Seafloor Noise and its Removal

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The seafloor noise spectrum

What is noise?

"Fluctuations or disturbances which are not part of a wanted signal or which interfere with its intelligibility of usefulness" (OED)

- Depends on your point of view
- "Seismological noise" is everything non-EQ

Noise < 1 Hz:

- Can be "cleaned" from seismological signals to improve teleseismic earthquake seismology and "ambient noise" seismology (*but be careful!*)
- Can be used to study the earth, ocean waves, atmosphere-ocean interactions, glacier calving, landslides, whale migration, boat traffic…

Bendat and Piersol (1986), *Random Data: Analysis and Measurement Procedures*

Calculating power spectral densities

Discrete Fourier Transform (DFT or FFT): $$Y_N(\omega) = \sum_{t=1}^{N} y_t e^{-j\omega t}$$

- Made on a finite segment of data
  - An approximation of the frequency content of the signal
  - Affected by random noise

Power Spectral Density (PSD): $$P(\omega) = \lim_{N \to \infty} E\left\{ \frac{1}{N} \left| Y_N(\omega) \right|^2 \right\}$$

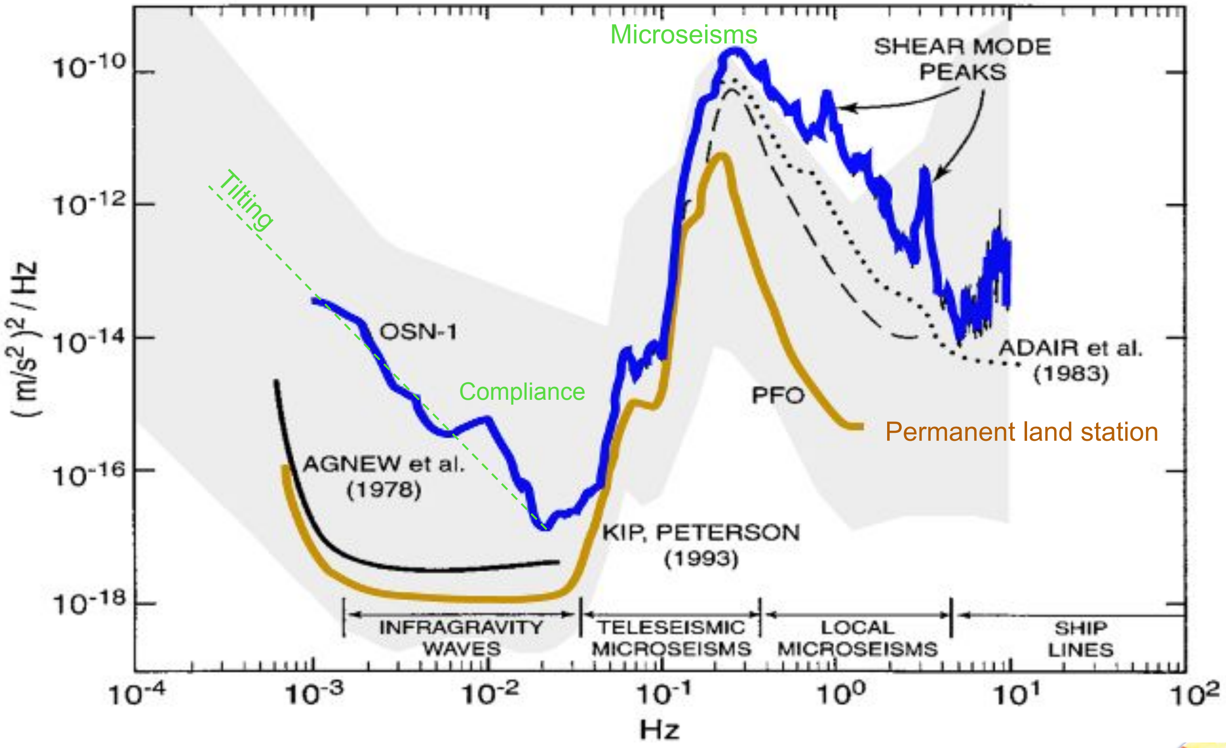
- Better estimate of frequency content of the signal
  - But lower frequency resolution, higher low-frequency limit
- Values are proportional to energy (conserved property)

Seafloor seismological noise spectrum

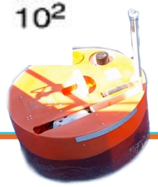
Higher microseism levels

LF noise due to Compliance and Tilting

HF noise due to wind waves, biological sources, ships



Based on [Webb [1998]]

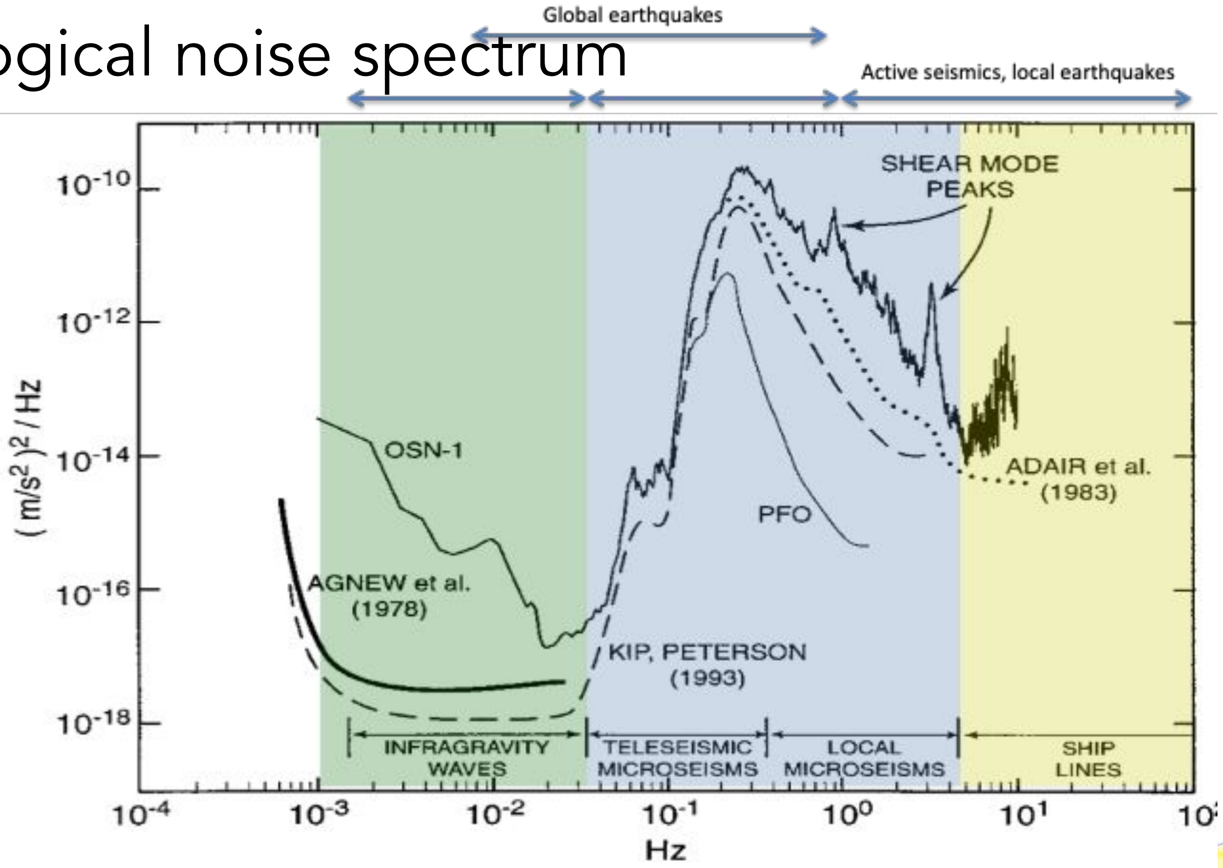


Seafloor seismological noise spectrum

Low frequencies:
Global earthquakes and complianc

Middle frequencies:
Microseisms (ambient noise)

High frequencies:
Local earthquakes, active seismics



Based on [Webb [1998]](#)

