Using a High- to Low-frequency Spectral Ratio to Distinguish Variations in Earthquake Source Properties (#37)

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What makes earthquakes *different* from each other?

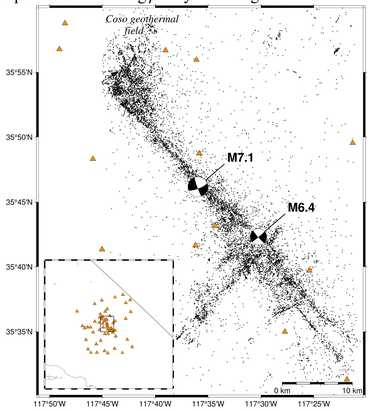
Earthquakes of similar magnitude can produce different amounts of shaking. Understanding the source characteristics that cause these differences is **critical for hazard mitigation**. Stress drop ($\Delta\sigma$) is a fundamental source parameter related to the amount of damaging high-frequency radiation released from an earthquake. However, $\Delta\sigma$ **estimates often have large uncertainties** (see Baltay et al., 2024).

For earthquakes of similar size, variation in ground motion is due to the relative amount of high-frequency radiation compared to low-frequency. We define a parameter $\log\beta$ as the logarithm of the ratio of the high-frequency spectral amplitude (A_{HF}) to the low-frequency spectral amplitude (A_{LF}) to study such variations:

$$\log\beta = \log A_{HF} - \log A_{LF}$$

We find that $\log\beta$ shows significant scatter between different stations. However, after correcting for station, path, and magnitude effects, **this value correlates strongly with corner frequency (f_c) and $\Delta\sigma$.**

We demonstrate this method by applying it to P- and S-wave spectra from the 2019 Ridgecrest earthquake sequence (**F1**, Baltay et al., 2024) and compare our results to $\Delta\sigma$ estimates in Vandevert et al. (2024) and find correlation spatially and between relative values of $\Delta\sigma$. We also apply this method to a synthetic dataset to explore how these $\log\beta$ vary with magnitude.

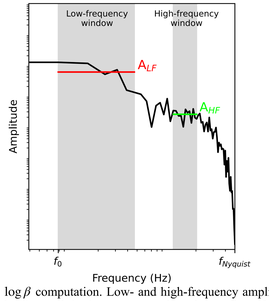


F1: 2019 Ridgecrest earthquake sequence between 4 and 18 July (black dots). Seismic stations used in this study shown as orange triangles, and the inset shows the greater southern California region.

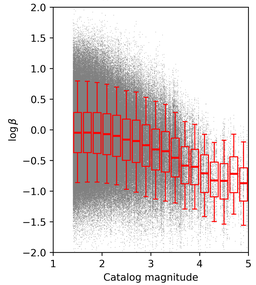
How does it work?

Step 1:

Compute $\log\beta$ for all earthquake-station pairs with a good signal-to-noise ratio:



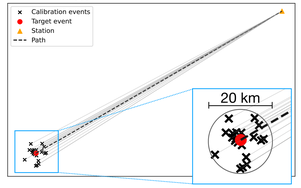
F2: $\log\beta$ computation. Low- and high-frequency amplitude levels (A_{LF} and A_{HF}) are computed as the median of their band. Bands of about 1-5 Hz and 12-20 Hz produce good correlation with previously estimated stress drop.



F3: $\log\beta$ for all station-earthquake pairs passing signal-to-noise criteria. Boxes represent 25 and 75 percentiles, whiskers represent 5 and 95 percentiles, and horizontal lines show the median values.

