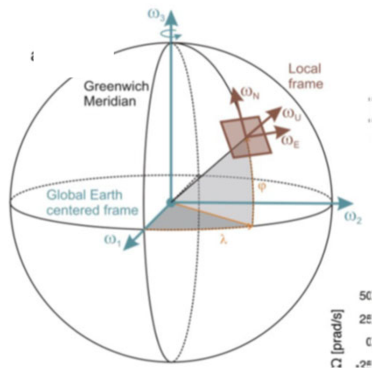
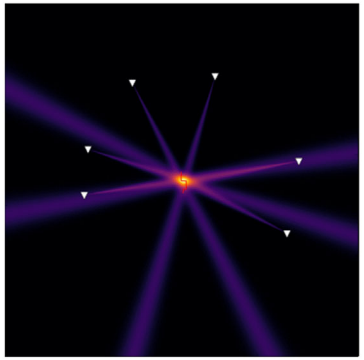
Earth's Rock'n'Roll:
Measuring rotational motions in Geodesy and Seismology





Heiner Igel[1], Andreas Brotzer[1], Felix Bernauer[1], Sabrina Keil[1], Chin-Jen Lin[1,9], Frederic Guattari[7], Fabian Lindner[1,3], ***Karl Ulrich Schreiber***[2], Frank Vernon[4], Joachim Wassermann[1], Shihao Yuan[1] and others

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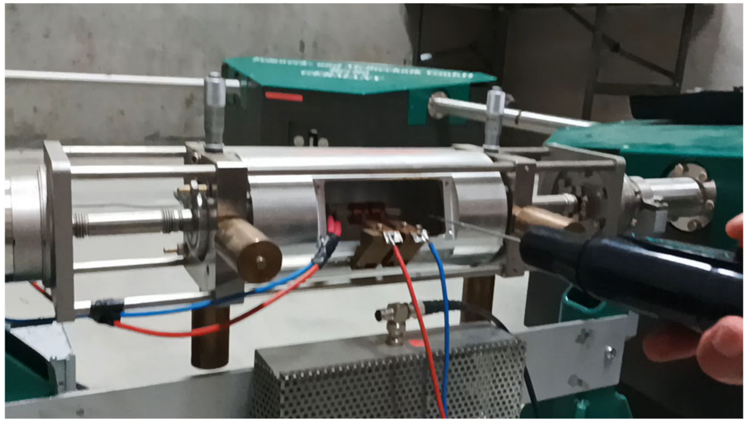
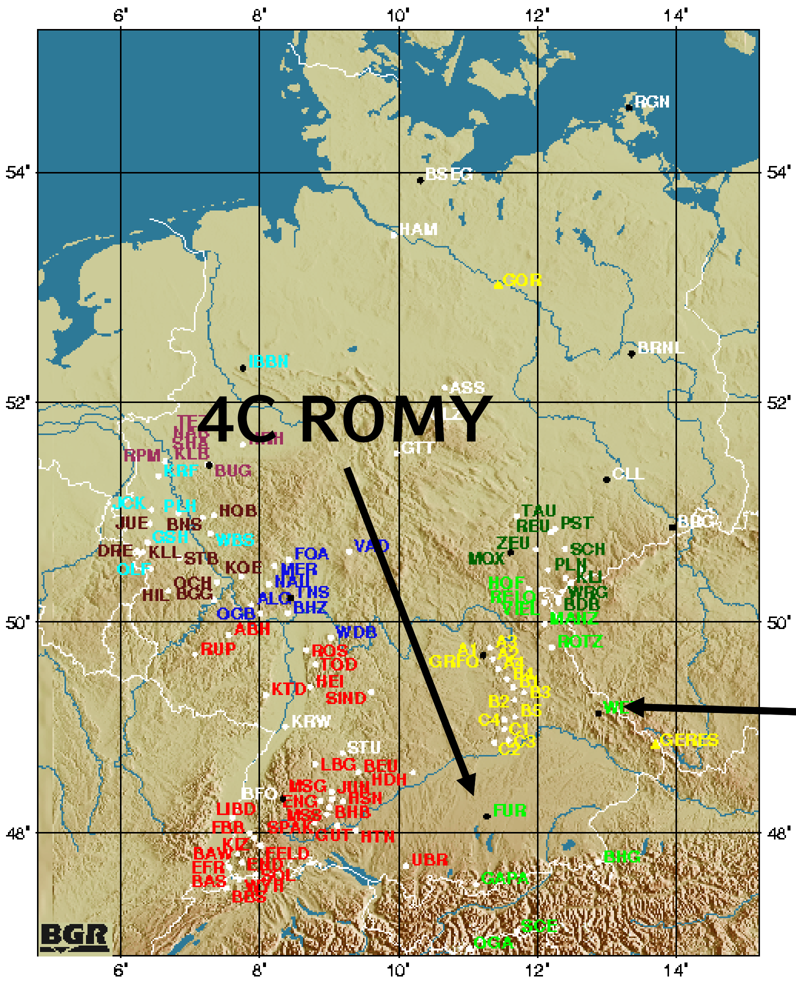
Outline

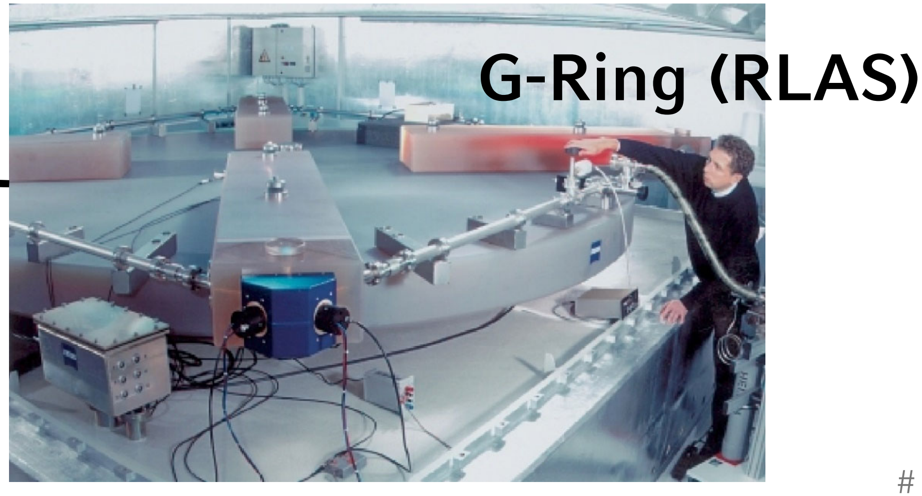
- How do ***ring lasers*** measure Earth‘s rotation?
- How their *noise* sparked a new field in seismology (**rotational seismology**)
- A **portable** rotation sensor for seismology
- Rotational ground motions, **what are they good for**?
    - Structural inversion
    - Volcano seismology
    - Seismic source tracking
    - Seismic anisotropy and mantle flow
    - Planetary seismology
    - Ocean bottom seismology
    - Earthquake engineering
- Outlook



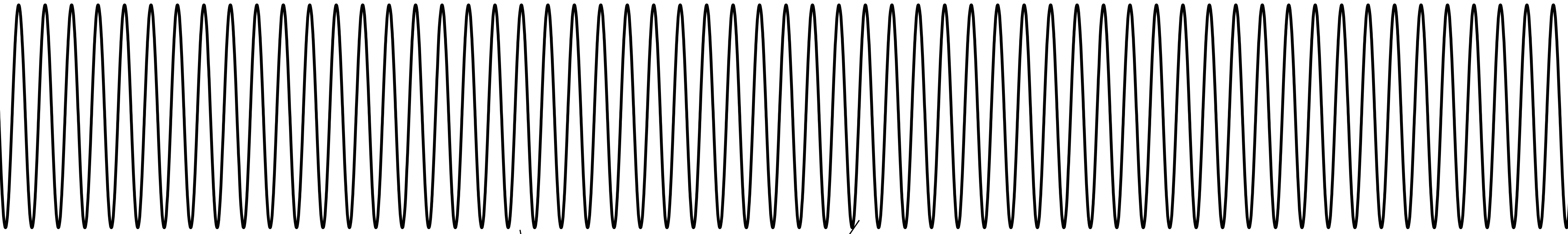
How to observe Earth‘s
(and local ground) **rotations**
(without VLBI and satellites)?

Geodetic Observatory Wettzell, SE Germany

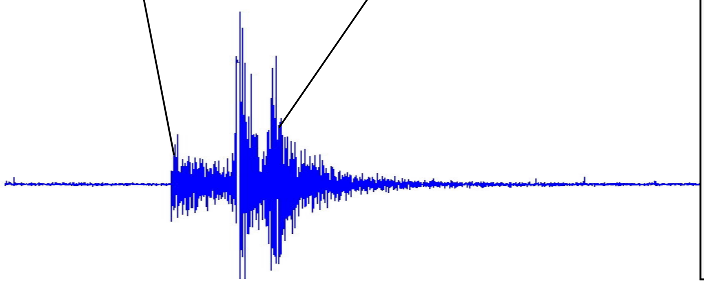




„FM radio“ – Earth‘s rotation



Sagnac frequency sampled with 1-5kHz



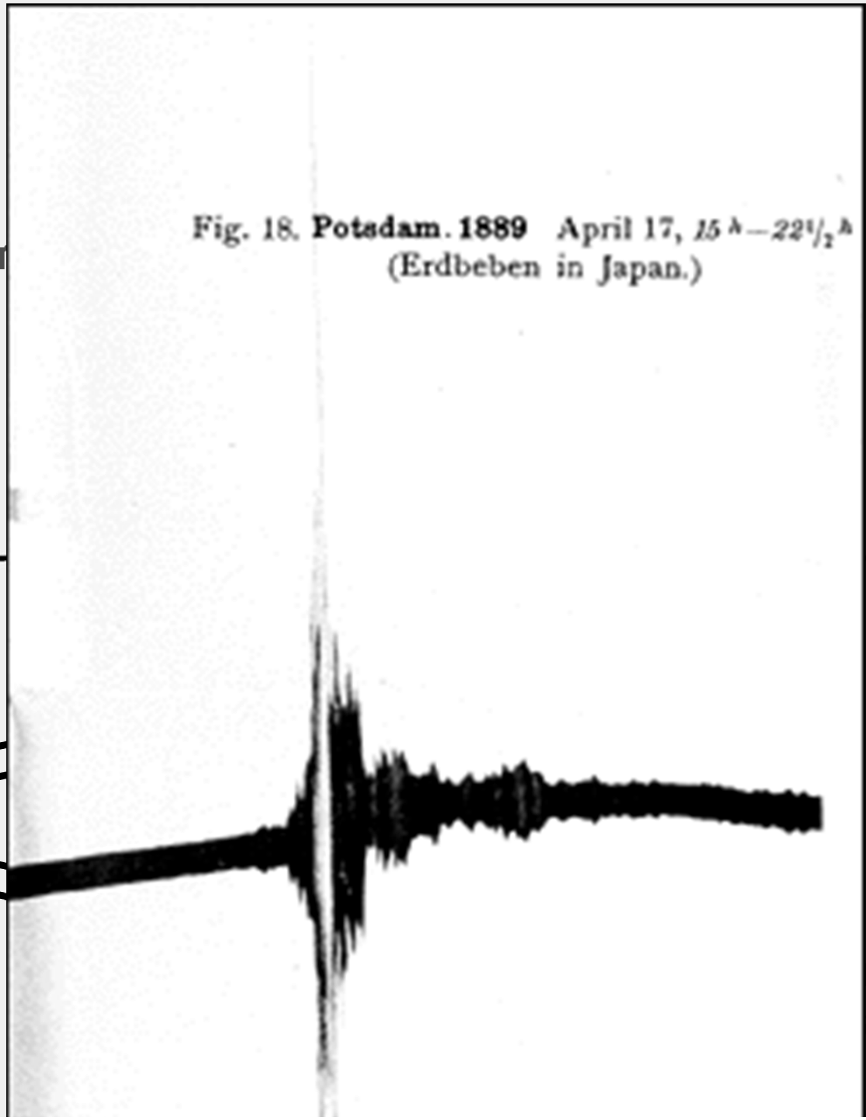
Rotation rate seismogram

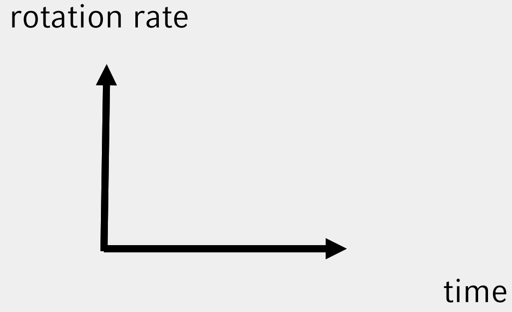
Tiny changes in the Sagnac frequencies are extracted to obtain the time series with rotation rate

