# Seismology on Mars

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J. Tromp, M. Dugué, D. Sollberger, D. Giardini
and
the InSight team

# InSight: Interior Exploration using Seismic Investigations, Geodesy and Heat Transport

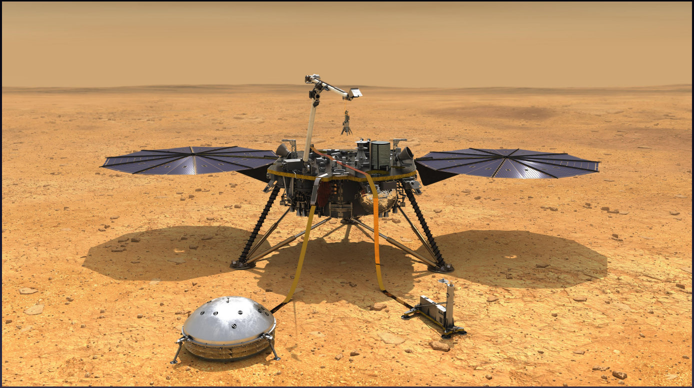

Figure: InSight on Mars. Landed: Nov. 26, 2018.

InSight is the first dedicated geophysical mission since Apollo and Viking.

# Summary of observed marsquake types

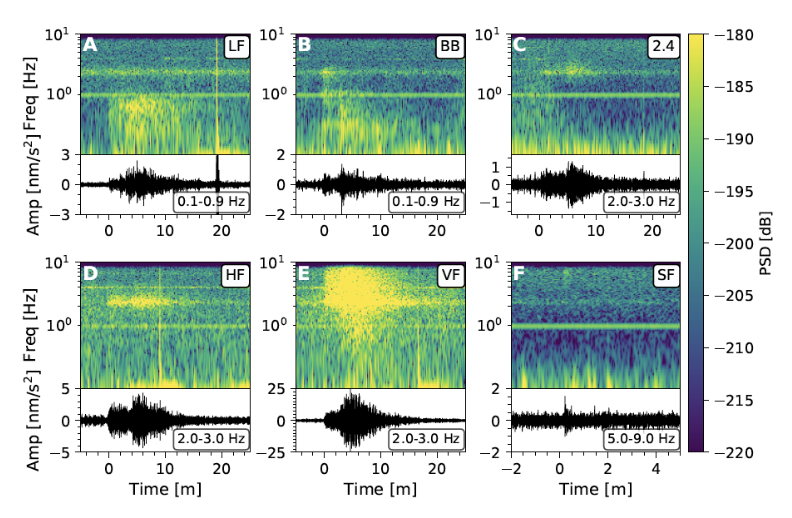


Figure: Verical-component spectrograms and filtered waveforms for the main seismic event types detected on Mars.

# Marsquakes and body waves

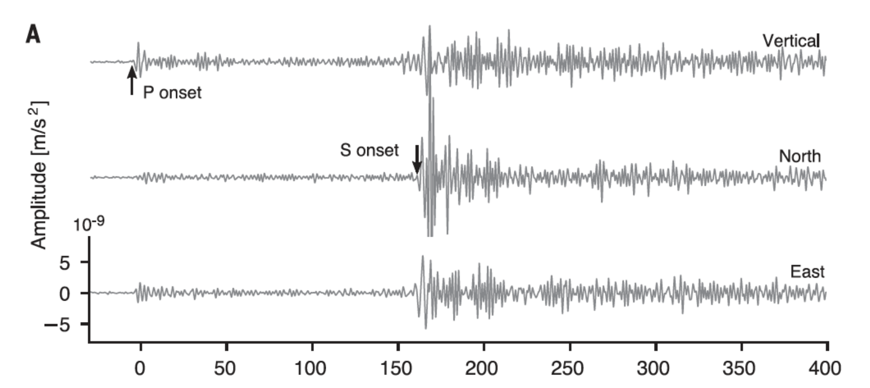


Figure: Filtered three-component waveforms of event S0235b.

