Tutorial 3: Compliance and tilt corrections

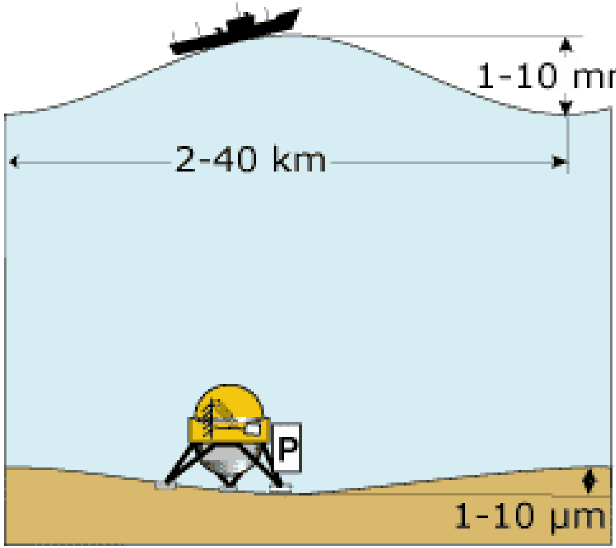
OBS training workshop, VUW, April 14-16, 2025 https://github.com/nfsi-canada

OBStools

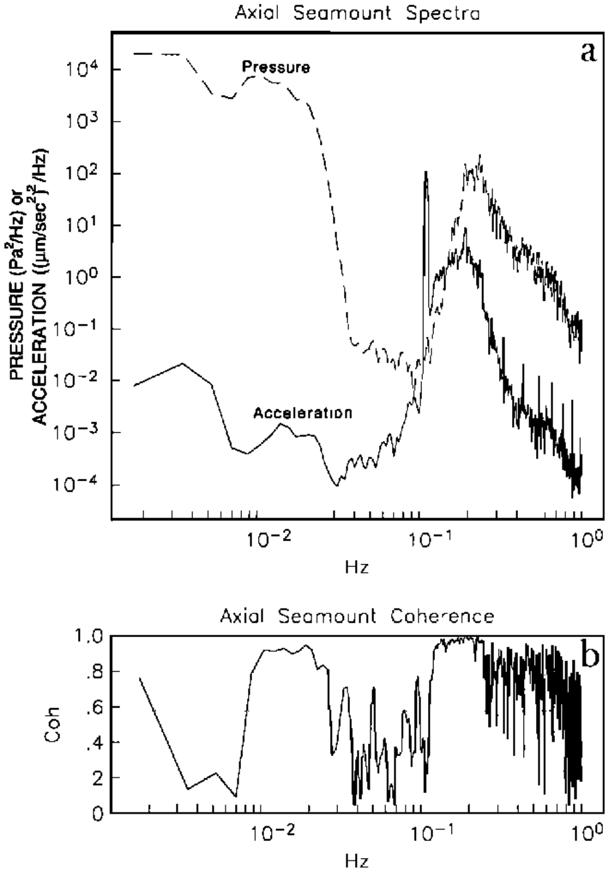
Software for processing broadband ocean-bottom seismic data

1. Removes tilt and compliance noise (`ATaCR` module)
2. Calculates compliance signal (`Comply` module)

Seafloor compliance



http://www.ipgp.fr/~crawford/Homepage/Compliance.html



Crawford et al., 1991

Deformation of seafloor due to infra-gravity waves

$$\xi(\omega) = -\frac{1}{k(\omega)}\left(\frac{V_P^2}{2\rho V_S^2(V_P^2 - V_S^2)}\right),$$

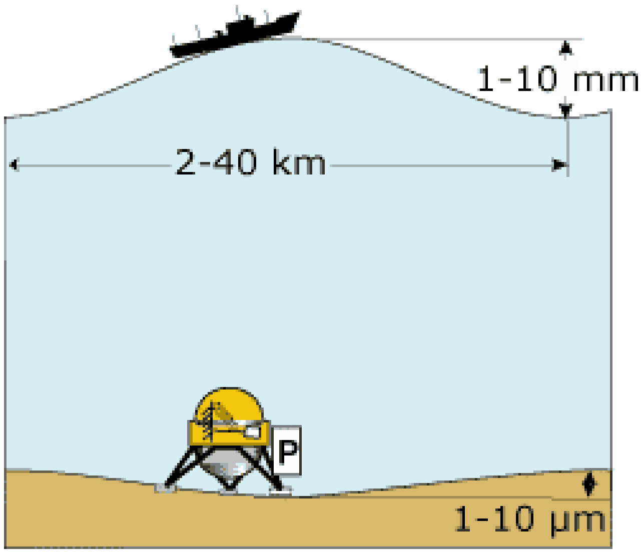
$$\eta(\omega) = k(\omega)\xi(\omega) = -\frac{V_P^2}{2\rho V_S^2(V_P^2 - V_S^2)}.$$

