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10 components of waveform at Pinon Flat Observatory (PFO), California

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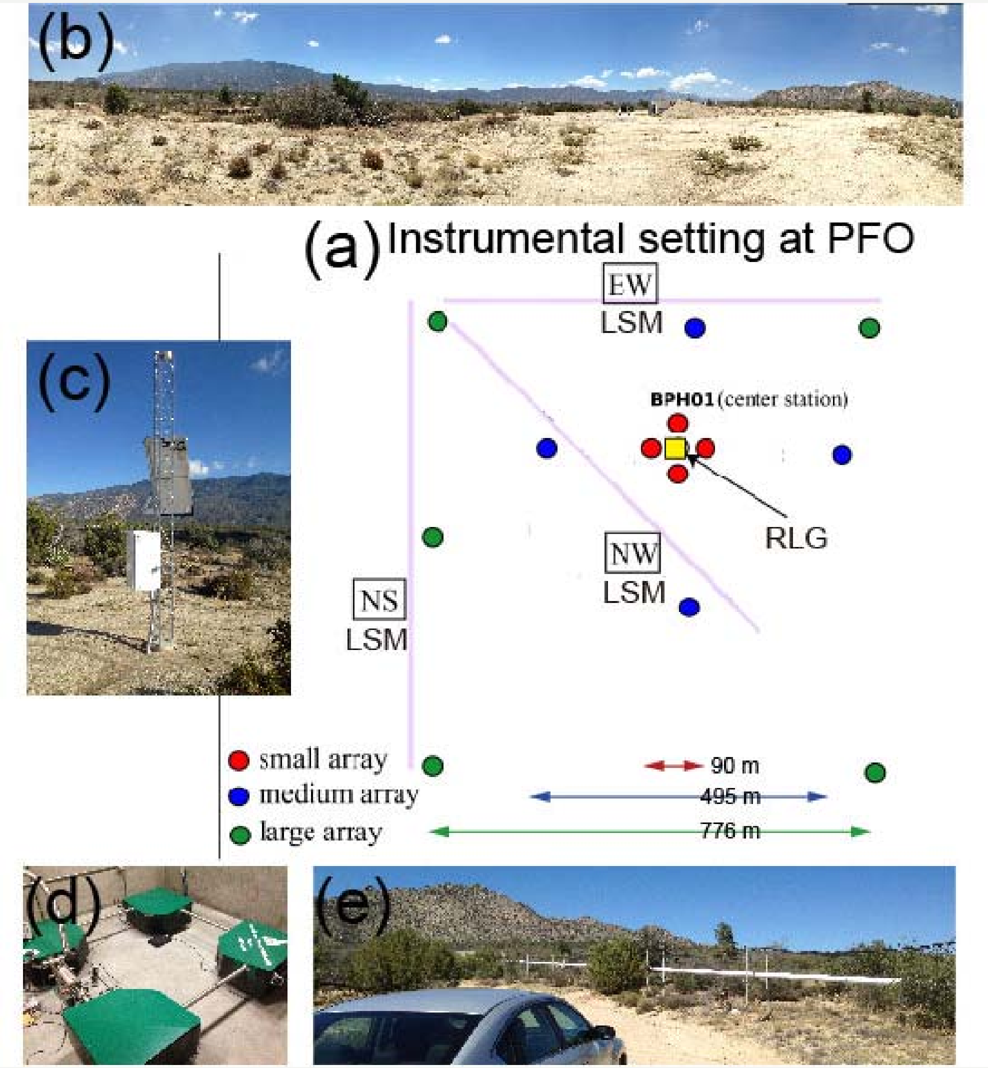
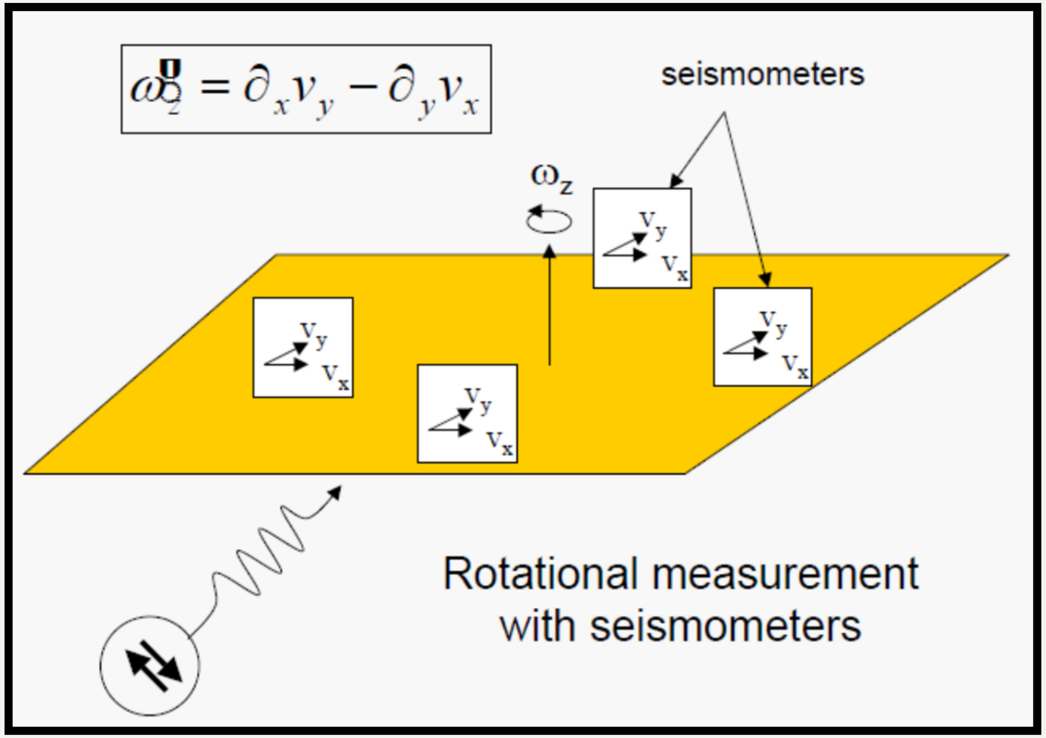
Instruments at PFO



