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Abstract

Observing and analysing seismicity with a permanent 6C station

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1 Why Rotational 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):

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

Over the past two decades, technical developments in instrumentation resulted in large-scale, stationary Sagnac interferometers (ring laser) and portable rotation sensors (e.g. high-sensitive beam balances, fiber optical gyroscopes), allowing to observe seismic rotational ground motions directly. Array-derived rotations (ADR) are based on a finite difference approach using well-designed seismic array data. A 6C (six component) station, comprising a co-located seismometer and rotation sensor, enables a variety of techniques comparable to a seismic array (e.g. local velocity estimation, backazimuth tracking), especially in challenging environments (e.g. structural health monitoring, volcano seismology, urban seismic monitoring, seismology on extraterrestrial bodies).

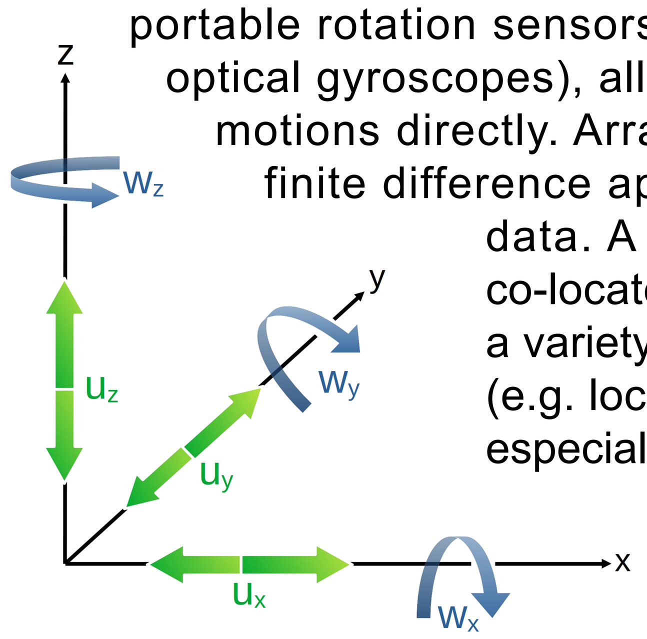
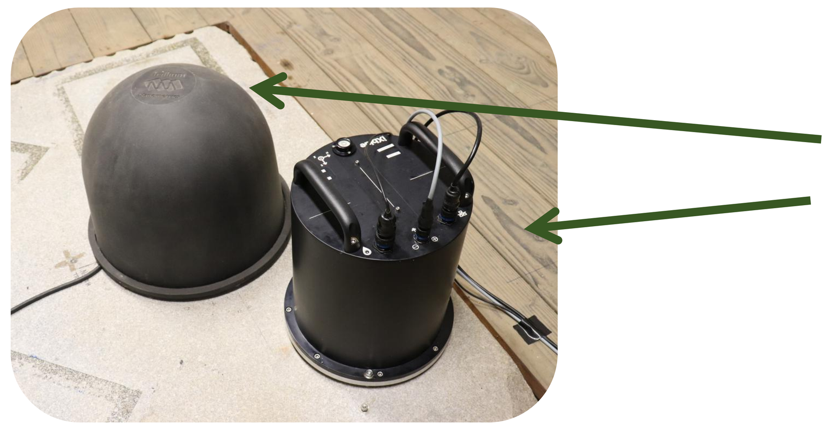


FIG 1: Schematic 3DoF of rotational and 3DoF of translational motions.

2 BSPF - Live Data Online

From October 2022 onwards, the 6C station named PY.BSPF is recording permanently at the Pinon Flat Observatory (PFO) near San Diego in California, USA. It is located on an isolated granite pillar and consists of a Trillium 240 seismometer (Nanometrics) sampled at 40 Hz and a blueSeis-3A fiber optic gyroscope (Exail, formerly iXblue) sampled at 200 Hz. Since April 2023 a STS-2 seismometer (Streckeisen) is co-located and also sampled at 200 Hz with seed code: PY.PFOIX..HH[Z,N,E]. The 6C station replaced the formerly hosted Geosensor 1C ring laser (Donner et al. 2017).

The data is streamed online and openly accessible!



Data online via FDSN Client IRIS:

Translation: II.PFO.10.BH[Z,1,2]

Rotation: PY.BSPF..HJ[Z,1,2]

or

check out the **Rotational Eventbase!!**

FIG 2: 6C station setup at PFO.

3 High Seismicity

- The BSPF 6C station is located in a seismically active area with a seismic low noise floor on site.
- Additionally, the PFO site offers the benefit of a well-designed seismic array of borehole stations to compute array-derived rotations and four optical strainmeters for strain observations.
- Of 4969 total events, so far 73 have been identified over 180 days using a recursive STA-LTA trigger.