Measurement:

$$\eta(\omega) = k(\omega)\gamma_{PZ}(\omega)\sqrt{\frac{|Z(\omega)|}{|P(\omega)|}},$$

$$\gamma_{PZ}(\omega) = \sqrt{\frac{|C_{PZ}(\omega)|^2}{C_{PP}(\omega)C_{ZZ}(\omega)}},$$

Seafloor compliance



http://www.ipgp.fr/~crawford/Homepage/Compliance.html

Amplitude of signal P_B at seafloor depth H from wave height z:

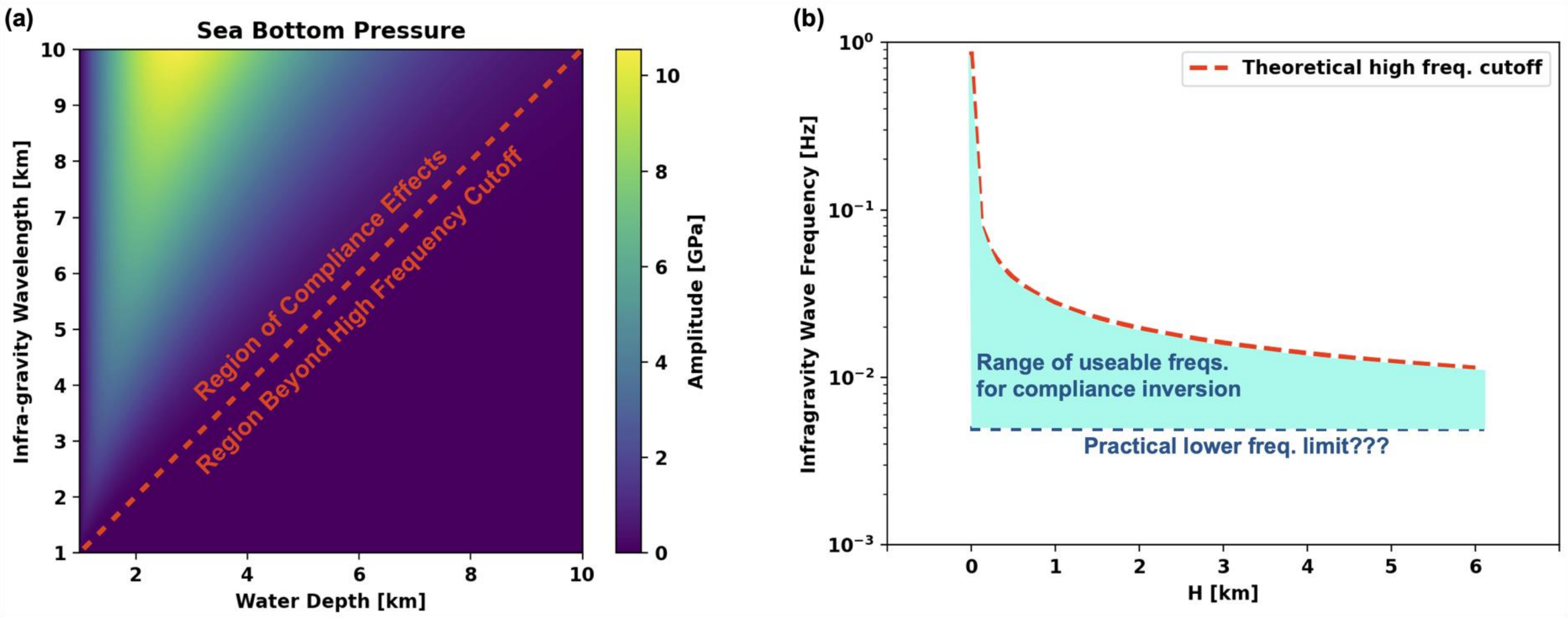
$$P_B = \frac{\rho_w g \zeta}{cosh(kH)} = \frac{\rho_w g \zeta}{cosh(2\pi H/\lambda)},$$

To produce compliance: $\lambda \geq H$

Maximum frequency where compliance is observed:

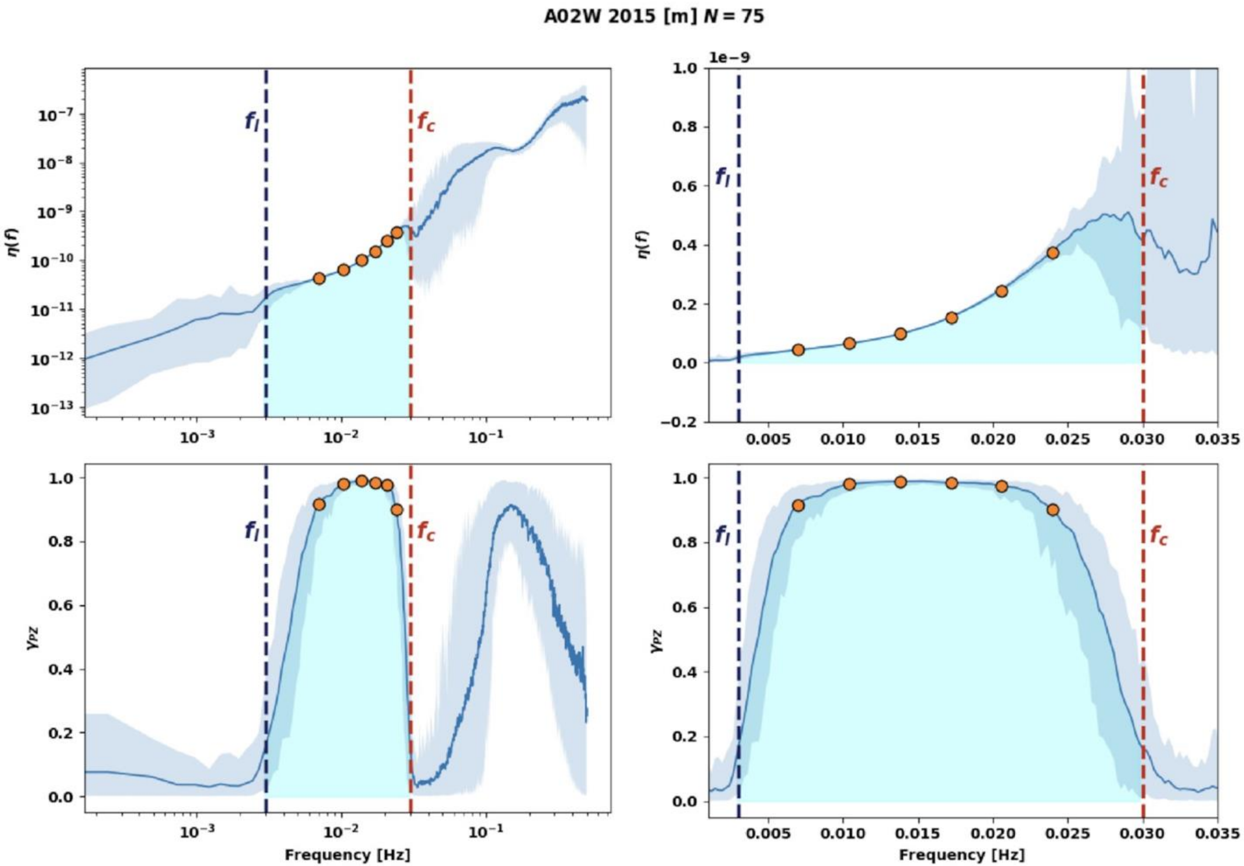
$$f_c \approx \sqrt{\frac{g}{\pi H}}.$$

Seafloor compliance



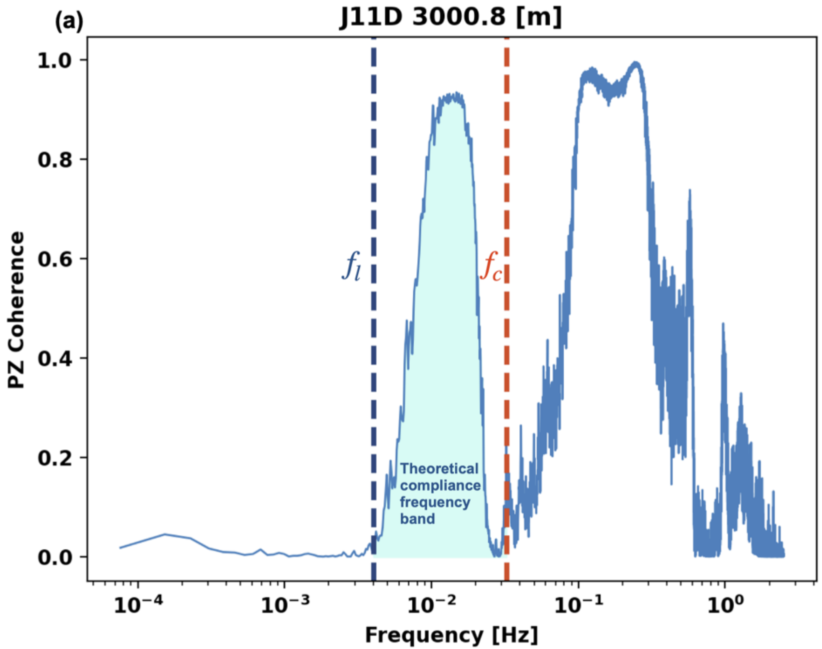
Mosher et al. (2021)

