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Quantifying earthquake source parameter uncertainties associated with local site effects using a dense array

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Abstract

We investigate the influence of local site effects on earthquake source parameter estimates using the LArge-n Seismic Survey in Oklahoma (LASSO). The LASSO array consisted of 1825 stations in a 25 km x 32 km region with extensive wastewater injection and recorded more than 1500 local events (M < 3) during spring 2016. We analyze the site amplification dependence on earthquake corner frequency (f_c), seismic moment (M_0), and stress drop estimated by modeling individual spectra. We evaluate and correct these site effects and compare the effectiveness of the correction to results using the spectral ratio method. We estimate local site amplification at each station using the average Peak-Ground-Velocity (PGV) of 14 regional earthquakes (~130 km away). The f_c from the single spectrum method negatively correlates with site amplification, whereas M_0 from the single spectrum method positively correlates with site amplification. This suggests the source parameters calculated by modeling individual spectra are biased by the local site effects. The high amplifications are typically located on young alluvial sedimentary deposits. We correct site effects by removing the trend between PGV and these two parameters in the regression analysis, which reduces the standard deviation of these parameters across the array and makes the calculated stress drop less site dependent. We compare corrections using other site-effect proxies such as the Root-Mean-Square (RMS) amplitude, surface geological formation, P-arrival-delay, and topographic slope. The PGV and the RMS corrections provide the greatest reduction of the spatial deviation of source parameters. In comparison, the spectral ratio method effectively removes the site effects using the Empirical Green's Function (EGF) approach. The trends being removed by EGF are close to the apparent trends between the single spectrum estimated parameters and the PGV, which suggests the consistency of these different correction approaches. Our results provide a potential way to remove the site effects when only the main event spectrum is available and demonstrates the effectiveness of using the EGF approach for removing site effects. The resulting inter-station variability provides an estimate of the likely uncertainty in source parameters estimated from smaller numbers of stations.

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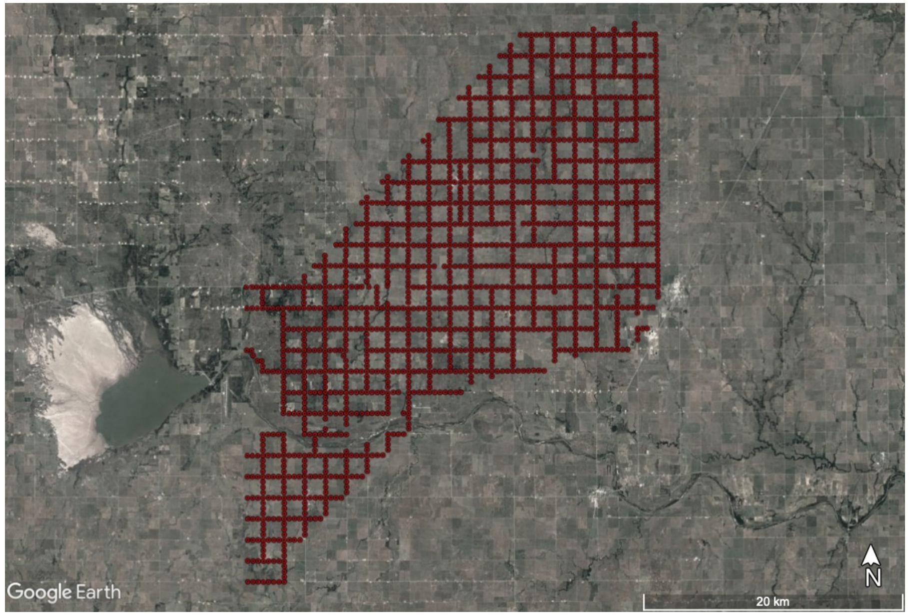
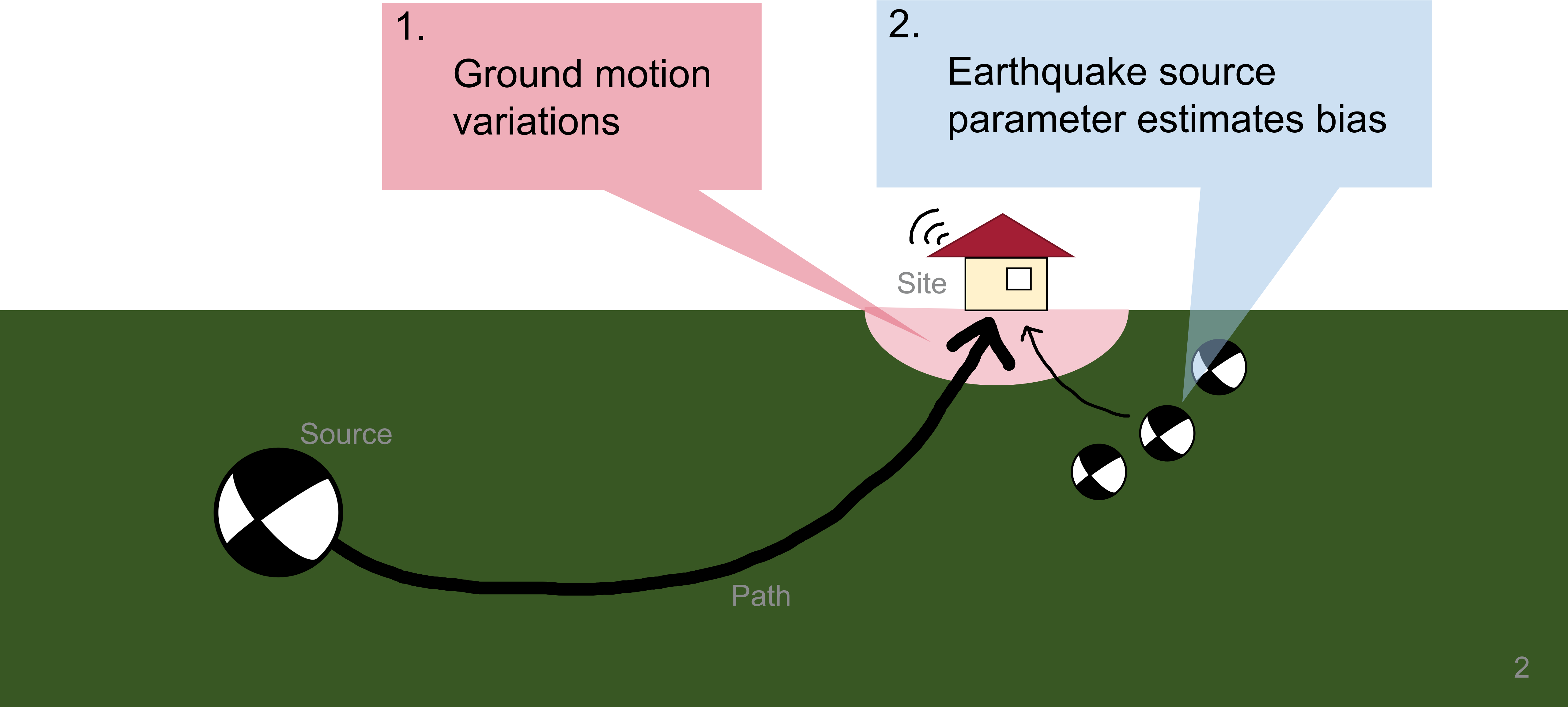
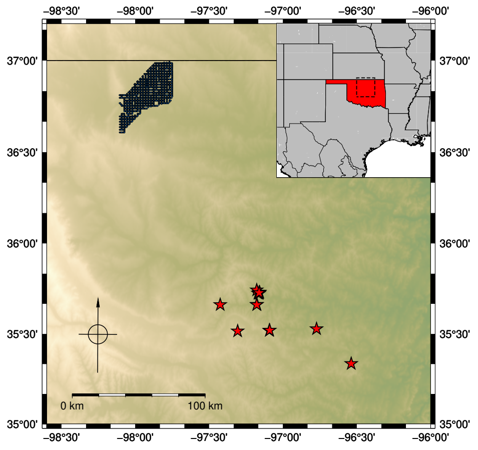