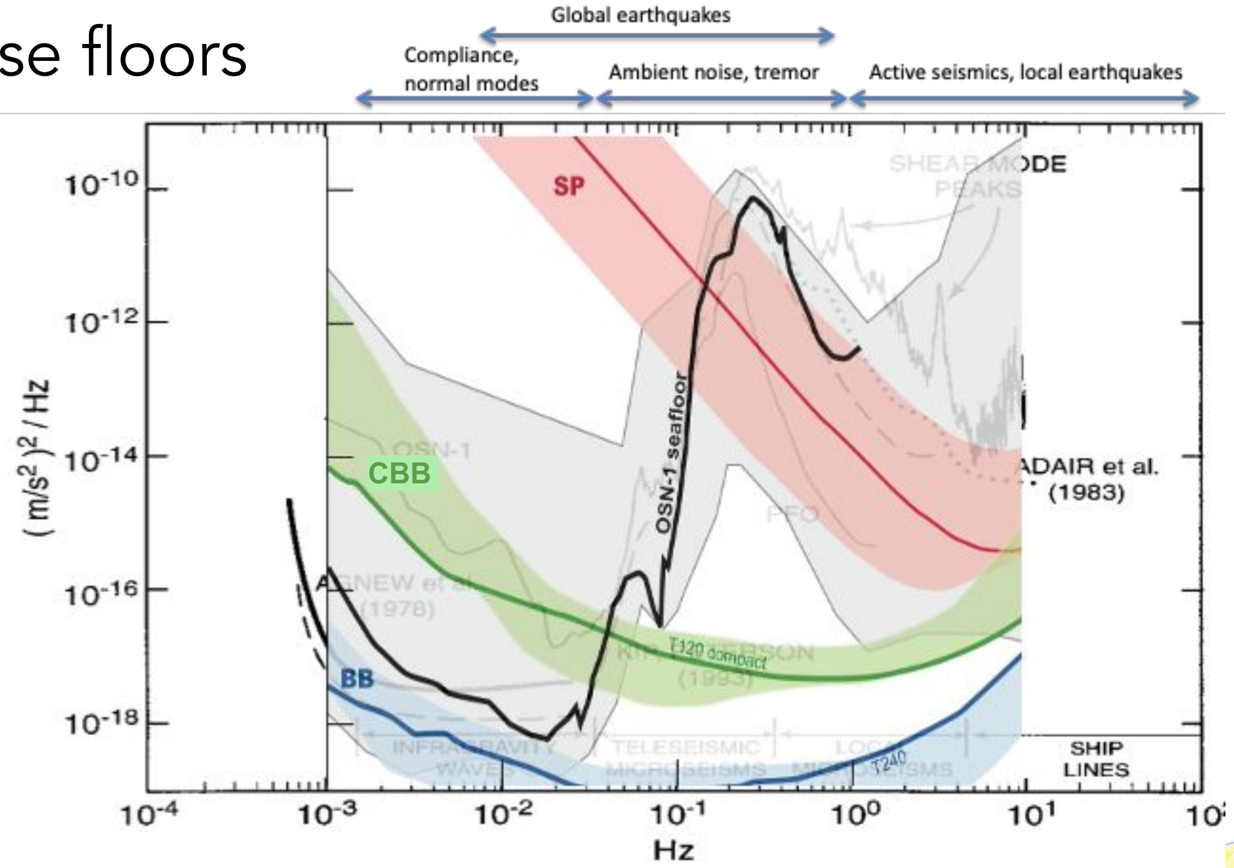
Seismometer noise floors

The signal you can obtain depends on the sensitivity of the seismometer

SP: short period

CBB: compact broadband

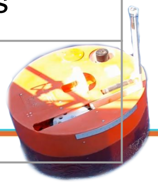
BB: broadband



Based on [Webb [1998]]

Principal noise sources

Frequencies	Periods	Sources
<1mHz	>1000s	**Tides (and temperature?)** - Temperatures are generally much more stable at the seafloor than at land stations
1-40 mHz	25-1000s	**Seafloor currents, infragravity waves** - Tilt the OBS through the gravitational field - Much stronger effect on horizontal channels than on vertical
3-20 mHz	~50-300s	**Infragravity waves** - Sea surface gravity waves at very low frequencies - Displace the seafloor - Can be used to estimate crust/sediment shear moduli (compliance)
30mHz - 3Hz	3-30s	**Microseisms** - Teleseismic Rayleigh waves (~30-300 mHz), useable for ambient noise seismology - Local signal (300mHz-3Hz) is nonlinear ocean surface gravity wave interactions
> 1 Hz	<1s	**“Soundscape”** - Animals, ships, currents, shear modes…

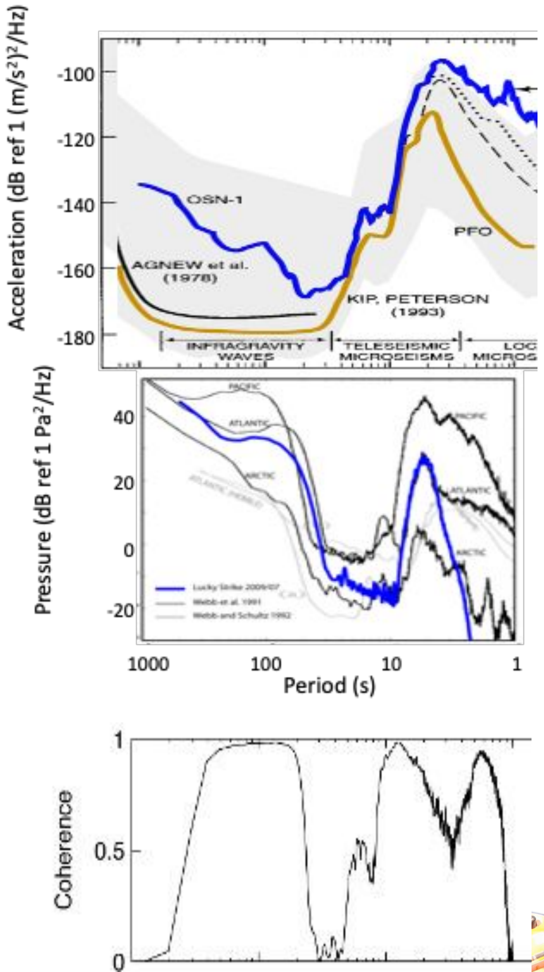


Seafloor spectra

Motion and Pressure

- Have different shapes, but share some sources

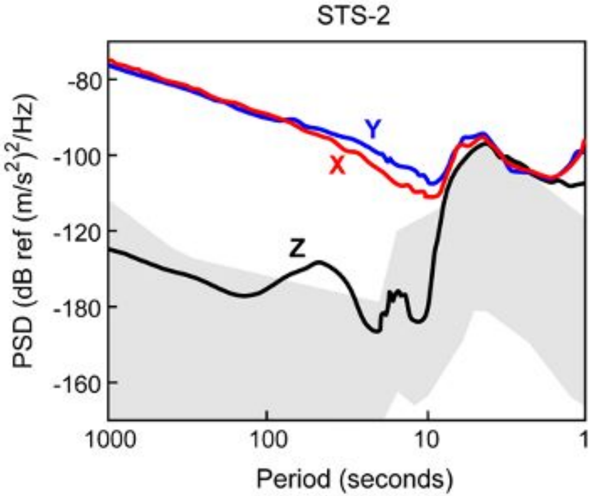
- Are coherent in the infragravity and microseism bands