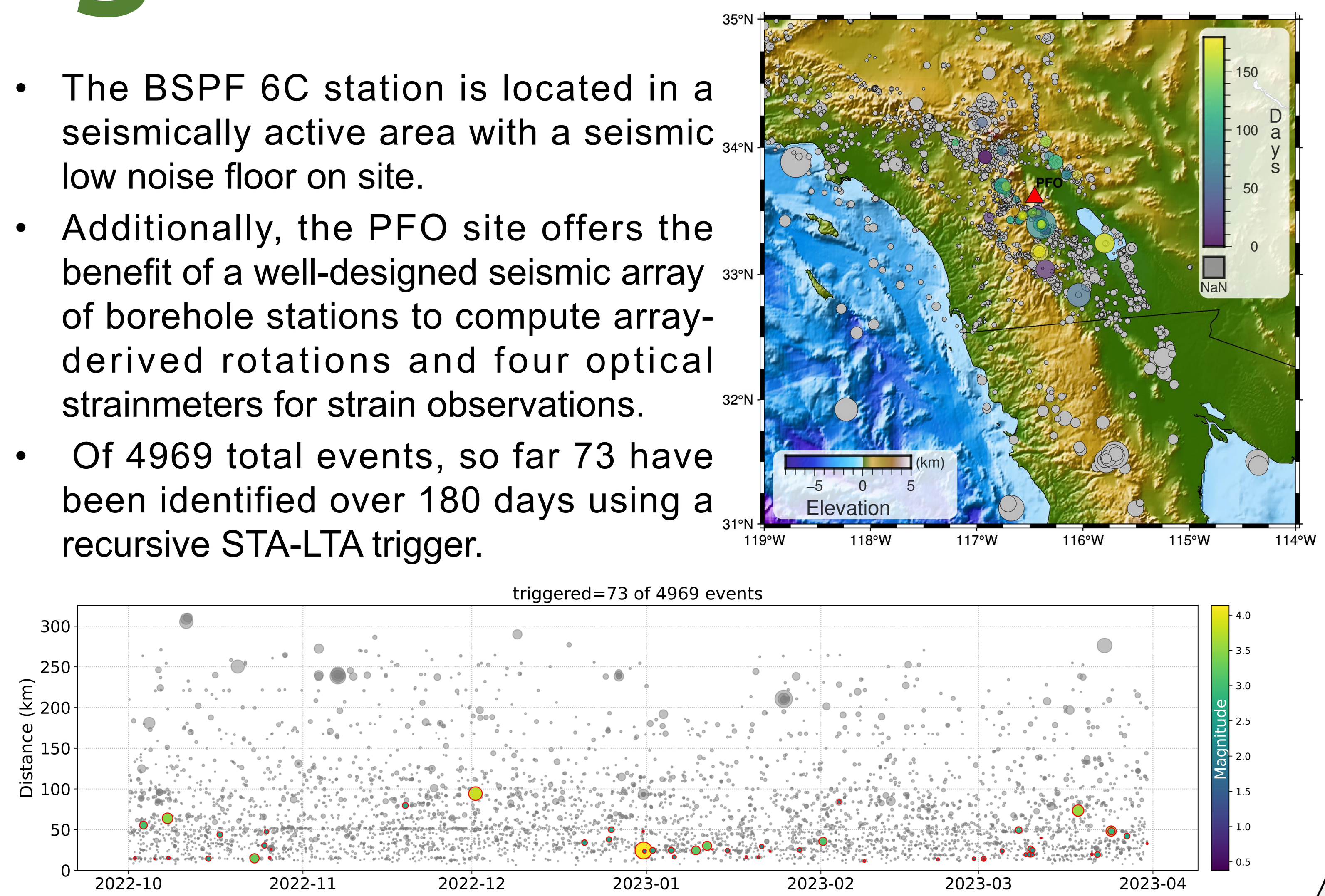


FIG 3: Regional seismicity at PFO for October 2022 - March 2023.