Thirteen broadband **seismic stations** **(c)**
+
Vertical ring-laser **rotation sensor** **(d)**
+
Three surface laser **strainmeters** **(e)**

- Array-derivation vs. direct observation
- (Teleseismic) Joint analysis of translation and rotation/strain
- (Microseismic) Joint analysis vs. F-K methods
  Back-azimuth

Array spatial calculation



courtesy of Heiner Igel

Suffer to the condition of zero traction at the free-surface …

$$u_{z,t} = -u_{t,z} \qquad u_{z,r} = -u_{r,z}$$

Rotation vector (3 components)

$$\begin{bmatrix} \theta_r \\ \theta_t \\ \theta_z \end{bmatrix} = \begin{bmatrix} u_{z,t} \\ u_{z,r} \\ \frac{1}{2}(u_{r,t} - u_{t,r}) \end{bmatrix}$$

Strain Tensor (4 components)

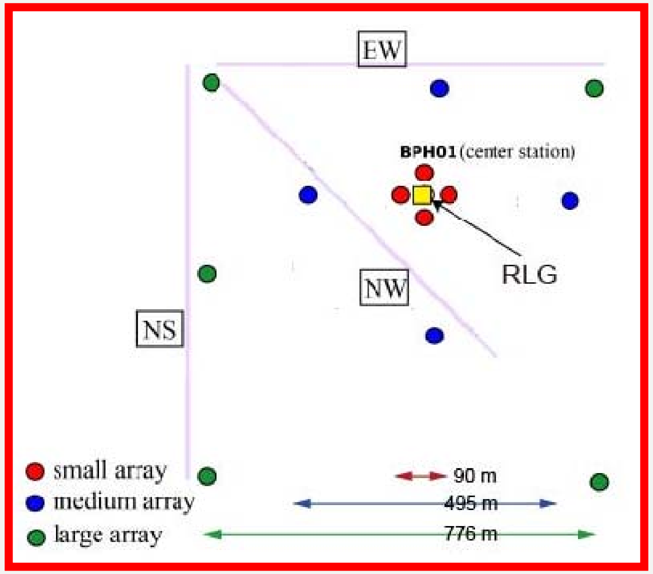
$$\begin{bmatrix} e_{rr} \\ e_{tt} \\ e_{zz} \\ e_{zr} \\ e_{zt} \\ e_{rt} \end{bmatrix} = \begin{bmatrix} u_{r,r} \\ u_{t,t} \\ -\eta(u_{r,r} + u_{t,t}) \\ 0 \\ 0 \\ \frac{1}{2}(u_{r,t} + u_{t,r}) \end{bmatrix}$$

← assuming plane wave propagation

All observable components on the ground are **10**

[Spudich et al., 1995]