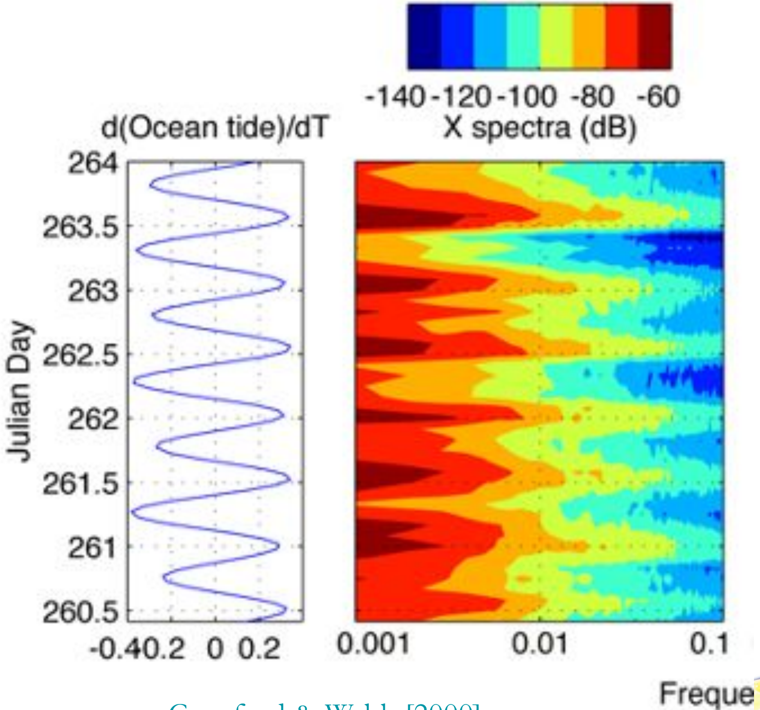


Low-frequency tilt noise (seafloor currents)

Observations

- Strongest on horizontal channel
- Has approximately $f^{-1.5}$ slope
- Amplitude varies with tides
- Coherent between horizontal and vertical channels





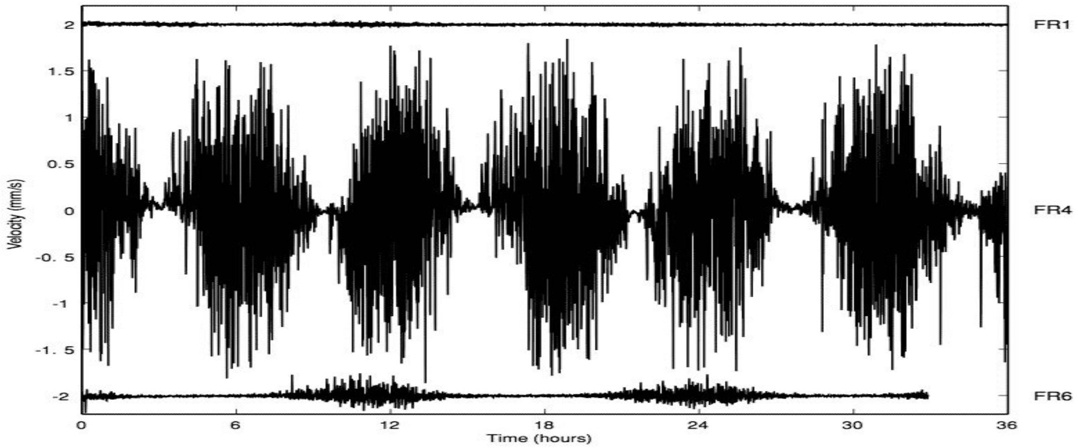
[Crawford & Webb [2000]]

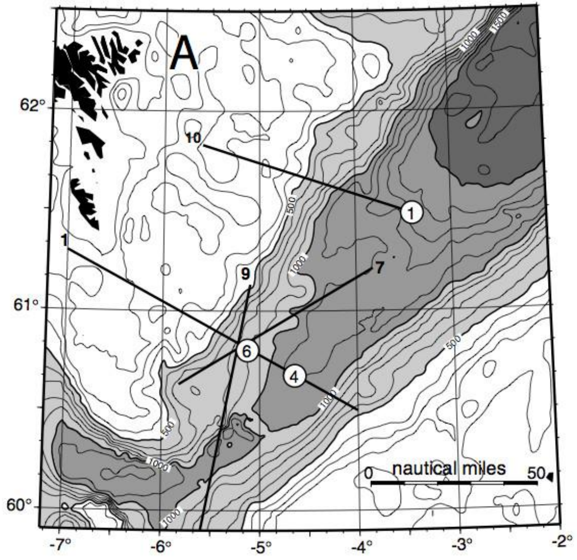
Low-frequency tilt noise (seafloor currents)

Faroes Islands example

Noise level different at each location

- Strongest and semidiurnal in the channel, near the bottleneck
- Weaker and diurnal 10 km to the west
- Weakest and diurnal further from the bottleneck





[Crawford & Singh [2008]]()

Low-frequency tilt noise (seafloor currents)

Why do we believe it is caused by currents?

- Seafloor currents have a $f^{-1.5}$ slope (Webb, 1988)
- Because the noise and currents vary tidally
- The noise is reduced by burying sensors or placing a “shield” over them (Shiobara et al., 2013)
- The principal noise direction is constant over time (An et al., 2021)

Low-frequency tilt noise (seafloor currents)

How does tilt generate noise?

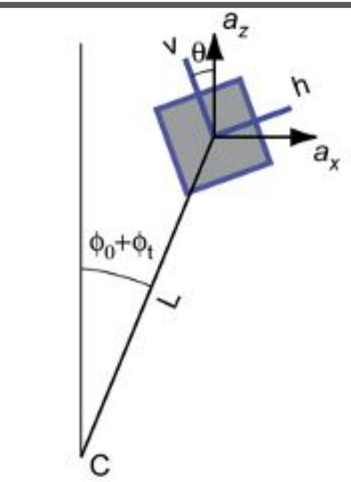
- "Dynamic" mechanism: mass is "thrown" around center of rotation

$$a_d = \frac{\partial^2 \mathbf{x}_t}{\partial t^2} = L\omega^2 \varphi_t \left[-\cos(\varphi_0)\hat{\mathbf{x}} + \sin(\varphi_0)\hat{\mathbf{z}} + h.o.t. \right]$$

  - Increases with increasing frequency
  - Depends on the distance and the angle of the mass from the c.o.r.
- "Gravity" mechanism: mass rotates through the gravitational field

$$a_g = g\varphi_t \left[\cos(\theta)\hat{\mathbf{x}} - \sin(\theta)\hat{\mathbf{z}} + h.o.t. \right]$$

  - Constant w.r.t frequency
  - Most noise is on the horizontal
  - g is 10 billion times stronger than the instrument noise floor



□	Seismometer mass
θ	(static) misalignment of the Z channel from vertical
φ_0	Angle of the mass from the c.o.r.
L	Distance of the mass from the c.o.r.
φ_t	Dynamic (current-induced) tilt

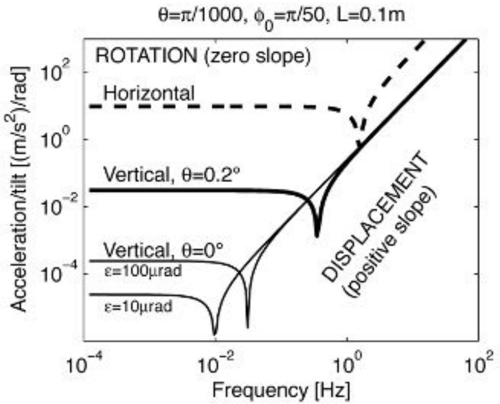
Crawford & Webb [2000]

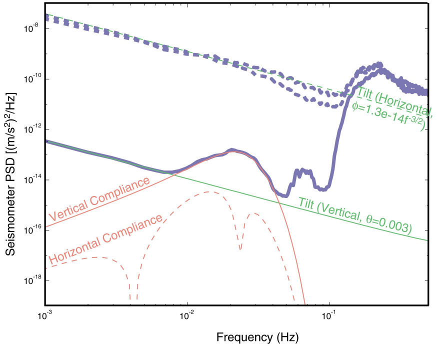
Low-frequency tilt noise (seafloor currents)

Displacement term dominates at higher frequencies (Lw >> g)

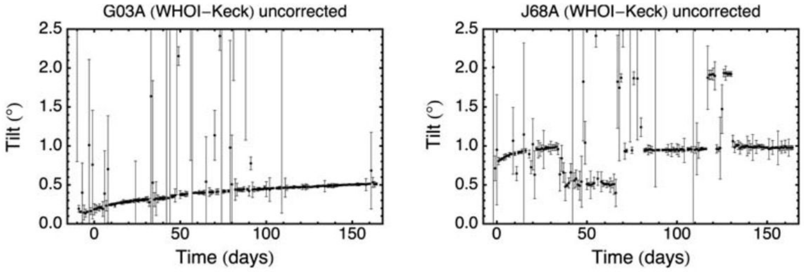
Gravity (rotation) term affects the vertical channel depending on how well it was leveled