# Locating marsquakes

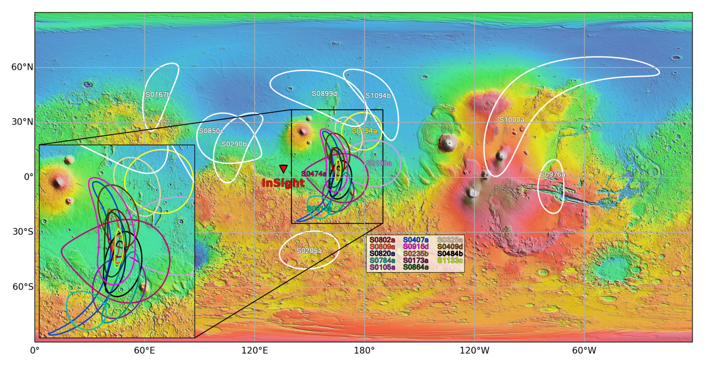


Figure: Location of the largest marsquakes (from Zenhäusern et al., 2022).

# Seismic velocity structure

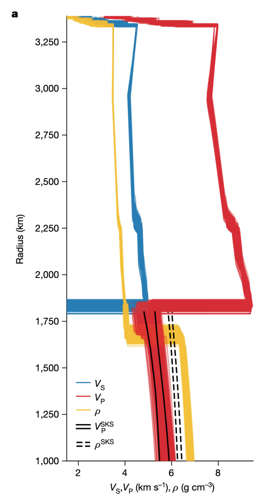


Figure: Seismic velocity structure of Mars from inversion of body wave travel time data (from Khan et al., 2023).

# Beyond seismic body waves

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- Free oscillation frequencies (0.001–0.01 Hz) are independent of source location and origin time.
- To deduce Mars's mantle velocity structure independently of body waves (0.1–1 Hz).

# Marsquakes and normal modes

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- S1222a ($M_W \sim 4.6$, $\Delta \sim 37^\circ$) (Kawamura et al., 2023).

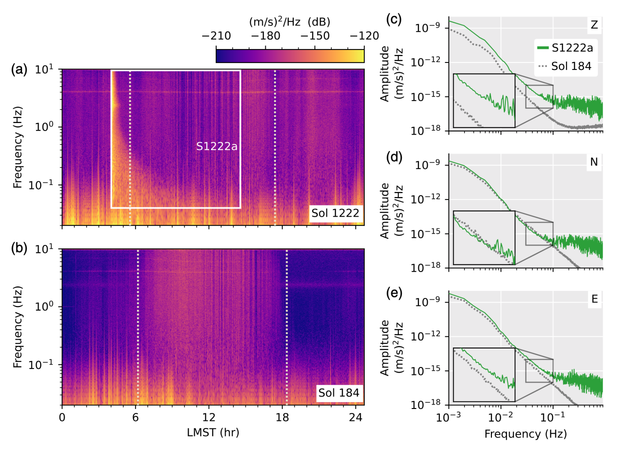


Figure: Vertical-component velocity spectrograms of Sols 1222 and 184 (from Durán et al., 2024).

# InSight seismic data overview

- Continuous excitation of the background free oscillations through environmental interaction (Nishikawa et al., 2019).

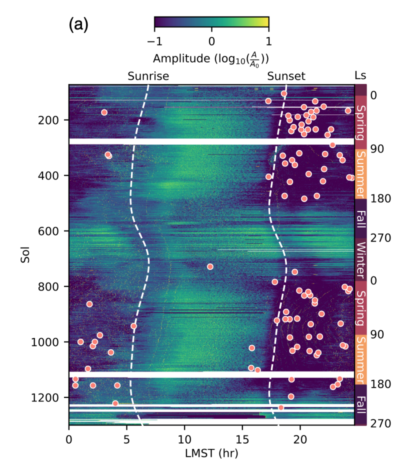


Figure: Evolution of Martian seismic background noise recorded by SEIS (from Durán et al., 2024).

# InSight seismic data overview – continued

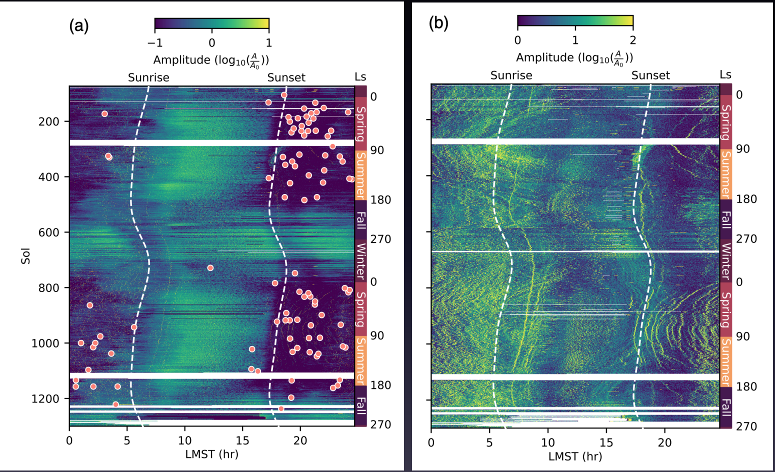


Figure: Evolution of Martian seismic background noise recorded by SEIS (a) 0.1–1 Hz and (b) 0.01–0.1 Hz (from Durán et al., 2024).