Seafloor compliance from noise

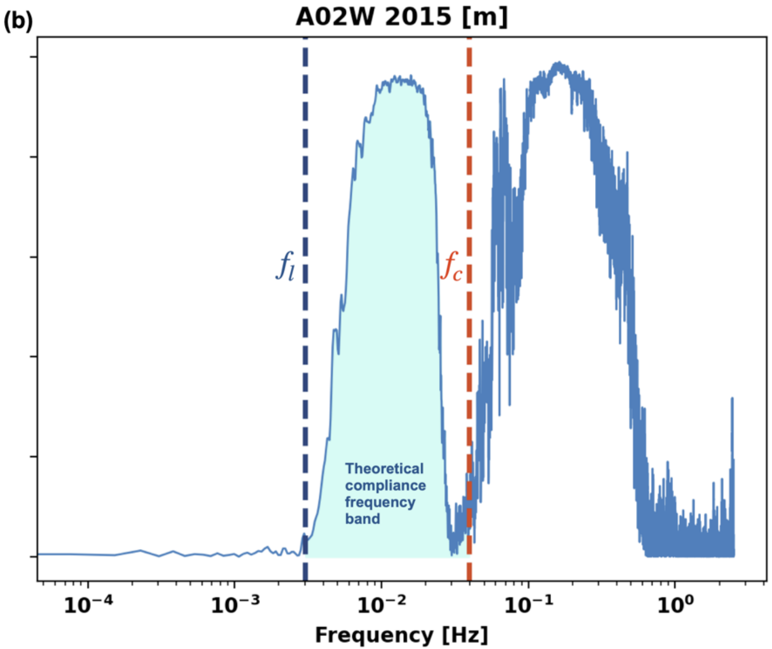


Mosher et al. (2021)

Seafloor compliance from noise



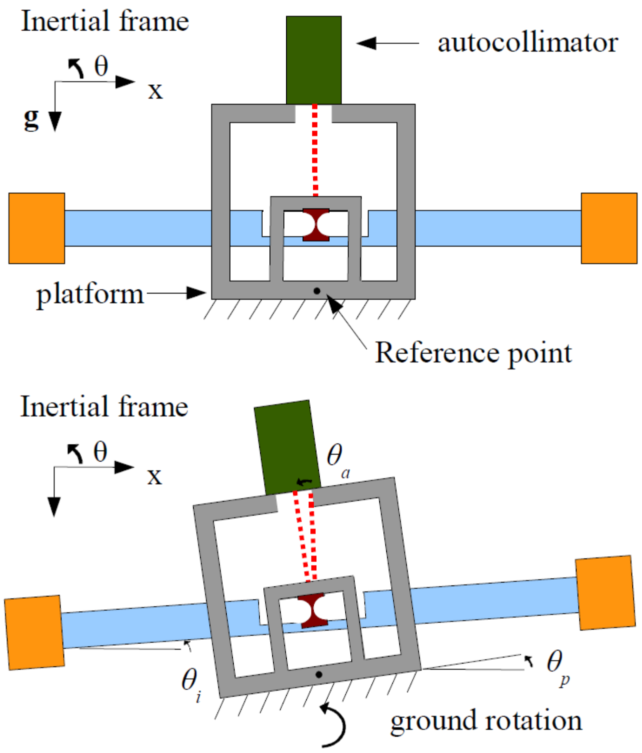
Cascadia Initiative, depth 3000 m



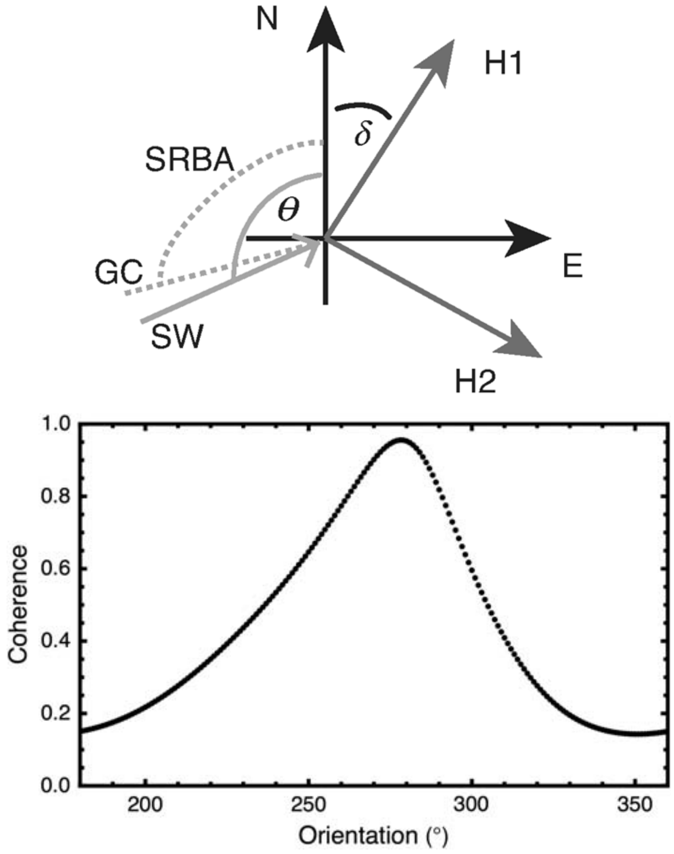
Eastern Lau spreading center, depth 2015 m

Mosher et al. (2021)

Station tilt



Venkateswara et al. (2017)



Bell et al. (2015)