- Typical mislevel is up to 2 degrees





Crawford & Webb [2000]



Bell et al. [2015]

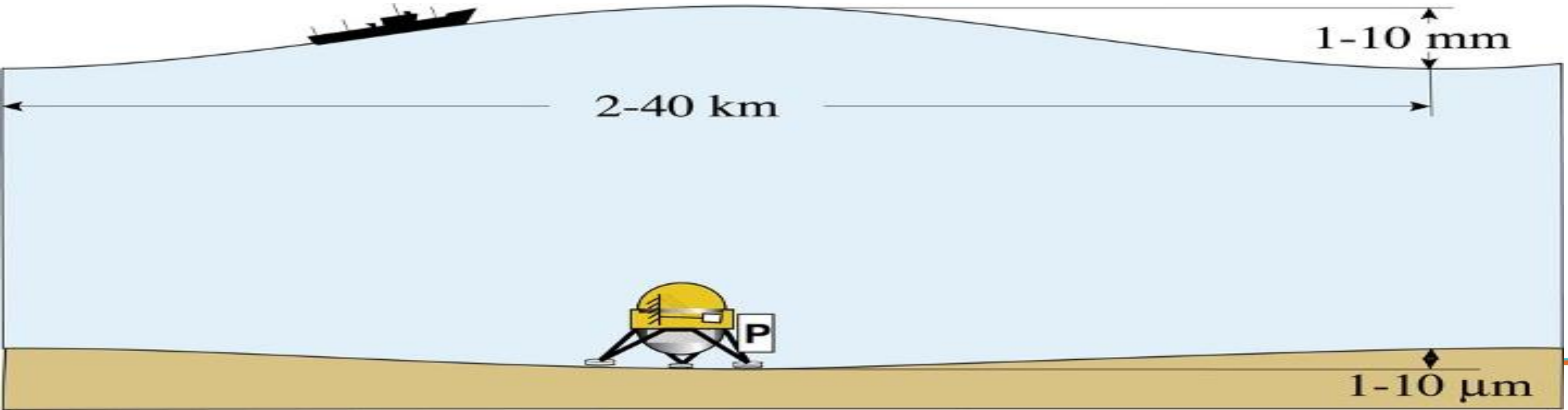
Infragravity wave noise

The seafloor moves under low-frequency linear ocean surface gravity waves

The motion depends on the pressure and on the crustal shear modulus structure

Seismological signal is small

- Has only been detected on the vertical channel
- At/near the self-noise of compact broadband seismometers



Infragravity waves

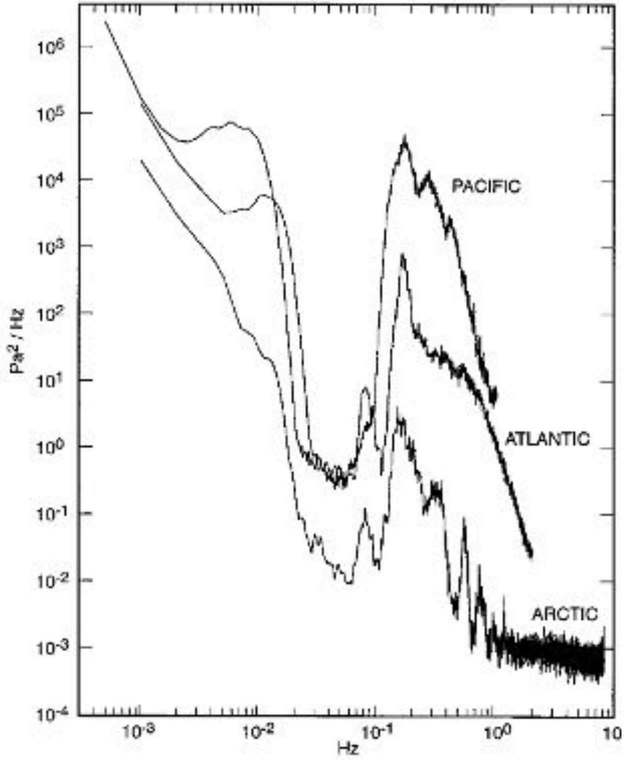
Have the same velocity as tsunamis

Much longer and smaller amplitude than wind waves

Amplitude depends on storms in the ocean basin

The highest frequencies detected at the seafloor depe
on the ocean depth

- Exponential decay with depth
- Only waves longer than the ocean depth are detected



Webb & Schultz [1992]

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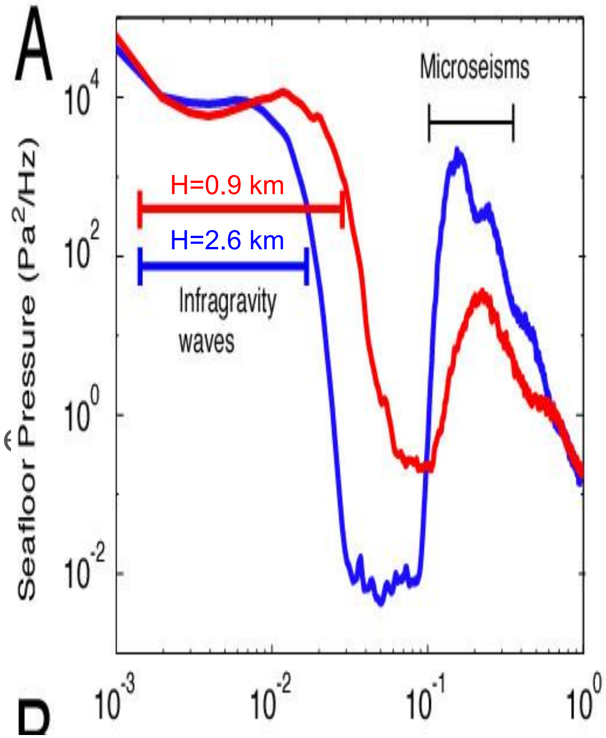


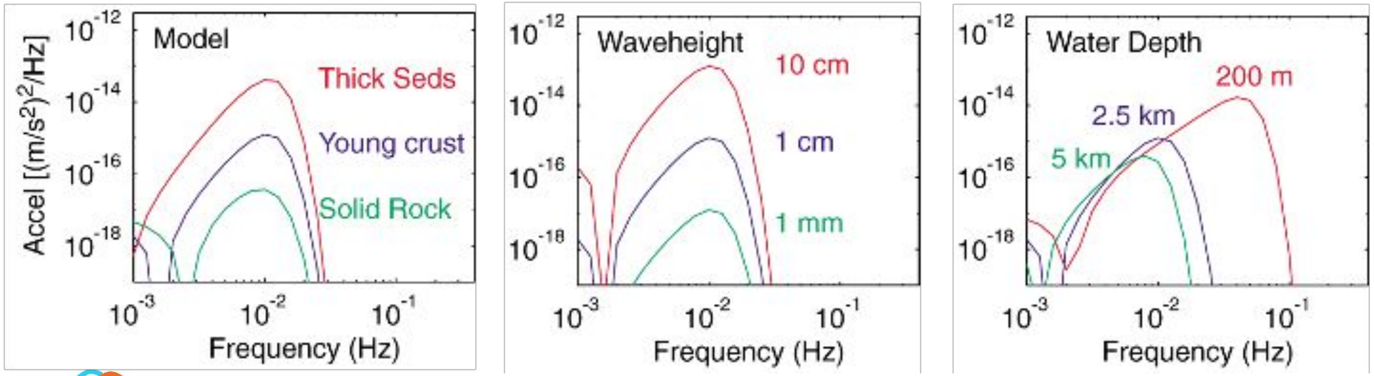
Crawford [2004]

Infragravity waves

Seafloor motion is the dynamic pressure multiplied by seafloor “compliance”

Compliance depends on the subsurface structure (mostly the shear modulus)