$\Delta f \rightarrow \Omega$

…One person‘s noise …

Earth‘s *constant* rotation r





nd local vertical axis after
arthquake December 2004

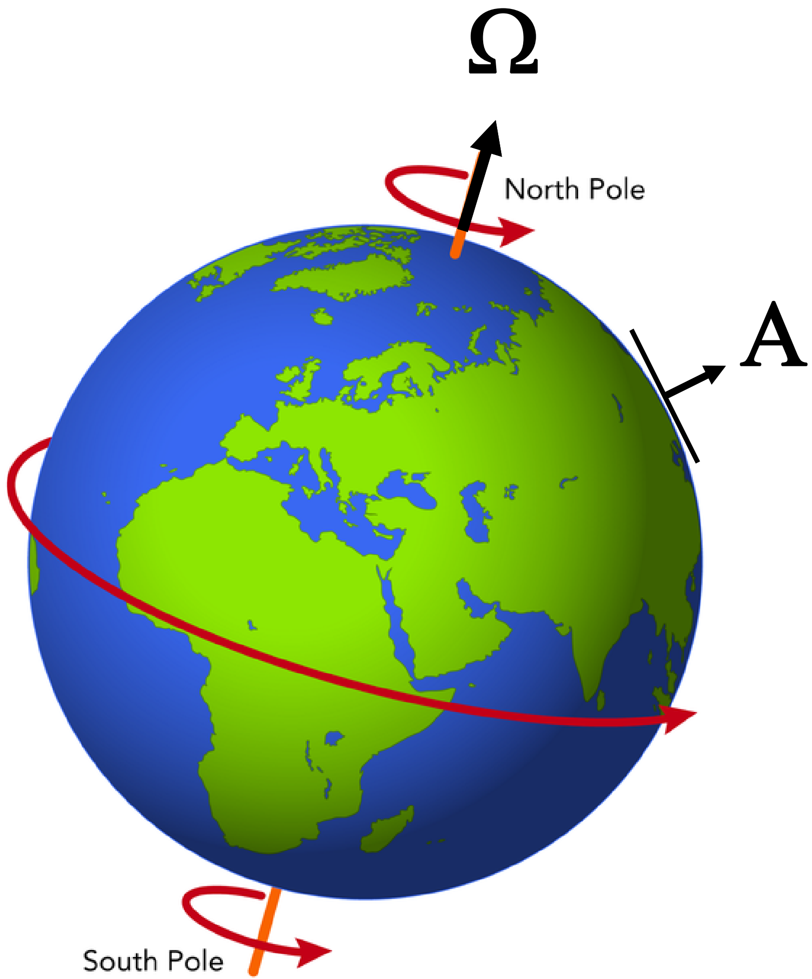
Sagnac Effect – Measuring Earth's rotation and more …

$$\Delta f_{Sagnac} = \frac{4\Omega \cdot A}{\lambda P}$$

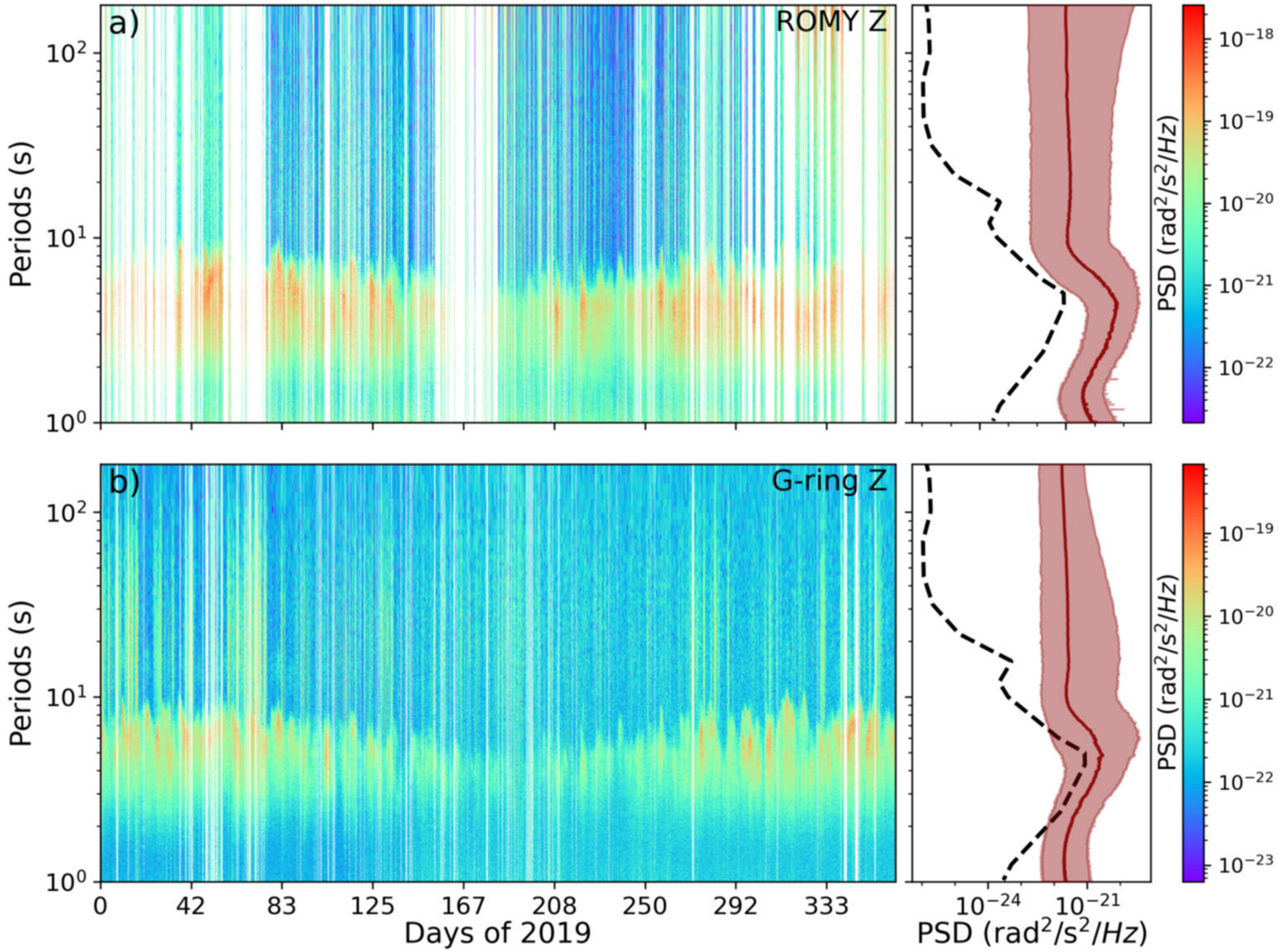
A	surface of the ring laser (vector)
Ω	imposed rotation rate (Earth's rotation + earthquake +...)
λ	laser wavelength (e.g. 632 nm, He-Ne)
P	perimeter (e.g. 4-36m)
Δf	Sagnac frequency (e.g. 348,6 Hz sampled at 1000Hz)

G-ring WET (Since summer 2009) resolution down to **~0.07 prad/s**

ROMY resolution expected ~0.04 prad/s



Earth' Background Rotations



- Background noise for ROMY (top) and G-ring (bottom) in 2019
- Theoretical rotational low noise model for Earth (dashed line)

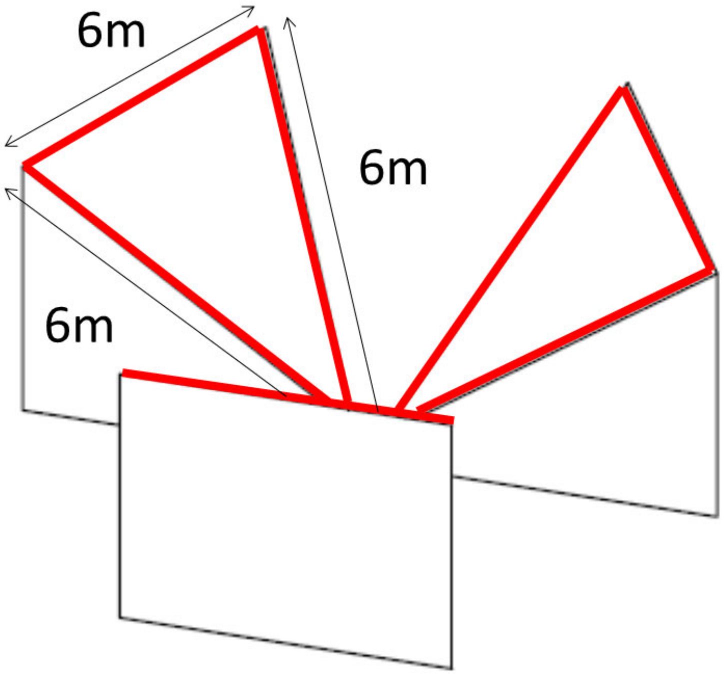
Brotzer et al., 2023 (SRL, submitted)

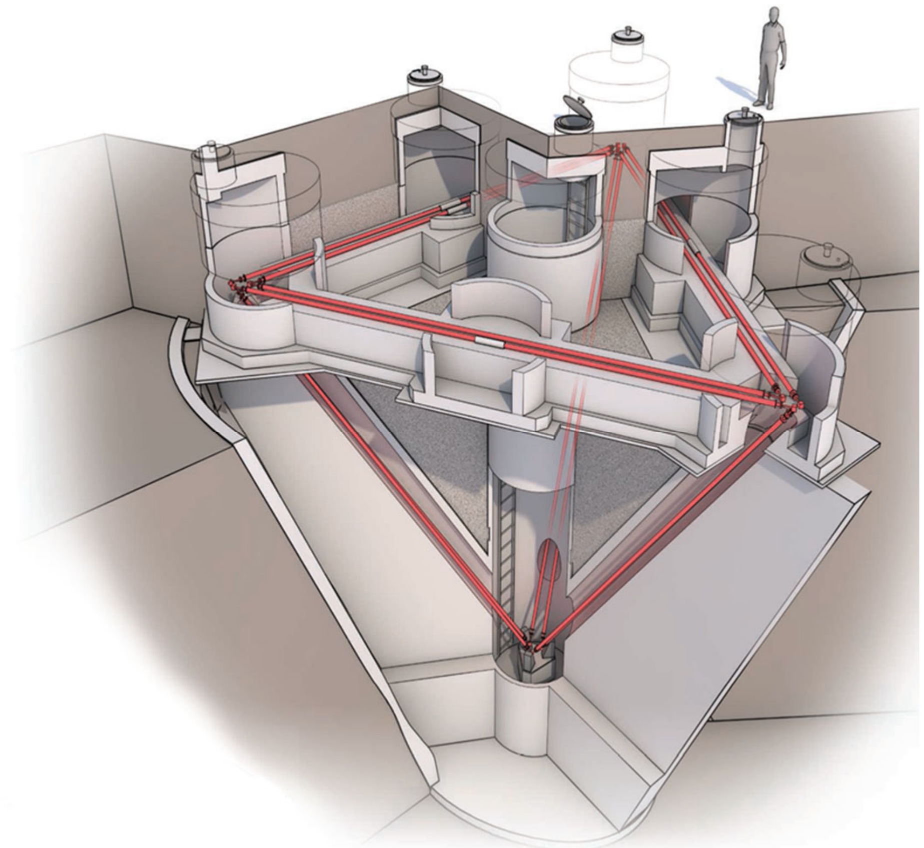
Measuring the complete
rotation vector:

