[1] LMU Munich, Germany
[2] IGPP Scripps, UCSD, USA

LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

On single-station, six degree-of-freedom observations of regional seismicity at the Piñon Flats Observatory in Southern California

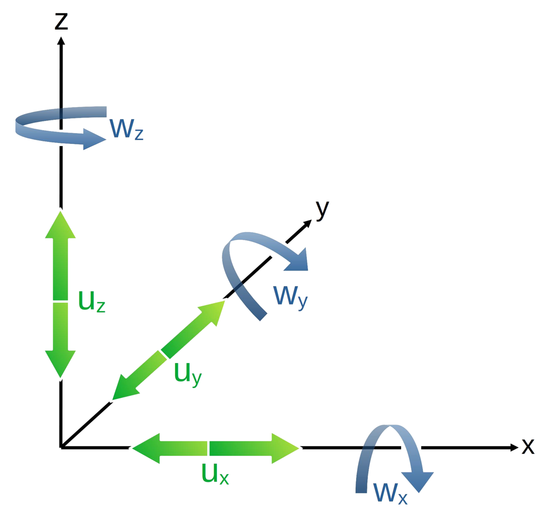
Andreas Brotzer[1] | Heiner Igel[1] | | Felix Bernauer[1] | Joachim Wassermann[1] | Robert Mellors[2] | Frank Vernon[2]

1 6 - Degree of Freedom Seismology

The full, linear elastic seismic displacement wavefield can be separated into **3 translational** (u), **3 rotational** (ω) and **6 strain** (ϵ) degrees of freedom (DoF):

$$\boldsymbol{u} + \delta \boldsymbol{u} = \boldsymbol{u} + \varepsilon \delta \boldsymbol{x} + \boldsymbol{\omega} \times \delta x \text{ with } \boldsymbol{\omega} = \frac{1}{2} \nabla \times \boldsymbol{u}$$

Since October 2022, the 6-DoF station, called BSPF (Fig. 1), records seismicity at the Piñon Flats Observatory (PFO) in southern California, USA. The station is located inside an underground vault on a granite pillar and consists of a co-located broad-band seismometer and a three component blueSeis-3A fiber optic gyroscope (Exail, formerly iXblue; Bernauer et al. 2018). The 6-DoF station replaced the 1C GEOsensor ring laser gyroscope for rotational ground motion observations (e.g. Donner et al. 2017). The seismic array at PFO is designed to compute array-derived rotations (ADR) for three sub-arrays (=frequency bands).



Trillium 240 (40sps): II.PFO.10.BH* (< 2023-04-02)
STS-2 (200sps): PY.PFOIX..HH* (> 2023-04-02)

blueSeis-3A (200sps): PY.BSPF..HJ*

FIG 1: 6-DoF station setup inside PFO vault.

First permanent 6-DoF data is streamed via IRIS FDSN or check out the **Rotational Eventbase**

2 Dataset at Piñon Flats Observatory

Data from 2022-10-01 to 2023-09-30 at the 6-DoF station is analyzed:

- recursive LTA-STA trigger detects events for 6 components (e.g. Fig.3)
- local / regional seismicity is observed within ~150 km radius (Fig. 2)
- signal-to-noise ratio for rotational components are mostly below 10