- “Hard” materials (higher shear modulus) move less than “soft” materials
- Low frequencies (longer waves) are sensitive to deeper structure



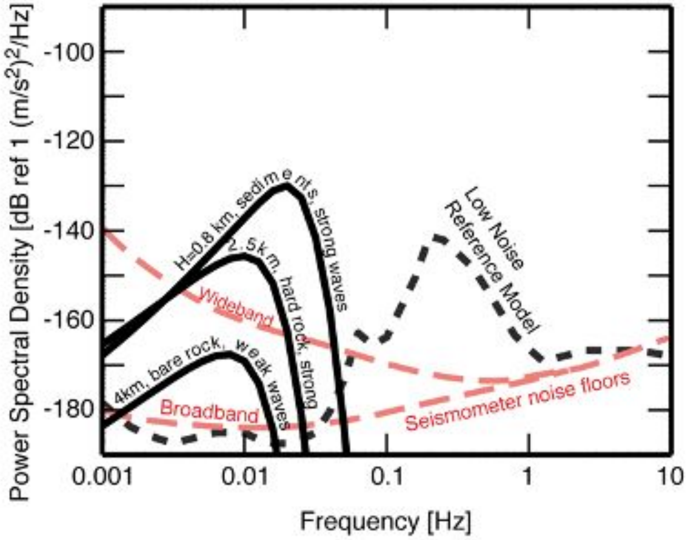
Reference model (purple):

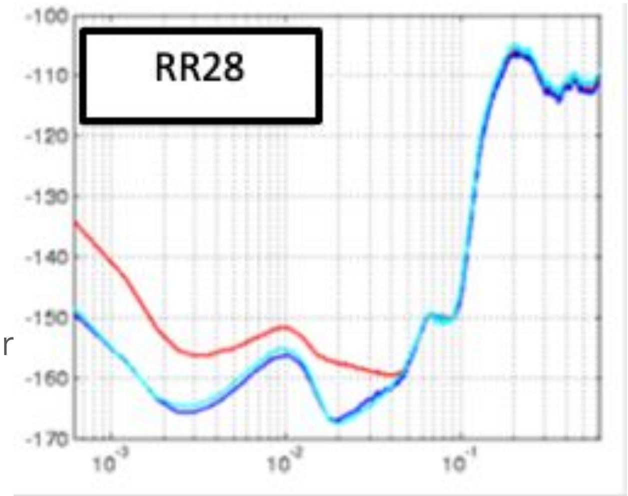
- Young crust
- 1 cm wave height
- 2.5 km water depth

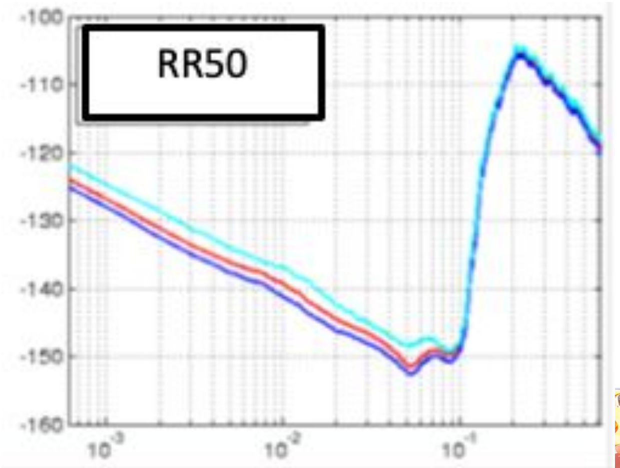
Infragravity waves

Create a peak centered at ~0.01 Hz on seafloor PSDs

- At/near the self-noise level of compact broadband seismometer
- Can be masked by the tilt effect







Microseisms

Generated by nonlinear wave-wave (double frequency) or wave-bathymetry (single frequency) interactions

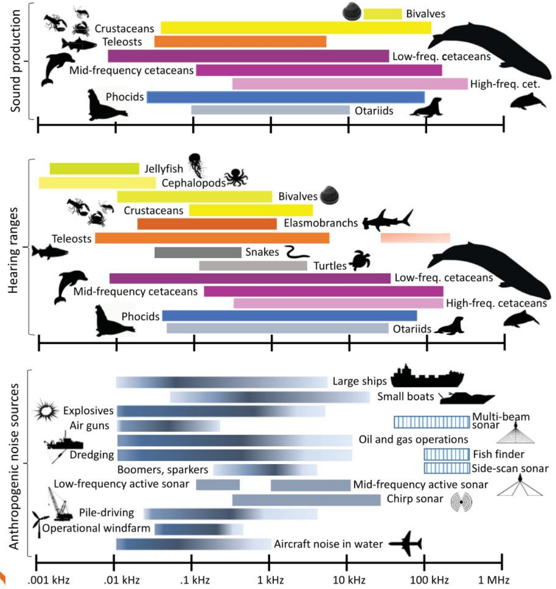
A small percentage of the energy matches seismic interface wave velocities and propagates away from the source

“Local” microseisms are caused by seismic interface (Scholte) waves propagating from strong local microseism sources

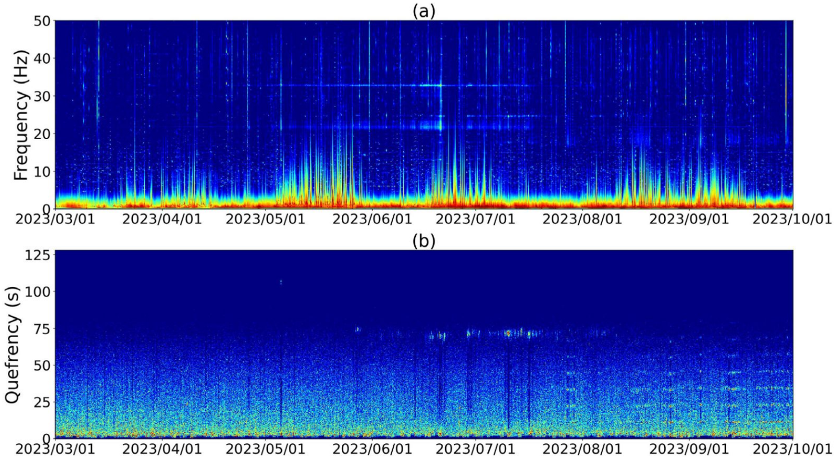
Rayleigh waves	Decay with increasing depth
Stoneley waves	Decay up and down from a non-surface interface
Scholte waves	Stoneley waves for which the maximum is at the liquid/solid interface

Noise above 1 Hz

“Soundscape” noise: Caused by currents (displacement term), ships and other human sources (airguns, sonar, windmills…), biological sources



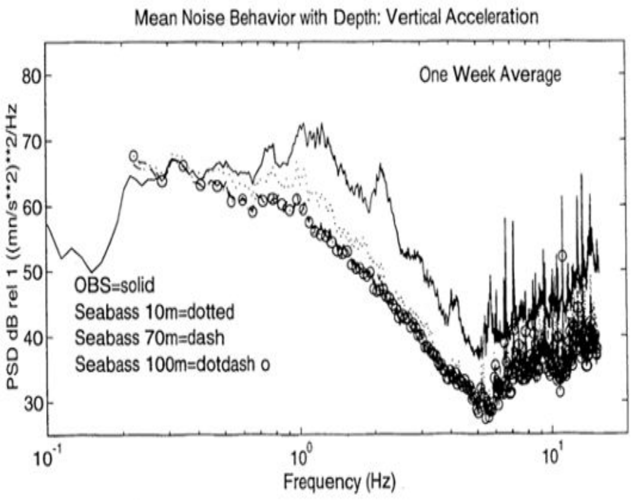
[Duarte et al. [2021]]



[Dreo et al. [2025]]