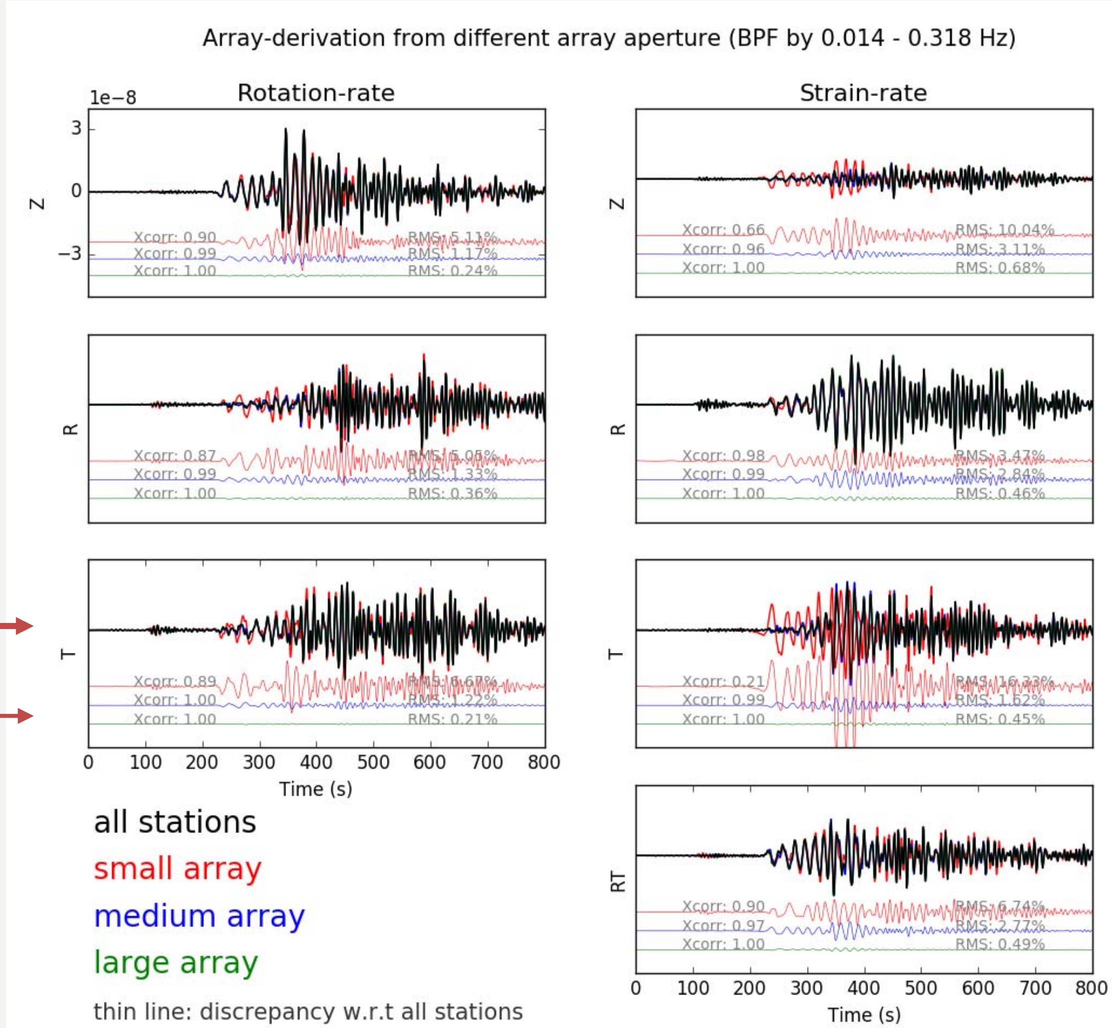
Array-derived rotation/strain



results

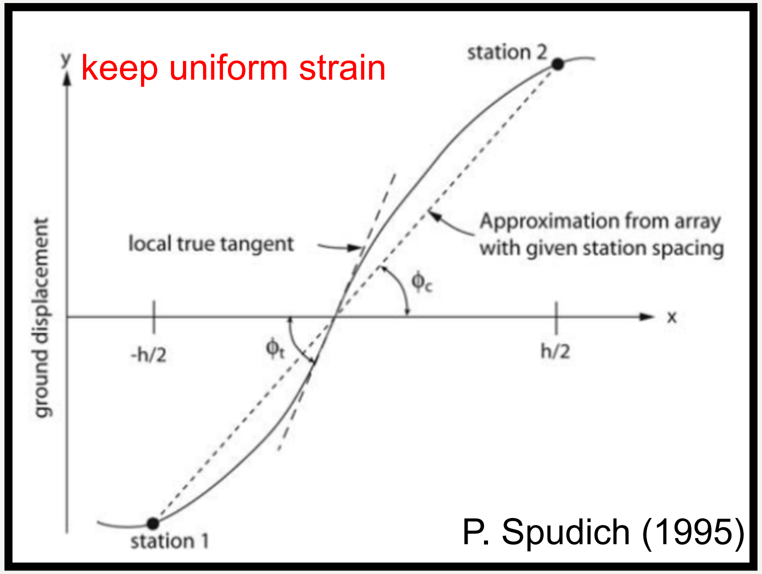
discrepancies

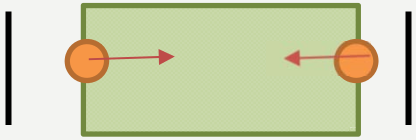
Smaller array are prone to error. why?



Limitation of array-derivation

…as small as possible…

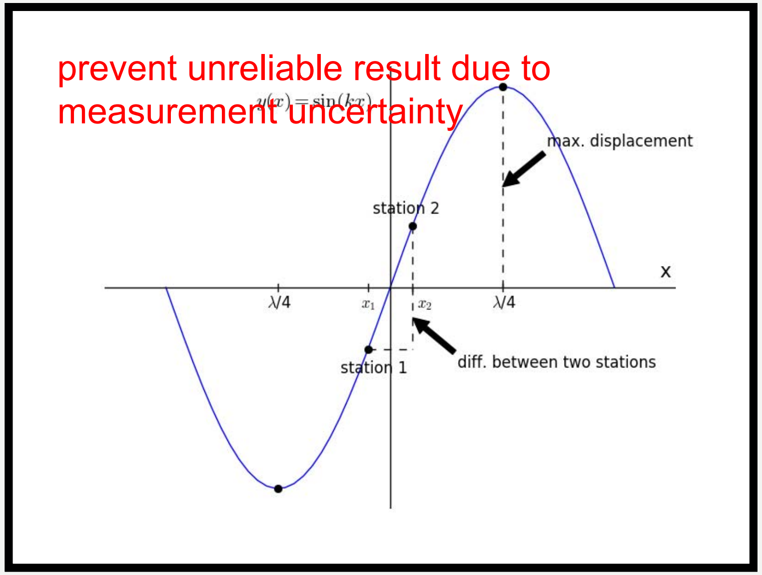


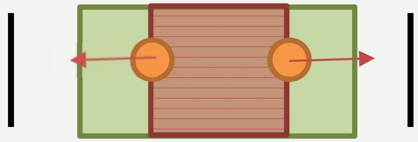


aperture ⟷ $h < \frac{1}{4}\lambda$

wavelength ⟷ λ

… cannot be too close…





aperture ⟷ $h > \frac{\lambda}{2\pi} e$

wavelength ⟷ λ

measurement uncertainty

$$sin\left(\frac{2\pi}{\lambda}x_2\right) - sin\left(\frac{2\pi}{\lambda}x_1\right) > e \times \sin(0.5\pi) \rightarrow \frac{2\pi}{\lambda}h > e$$