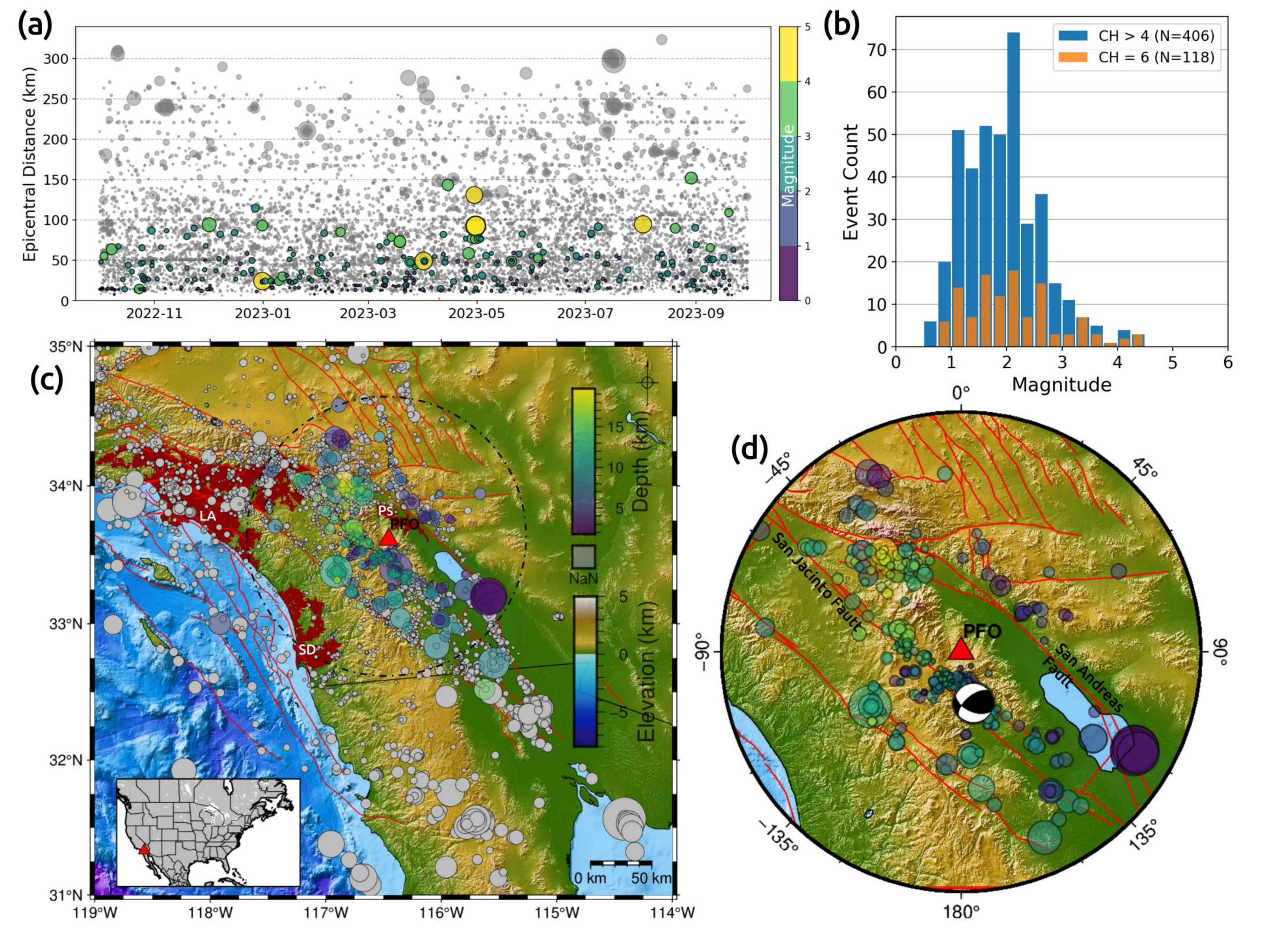


FIG 2: Dataset shown (a) over time and (c) as geospatial distribution with triggered events color-coded by magnitude. (b) Histogram of triggered events on 4 vs. all 6 channels shown as a histogram. (d) Detected events near PFO with CMT of M_w=4.1.