Step 2:

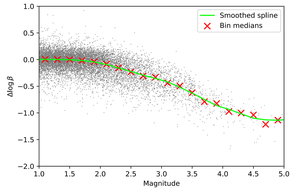
Correct $\log\beta$ for station and path effects:



F4: Station and path corrections using small, nearby calibration events. This is analogous to the spectral decomposition method in Shearer et al. (2022), where f_c of calibration events are fixed

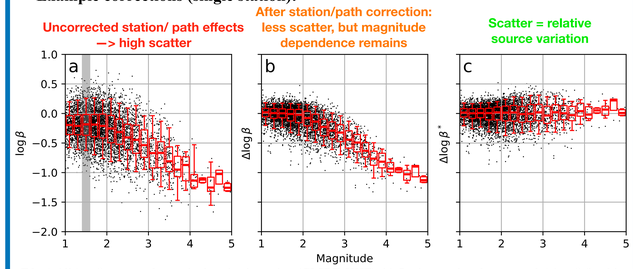
Step 3:

Correct $\Delta\log\beta$ for magnitude dependence:



F5: Magnitude correction of $\Delta\log\beta$. A spline is fit to the bin medians, smoothed, and then subtracted from $\Delta\log\beta$ to get magnitude-corrected $\Delta\log\beta^*$

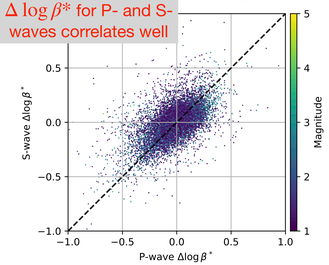
Example corrections (single station):



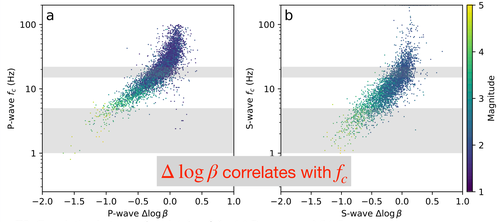
F6: a) All $\log\beta$ measured at a single seismic station (CI.SRT..HHZ); b) Station- and path-corrected $\Delta\log\beta$ for this station; c) Magnitude-corrected $\Delta\log\beta^*$ for the same earthquakes. Note the larger scatter in the M2-3.5 earthquakes.

$\Delta\log\beta$ characterizes earthquake source properties

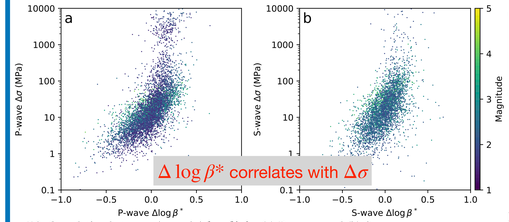
$\Delta\log\beta^*$ for P- and S-waves correlates well



F7: Correlation between $\Delta\log\beta^*$ of P-waves and S-waves



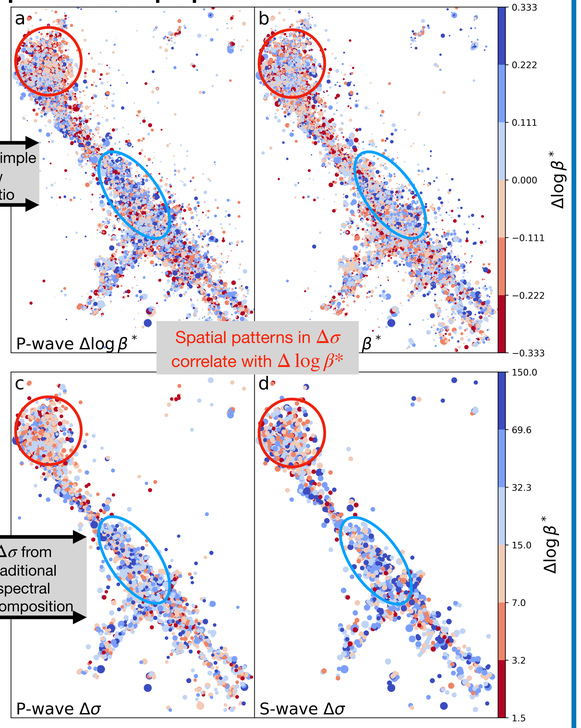
F8: Correlation between f_c and $\Delta\log\beta$ for (a) P-waves and (b) S-waves