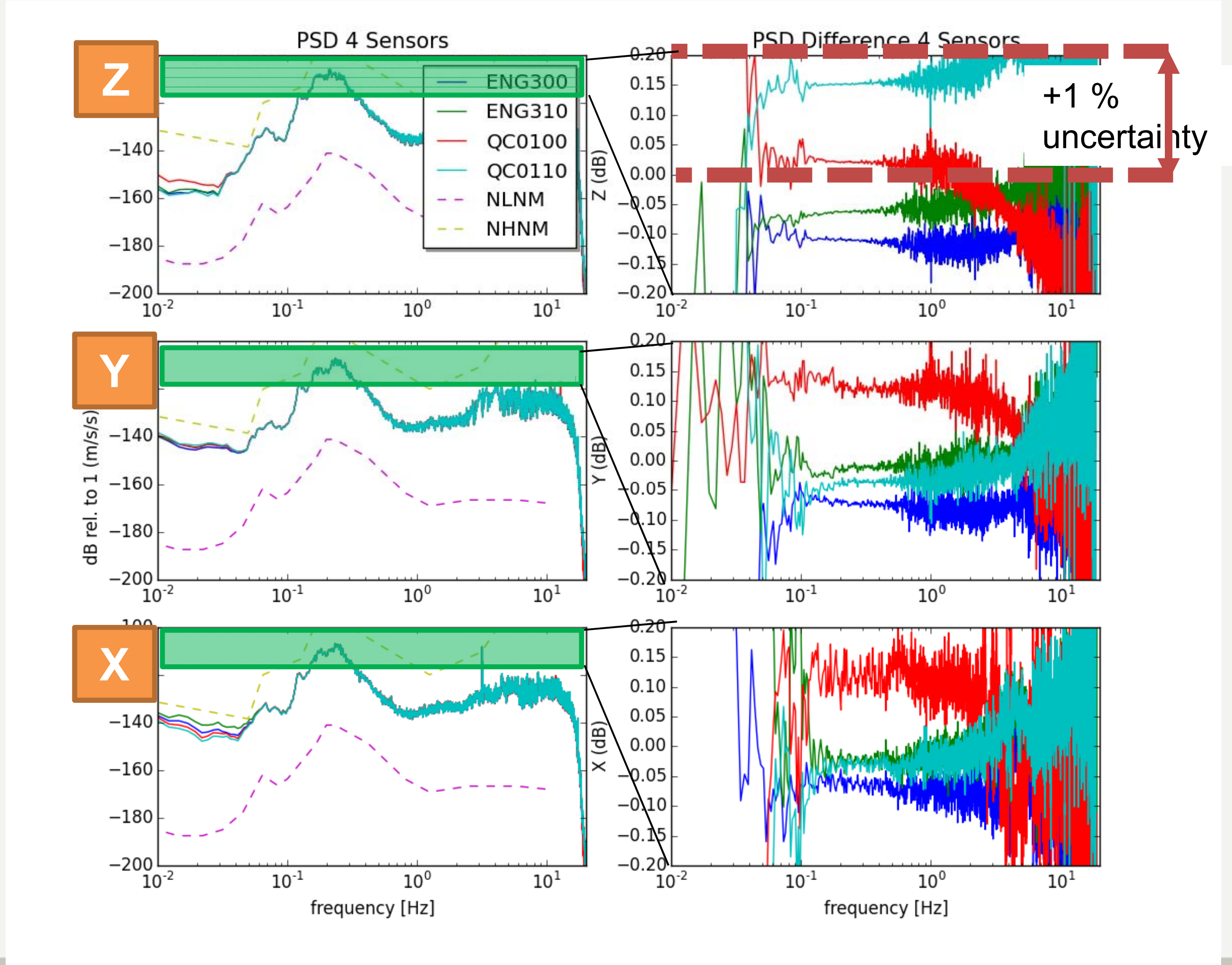
Measurement uncertainty

4 co-located STS-2 seismometers

Small array aperture $h = 90m$
e=0.01
c=3000 m/s

$\frac{2\pi}{\lambda} h > e$

$f_{min} = 0.05\ Hz$



10 components of waveform

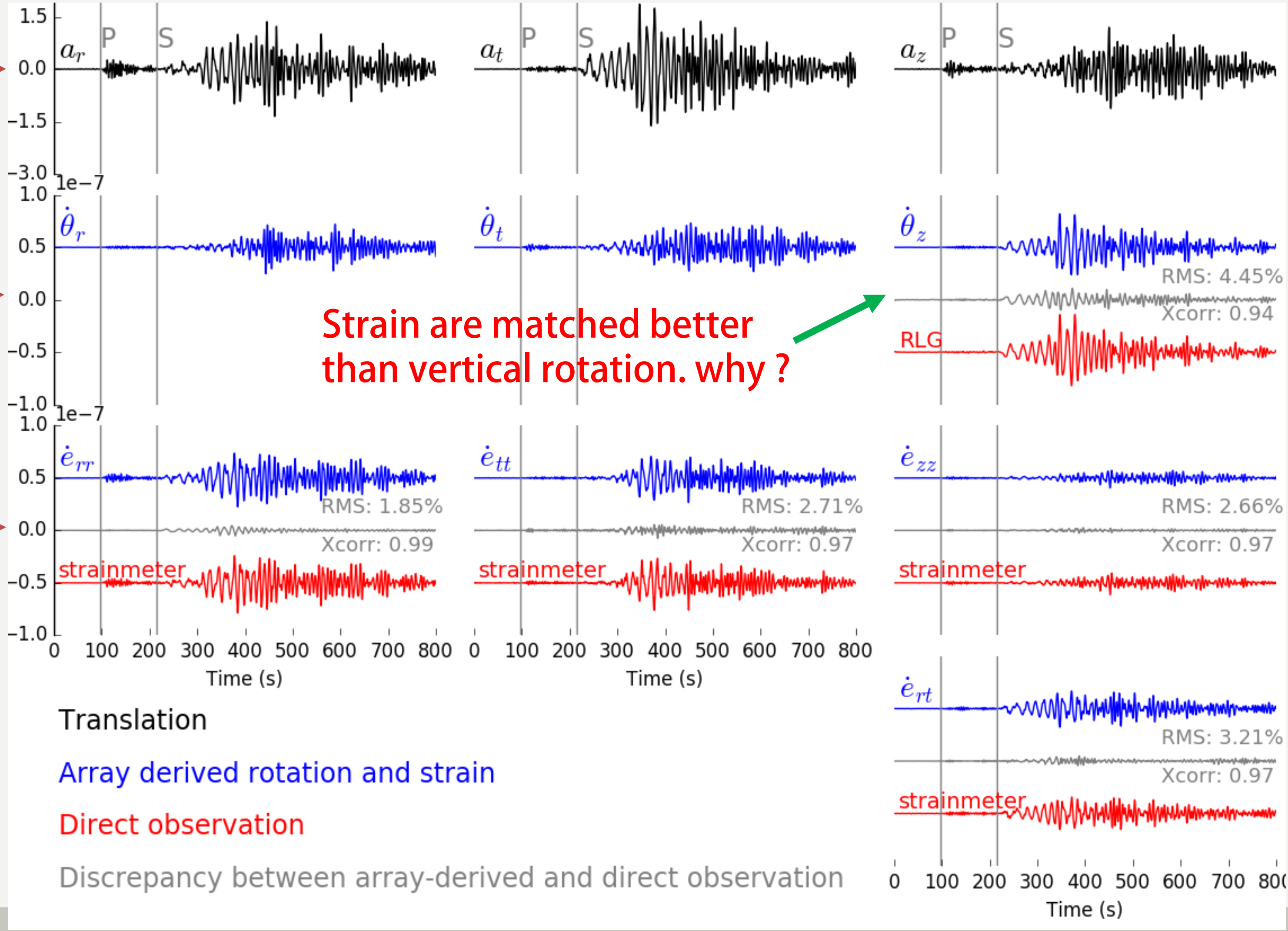
(f = 0.014 – 0.318 Hz)