Tilt and compliance noise removal

- Start with $X(t)$ and $Y(t)$, two different components of the OBS station (e.g., 1 and Z, or P and Z, etc.)
- Calculate noise cross-spectrum and power spectra: G_{xy}, G_{xx} and G_{yy}

$$G_{xy}(f) = \frac{1}{n_d} \sum_{i=1}^{n_d} X_i^*(f) Y_i(f),$$

- **NOTE**: Because this is a mean value (L2 estimate), it is very sensitive to outliers
- From these spectra, we can calculate a transfer function that allows us to predict one component from the other:

$$H_{xy}(f) = \frac{G_{xy}(f)}{G_{xx}(f)}.$$

- The admittance, coherence and phase are simply:

$$A_{XY}(f) = |H_{xy}(f)|$$

$$\gamma^2_{XY}(f) = H_{XY}(f)\, H_{YX}(f)$$

$$\varphi_{XY}(f) = \tan^{-1}(\mathrm{Imag}(H_{XY}(f))/\mathrm{Real}(H_{XY}(f)))$$

Tilt and compliance noise removal

- To remove noise from component $Y(t)$ due to component $X(t)$ (e.g., tilt noise, compliance noise), we perform the following steps:
  - Calculate Fourier Transform of $X(t)$ and $Y(t)$ to get $X(f)$ and $Y(f)$
  - Multiply $X(f)$ by $H_{XY}(f)$, which results in a “predicted” $Y'(f)$
  - Inverse Fourier Transform $Y'(f)$ to get $Y'(t)$
  - Calculate $Y(t) - Y'(t)$

Tilt and compliance noise removal

a) Original HZ

b) Original H1

c) Original H2

d) H rotated along max coherence with HZ

e) Scaled HZ

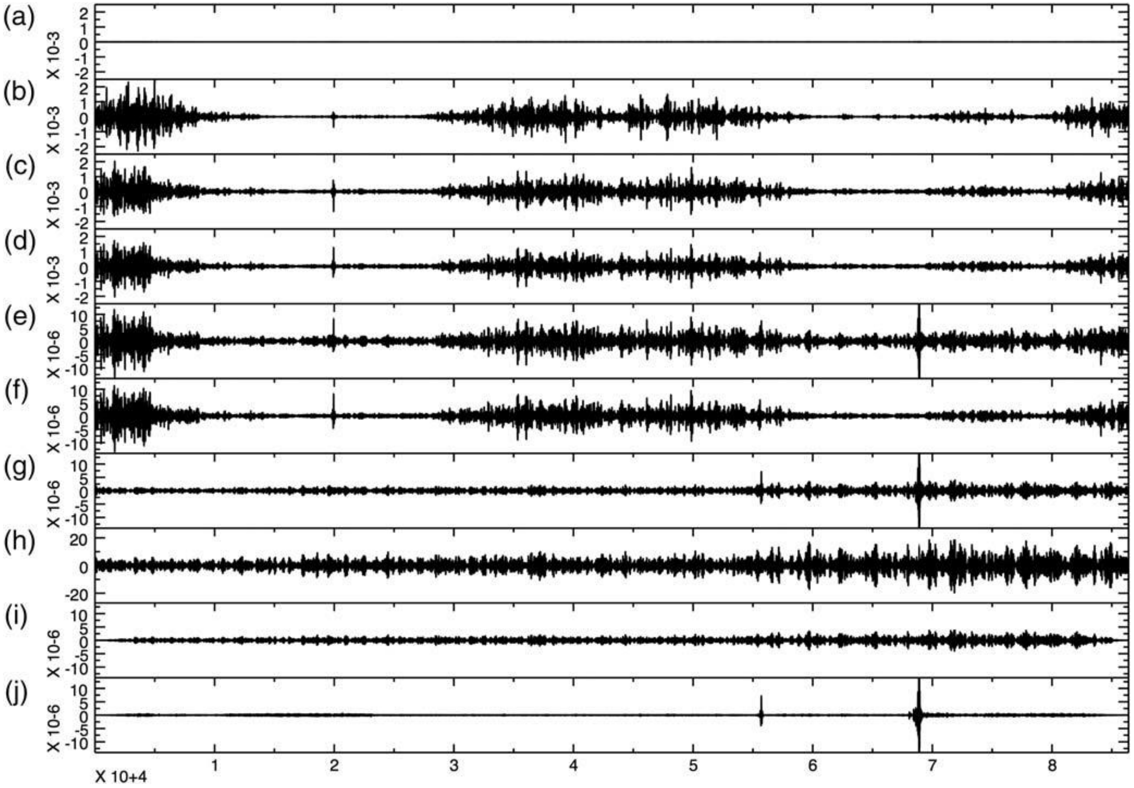
f) Predicted tilt noise

g) HZ with tilt noise removed (f – e)

h) Differential pressure (XH)

i) Predicted compliance noise

j) HZ with tilt + compliance noise removed (i – h)