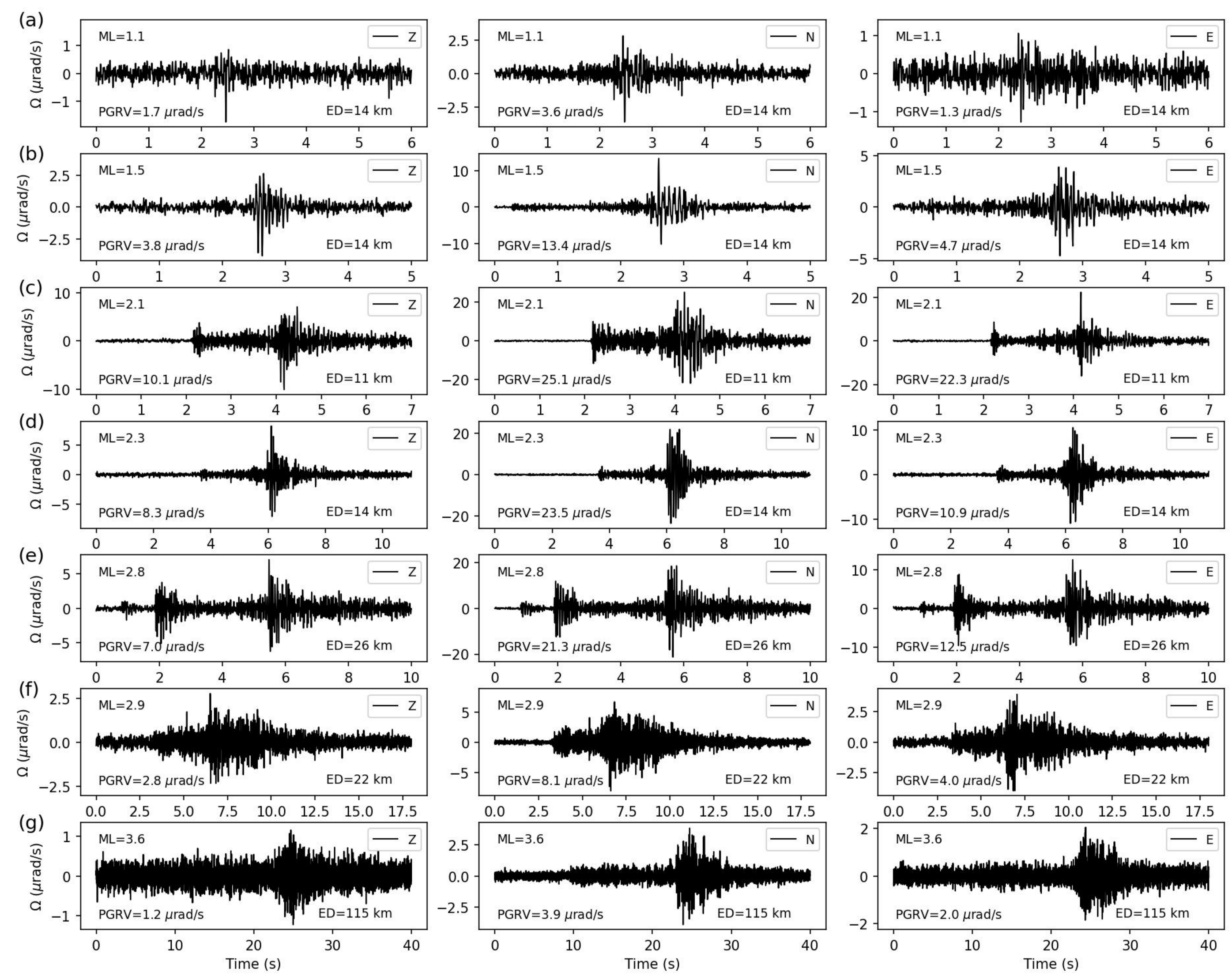


FIG 3: Selected events for different magnitude, epicentral distance (ED) with the max. peak ground rotation velocity (PGRV) for all axes of PY.BSPF.

3 Backazimuth

The potential of 6-DoF single-stations includes backazimuth estimation, local 1-D velocity inversion or polarization analysis (e.g. Sollberger et al. 2020). In Fig.4, we compare three different approaches of backazimuth (BAz) estimation for a local M_w = 4.1 event (CMT in Fig. 2):

- grid search for Rayleigh wave polarization
- grid search for Love wave polarization
- tangent of horizontal components with a covariance minimization (=CoVar)

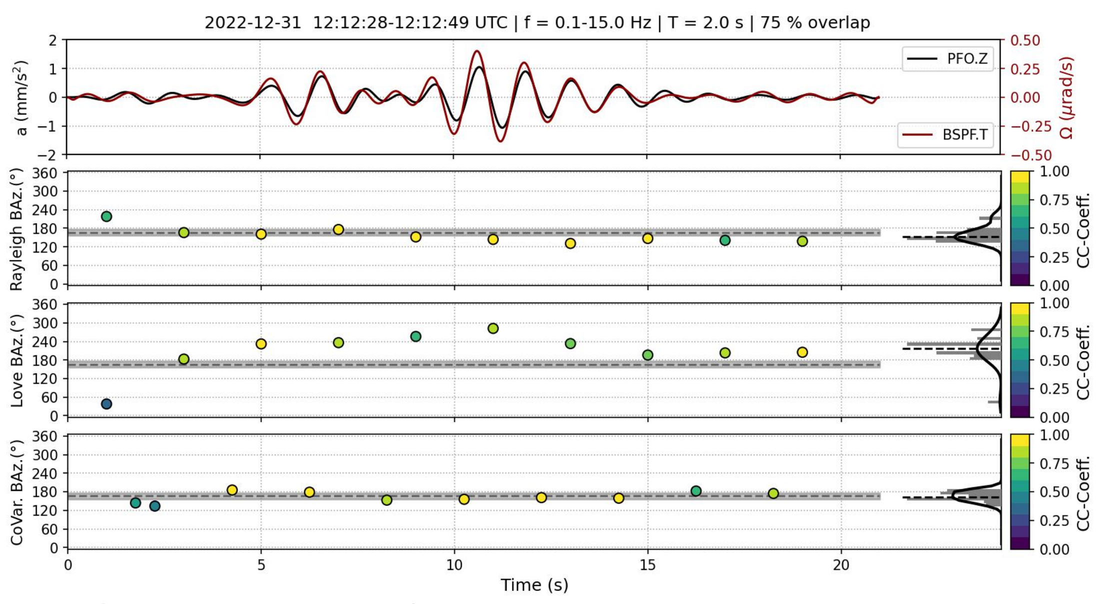


FIG 4: BAz estimation for the M_w=4.1 event using a Love, Rayleigh and CoVar approach. Black dashed line is theoretical backazimuth with gray 10° confidence interval.