radial | transverse | vertical

acceleration

rotation

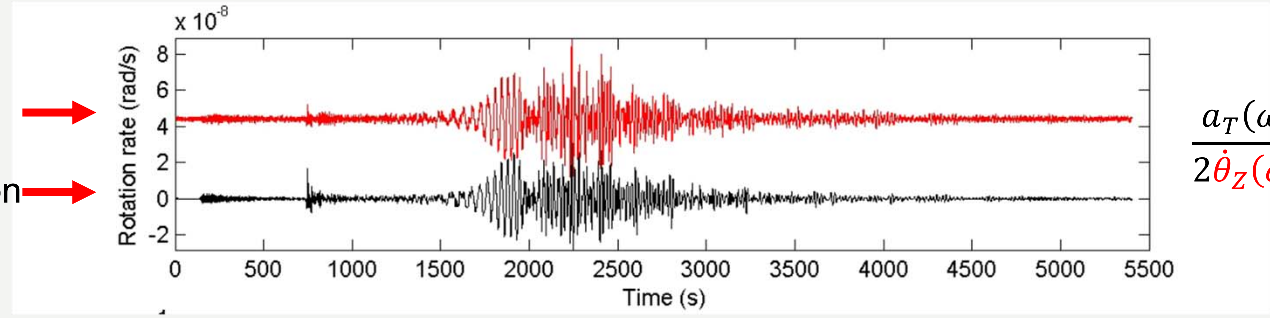
strain



Assuming plane wave propagation …

Vertical rotation

Transverse acceleration



$$\frac{a_T(\omega)}{2\dot{\theta}_Z(\omega)} = c(\omega)$$

Heiner Igel, Ulrich Schreiber, et.al. (2005)

	Rotation	**Strain**	
Love wave	(1) $\mathbf{c_L = \frac{-\dot{u}_t}{2\theta_z}}$ (Igel et al., 2005)	(2) $\mathbf{c_L = \frac{-\dot{u}_t}{2e_{rt}}}$ (Gomberg & Agnew, 1996)	
Rayleigh wave	(3) $\mathbf{c_R = \frac{\dot{u}_z}{\theta_t}}$ (Lin et al., 2011)	(4) $\mathbf{c_R = -\frac{\dot{u}_r}{e_{rr}}}$ (Gomberg & Agnew, 1996)	(5) $\mathbf{c_R = \frac{-\upsilon}{1-\upsilon}\frac{\dot{u}_r}{e_{zz}}}$ (Blum et al., 2010)

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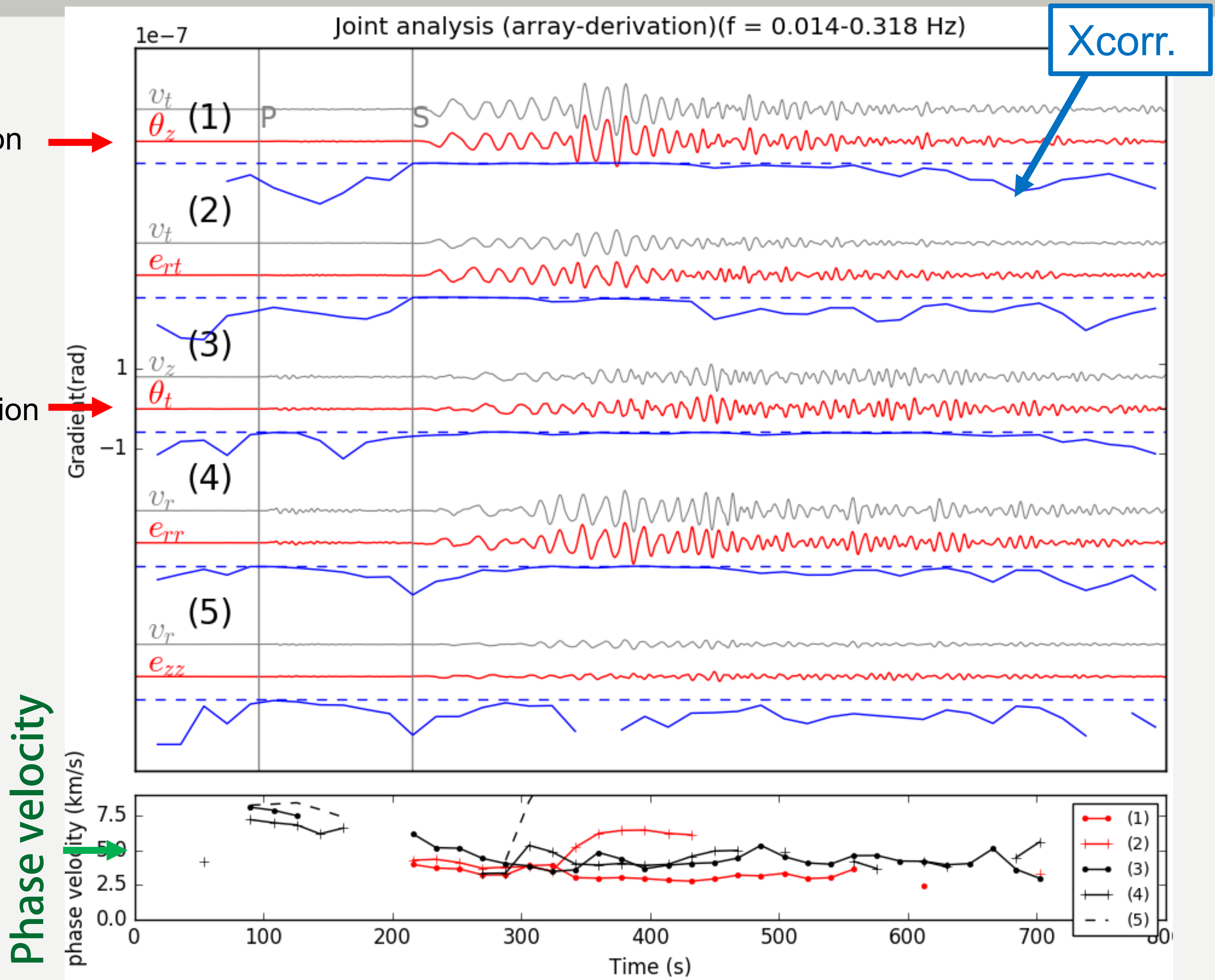
Teleseismic event