Quantifying the influence of site-effect

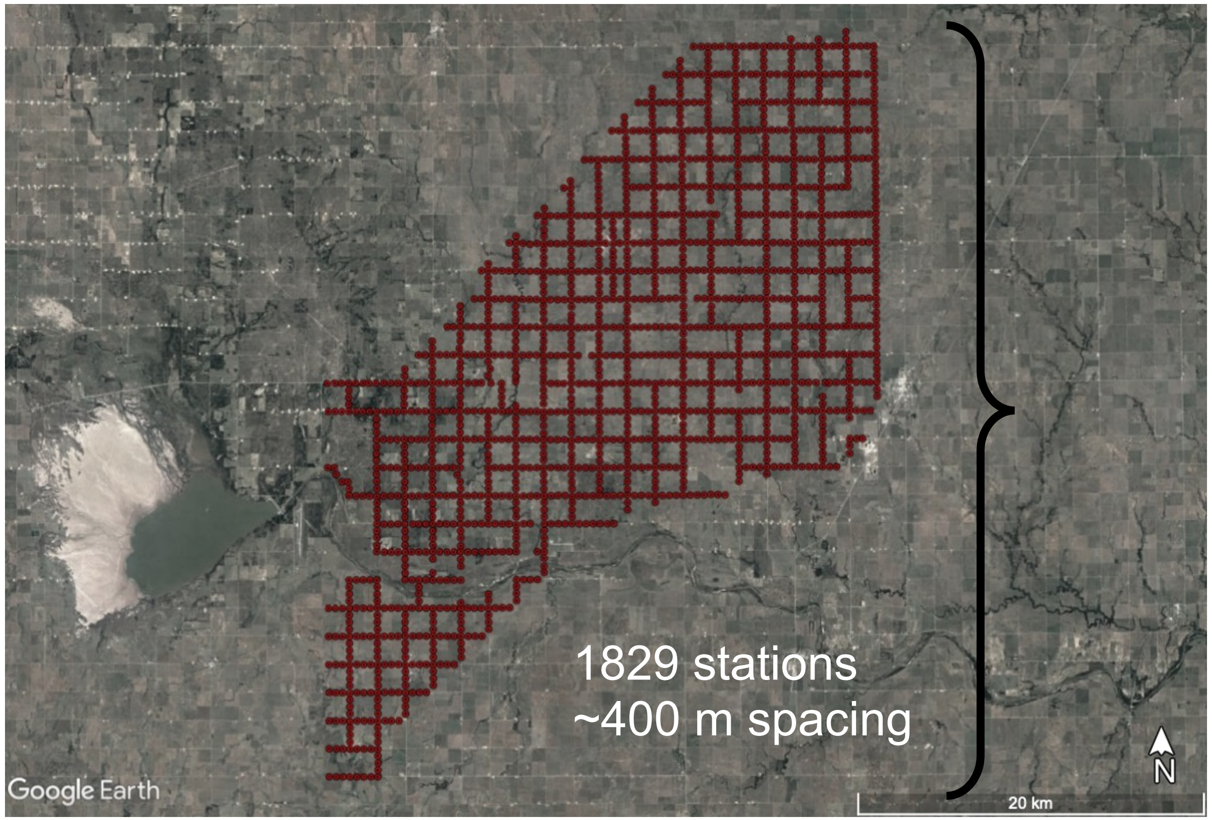


The LArge-n Seismic Survey in Oklahoma (LASSO)

- Analyze spatial ground motion variations
  - Using 14 regional earthquakes (~140 km away)