The ROMY Ring Laser

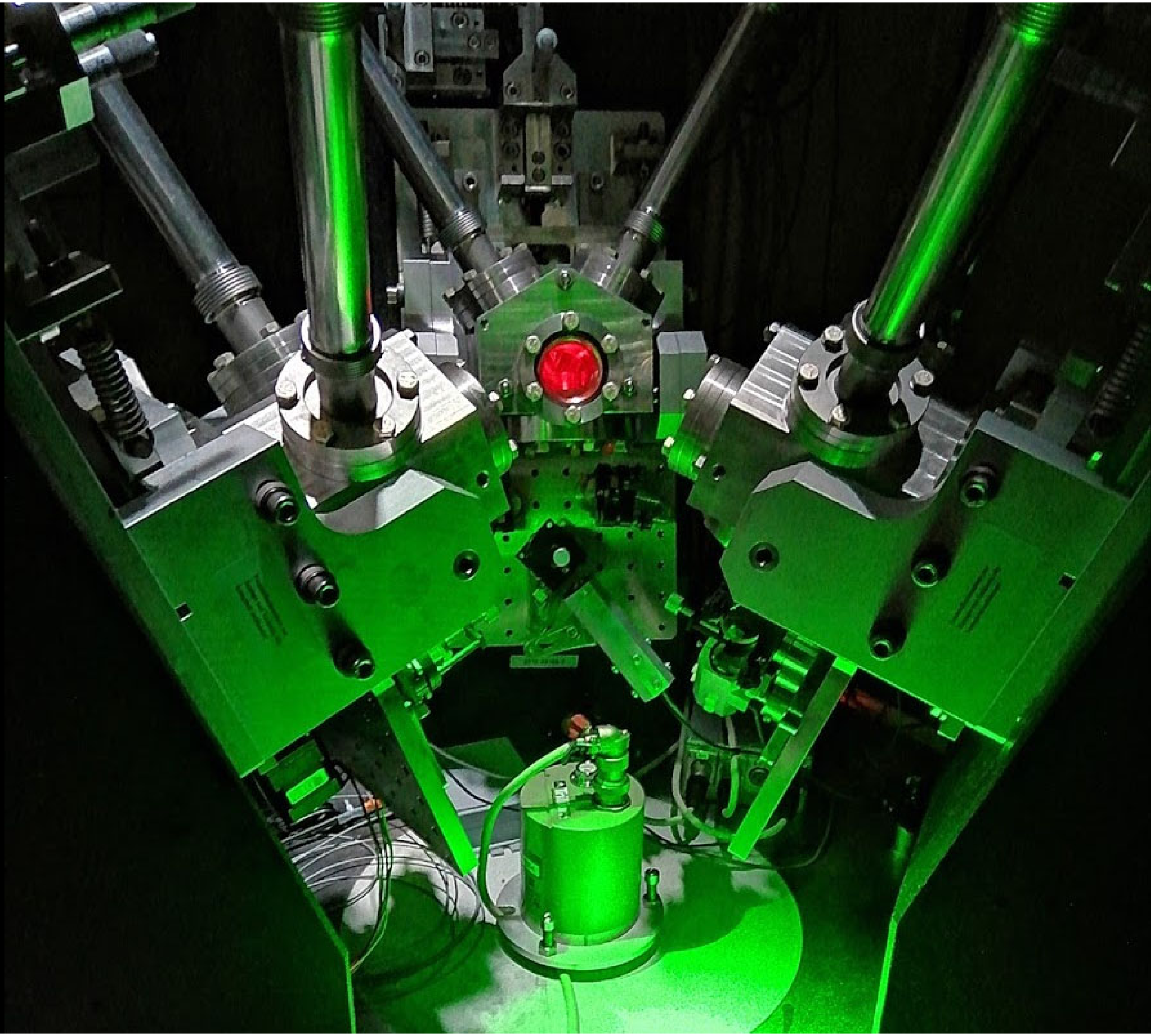
The ERC ROMY Project

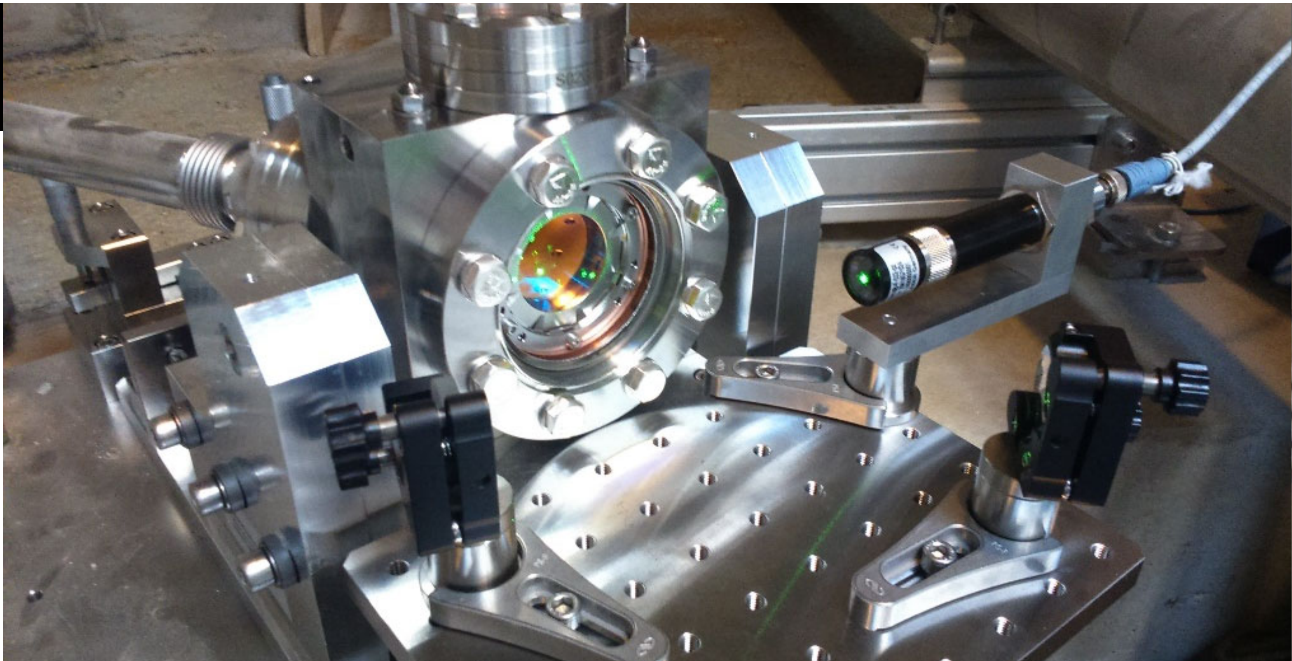
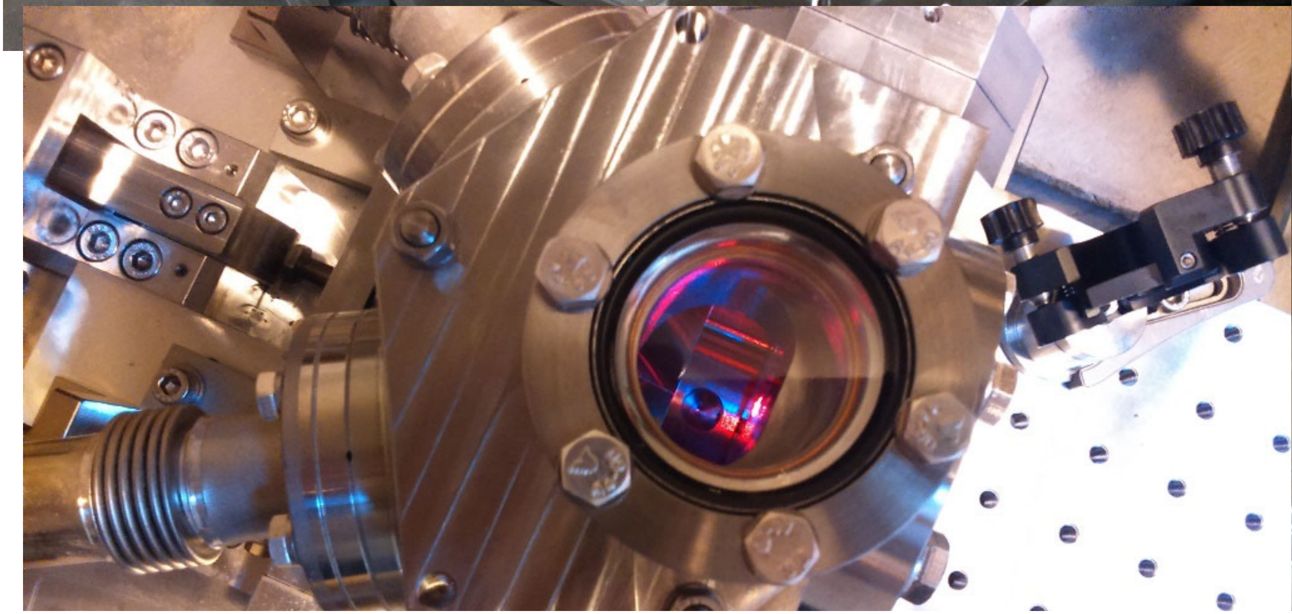
3-component planned -> finally 4 components (redundancy)



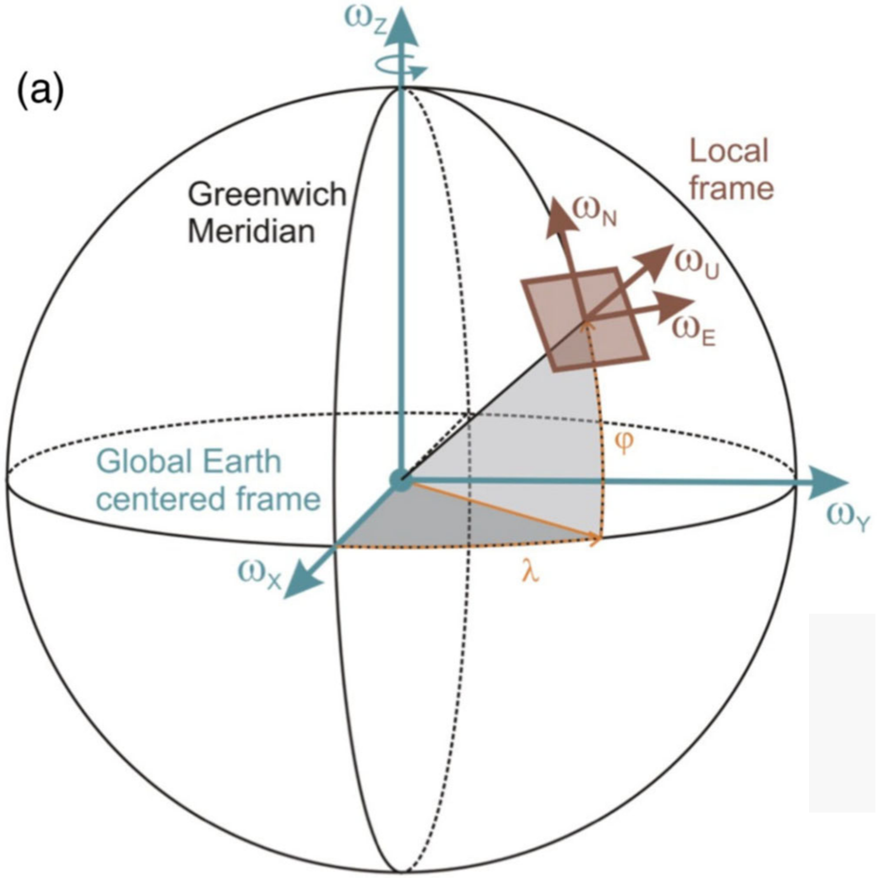


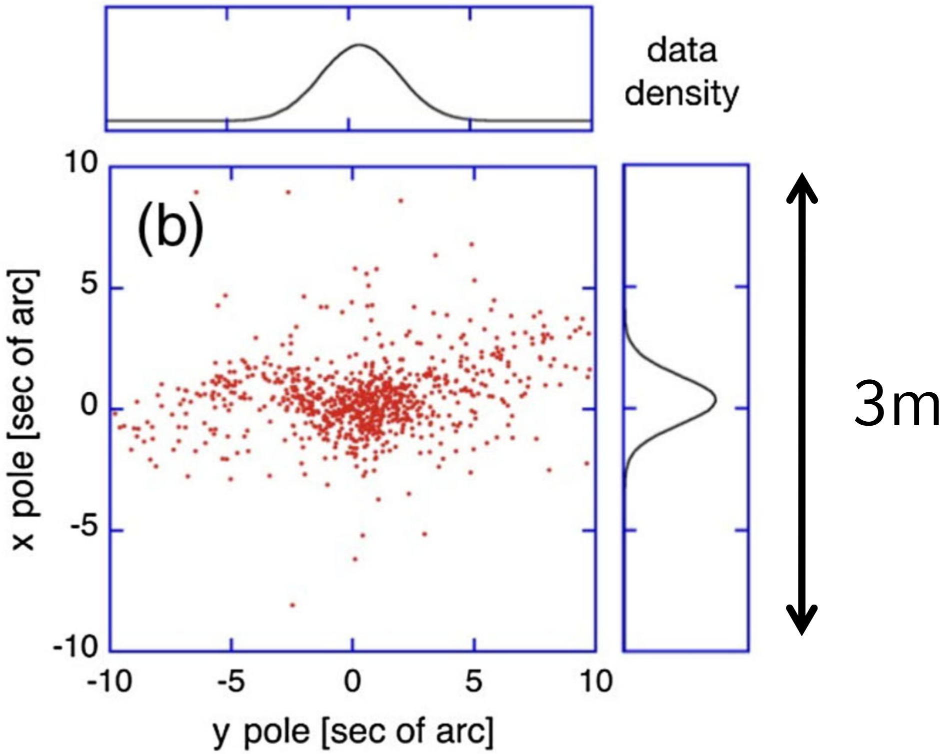
Hand, „Lord of the rings“, *Science, 2017 (video on youtube)*



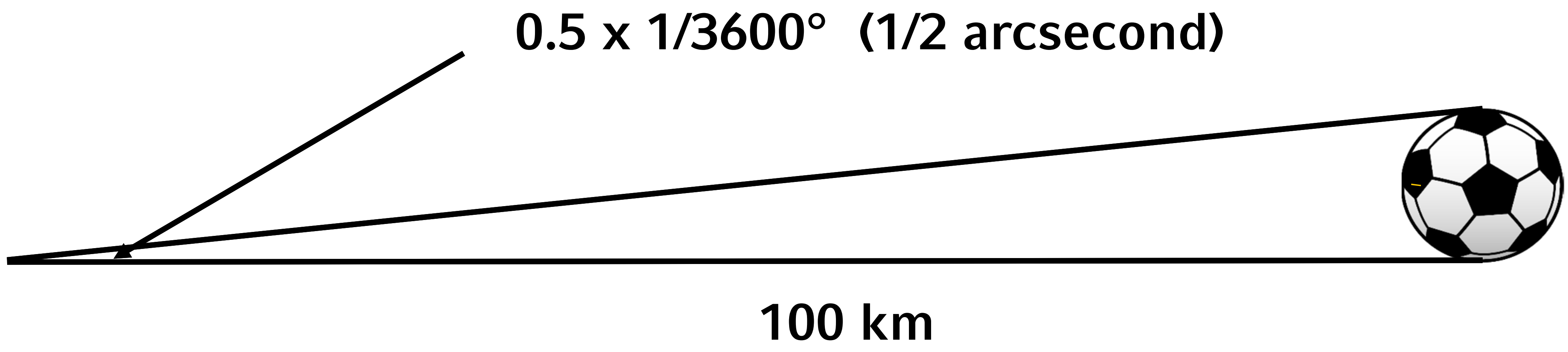

Polar Motion – Rate change (world record, but …)





Gebauer et al., PRL, 2020, ***Editor's Highlight***

Angular Resolution



Conclusions – Geodetic applications

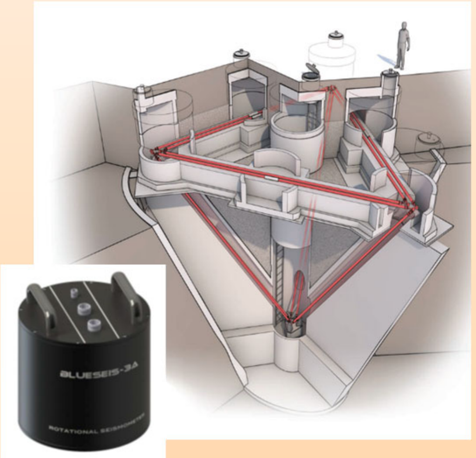
- Most accurate **direct observation** of Earth‘s complete vector of rotation
- Stability over one week less than 0.1 asec of **polar motion** (3m)
- 4 x 10-7 relative resolution of **Earth‘s rotation rate** (over one week)
- We observe **drifts** (settling of concrete structure?)
- Lasing difficult to **stabilize** due to proximity of resonance frequencies -> split mode (benefit and curse of ring laser size)
- Exact mixing of **isotopes** for two beam directions critical
- Efficient extraction of **Hydrogen** atoms crucial (getter)

Future:

- **Geometry stabilization** for better long term stability and resolution

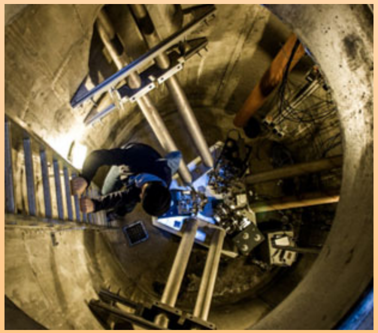
What about seismology?

… **seismic instrumentation** for ground motion?