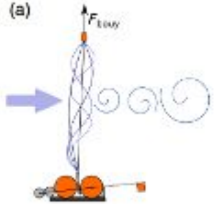
Noise above 1 Hz

Shear modes

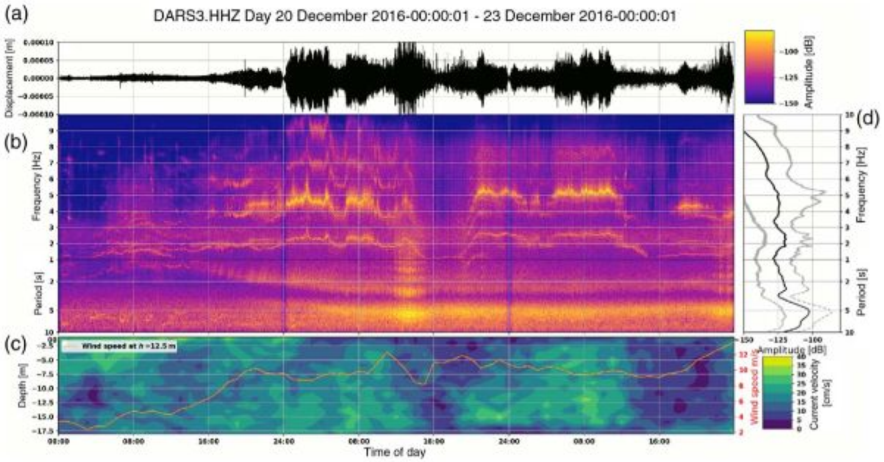


Bradley et al. [1997]

Instrument resonances (e.g. floats and flags)



Stahler et al. [2018]



The pressure channel

Is another seismological channel

- "Backup" for vertical
- Sometimes better P-wave arrivals
- Can go to lower frequencies for less energy consumption

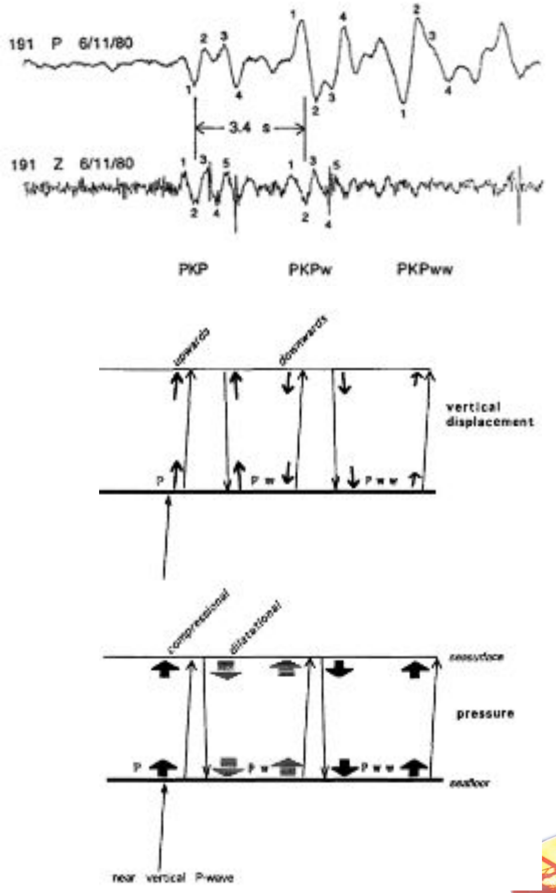
Can remove "pegleg" multiples

Necessary to exploit seafloor compliance

Three main sensor types:

- H: Hydrophones (1-30s to kHz)
- G: Differential pressure gauges (1000s to 100s of Hz)
- O: Absolute pressure gauges (DC to ~10Hz)

Pegleg multiples | Blackman et al. [1995]



Summary

<0.001 Hz: We don’t know how to remove

0.001-0.02Hz Current (Tilt) noise

- Cannot exploit for geological information

0.003-0.02 Hz: Infragravity waves

- Can use to study crustal structure

0.03 - 1 Hz: Microseisms

- Can use teleseismic part to study crust/mantle structure (strong “ambient noise” signal

>1Hz: Soundscape

- Useful for environmental/biodiversity/human activity monitoring
- We are just beginning to understand what we can use for earth structure

Avoiding seafloor noise

Isolating the seismometer

Separate the seismometer from the instrument body

- Reduces the profile affected by seafloor currents, avoids parasitic noise
- Makes for more complicated deployments

Cambridge miniDOBS

Scripps/IPGP BBOBS

Shielding the seismometer

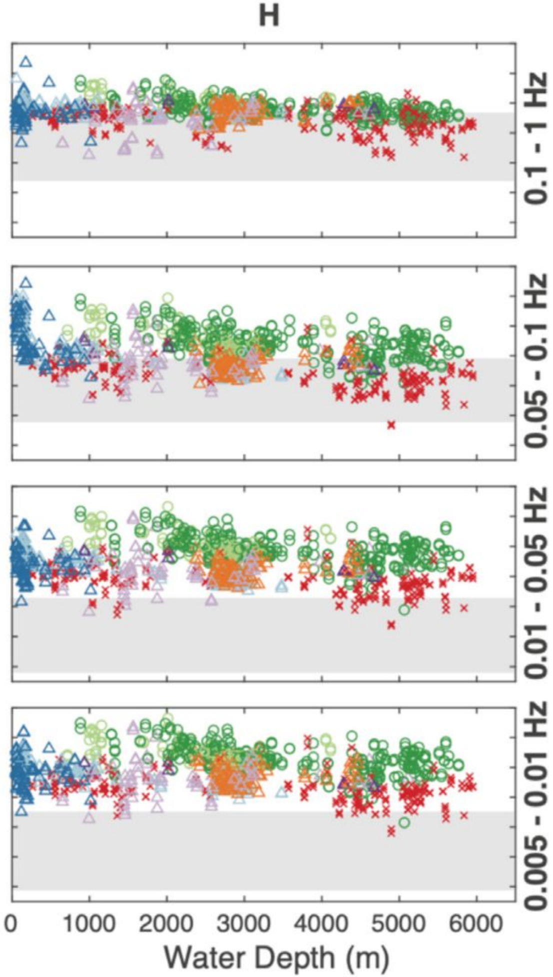
Seems that it should reduce tilt noise, but no proof that it does

"Abalone" (AB)

"Trawl Resistant" (TRM)

Seismometer: × Trillium 240 △ Trillium Compact ○ Guralp CMG-3T

Instrument Design: △ AB △ AR × B2 △ BA △ BD ○ BG ○ KE △ TRM

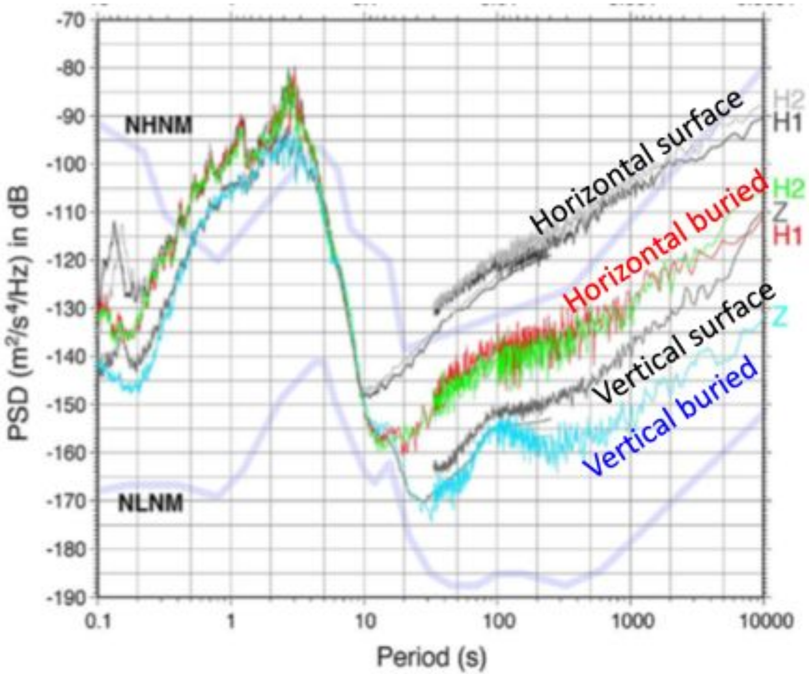


[Janiszewski et al. [2023]](#)

Burying the seismometer

Significantly reduces noise on horizontal components

Very expensive and time-consuming



Shiobara et al. [2013]