25 km

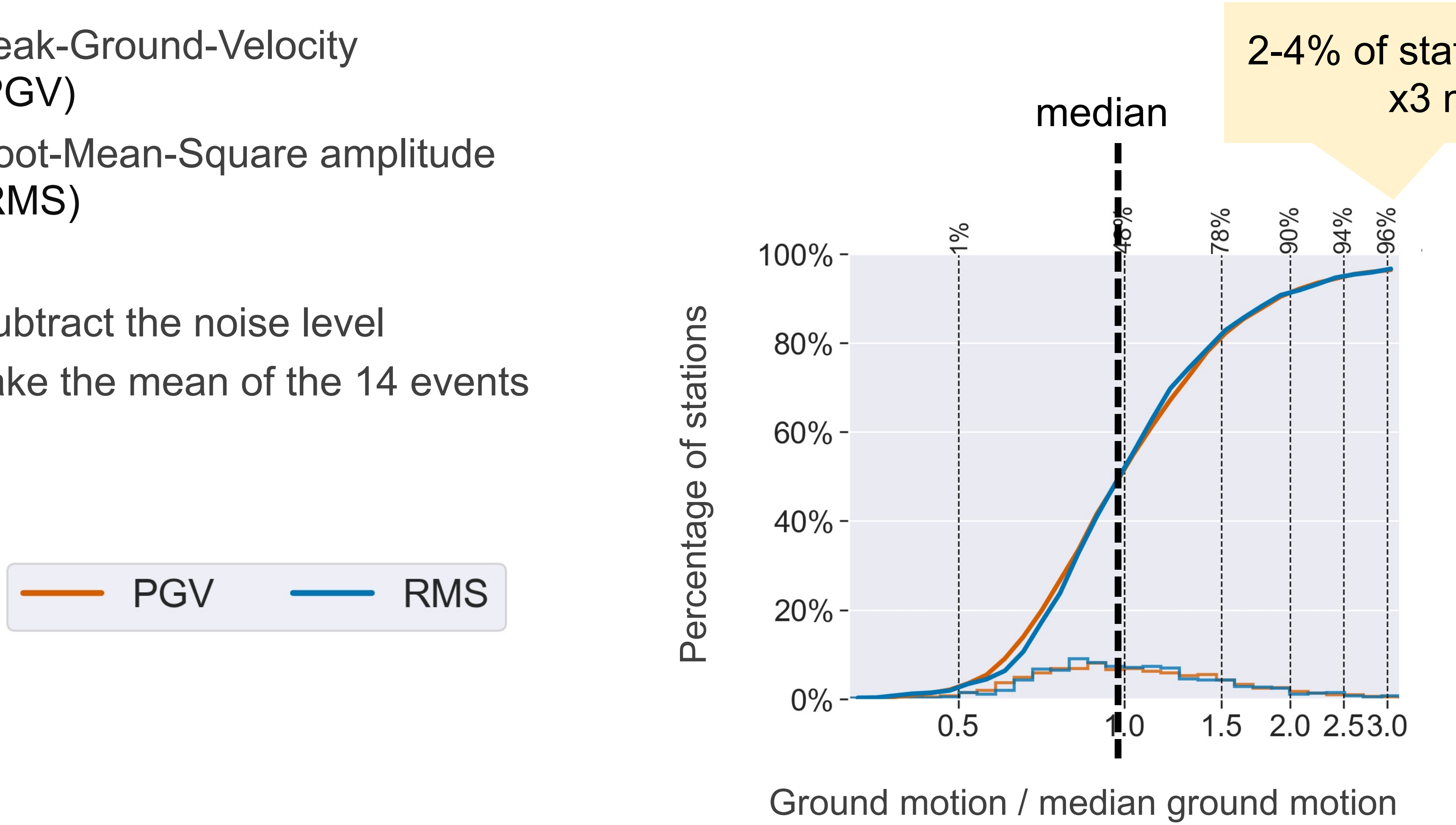


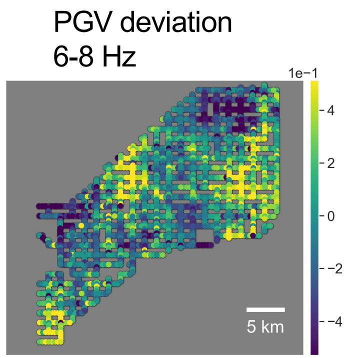
32 km

The ground motion variation is large across the array.

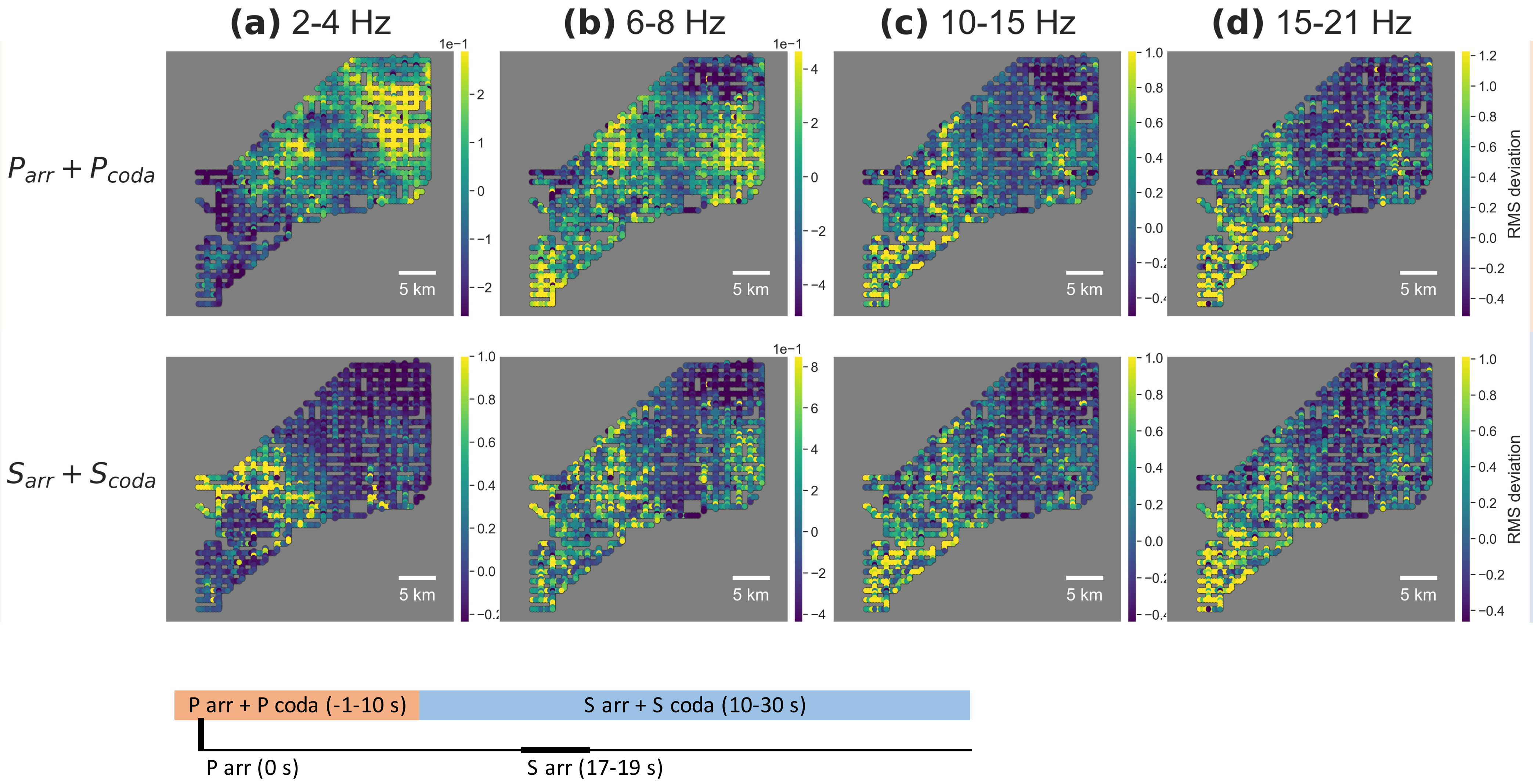
- Ground motions above the noise level
  - Peak-Ground-Velocity (PGV)
  - Root-Mean-Square amplitude (RMS)