Many components
Very sensitive
Difficult installation

Single point



ROMY ring laser

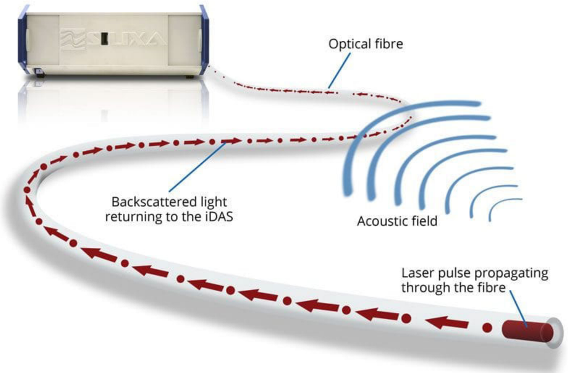
Nodal arrays
Low sensitivity
„Cheap“

myshake.berkeley.edu

Billions of sensors

… any combination …

But how?



distributed acoustic sensing (DAS)
Graphics, silixa.com

Complete ground motion - Translation, strain, rotation

$$\mathbf{u}(\mathbf{x}+\delta\mathbf{x}) \approx \mathbf{u}(\mathbf{x}) + \mathbf{G}\,\delta\mathbf{x}$$
$$= \mathbf{u}(\mathbf{x}) + \boldsymbol{\varepsilon}\,\delta\mathbf{x} + \boldsymbol{\Omega}\,\delta\mathbf{x}$$
$$= \mathbf{u}(\mathbf{x}) + \boldsymbol{\varepsilon}\,\delta\mathbf{x} + \boldsymbol{\omega}\times\delta\mathbf{x}$$

translation

$$\varepsilon_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$

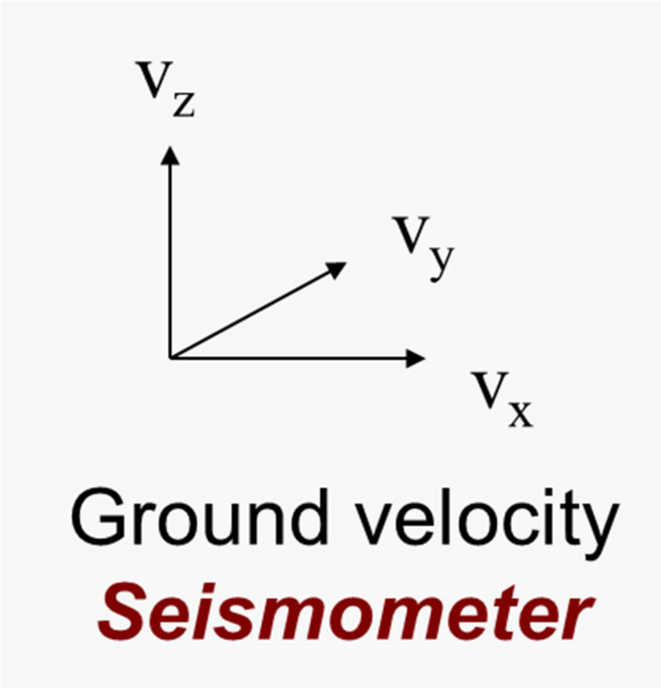
strain

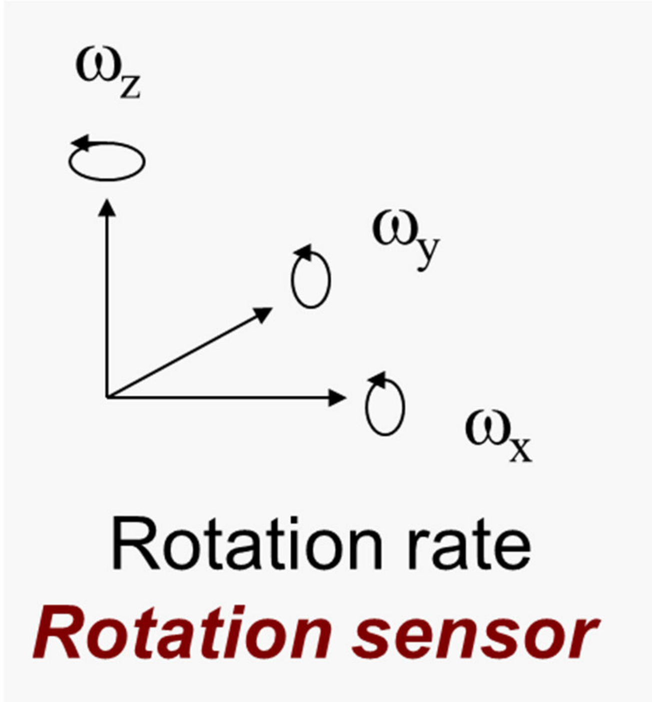
$$\omega_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} - \frac{\partial u_j}{\partial x_i}\right)$$

rotation

$$\Rightarrow \quad \omega = \frac{1}{2}\,(\nabla \times \mathbf{u})$$

6 DoF seismic observations for seismology

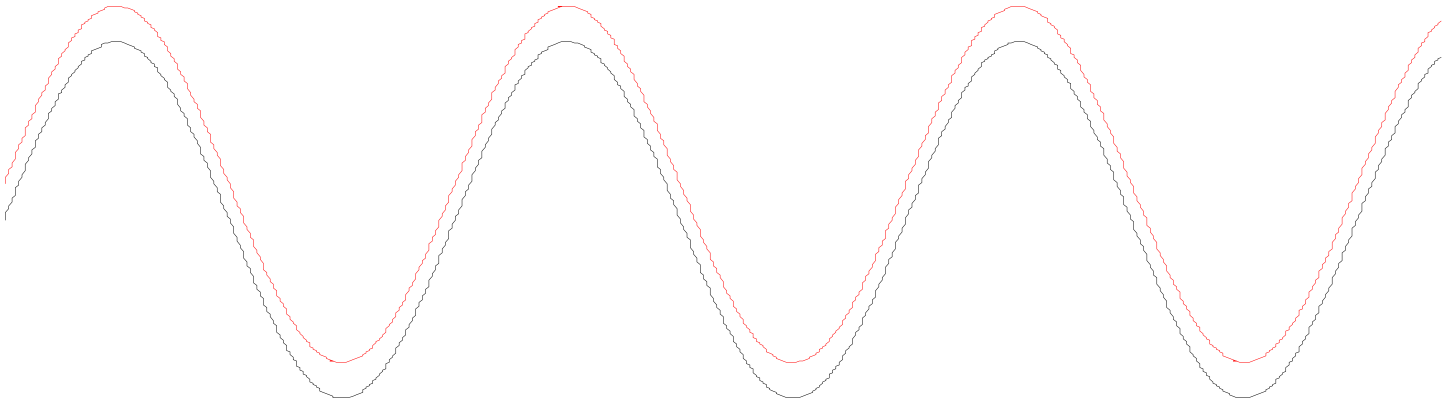




Primer - Rotational Seismology

Plane transversely polarized (S or Love) wave propagating in x-direction with phase velocity c

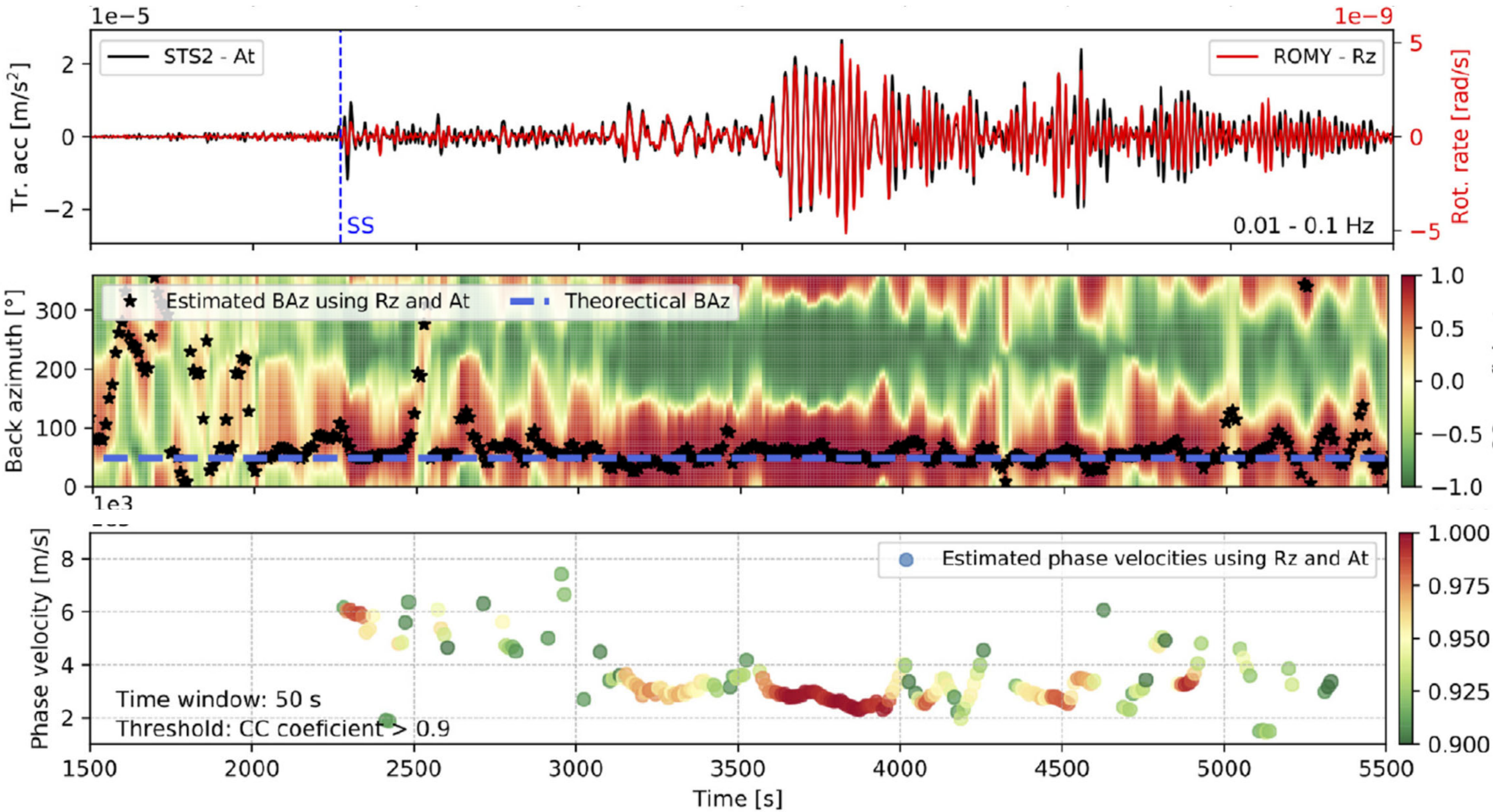
rotation rate – transverse acceleration



$$\frac{\ddot{u}_y(x,t)}{\Omega_z(x,t)} = -2c$$

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

Real data – P.N.G. M7.6, 2019 (Igel et al., GJI, 2021)

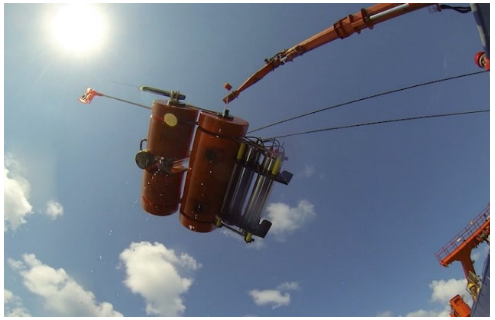


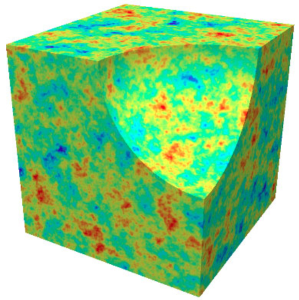
Why 6+ DoF (same ideas apply to strain!)?

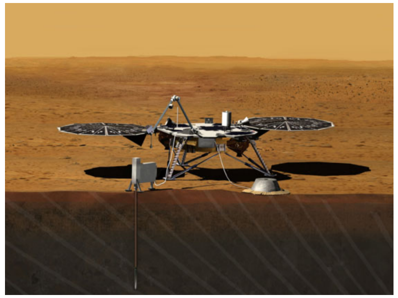
6+ DoF **point observations** provide wavefield information **similar to small-scale seismic arrays** (slowness, backazimuth, phase separation)

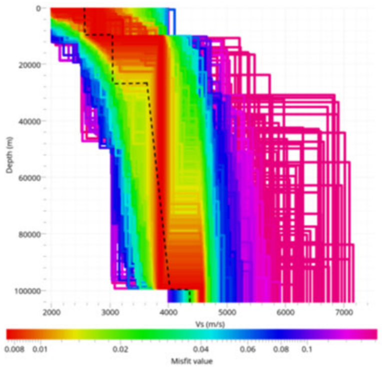
(e.g., Schlüter 1903; Sollberger et al., GJI, 2017; Sollberger et al., Sensors, 2020)

