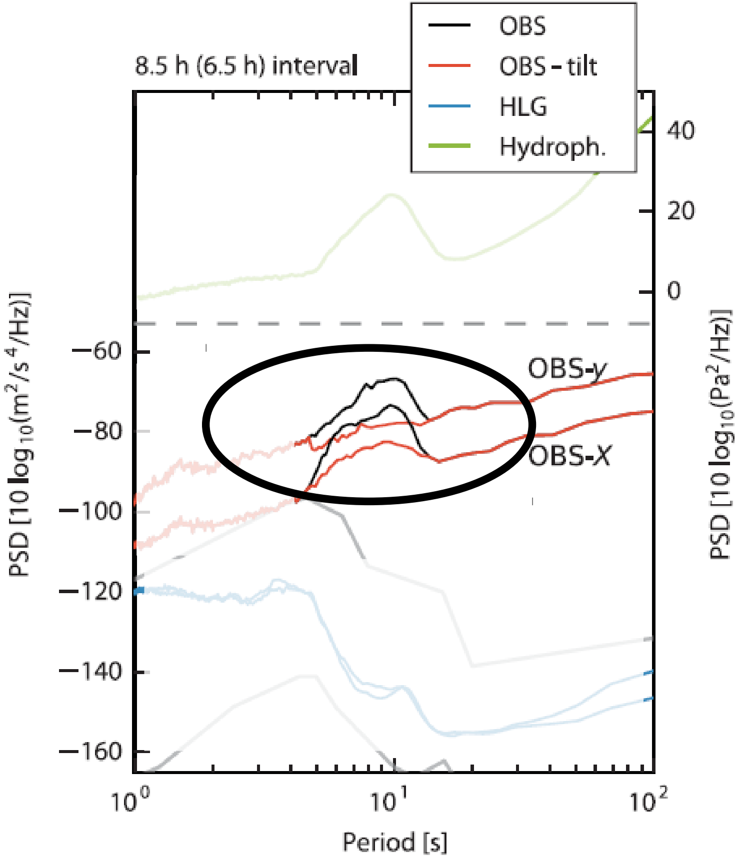




Ocean bottom seismometer

Tilt correction → improved SNR

Independent Tilt measurement: applications on volcanoes?



Lindner et al., SRL 2016

Summary

Source
- MT inversion
- Microseisms

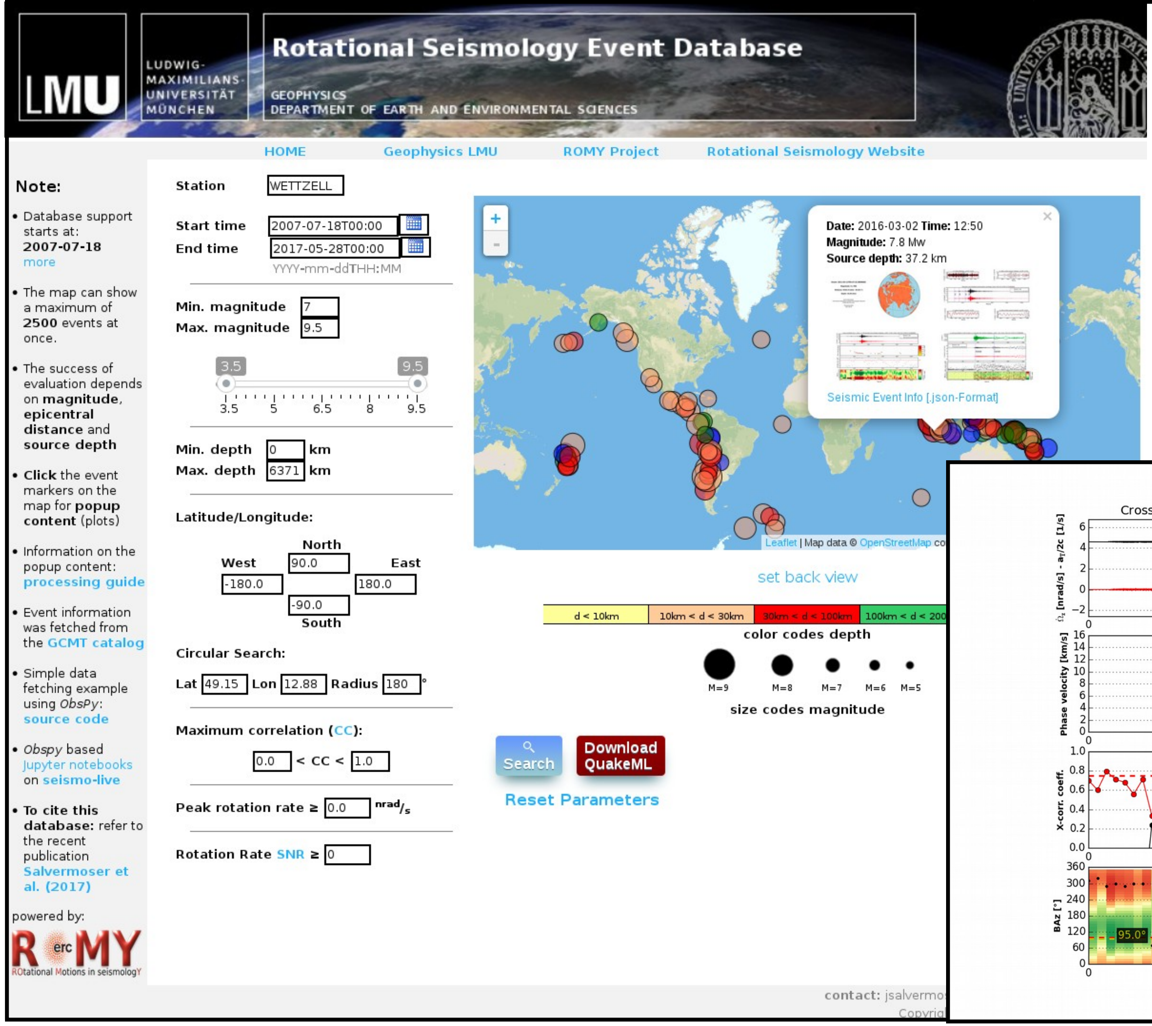
Wavefield
- Wavetype separation
- Scattering
- Wavetype ratios
- Tilt (OBS?)