4 Data Examples, Quality & Preliminary Analysis

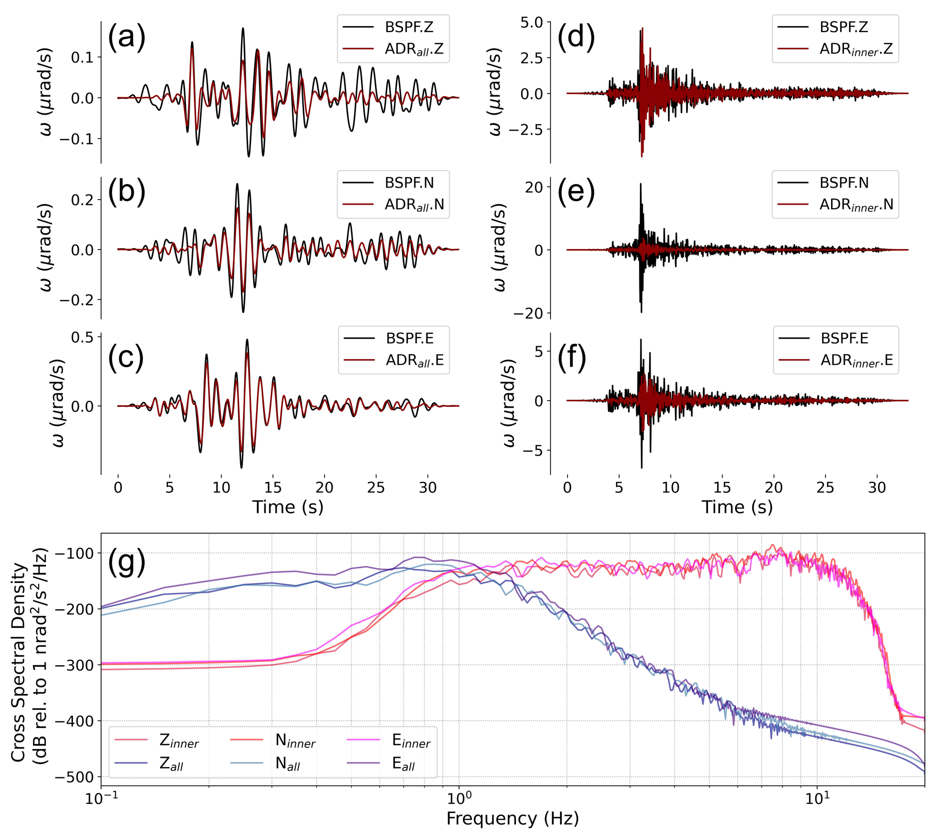


FIG 4: Waveforms for array-derived rotations (a-c) and for BSPF (d-f). (g) shows the cross spectral density for array-derived rotations of BSPF and the inner [1-10Hz] and outer array [0.15-1.2 Hz].

- The self-noise level of the portable blueSeis-3A sensor is currently at about 10^{-15} rad²/s²/Hz and poses the main limitation for observations at the 6C station. The focus is on the local and regional seismicity.
- The example shown is a M_w4.2 event near Borrega Springs (California) in about 24 km distance from BSPF on 2022-12-31 12:12:26 UTC).
- Frequency limits for subarrays of the PFO seismic array for array-derived rotations following Poppeliers & Evans (2015):
  - inner (4 stations, aperture~90m): 1.3 Hz < f < 10 Hz (Fig.4a-c)
  - outer (7 stations, aperture~730m): 0.15 Hz < f <1.3 Hz (Fig4d-f)
- A complete consistency validation of array-derived rotations versus direct measurements of a portable sensor for all three components is planned with these event data. Good agreement can be seen for both subarrays within the frequency limits using cross spectral densities (see Fig.4g).