Vertical rotation

horizontal rotation



Assuming plane wave propagation …

L.	(1) $\mathbf{c_L} = \frac{-\dot{u}_t}{2\theta_z}$
	(2) $\mathbf{c_L} = \frac{-\dot{u}_t}{2e_{rt}}$
R.	(3) $\mathbf{c_R} = \frac{\dot{u}_z}{\theta_t}$
	(4) $\mathbf{c_R} = -\frac{\dot{u}_r}{e_{rr}}$
	(5) $\mathbf{c_R} = \frac{-\upsilon}{1-\upsilon}\frac{\dot{u}_r}{e_{zz}}$

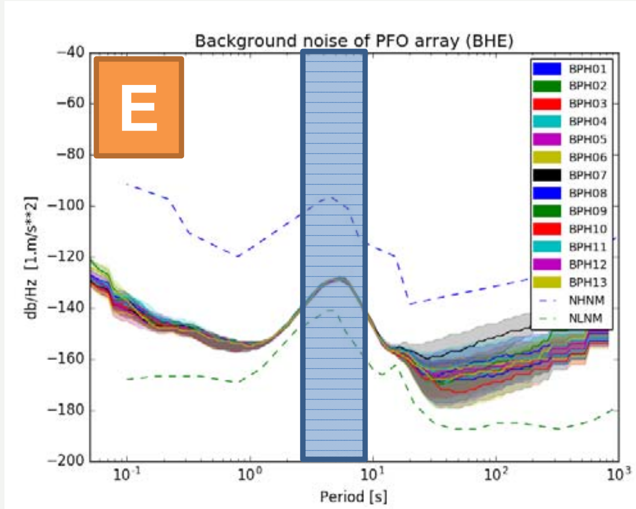
Background noise

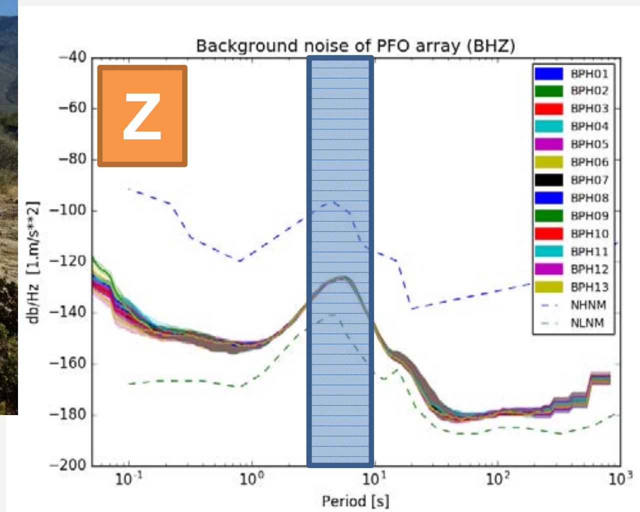