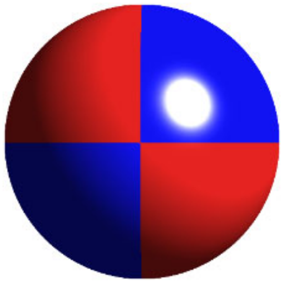
… wide range of applications …



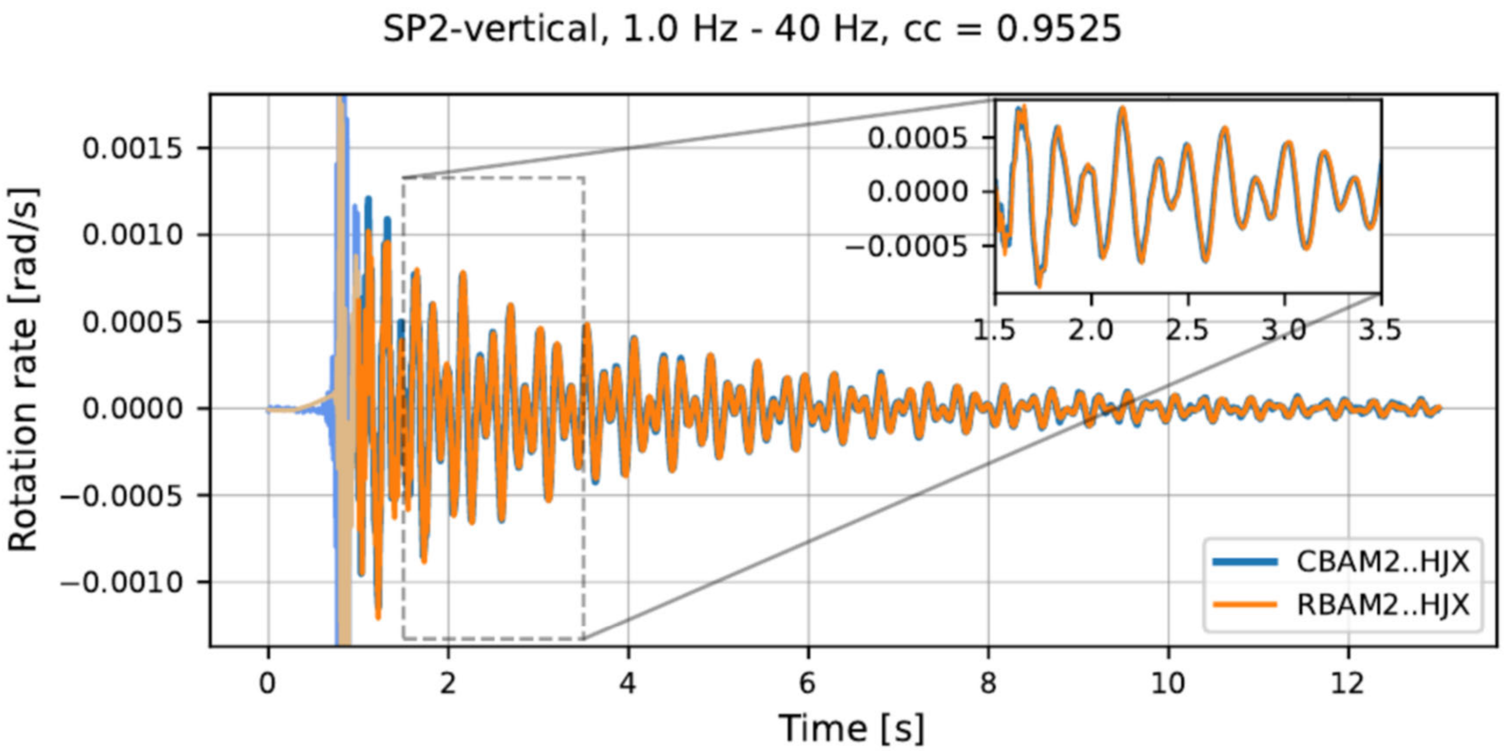


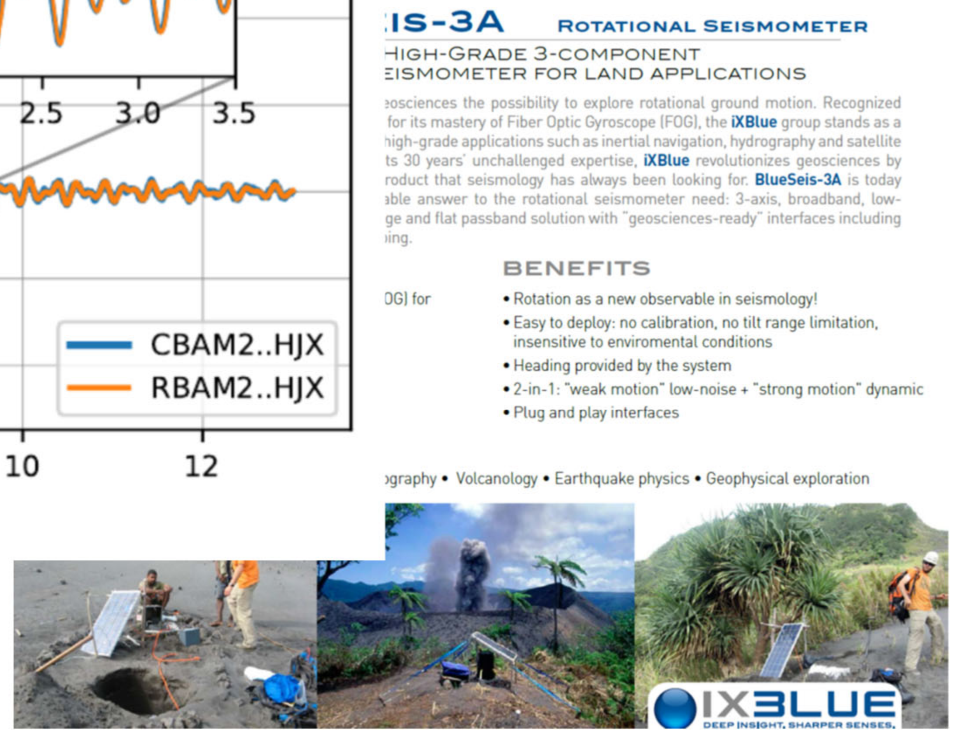






Seismology needs a portable sensor!

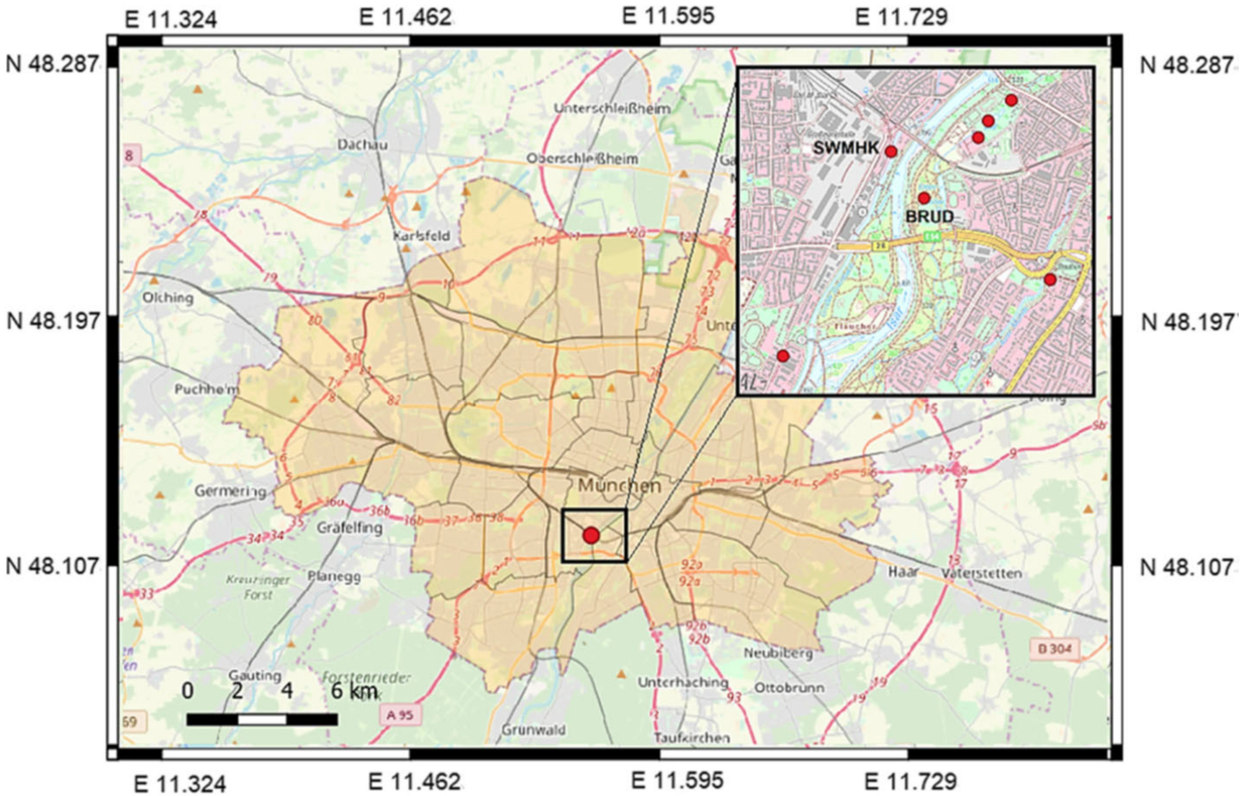




Measuring site effects in an urban environment

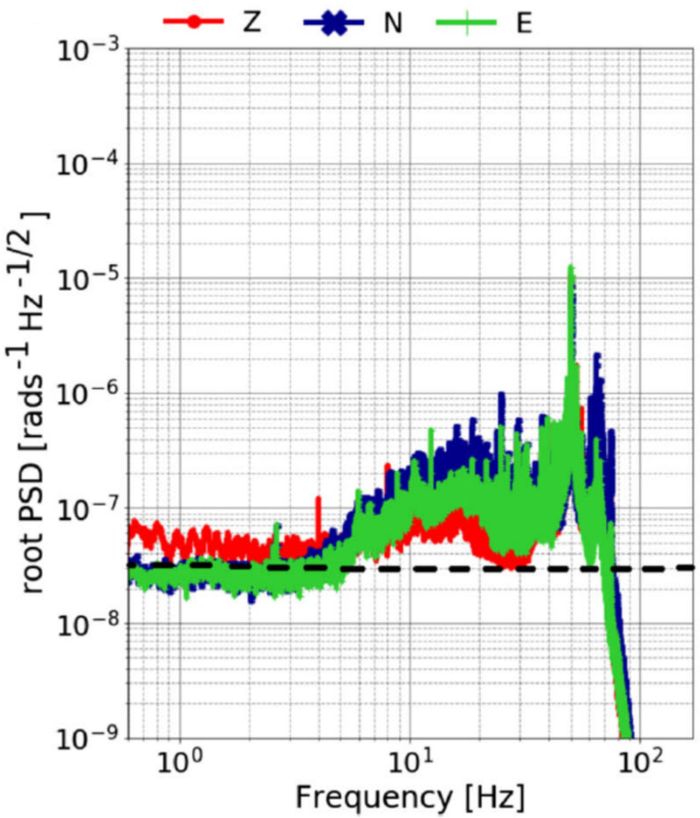
Microzonation Downtown Munich

Single-site seismic tomography

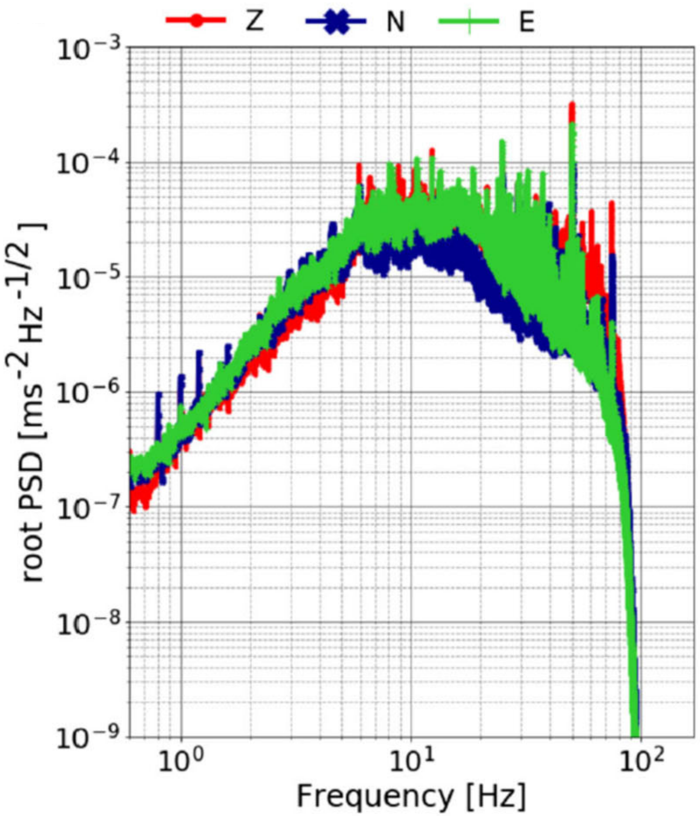


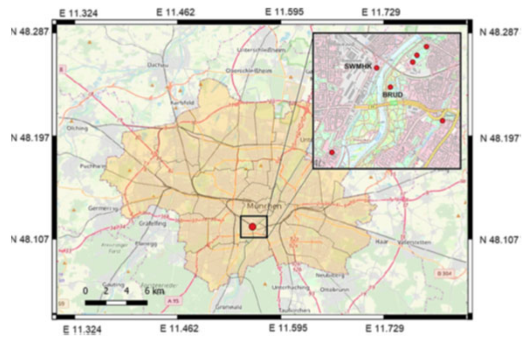
Microzonation Downtown Munich- City Noise