# Glitch removal

- Three-stage process: 1) SEISGlitch (Scholz et al., 2021); 2) TwistPy (Sollberger, 2023); 3) Manual removal.

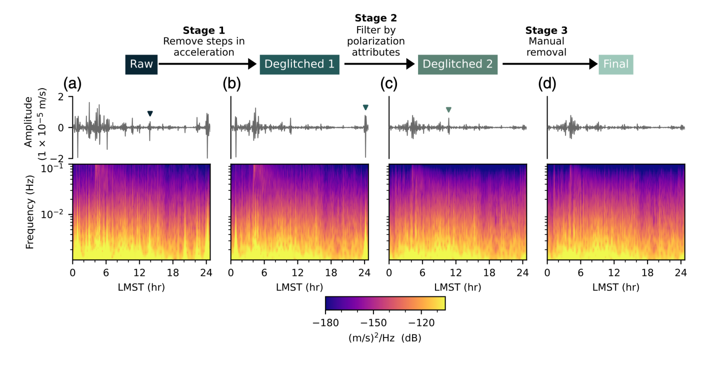


Figure: Deglitching scheme applied to S1222a (from Durán et al., 2024).

# Post-processed data

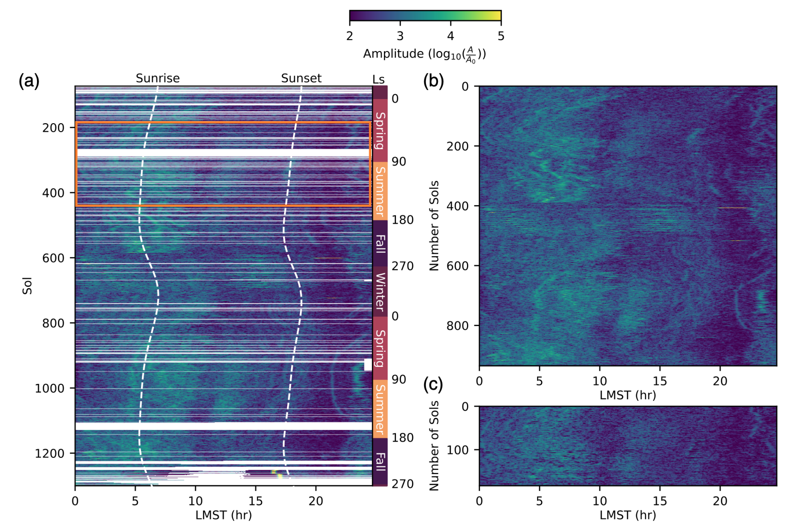


Figure: Summary of data after glitch removal (from Durán et al., 2024).

# Auto-correlation analysis and spectral computation

- Cross-correlation (CC):

$$\mathrm{CC}(\tau) = \sum_{t=1}^{T} s_1(t)s_2(t+\tau), \qquad (1)$$

- Geometrically-normalized cross-correlation (GNCC):

$$\mathrm{GNCC}(\tau) = \frac{\sum_{t=1}^{T} s_1(t)s_2(t+\tau)}{\sqrt{\sum_{t=1}^{T} s_1^2(t)}\sqrt{\sum_{t=1}^{T} s_2^2(t+\tau)}}, \qquad (2)$$

- Phase cross-correlation (PCC):

$$\mathrm{PCC}(\tau) = \frac{1}{2T}\sum_{t=1}^{T} |e^{i\Phi(t)} + e^{i\Psi(t+\tau)}|^{\nu} - |e^{i\Phi(t)} - e^{i\Psi(t+\tau)}|^{\nu} \qquad (3)$$

Stacked spectra are computed using linear, non-linear nth-root and phase-weighted stacking (Schimmel et al., 2018).