Removing seafloor noise

Removing seafloor noise

Transfer function method (most commonly used)

- Method
    - Identify another channel that is dominated by this noise (SOURCE)
    - Calculate the frequency response transfer function between the SOURCE and the channel of interest (RESPONSE)
    - Remove SOURCE times the transfer function from the RESPONSE channel
- Limitations
    - Can only be applied of the noise transfer function (RESPONSE/SOURCE) is much smaller than any signal transfer function (e.g. Rayleigh wave Z/H)
    - We have only successfully removed noise from the vertical channel

Process-specific methods

- Simple rotation: To reduce tilt noise, rotate the vertical channel to minimize signal variance
    - Must limit variance measurement to the tilt band, not the microseisms

Removing seafloor noise using transfer functions

In theory (using the Z channel as the RESPONSE channel):

- Assume the Z channel is the sum of a "Z" signal, S_Z, and some function(s) times the signal from other channels (D_X is the signal recorded on the X channel)

$$D_H = S_H$$
$$D_P = S_P$$
$$D_Z = S_Z + \alpha S_H + \beta S_P$$

- Quantify what portion of Z's signal matches that on the SOURCE channel

$$\gamma_{ZH} = \frac{\alpha \bar{S}_H}{\bar{D}_Z}$$

- Combine the previous equations to remove the "other" signals from the Z channel

$$\begin{aligned} S_Z &= D_Z - \alpha S_H - \beta S_P \\ &= D_Z - \gamma_{ZH} \underbrace{\left[\frac{\bar{D}_Z}{\bar{D}_H}\right]}_{T_{ZH}} D_H - \gamma_{ZP} \underbrace{\left[\frac{\bar{D}_Z}{\bar{D}_P}\right]}_{T_{ZP}} D_P \end{aligned}$$

Transfer functions: T_{ZH} T_{ZP}

Removing seafloor noise using transfer functions

In practice:

- Use the coherence to measure the portion of the signal matching the SOURCE channel
- Use PSDs to calculate the signal ratios

$$T_{AS}(f) = \gamma_{AS}(f)\sqrt{\frac{G_{AA}(f)}{G_{SS}(f)}}, \qquad (1)$$

- The SOURCE channels can be partly coherent with each other, so use multivariate coherences or an iterative approach that cleans the response and subsequent SOURCEs at each step.
    - Start with the channel with the highest coherence with the Z channel (“P” in the example below)

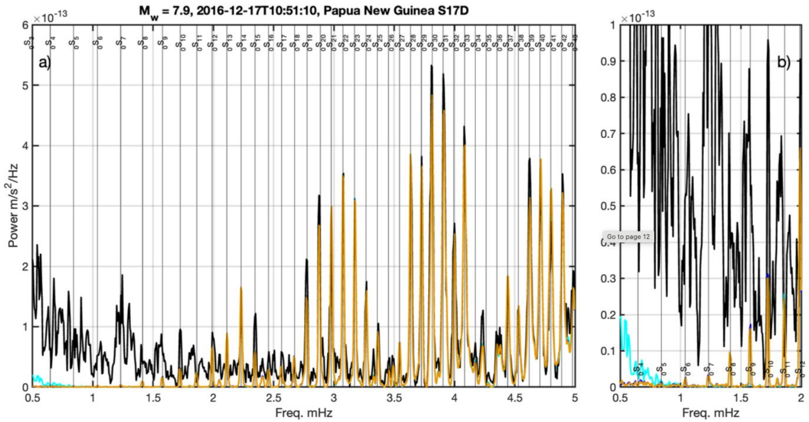
$$D'_Z = D_Z - T_{PZ} D_P$$
$$D'_X = D_X - T_{PX} D_P$$
$$S_Z = D''_Z = D'_Z - T_{XZ} D'_X$$

Removing seafloor noise using simple rotation

Rotate the 3 axes so that the Z channel has the lowest variance

- Gives similar tilt estimations as the transfer function method
- Does not distort signals or remove Rayleigh waves
- Should be applied before the transfer function method

There is room for improvement in calculating the best angle correction



Harmon et al. [2022]

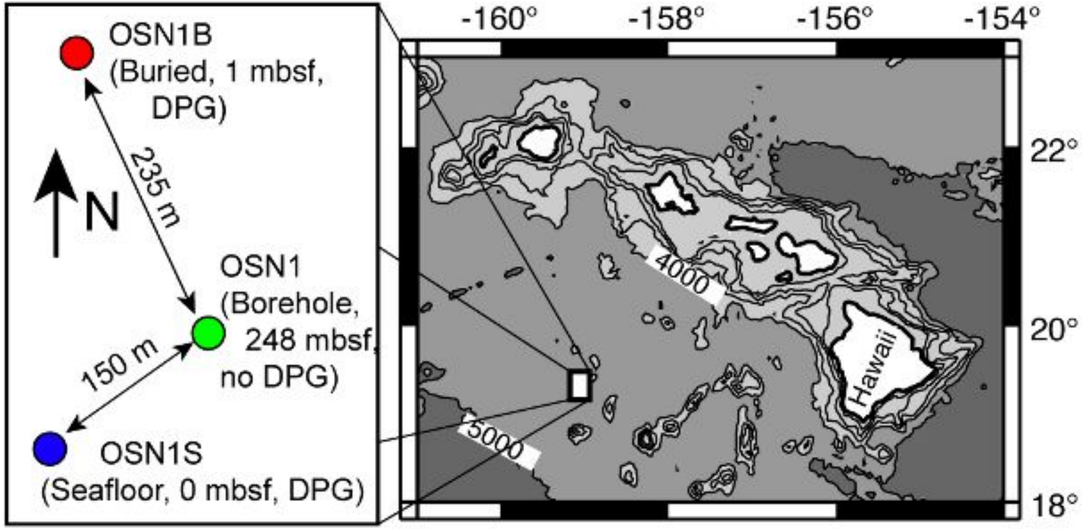
Removing seafloor noise

Lessons learned:

- Do not apply transfer functions in the microseism band unless you don’t want to study Rayleigh waves/ ambient noise (or at least confirm that the transfer function you calculate there doesn’t correspond to Rayleigh/Scholte waves).
- Rotate the Z channel to the vertical before applying the transfer function method

Transfer function example: the OSN1 experiment

The OSN1 experiment had colocated seafloor, buried (1 m) and borehole (248 m) seismometers, offering an ideal natural laboratory to evaluate the effectiveness of transfer-function based noise removal.

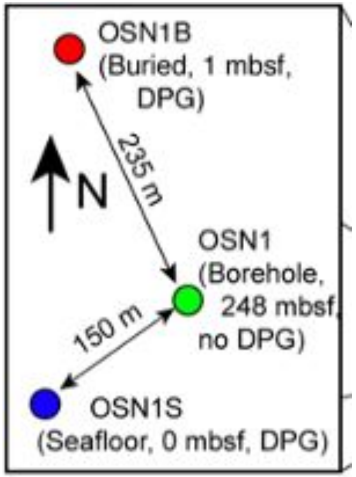


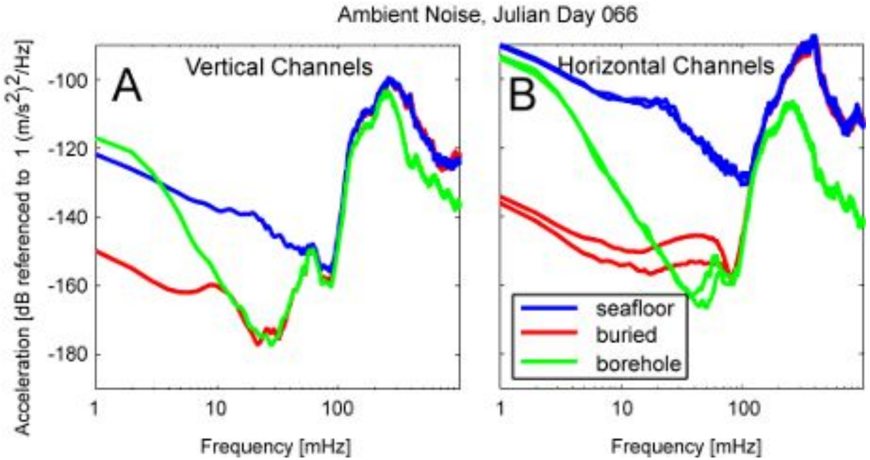
[Crawford et al. [2006]](#)

Transfer function example: the OSN1 experiment

Original data

- Noise was highest at the seafloor station
- Noise was surprisingly high at low frequencies in the borehole (cork leakage?)