Rotation Rate



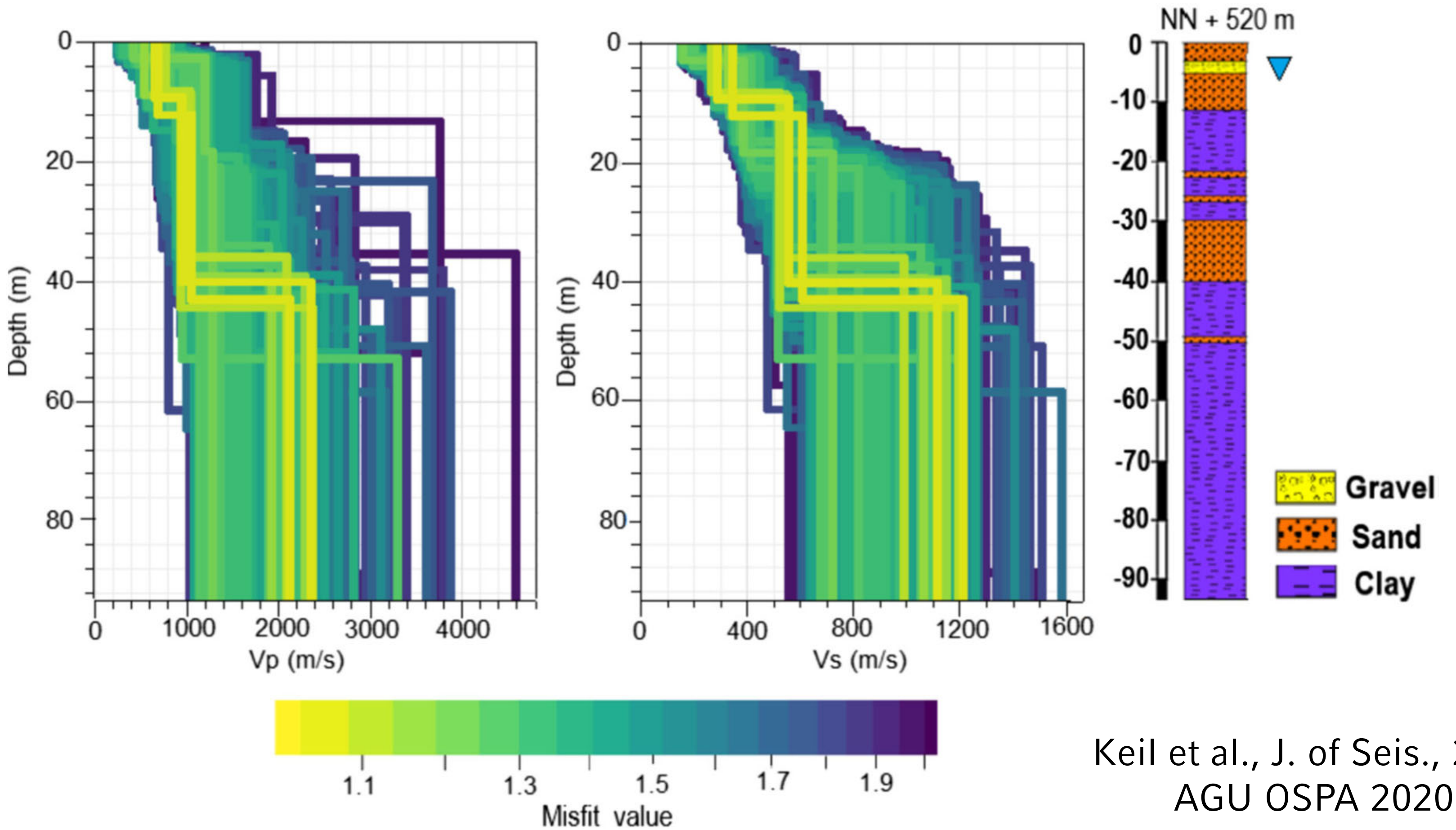
Acceleration





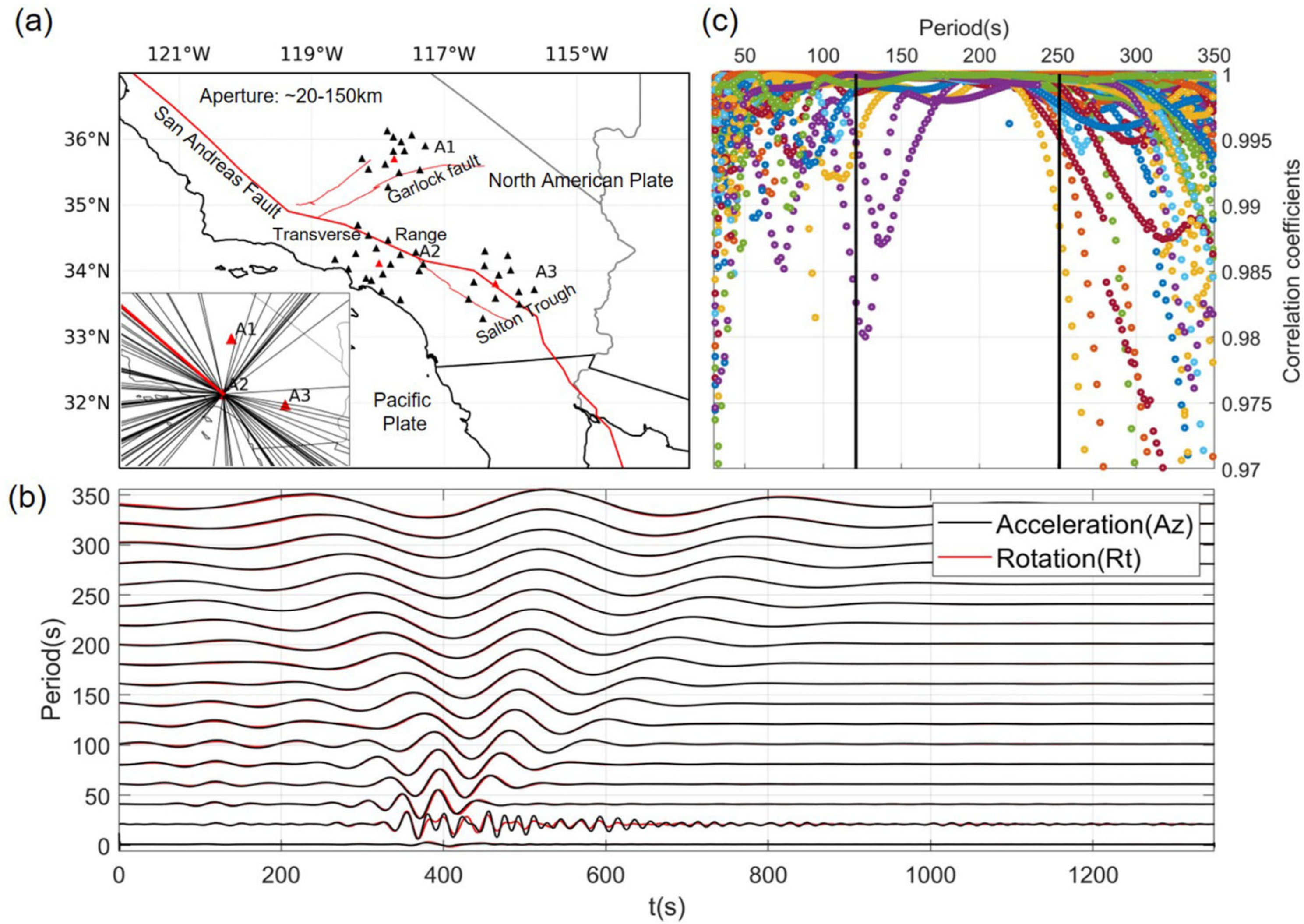
The spectral ratio leads to phase velocities -> (dispersion)

Local 1D velocity – 6 DoF and H/V

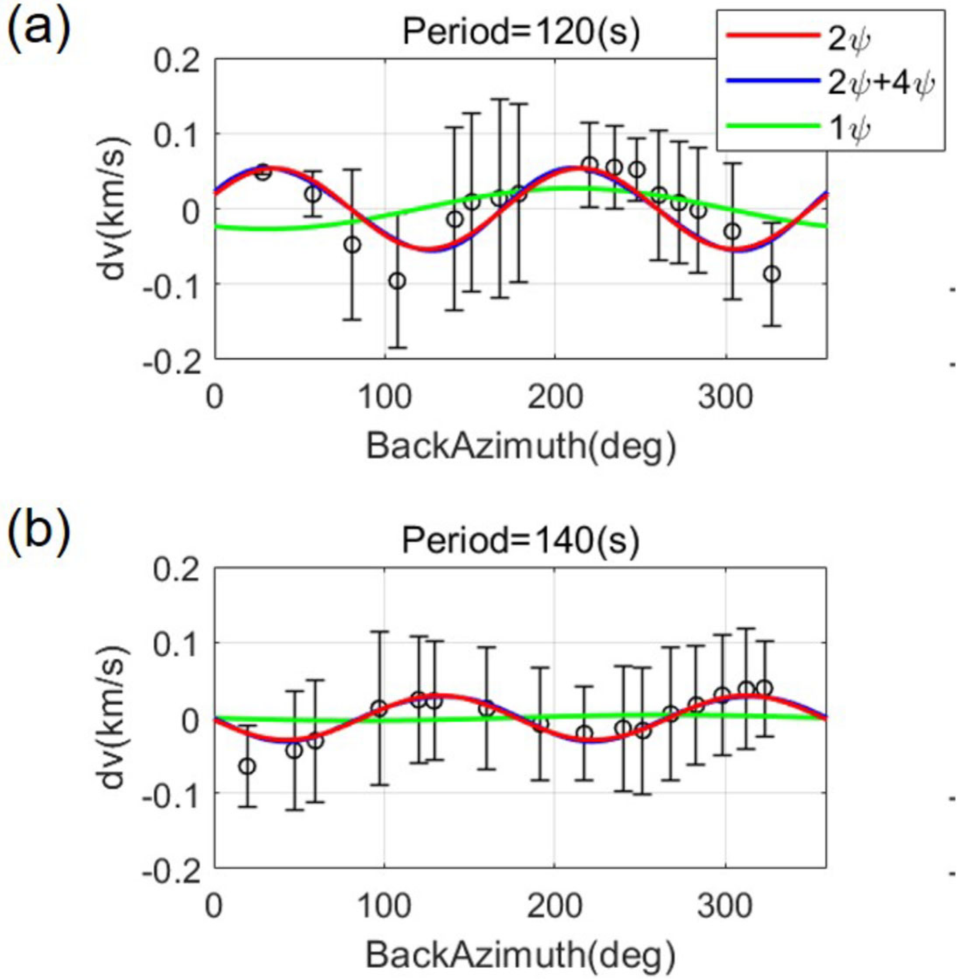


Keil et al., J. of Seis., 2020
AGU OSPA 2020

Anisotropy from rotations

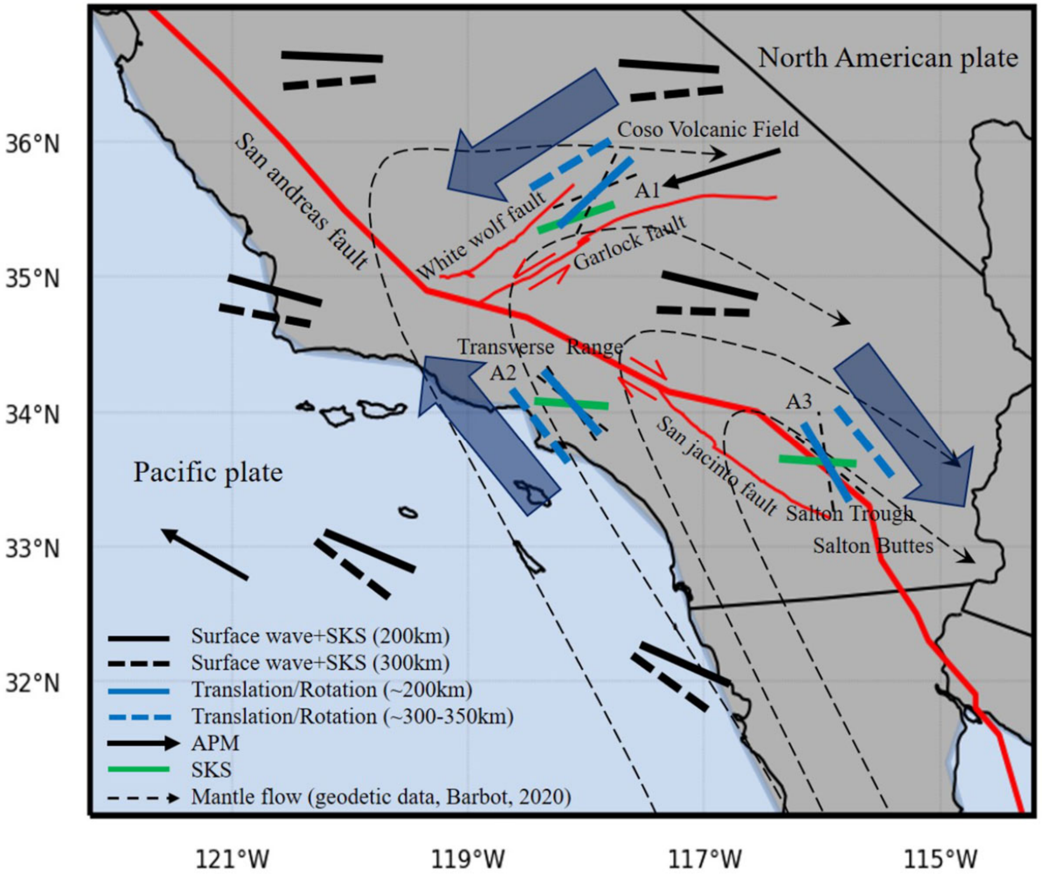


Anisotropy from rotations



- Azimuthal variations of surface wave velocity from **point observations** of rotations and translations
- Clear evidence for azimuthal anisotropy (upper mantle tectonic flow)