  - Subtract the noise level
  - Take the mean of the 14 events

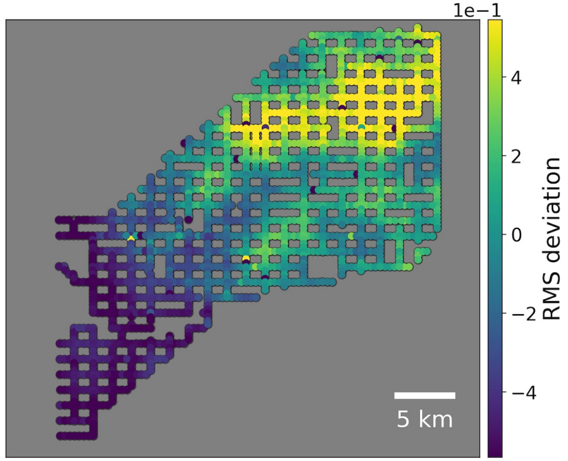




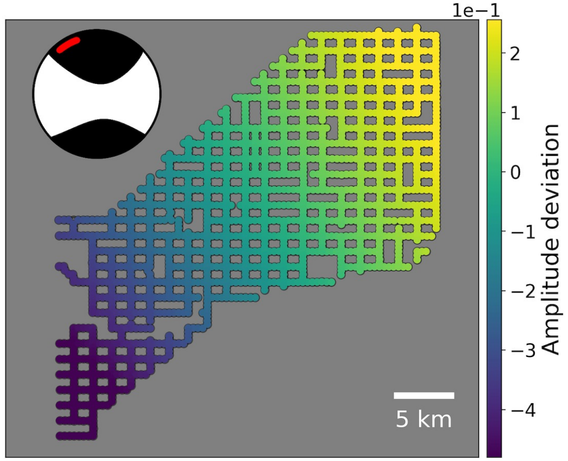
Ground motion patterns vary with frequency and time window



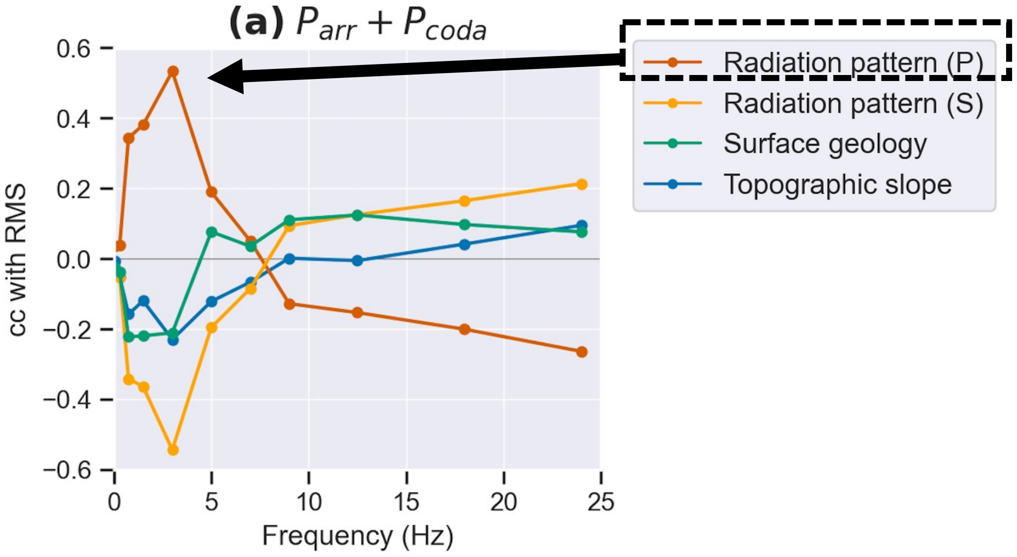
P wave window at lower frequency correlate with P wave radiation patterns



RMS
P arr + P coda
2-4 Hz



Calculated far-field
radiation pattern



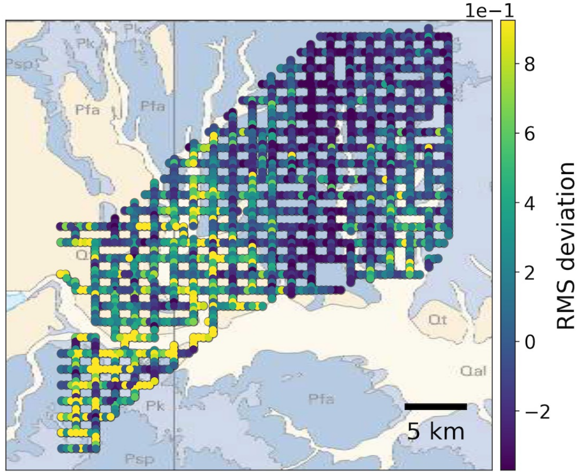
The largest event (ML 3.7)