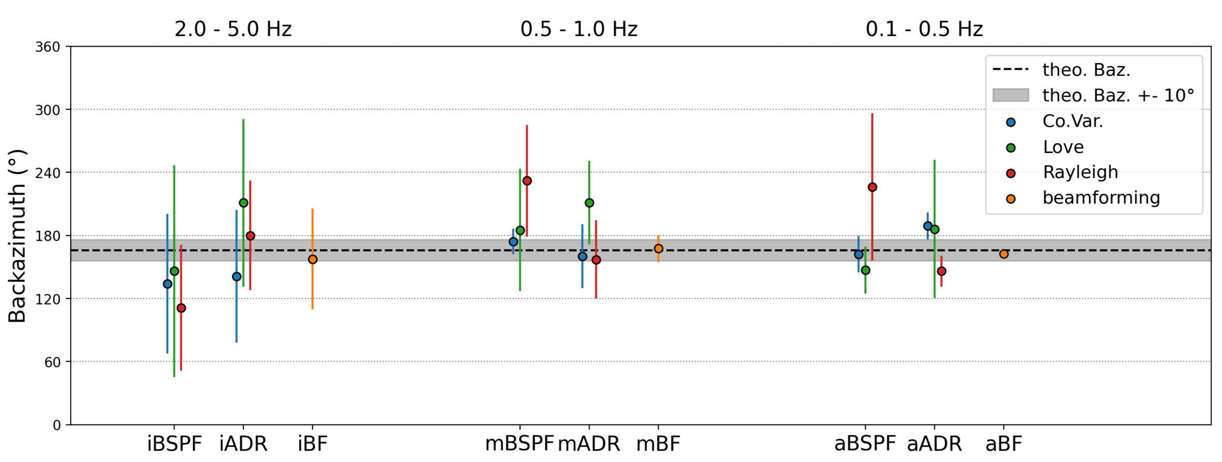


FIG 5: BAz estimation with BSPF, ADR and beamforming data for 3 freq. bands (i=2-5 Hz; m=0.5-1 Hz; a=0.1-0.5 Hz) is compared to theoretical BAz.

The comparison in Fig. 5 shows:

- high variance for i-band, likely due to scattering effects compromising a plane wave assumption.
- the CoVar estimation works well for BSPF for the m- and a-band despite a poor S/N ratio for BSPF in a-band.
- Rayleigh and Love grid search estimations rely on a good S/N ratio and phase separation.

4 Amplitude Relation for Rotation Rate

The peak ground rotation velocity (PGRV) of detected events on all 6 components are used to infer the coefficients of a local magnitude relation: $M_L = \log_{10}(A_{max}) + \boldsymbol{\alpha} \log_{10}(R) + \boldsymbol{\beta} R + \boldsymbol{\gamma}$, with R as hypocentral distance in km and A_{max} as max. vertical or horizontal amplitudes.