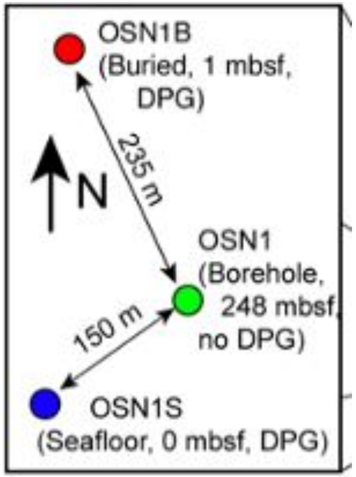


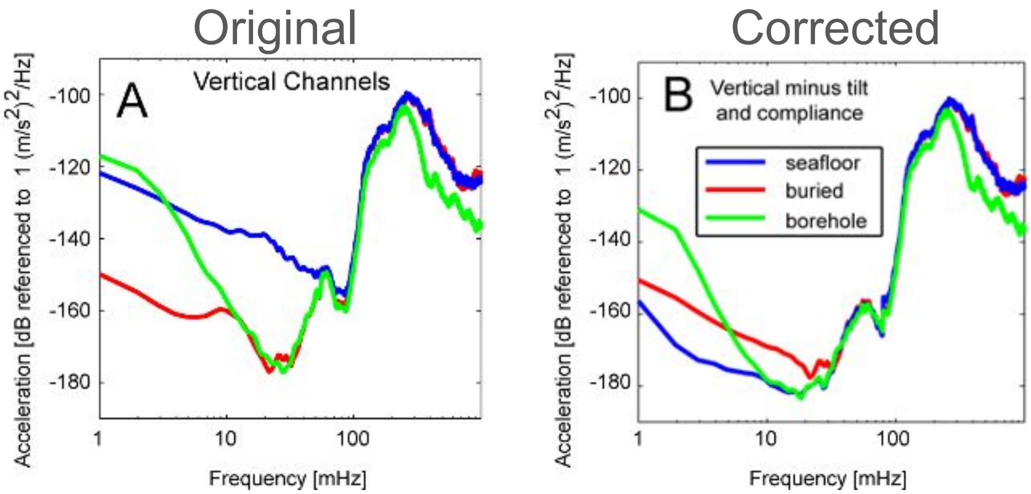


[Crawford et al. [2006]]

Transfer function example: the OSN1 experiment

We applied transfer-function based tilt (SOURCE=horizontals) and compliance (SOURCE=pressure) noise removal to the Z channels at all three stations

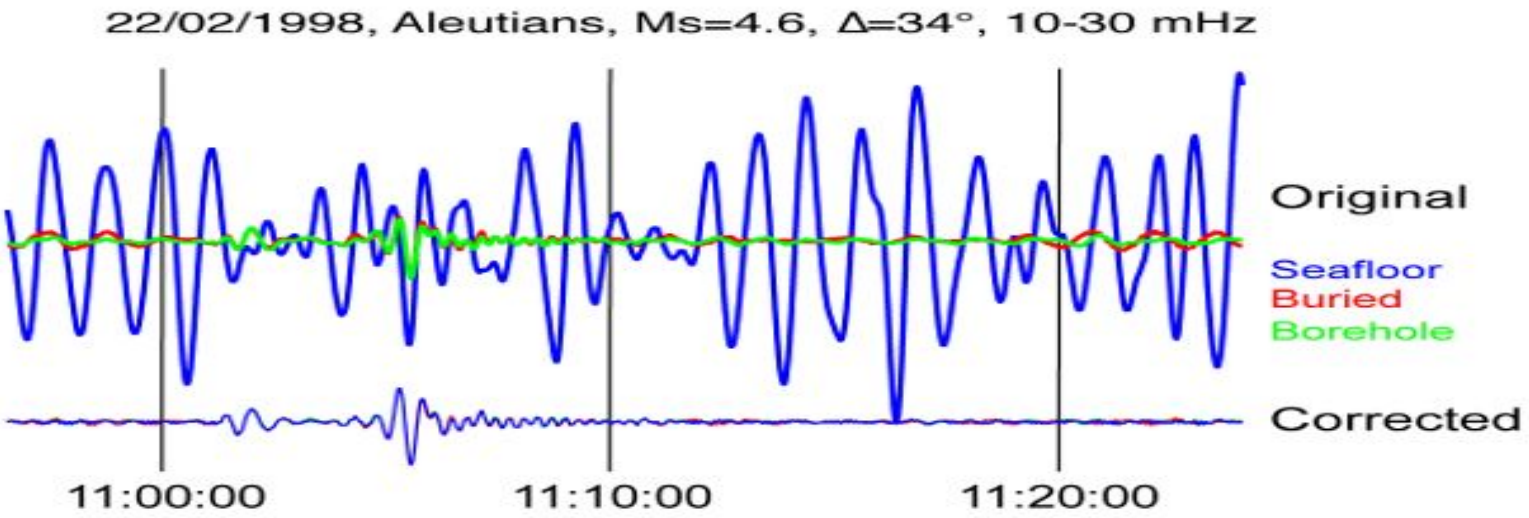




Crawford et al. [2006]

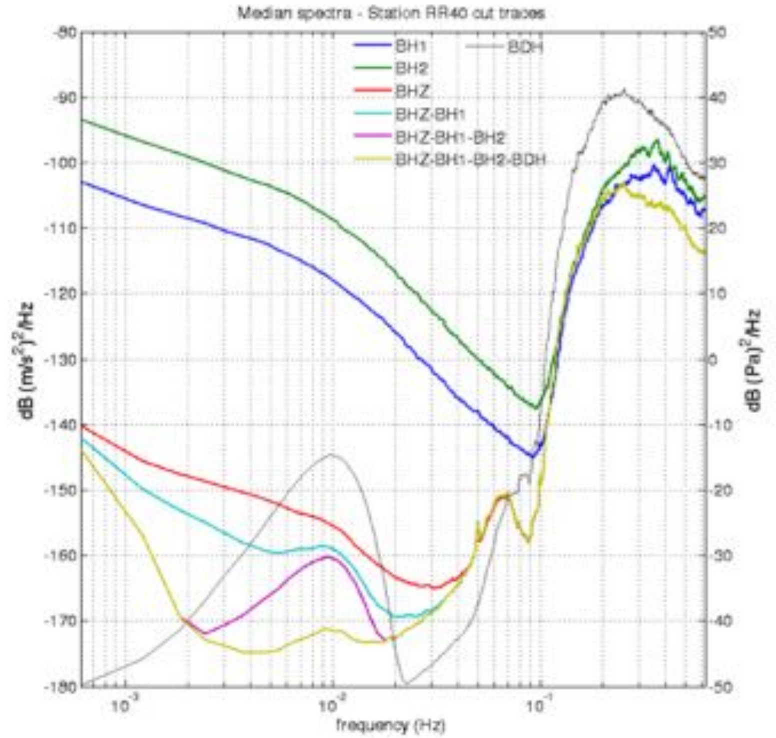
Transfer function example: the OSN1 experiment

The same data viewed as time series waveforms



Crawford et al. [2006]

Transfer function example: RHUM-RUM



Deen et al. [2017]

Summary and Caveats

Simple rotation and transfer function corrections can be applied at all broadband seafloor sites showing current or infragravity wave noise

Could open up seafloor ambient noise seismology at low frequencies

Caveats

- The technique does not work if you cannot get a good coherence between your SOURCE and RESPONSE channels
  - Really quiet data (yay!)
  - Instruments with insufficient sensitivity
  - Other signal sources (earthquakes, storms) in the data
- It is often better to use a good measurement from another day than a low-coherence measurement from the same day
- The tilt transfer function can change over time (instrument settling, releveling)