F9: Correlation between $\Delta\sigma$ and $\Delta\log\beta^*$ for (a) P-waves and (b) S-waves

$\Delta\log\beta^*$ from simple high-to-low frequency ratio

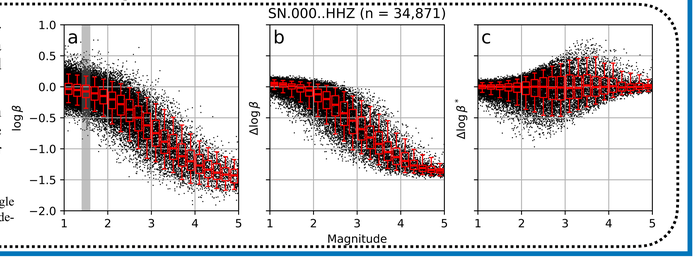
$\Delta\sigma$ from traditional spectral decomposition



F10: Spatial similarities between $\Delta\log\beta^*$ (panels a and b) and $\Delta\sigma$ (panels c and d) for P waves (panels a and c) and S waves (panels b and d). $\Delta\sigma$ values are from Vandevert et al. (2024).

We generated synthetic events with lognormally-distributed stress drop with a median of 5 MPa. Spectra were generated using Brune models with white noise, and $\Delta\log\beta^*$ computed from the resulting spectra.

Medium-sized events (2<M<3.5) have more scatter than smaller and larger events, which is also observed in the real data (**F6**). This scatter is likely due to the non-linear relationship between $\Delta\log\beta^*$ and $\Delta\sigma$.



F11 (right): Synthetic experiment version of **F6**: a) all $\log\beta$ at a single example station; b) Station- and path-corrected $\Delta\log\beta$; c) Magnitude-corrected $\Delta\log\beta^*$

Conclusions

- This method makes **no modeling assumptions** (e.g. attenuation, rupture properties), so it is **closer to the actual data**.
- $\Delta\log\beta$ **correlates with f_c of the source spectrum (F8)**.
- $\Delta\log\beta$ vs. f_c relationship is most **linear when f_c is between the two amplitude bands (F8)**, around 2 < M < 3.5.
- $\Delta\log\beta^*$ **correlates with stress drop (F9)**
- Variations in $\Delta\log\beta^*$ are **due to differences in source**, since effects from path, station, and magnitude are removed.
- Spatial variation of aftershock $\Delta\log\beta^*$ does not correlate with mainshock slip, but **values are lower in the Coso geothermal field (F10)**. This suggests that we can use $\Delta\log\beta^*$ to **infer properties of the underground environment**.
- **Similar spatial variation** in $\Delta\sigma$ **(F10)** resolved in Trugman (2020) and Vandevert et al. (2024).
- Correlation to $\Delta\sigma$ **is somewhat insensitive to the high-frequency band choice**. Exploring other bands could improve the magnitude range this is effective on.
- We will release an open-source package on GitHub soon.
- We plan to apply the method to **earthquakes of the entire state of California** to analyze the spatial patterns of $\Delta\log\beta^*$ and infer physical causes of the variations.

References

- **Baltay, A., Abercrombie, R., Chu, S., & Taira, T.** (2024). The SCEC/USGS community stress drop validation study using the 2019 Ridgecrest earthquake sequence. Seismica, 3(1), 1–12.
- **Shearer, P. M., R. E. Abercrombie, and D. T. Trugman**, Improved stress drop estimates for M 1.5 to 4 earthquakes in Southern California from 1996 to 2019, *J. Geophys. Res.*, 2022.
- **Trugman, D. T.** (2020). Stress-drop and source scaling of the 2019 Ridgecrest, California, earthquake sequence. Bulletin of the Seismological Society of America, 110(4), 1859–1871.
- **Vandevert, I. C., Shearer, P. M., & Fan, W.** (2024). Ridgecrest Aftershock Stress Drops from P- and S-Wave Spectral Decomposition. Bulletin of the Seismological Society of America.

Acknowledgements

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