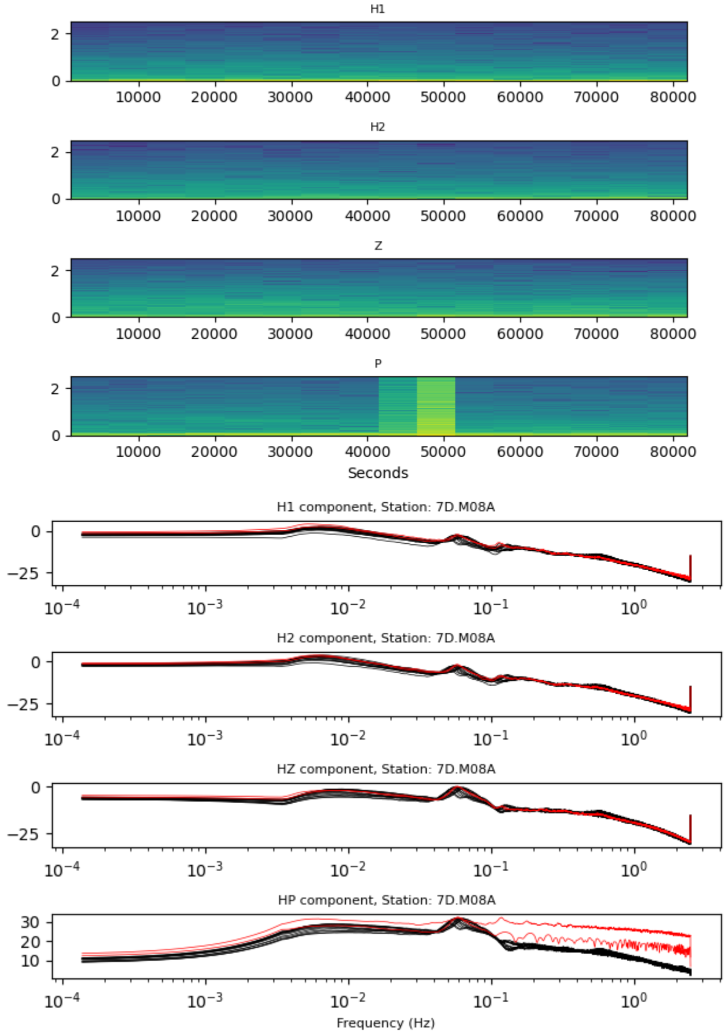


Bell et al. (2015)

OBStools implementation

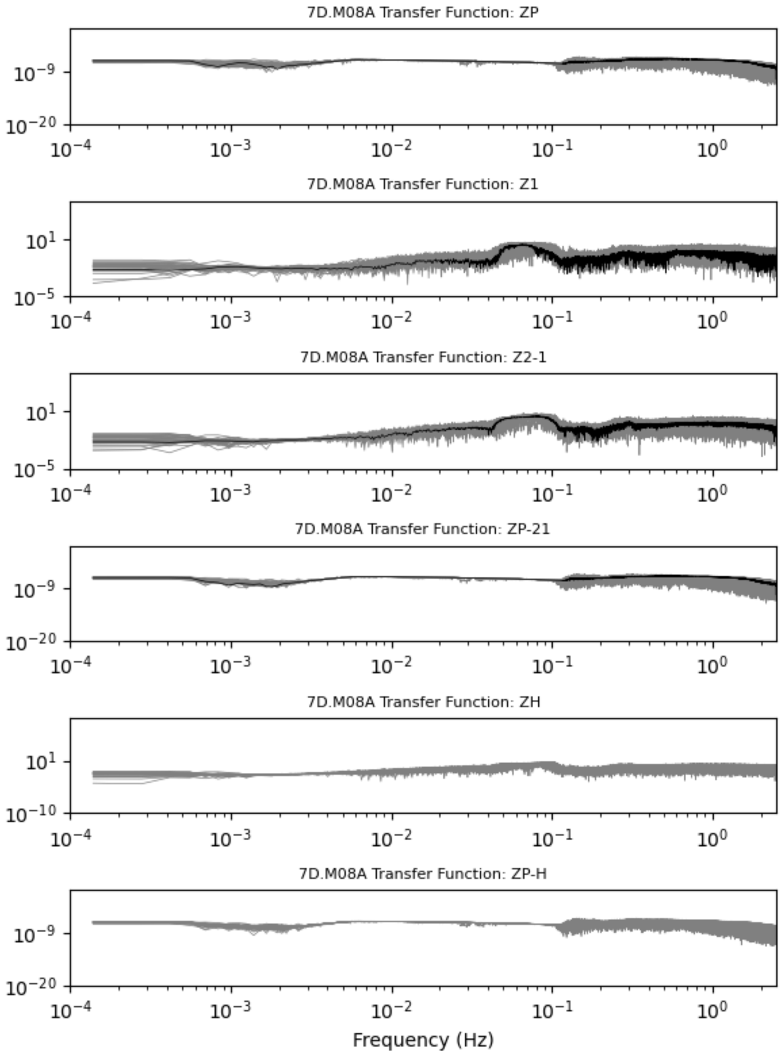
Based on Janiszewski et al. (2019)