Mean of 14 events

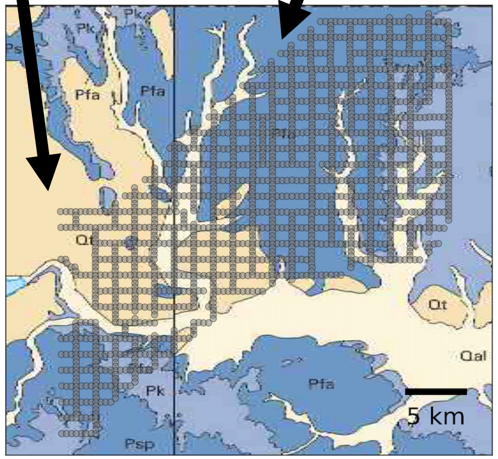
S wave window or higher frequency correlates with surface geology

Quaternary alluvial sediments

Permian shales

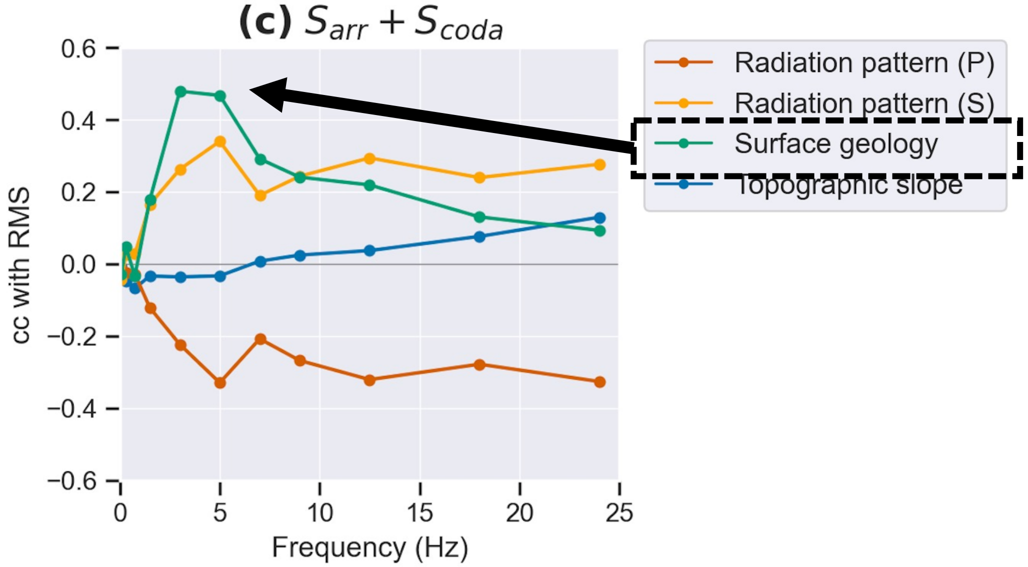


RMS
S arr + S coda,
10-15 Hz



Geology
Heran et al. (2003)

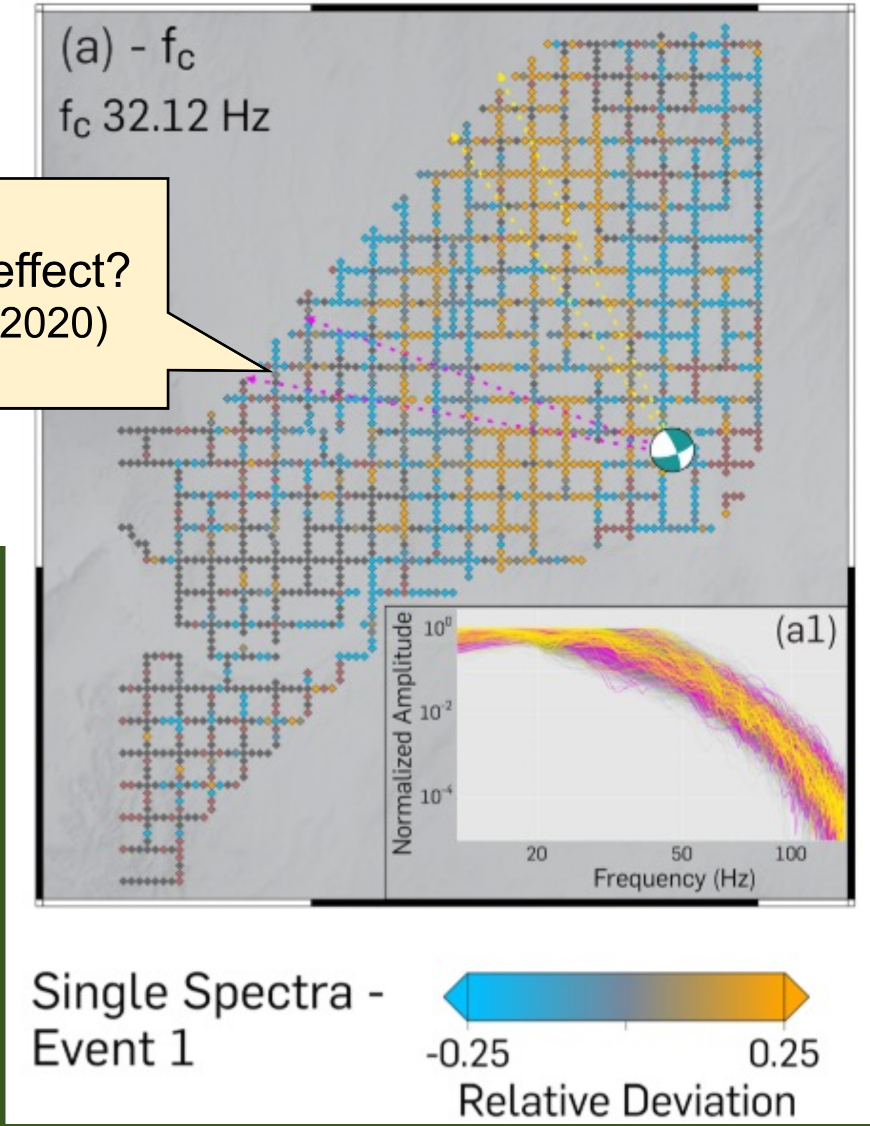
The largest event (ML 3.7)