PFO

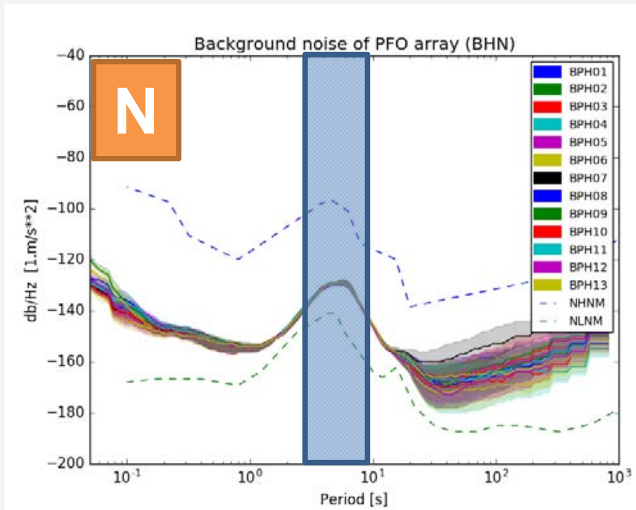
seismograms

seismic station at PFO

Seismometers are installed at depth of 2-3 m



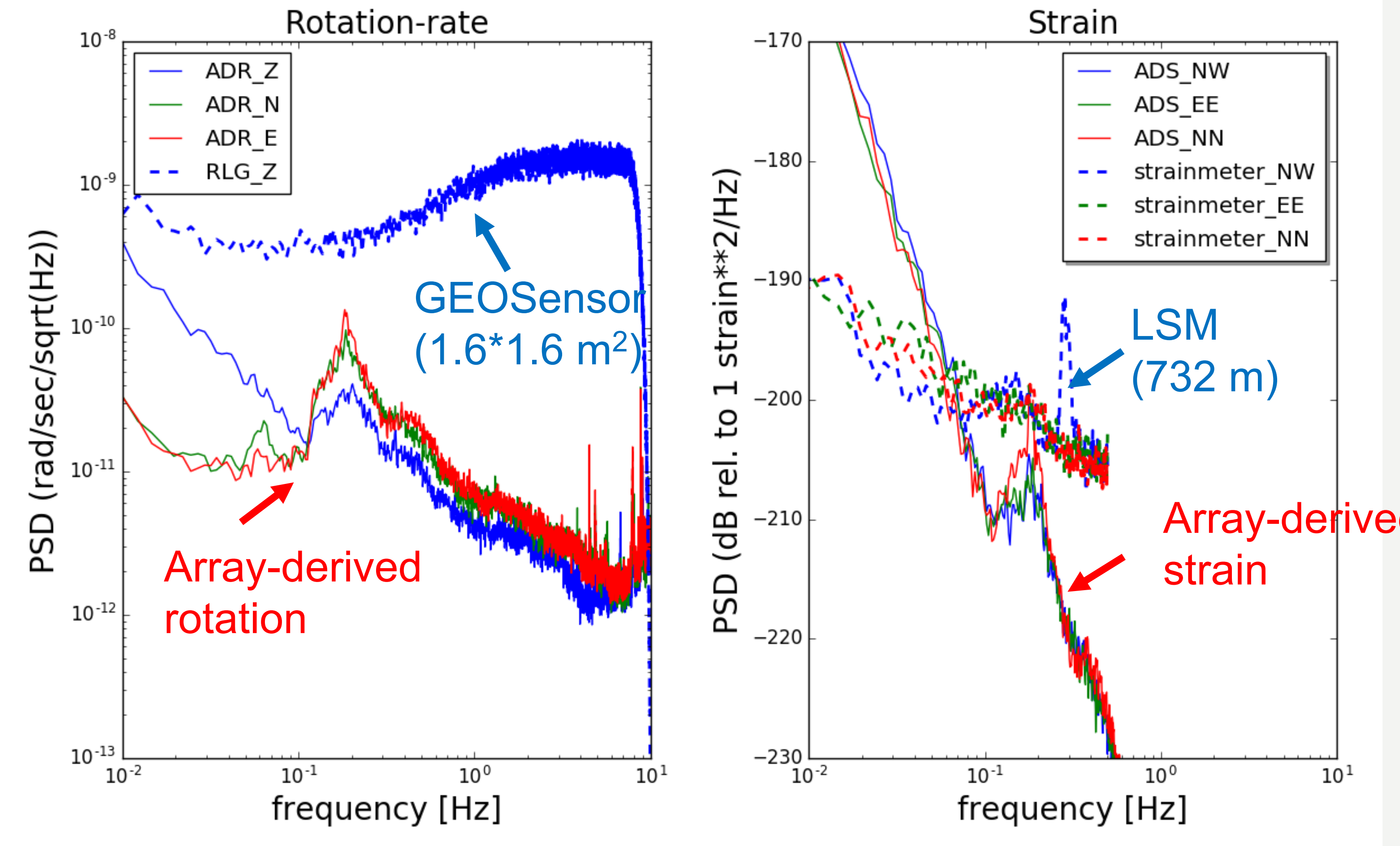




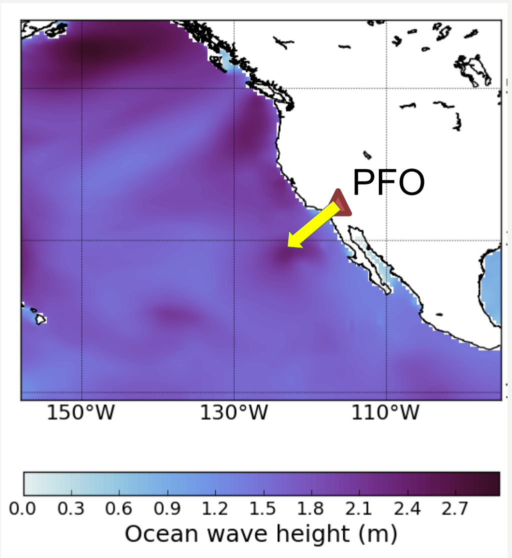
Background noise

rotation

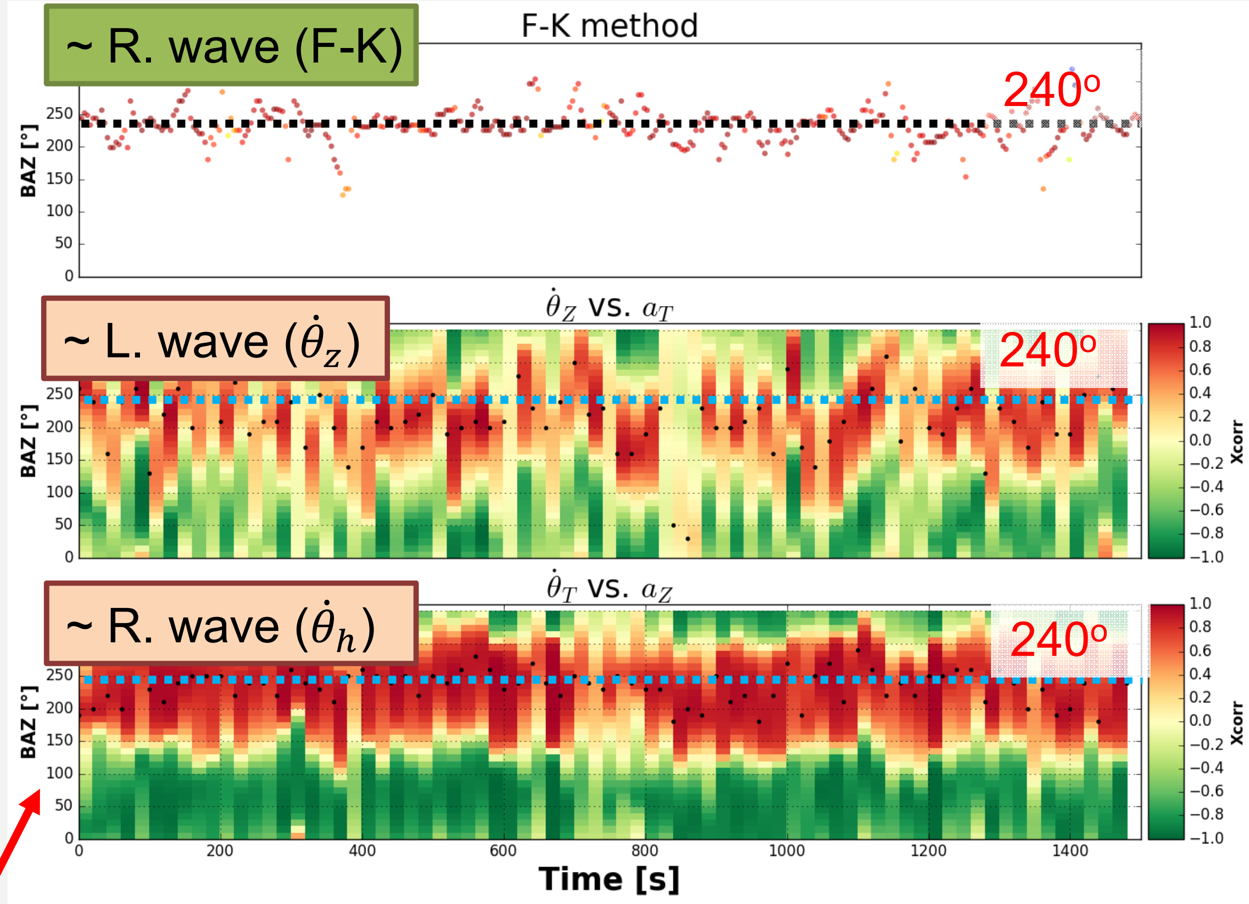
strain



Microseismic signal (f=0.1~0.3 Hz)



Courtesy of C. Juretzek



orientation

Conclusions

- **Array-derived rotation** vs. **point measurement**