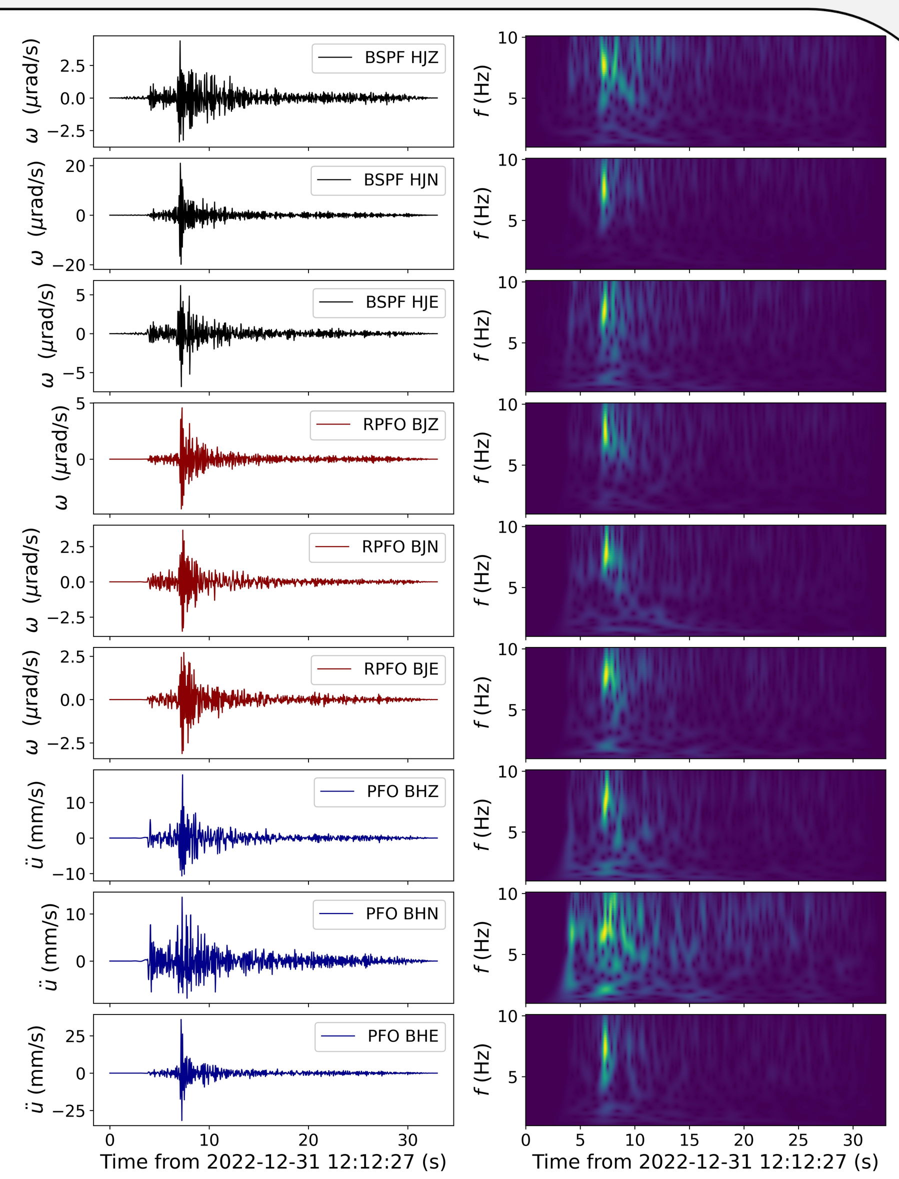


FIG 5: Waveforms [1-10 Hz] (left) of PFO (blue), BSPF (black), array-derived rotations (red) and S-transform (right).

5 What's next?

6DoF observations offer complementary seismic monitoring in challenging areas for seismic arrays. The dataset of high-quality 6DoF observations will increase since the installation is open end. Having a setup of **a single 6C station** and a co-located seismic array as well as a seismic network, enables finally a systematic investigation and validation of proposed techniques for 6DoF processing:

- **enhanced localization** of hypocenters using 6DoF versus 3DoF.
- **enhanced polarization analysis** and wavetype classification using 6DoF observations versus 3DoF (Sollberger et al. 2023). The open source package **TwistPy** will be used for the analysis.

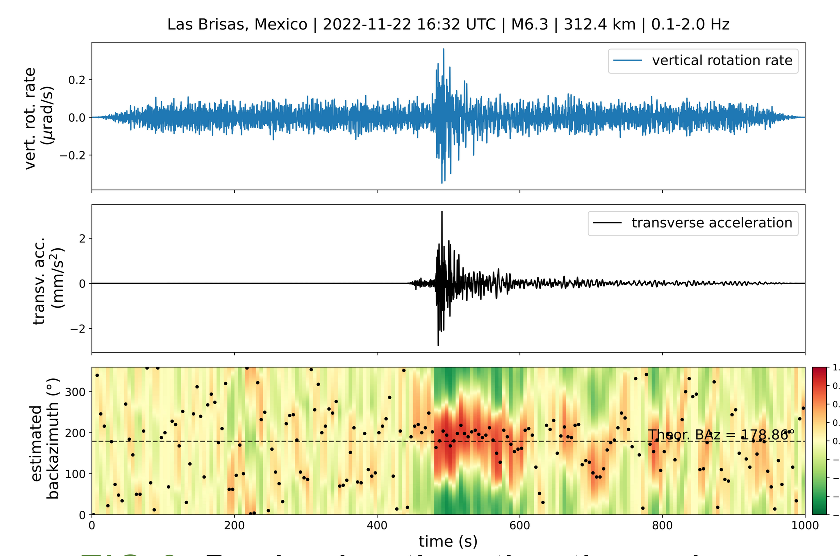


FIG 6: Backazimuth estimation using Love waves for a regional M_w6.3 event.

Sources:

- **Donner et al. (2017)** Comparing Direct Observation of Strain, Rotation, and Displacement with Array Estimates at PFO, California. SRL. doi: doi.org/10.1785/0220160216
- **Sollberger et al. (2020)** Seismological Processing of Six Degree-of-Freedom Ground-Motion Data. Sensors. doi: doi.org/10.3390/s20236904
- **Sollberger et al. (2023)** Efficient wave type fingerprinting and filtering by six-component polarization analysis. GJI. doi: doi.org/10.1093/gji/ggad071
- **Poppeliers & Evans (2015)**. The effects of measurement uncertainties in seismic-wave gradiometry. BSSA. doi: doi.org/10.1785/0120150043

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