Mean of 14 events

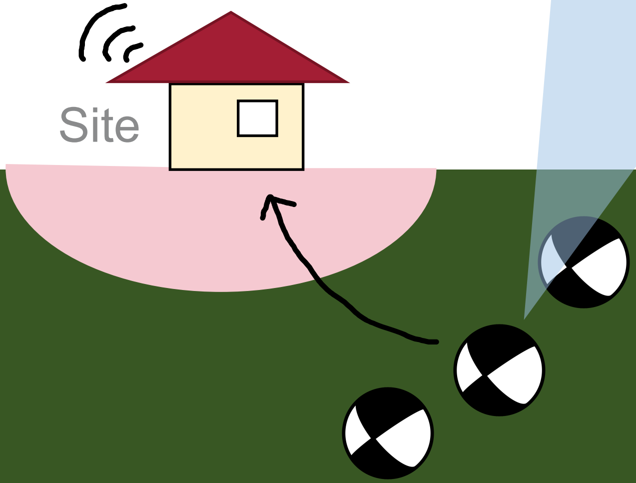
Quantifying the influence of site-effect

Source? Site-effect?
(Kemna et al., 2020)



2.

Earthquake source parameter estimates bias

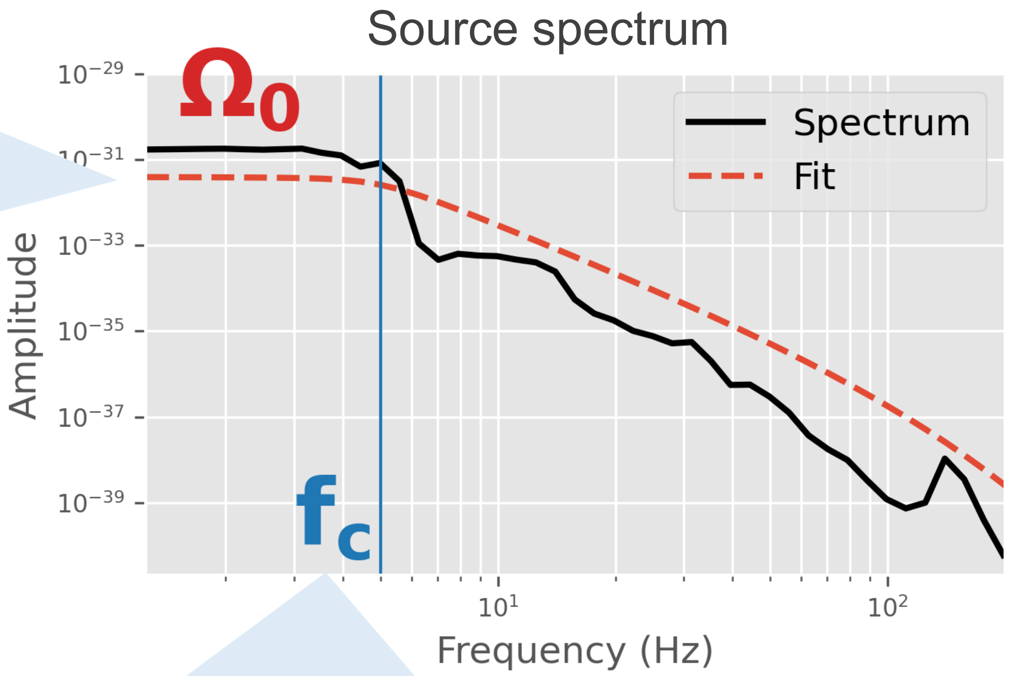


Introduction on earthquake source parameters

Related to **seismic moment (M0)**:

$$M_0 = \frac{4\pi\rho c^3 R\Omega_0}{U_{\phi\theta}}$$

Rupture size



Stress drop ($\Delta\sigma$):

$$\Delta\sigma = \frac{7}{16}\frac{M_0}{r^3}$$

$$r = \frac{k\beta}{f_c}.$$

Constant stress drop implies self-similarity

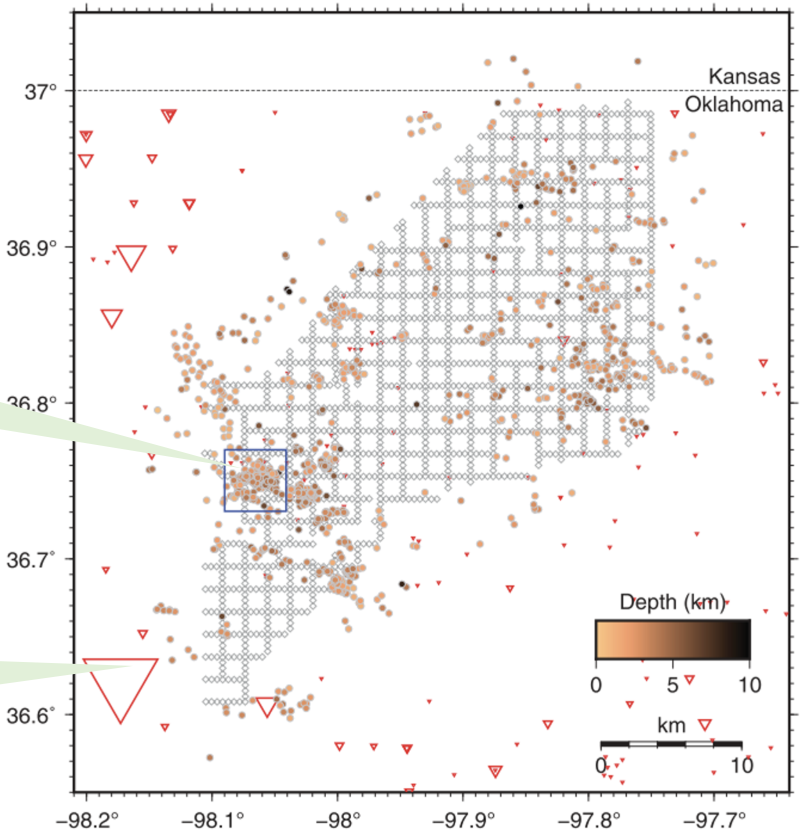
Corner frequency (fc):
Rise time, rupture duration