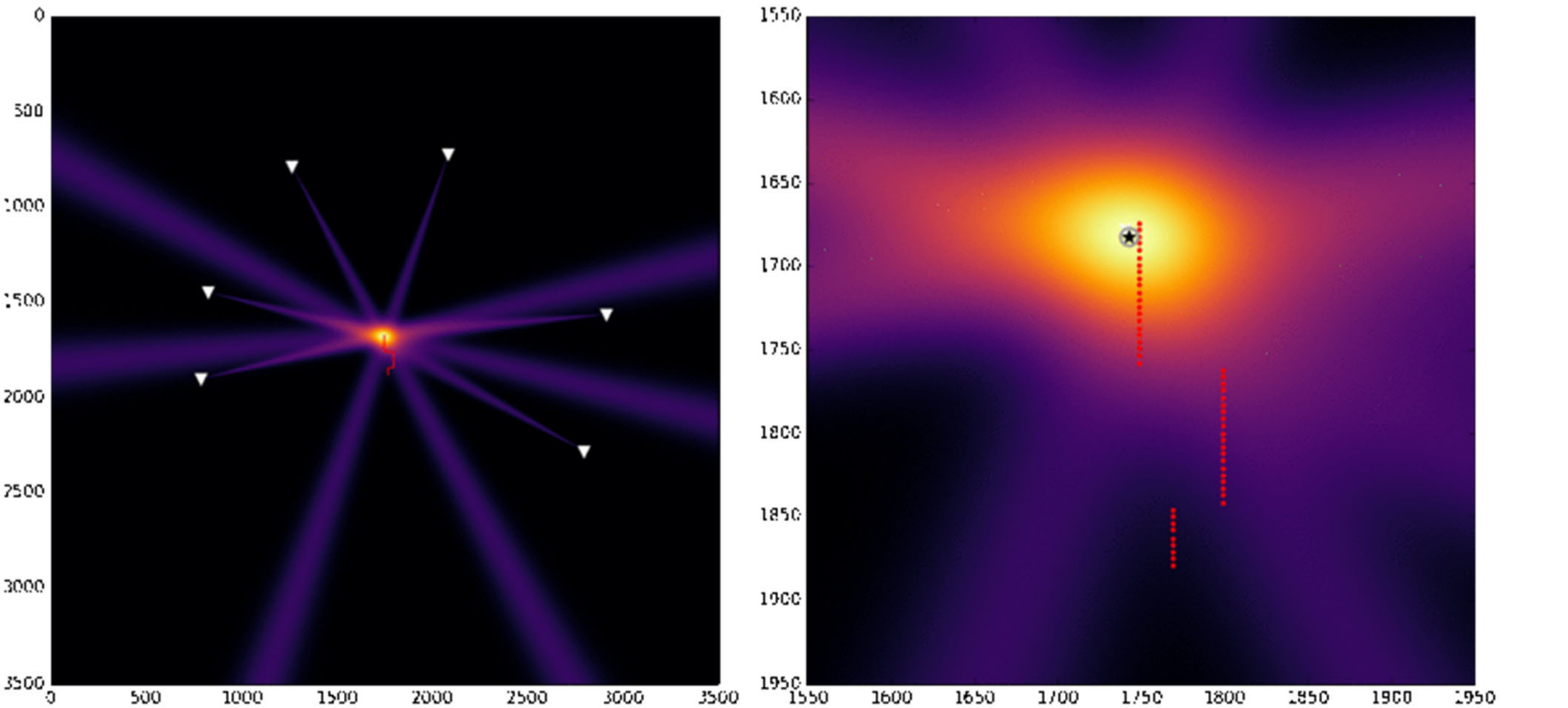
Anisotropy and mantle flow



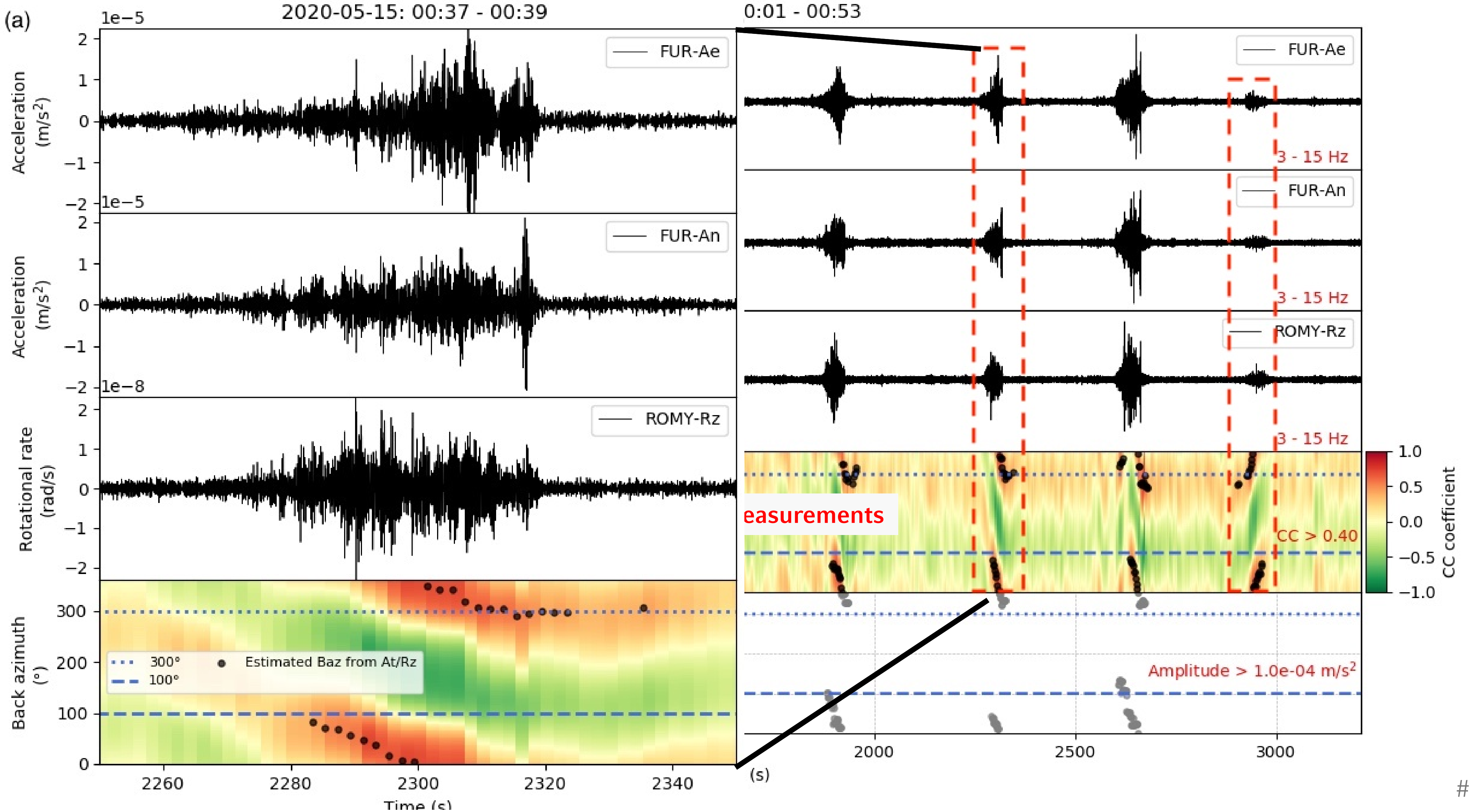
- Azimuthal variations of surface wave velocity from **point observations** of rotations and translations
- Clear evidence for azimuthal anisotropy (upper mantle tectonic flow)
- Fast velocity directions compatible with GPS observations

Tang et al. (to be submitted)

Tracking seismic sources

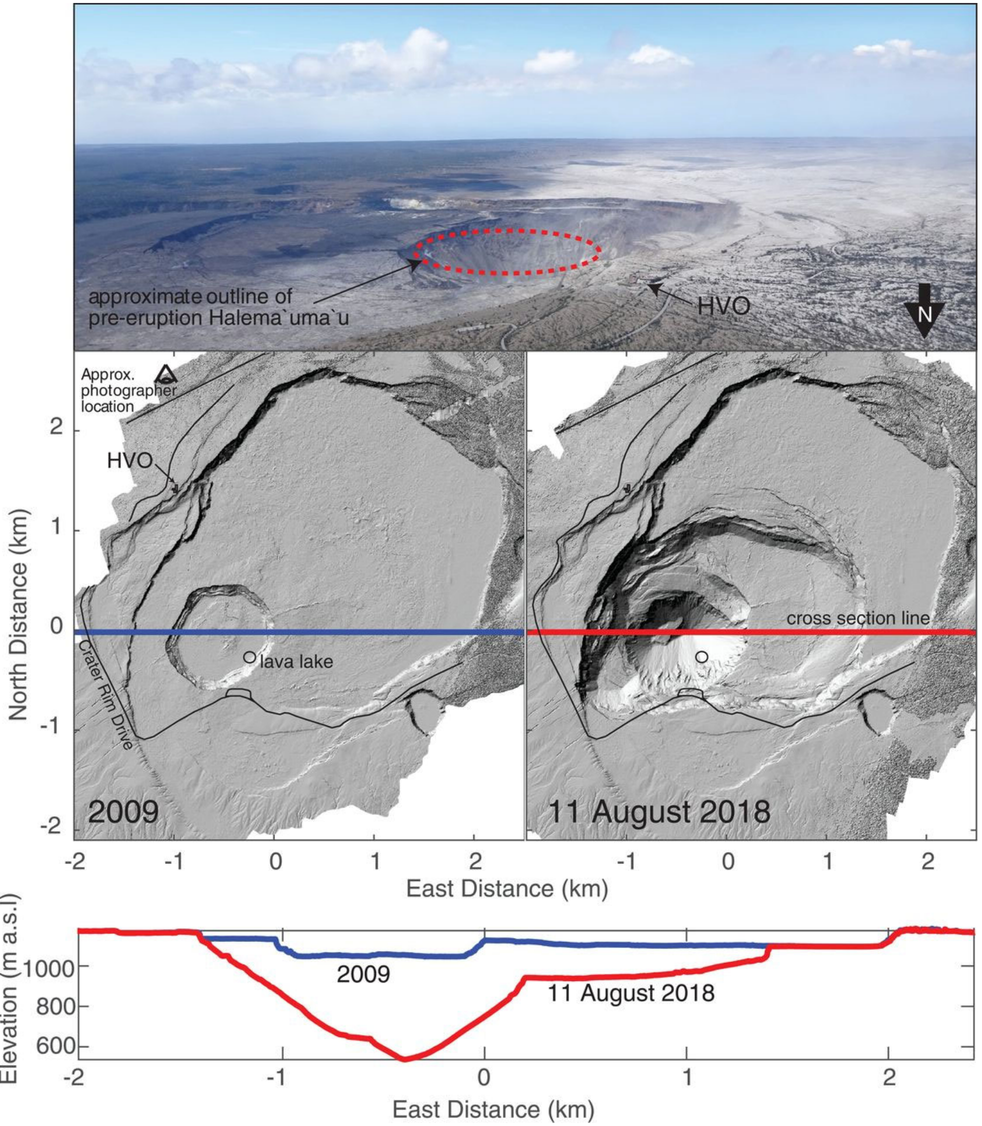


Singe-station speed control (Yuan et al., JGR, 2021)