Instrumentation
- Observatory
- Field instruments
- Dense arrays

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

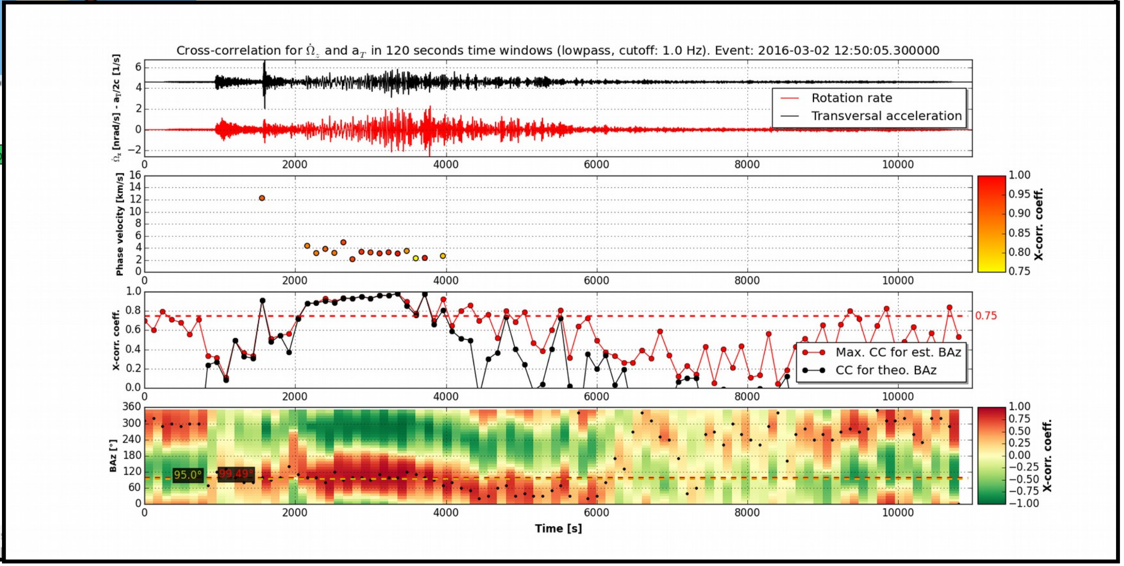
Structural engineering
- Torsional modes
- Interstory drift
- ...

Rotational seismology database



Access via www.romy-erc.eu

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



Summary

Source
- **MT inversion**
- **Microseisms**

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

Instrumentation
- **Observatory**
- **Field instruments**
- Dense arrays

6C:
- New observables
- do more with less stations
- Or with **single station**

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

Structural engineering
- Torsional modes
- Interstory drift
- ...

Thanks to:

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...and many more

LMU Munich, Germany
TU Munich, Germany
ETH Zurich, Switzerland
UCSD, La Jolla, USA
UC Santa Barbara, USA
University of Pisa, Italy

References (not exhaustive!)

General Rotational seismology

- Cochard, A., Igel, H., Schuberth, B., Suryanto, W., Velikoseltsev, A., Schreiber, U., Wassermann, J., Scherbaum, F. & Vollmer, D. (2006). Rotational motions in seismology: theory, observation, simulation. In Earthquake source asymmetry, structural media and rotation effects (pp. 391-411). Springer Berlin Heidelberg.

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Instrumentation

- Portable sensor (iXBlue): http://www.blueseis.com/
- "Lord of the Rings", Science 21 Apr 2017: Vol. 356, Issue 6335, pp. 236-238 DOI: 10.1126/science.356.6335.236 http://science.sciencemag.org/content/356/6335/236
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Rotational seismology database

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

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- www.rotational-seismology.org (with mailing list!)