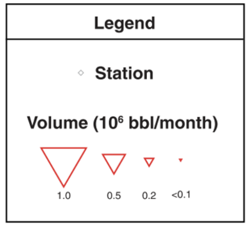
$$\Omega_t(f) = \frac{\Omega_0 e^{-(\pi f t/Q)}}{[1 + (f/f_c)^{\gamma n}]^{1/\gamma}}$$

Use 906 local earthquakes to quantify the site-effect

906 local events
(available stations: 5~1202)

Likely related to local
wastewater disposal



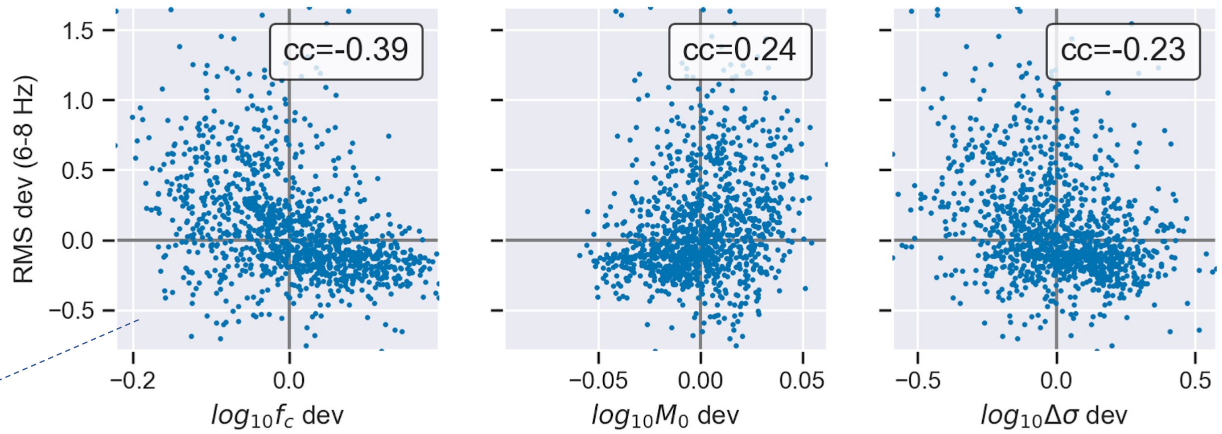


Single-spectrum results correlate with the site-effect.

Site-effect proxy:
Mean (RMS of the 14 regional earthquakes)

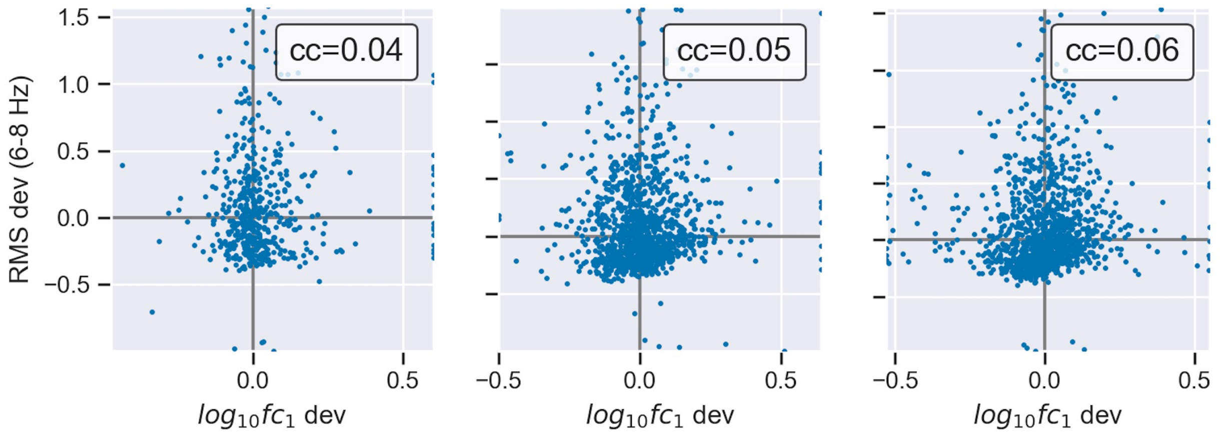
1202 stations

- Single spectrum method



- More data (x10)
- Biased by site-effect

- Spectral ratio method



- Reduce site-effect bias
- Less data
- Introduce other uncertainties
(Abercrombie, 2015)