1. Downloads day-long data for given period of time.
2. For each day:
   a. Divide into 3-hour long (overlapping) windows and calculate power spectra of all components.
   b. Perform quality control to exclude windows with anomalous spectra.
   c. Average « good » windows into spectra representative of noise on each day -> **Daynoise** objects
3. Given a specific time period:
   a. Perform quality control to exclude Daynoise objects with anomalous spectra.
   b. Average « good » days into spectra representative of noise in that time period -> **Stanoise** objects



OBStools implementation

4. For each Daynoise and Stanoise object:
    a. Calculate cross-spectra (admittance and coherence) between all component pairs (Z1, Z2, 12, ZP, 1P, 2P).
    b. Calculate transfer functions between relevant components (Z1, Z2-1, ZP, ZP-21)
5. Download earthquake data
6. Use the transfer functions for that day – or for the station average – to predict the Z noise from compliance and tilt; take the difference

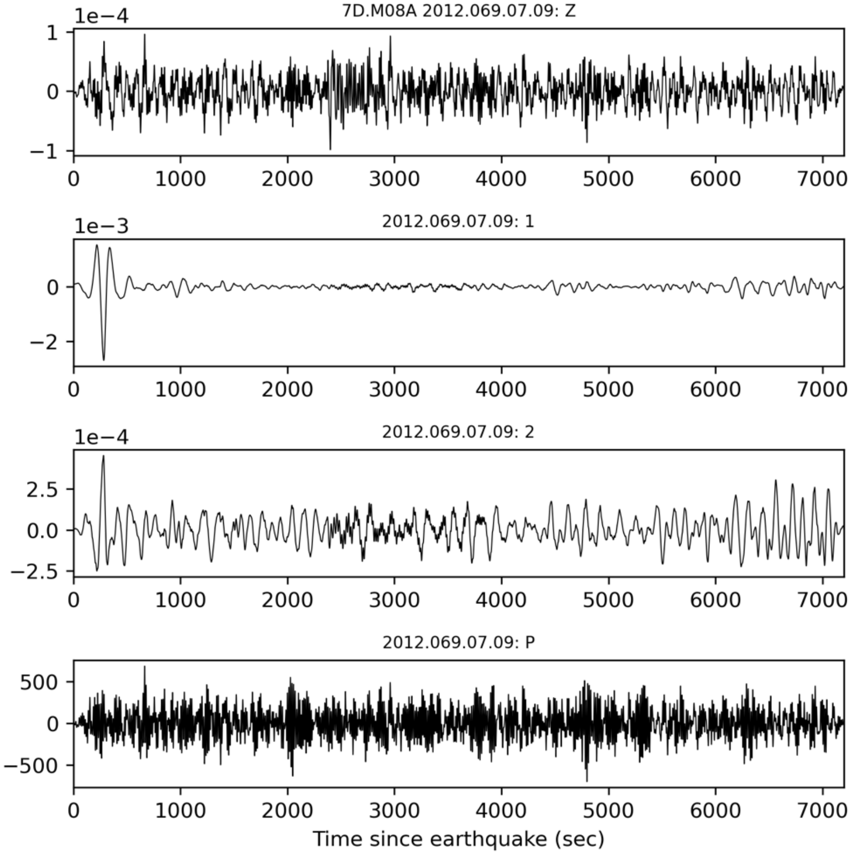


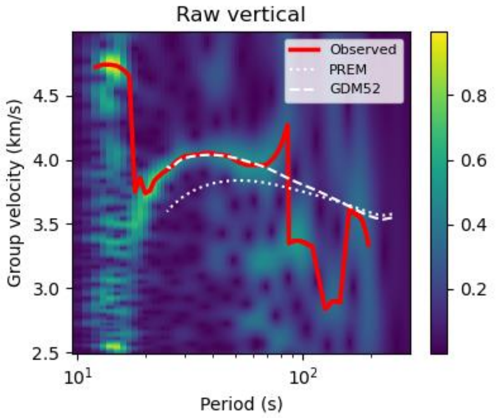
Example compliance correction

Station M08A, Cascadia Initiative: https://ds.iris.edu/gmap/#network=7D&station=M08A&planet=earth