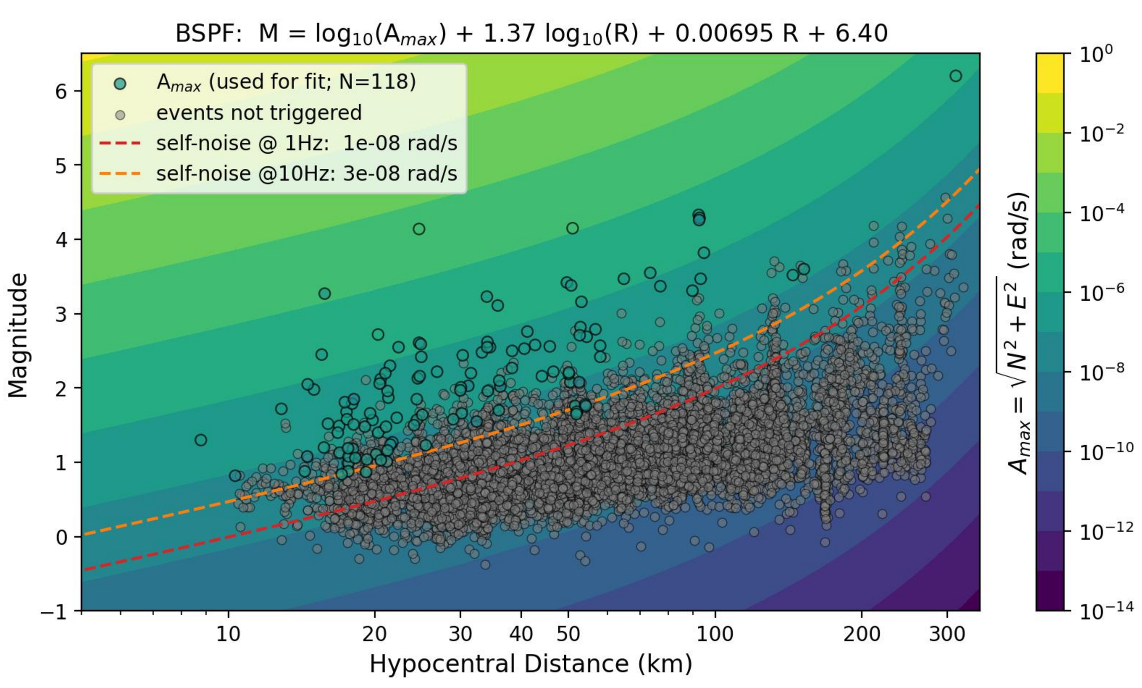


FIG 6: Local amplitude relation for max. horizontal rotational rate based on 118 all component observation at PFO.

The map for expected max. horizontal rotation rate is shown in Fig. 6 and relates the local seismicity at PFO via magnitude and hypocentral distance to PGRV of a blueSeis-3A sensor. This can be used as guidance for other experiments with seismicity involving this sensor. The current limitation results from the blueSeis' high self-noise (Fig. 6) that limits observations of small local events (grey) or teleseismic events.

5 Conclusions

- In order to fully exploit the potential of single-station 6-DoF monitoring of seismicity and ambient noise, more sensitive rotational sensors are required (~3 orders of magnitude better than the blueSeis-3A; Brotzer et al. 2023).
- rotational waveforms of single-point BSPF observations match array-derived rotations for high signal-to-noise ratios (Fig. 7).
- one year data of local events allowed to map max. expected rotation rates for a blueSeis-3A for local / regional seismicity.

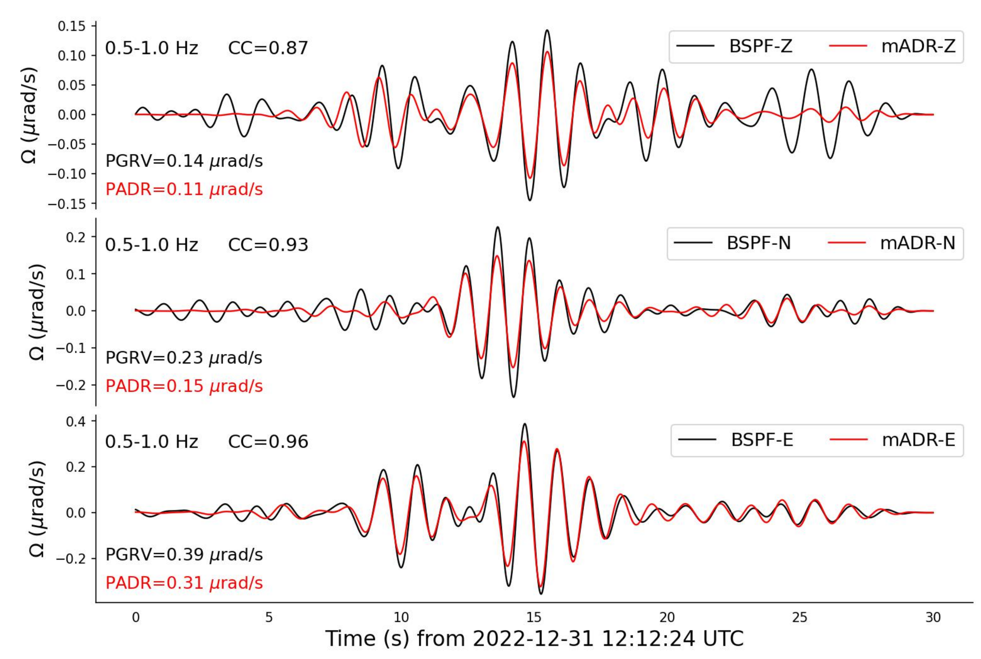


FIG 7: Waveform comparison for direct and array-derived rotations (0.5 - 1.0 Hz) for the local M_w= 4.1 event.

References:

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www.rotational-seismology.org

Andreas Brotzer | LMU | andreas.brotzer@lmu.de