# Earth

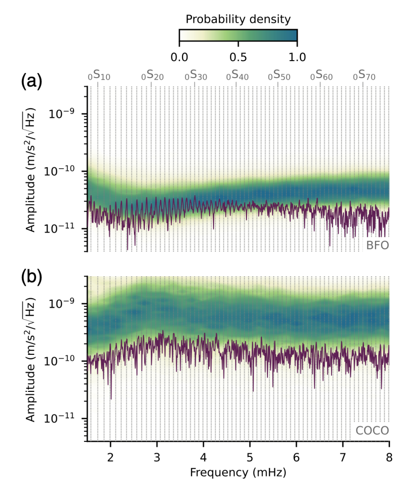


Figure: Acceleration power density spectra for stations Black Forest Observatory (BFO) and Cocos Island (COCO) based on 244 days of 24-hr autocorrelations (from Durán et al., 2024).

# Earth – continued

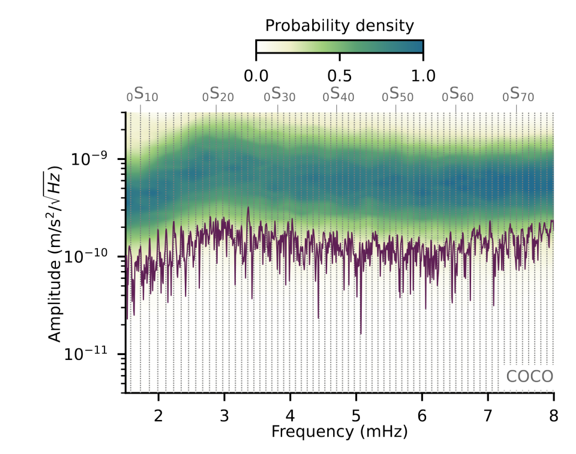


Figure: Acceleration power density spectra for Cocos Island (COCO) based on 800 days of 24-hr autocorrelations (from Durán et al., 2024).

# Mars

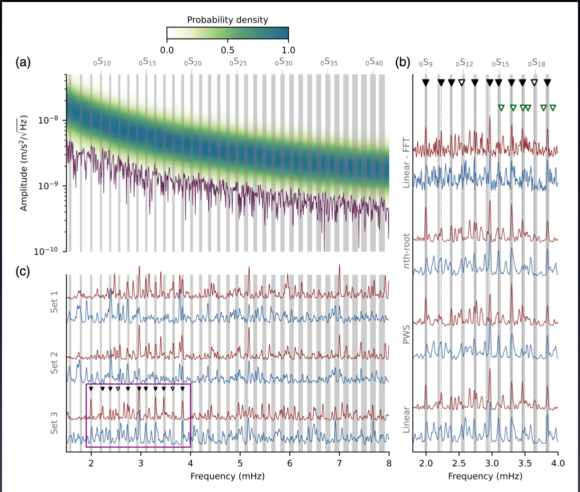


Figure: Acceleration power density spectra for Mars (from Durán et al., 2024).

# Cluster analysis and feature extraction

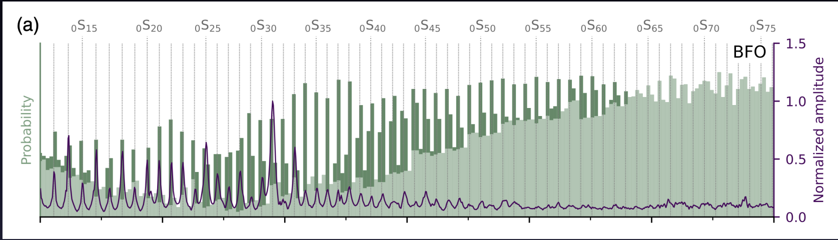


Figure: Comparison of stacked spectra, normal-mode predictions and spectral features (peaks) based on clustering analysis (from Durán et al., 2024).

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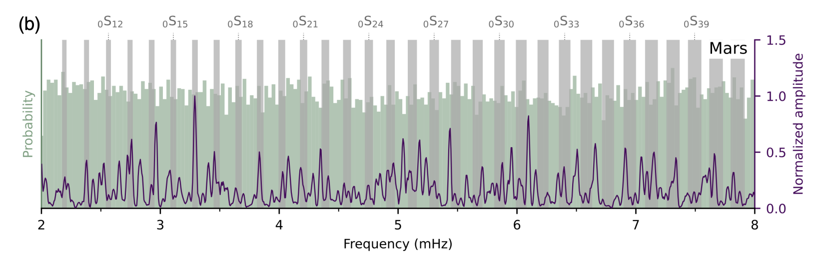


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# Outlook – Seismology on the Moon