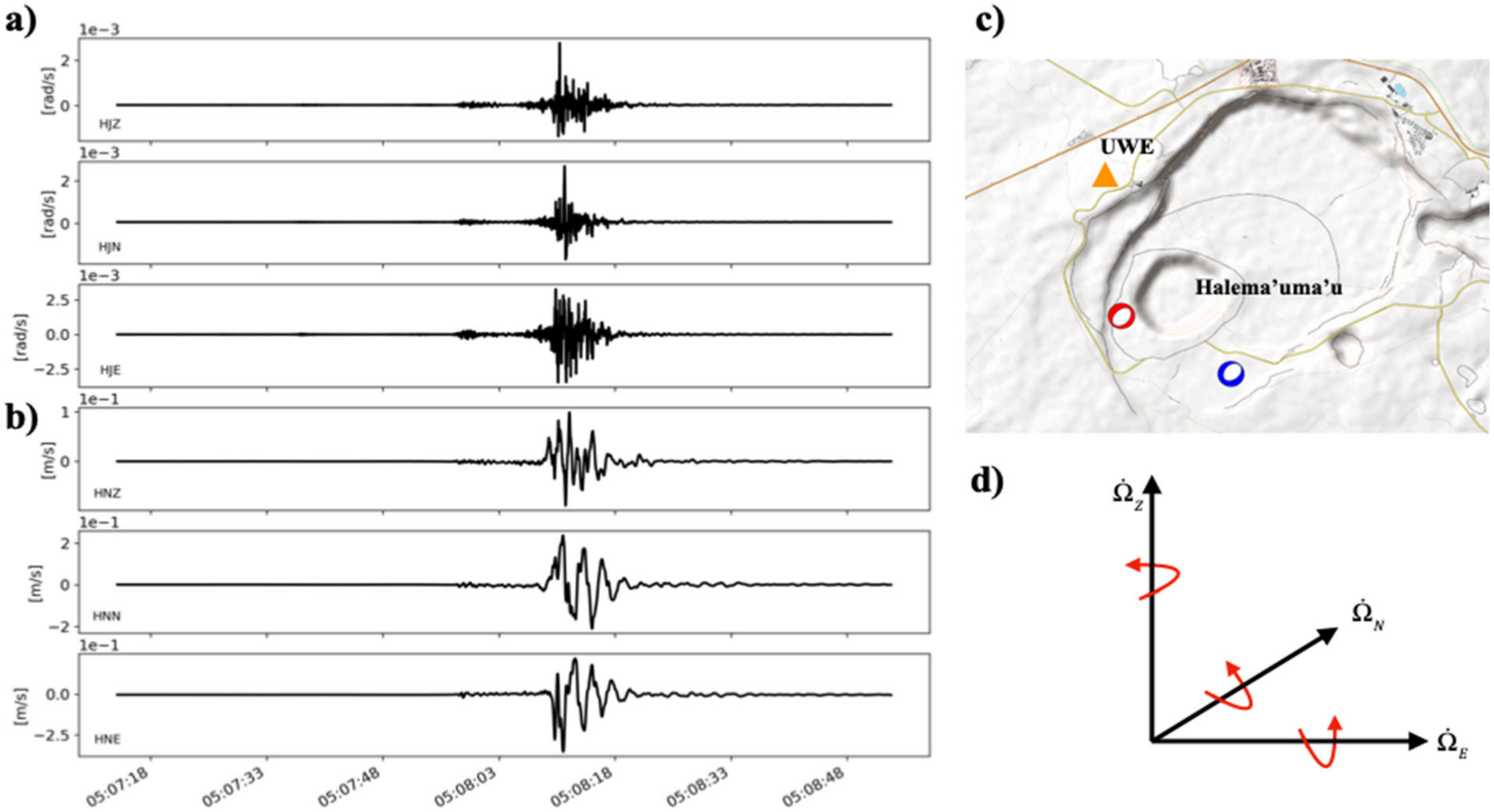


Caldera collaps:
Strong ground motions

Before - After

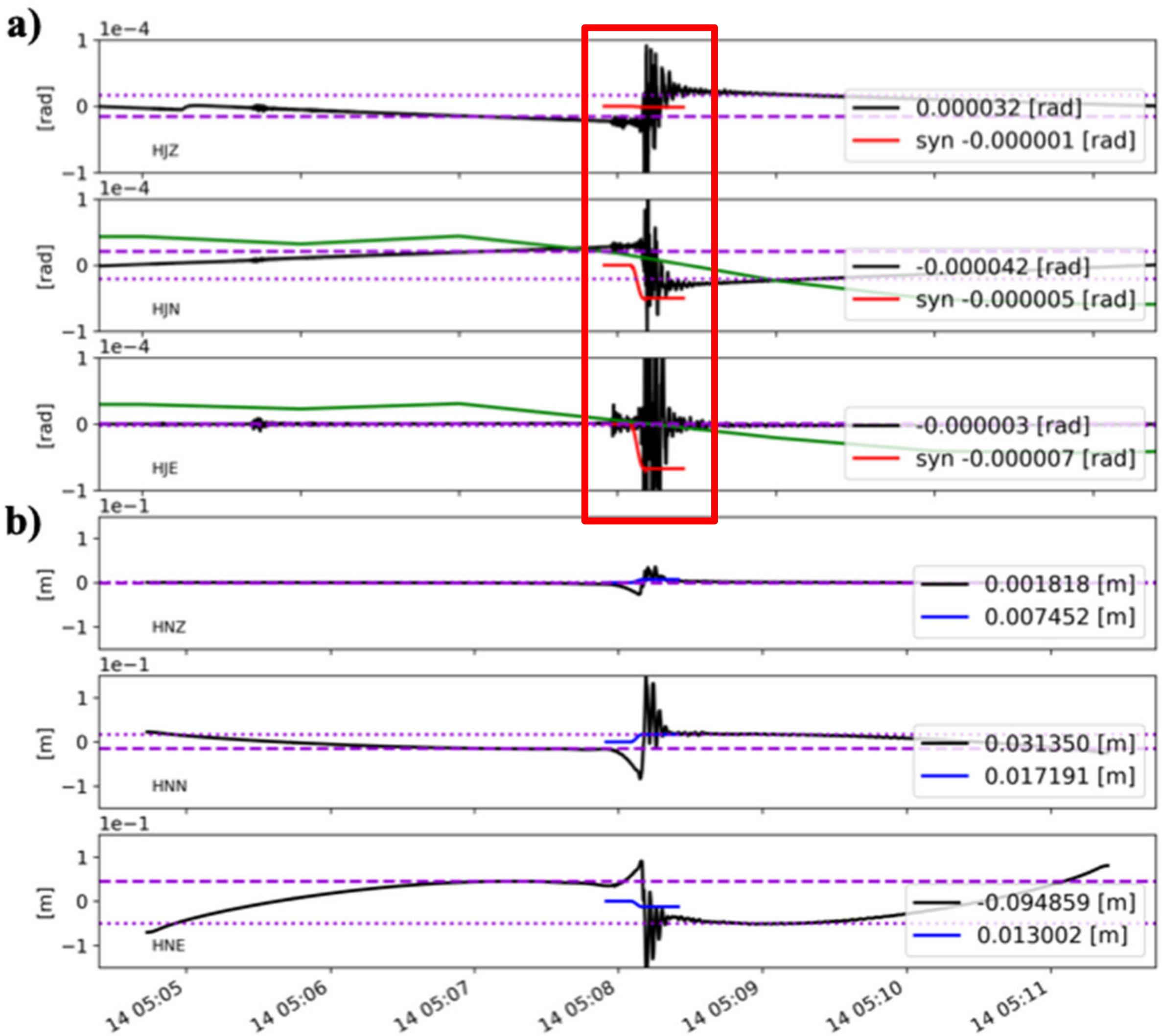


6 DoF Observations Hawaii



(Wassermann et al., GRL, 2020)

Static Rotation Observations



First dynamic observation of **static rotation changes** with blueSeis

- Additional constraints on caldera collapse
- Tilt correction for displacement sensors

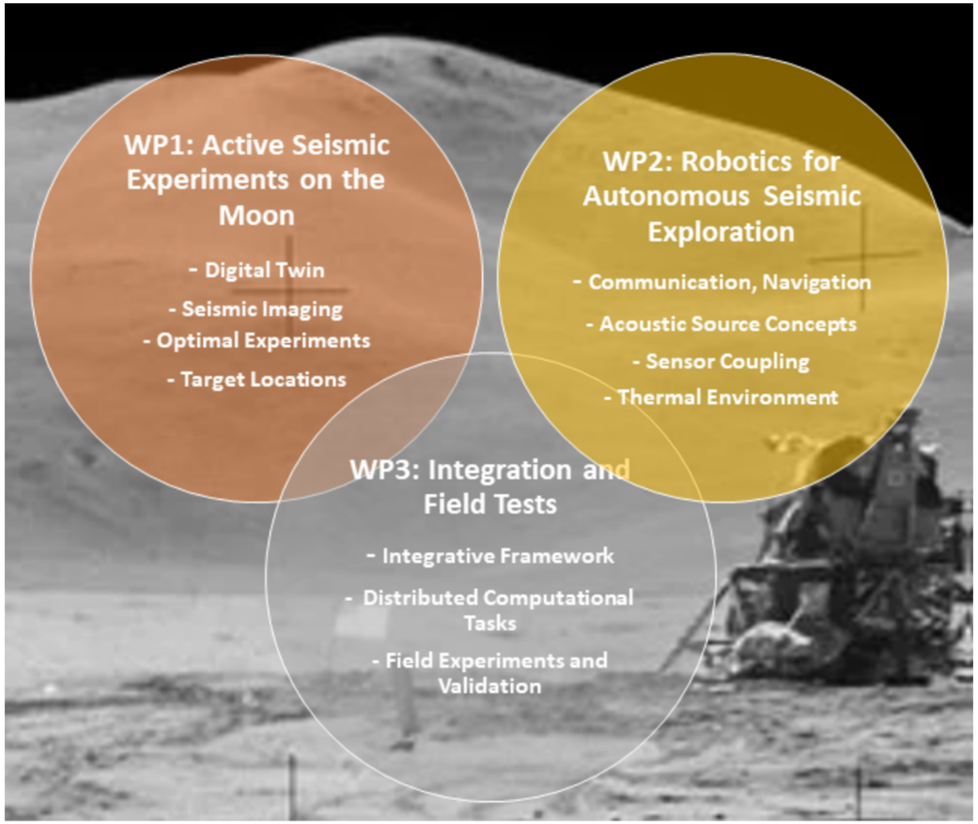
(Wassermann et al., GRL, 2020)

Not shown here …

- 6C allows **correcting tilt contamination** (OBS, strong ground motion) – Lindner et al. (2016), Bernauer et al. (2020a)
- 6C allows new ways of **seismic tomography without travel times** - Fichtner et al. (2009), Bernauer et al. (2012)
- 6C is interesting for **planetary seismology**, prototype in development – Bernauer et al. (2020b)
- 6C is interesting for **structural health monitoring** – GIOTTO project, see youtube movie (https://youtu.be/szYqnmuEoNw)
- 6C has benefits when inverting for **moment tensors** – Donner et al. (2018,2020)
- 6C has benefits for **finite-source inversion** – Bernauer et al. (2014), Reinwald et al. (2016)

Outlook

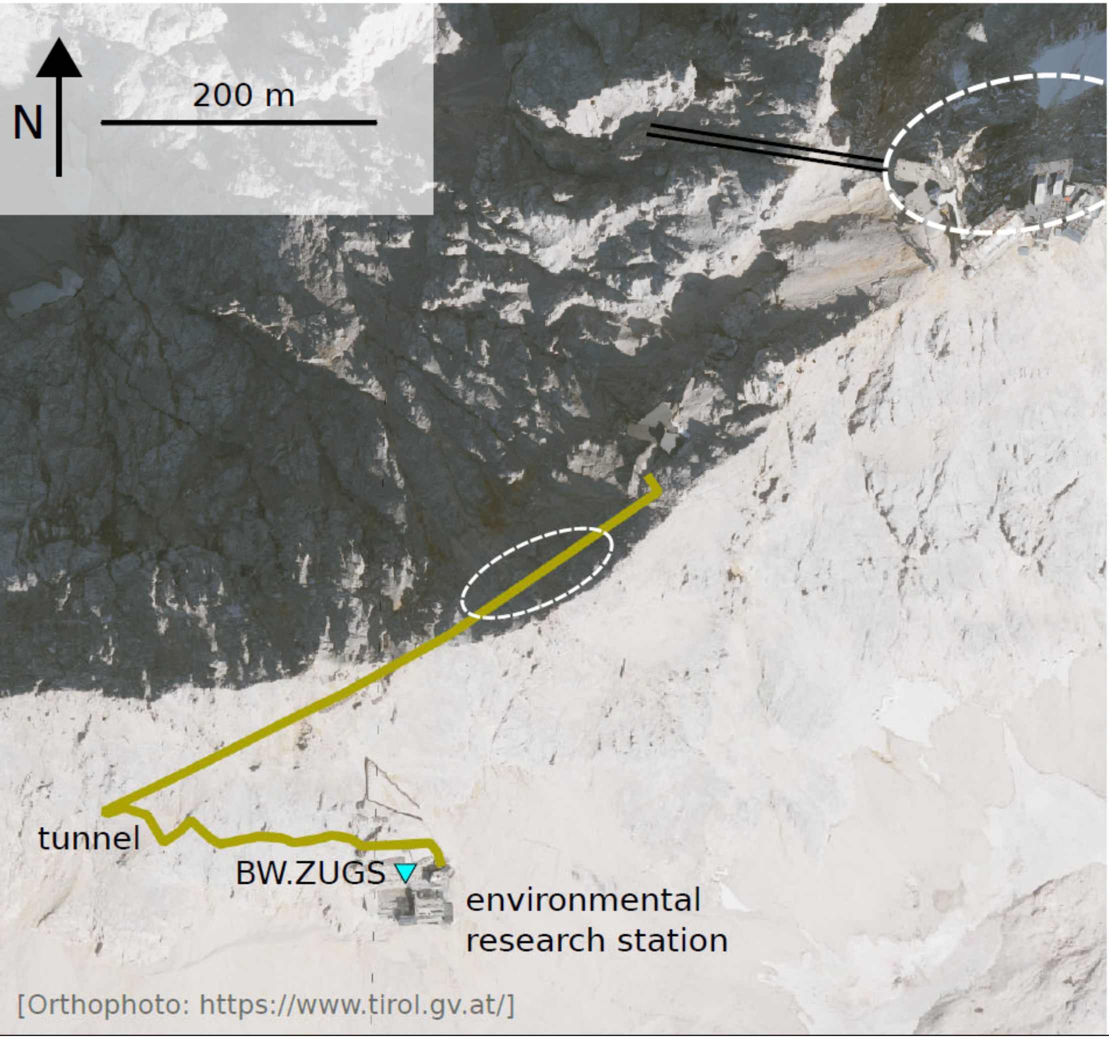
Robotic seismic networks

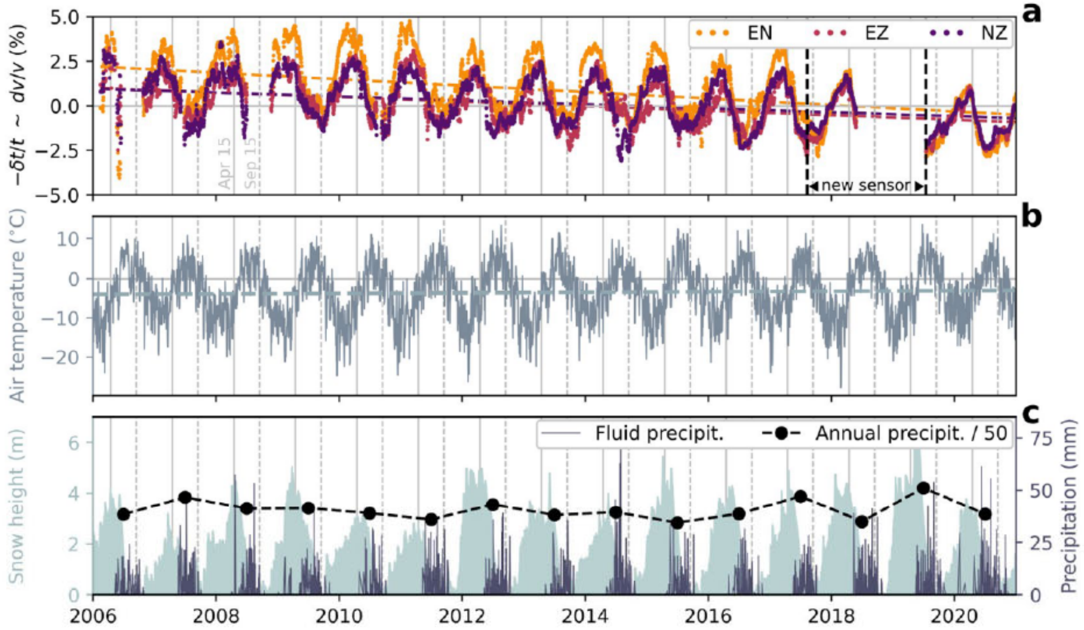


- **Wave propagation in strongly scattering media**
- **Coda wave interferometry**
- **Near surface imaging**
- **Gradient observations (rotations, strain)**
- **Characteristic wavefields for target objects**
  - ice-bearing rocks
  - Cavities
- **Robotic concepts**
  - Navigation
  - Distributed computing
  - Tomography
  - Mobility

Monitoring permafrost change – Mt Zugspitze, Germany

[Lindner et al., GRL, 2021]





(Substantially) **increased sensitivity of gradient observations** (strain, rotations) w.r.t. near-receiver structure!

Conclusions

- **Ring lasers** deliver most accurate rotation sensing for geodesy and seismology
- **Fibre-optic gyros** are the most promising rotation sensing instruments for 6C broadband seismology (but ...)
- Seismology now has a **portable broadband rotation sensor** (blueSeis-3A family)
- **Field studies** are only now beginning
- The most promising application domains are:
  - Microzonation (in cities)
  - Volcano monitoring
  - Ocean-bottom seismology
  - Earthquake physics (source studies)
  - Earthquake engineering (building vibrations)
  - Environmental seismology (permafrost, groundwater)
  - Planetary seismology (active seismics, lander interaction)

Interested? Check out:

- www.rotational-seismology.org
- www.romy-erc.eu
- https://www.mdpi.com/journal/sensors/special_issues/Rotatin_Rate_Sensors


Deadline
Thank you for your attention!