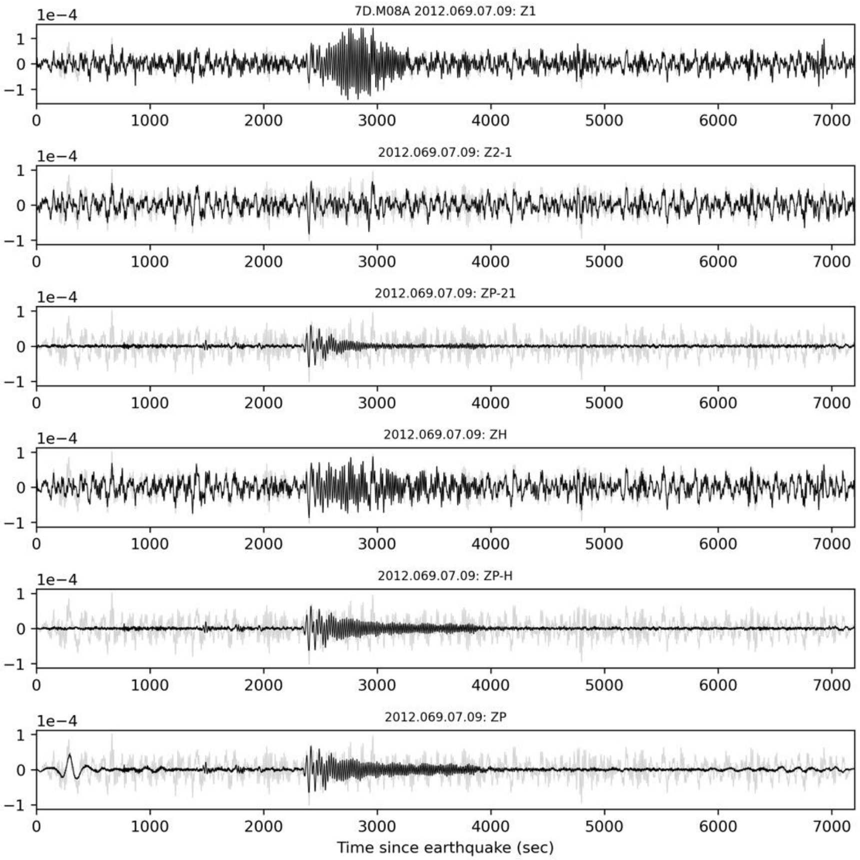
Seafloor depth: 126.4 m

Earthquake: [link]()

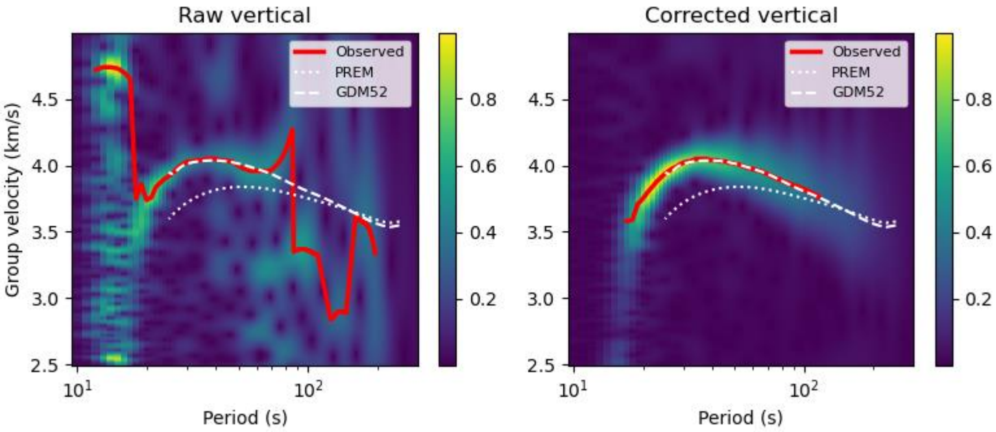




Example tilt + compliance correction



Dispersion: raw and corrected



References

- Samuel W. Bell, Donald W. Forsyth, Youyi Ruan; Removing Noise from the Vertical Component Records of Ocean-Bottom Seismometers: Results from Year One of the Cascadia Initiative. Bulletin of the Seismological Society of America 2014;; 105 (1): 300–313. doi: https://doi.org/10.1785/0120140054
- Crawford, W. C., Webb, S. C., & Hildebrand, J. A. (1991). Seafloor compliance observed by long-period pressure and displacement measurements. Journal of Geophysical Research: Solid Earth, 96(B10), 16151-16160. https://doi.org/10.1029/91JB01577
- Janiszewski, H. A., Gaherty, J. B., Abers, G. A., Gao, H., & Eilon, Z. C. (2019). Amphibious surface-wave phase-velocity measurements of the Cascadia subduction zone. Geophysical Journal International, 217(3), 1929-1948. https://doi.org/10.1093/gji/ggz051
- Mosher, S. G., Eilon, Z., Janiszewski, H., & Audet, P. (2021). Probabilistic inversion of seafloor compliance for oceanic crustal shear velocity structure using mixture density neural networks. Geophysical Journal International, 227(3), 1879-1892. https://doi.org/10.1093/gji/ggab315
- Krishna Venkateswara, Charles A. Hagedorn, Jens H. Gundlach, Jeffery Kissel, Jim Warner, Hugh Radkins, Thomas Shaffer, Brian Lantz, Richard Mittleman, Fabrice Matichard, Robert Schofield; Subtracting Tilt from a Horizontal Seismometer Using a Ground-Rotation Sensor. Bulletin of the Seismological Society of America 2017;; 107 (2): 709–717. doi: https://doi.org/10.1785/0120160310