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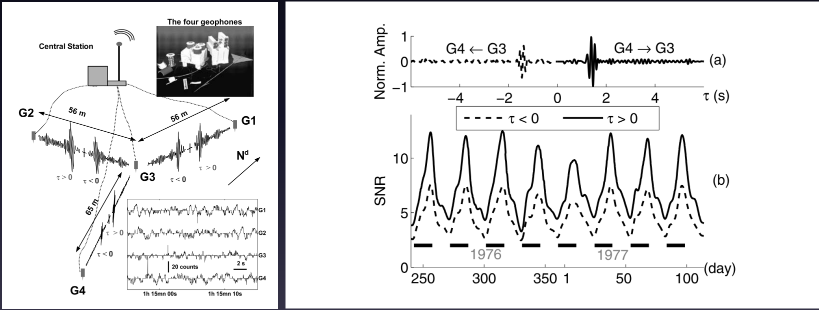


Figure: Lunar subsurface investigated from correlation of seismic noise. From Larose et al. (2005).

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- We implemented automated and manual processing schemes to remove glitches in the InSight data.
- Spectral amplitudes associated with normal modes excited by the largest recorded events are well below the background noise.
- We computed and stacked spectra from 1-Sol long autocorrelations for 966 Sols of continuous data to enhance any background free oscillations present in the data.
- Some spectral peaks align with fundamental spheroidal normal-mode predictions and may be atmosphere-induced. Yet, unambiguous detection remains difficult.

# Conclusions – continued

- Additional deglitching strategies (manual) may possibly improve chances of detection, although the available data quantity is likely to prove a limiting factor.

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- Additional deglitching strategies (manual) may possibly improve chances of detection, although the available data quantity is likely to prove a limiting factor.
- For seismology on Mars to maximize gain, the seismometer should not only be placed on the ground but needs to be removed from full-scale environmental exposure.

# Further reading

## Searching the InSight Seismic Data for Mars's Background-Free Oscillations

Cecilia Durán*[1], Amir Khan*[1,2], Johannes Kemper[1], Iris Fernandes[3], Klaus Mosegaard[3], Jeroen Tromp[4], Marion Dugué[1], David Sollberger[5], and Domenico Giardini[1]

### Abstract

**Mars's atmosphere has theoretically been predicted to be strong enough to continuously excite Mars's background-free oscillations, potentially providing an independent means of verifying radial seismic body-wave models of Mars determined from marsquakes and meteorite impacts recorded during the Interior Exploration using Seismic Investigations, Geodesy, and Heat Transport (InSight) mission. To extract the background-free oscillations, we processed and analyzed the continuous seismic data, consisting of 966 Sols (a Sol is equivalent to a Martian day), collected by the Mars InSight mission using both automated and manual deglitching schemes to remove nonseismic disturbances. We then computed 1-Sol-long autocorrelations for the entire data set and stacked these to enhance any normal-mode peaks present in the spectrum. We find that while peaks in the stacked spectrum in the 2–4 mHz frequency band align with predictions based on seismic body-wave models and appear to be consistent across the different processing and stacking methods applied, unambiguous detection of atmosphere-induced free oscillations in the Martian seismic data nevertheless remains difficult. This possibly relates to the limited number of Sols of data that stack coherently and the continued presence of glitch-related signal that affects the seismic data across the normal-mode frequency range (~1–10 mHz). Improved deglitching schemes may allow for clearer detection and identification in the future.**

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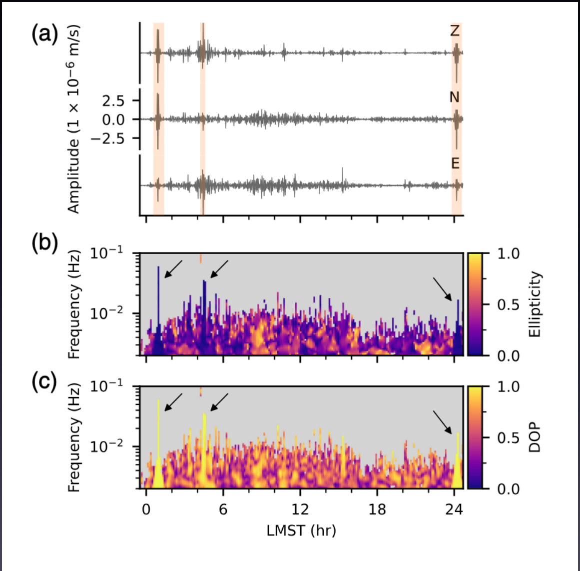
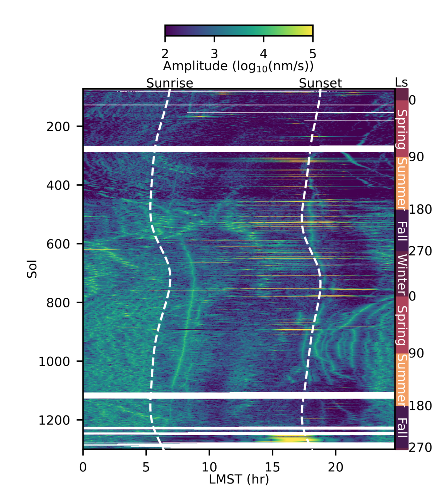
**Supplemental Material**