✓ The result is slightly different due to effect of measurement scale

- **Assuming plane wave propagation**

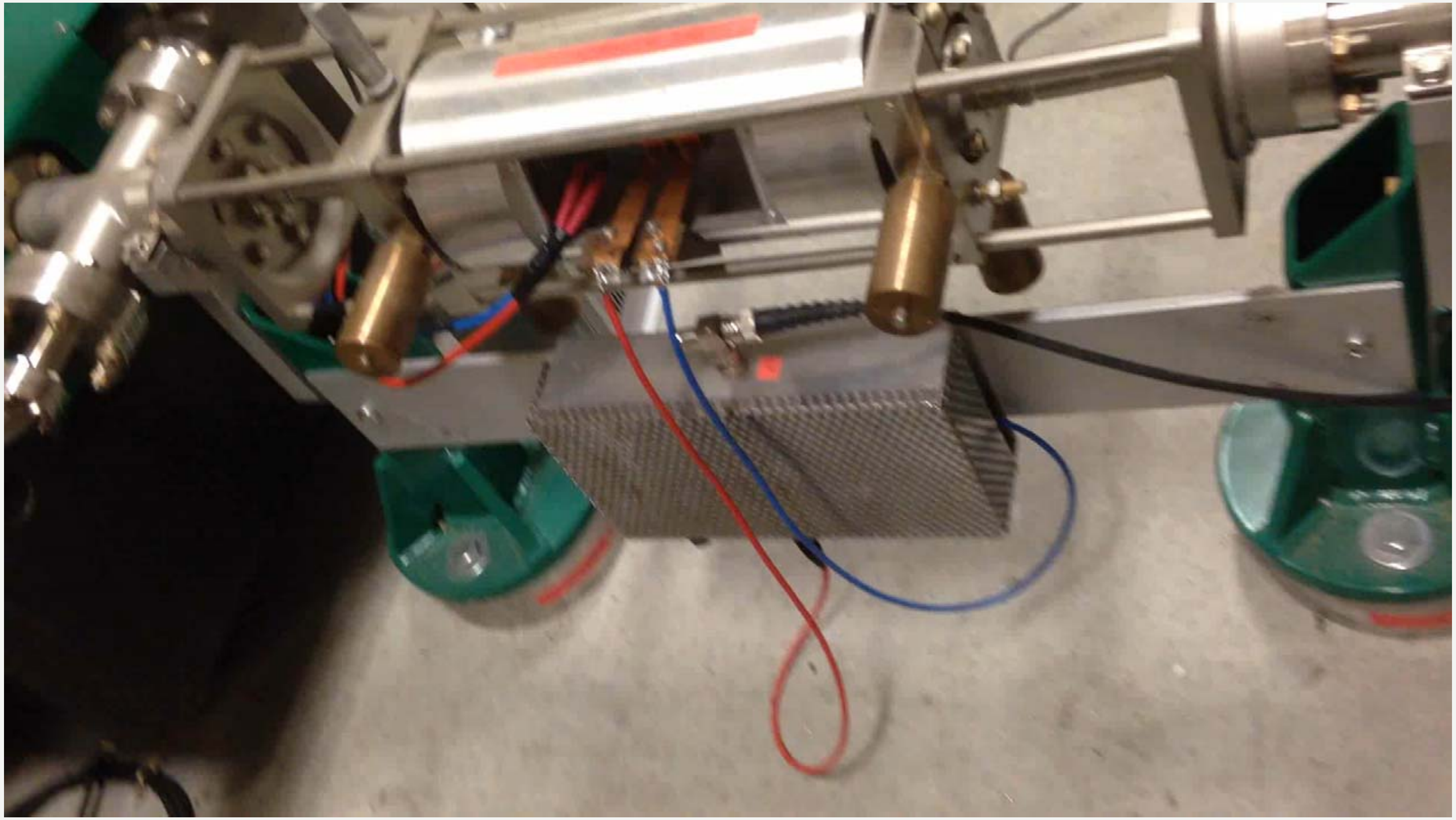
✓ Translations can be scaled to the rotation/strain

✓ Derived apparent velocities, from rotation and strain, are consistent.

- **Microseismic signal**

✓ Back-azimuth of the source determined by three methods are consistent.

Acknowledgements



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