# Back-up slides

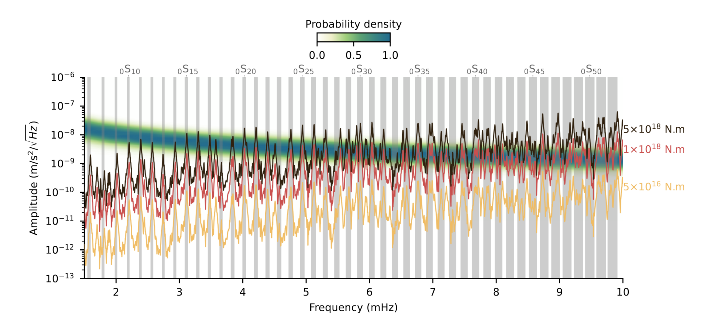
# Deglitching: polarisation attributes



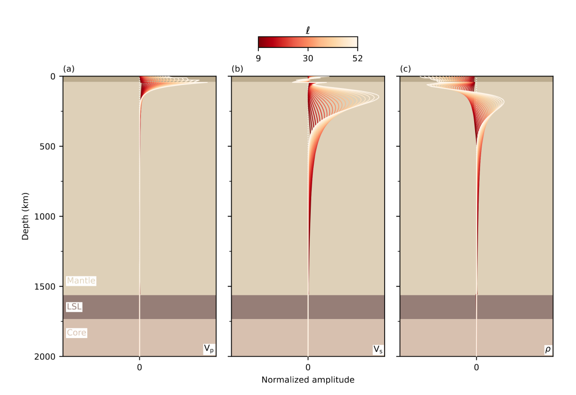
# Insight seismic data overview (0.001–1 Hz)



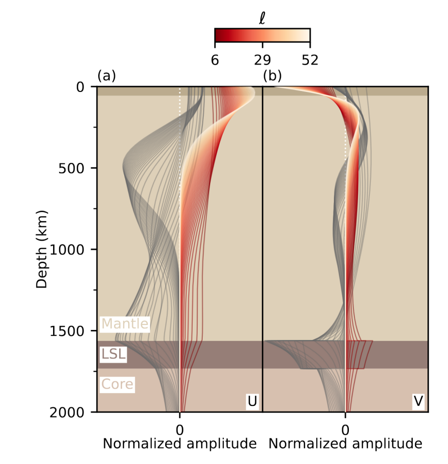
# Magnitude estimate of BFOs



# Normal mode sensitivity kernels



# Eigenfunctions



# Data processing

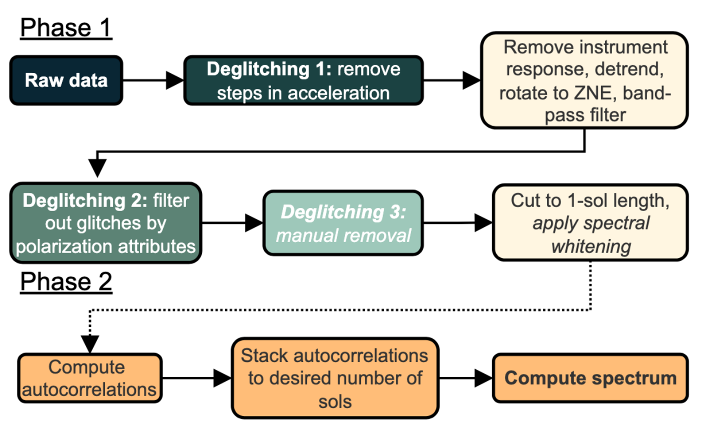



Figure: Data processing workflow (from Durán et al., 2024).