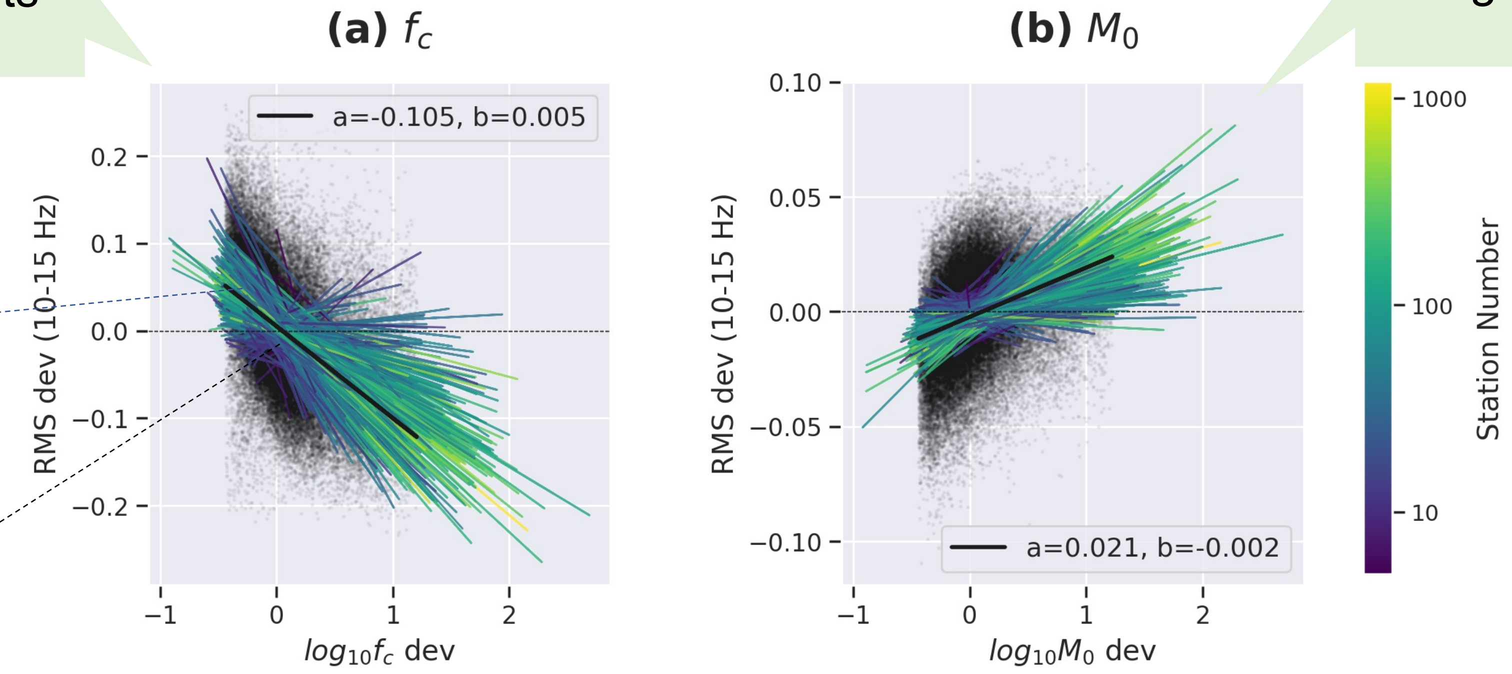
Local events show systematic bias related to site-effect.

fc vs **mean RMS** of regional events

M0 vs **mean RMS** of regional events

906 local events

Determined using all data



Empirical correction

The correction term for station i:

$$cor_i = a \ dev(x)_i + b$$

1. Correct the spatial deviation of fc and M0

$$dev(x)_{cor,i} = dev(x)_i - cor_i$$

2. Convert back to fc and M0

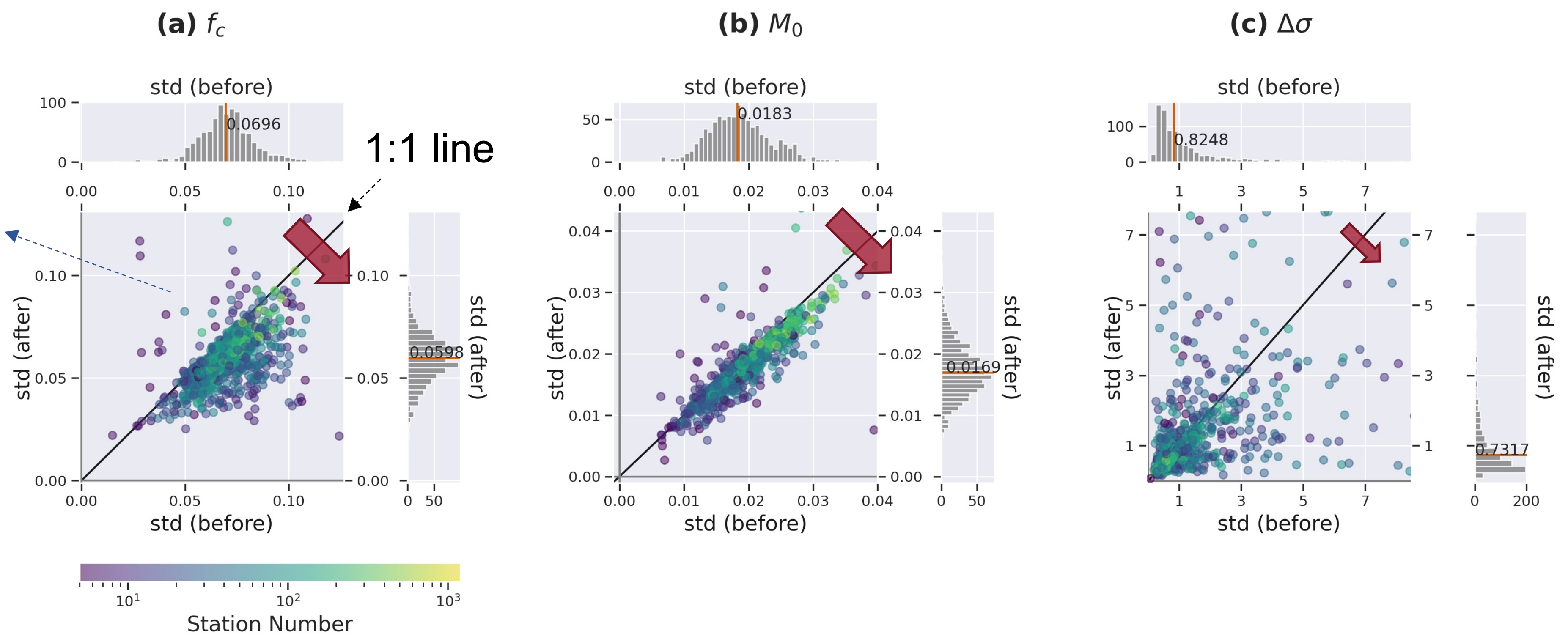
$$x_{cor,i} = dev(x)_{cor,i} \times |median(x)| + median(x)$$

3. Recalculate stress drop $\Delta\sigma$

$$\Delta\sigma = \frac{7}{16}\frac{M_0}{r^3}$$
$$r = \frac{k\beta}{f_c}.$$

After correction, spatial variabilities of source parameters are reduced.

906 local events



On average,
std decreases:

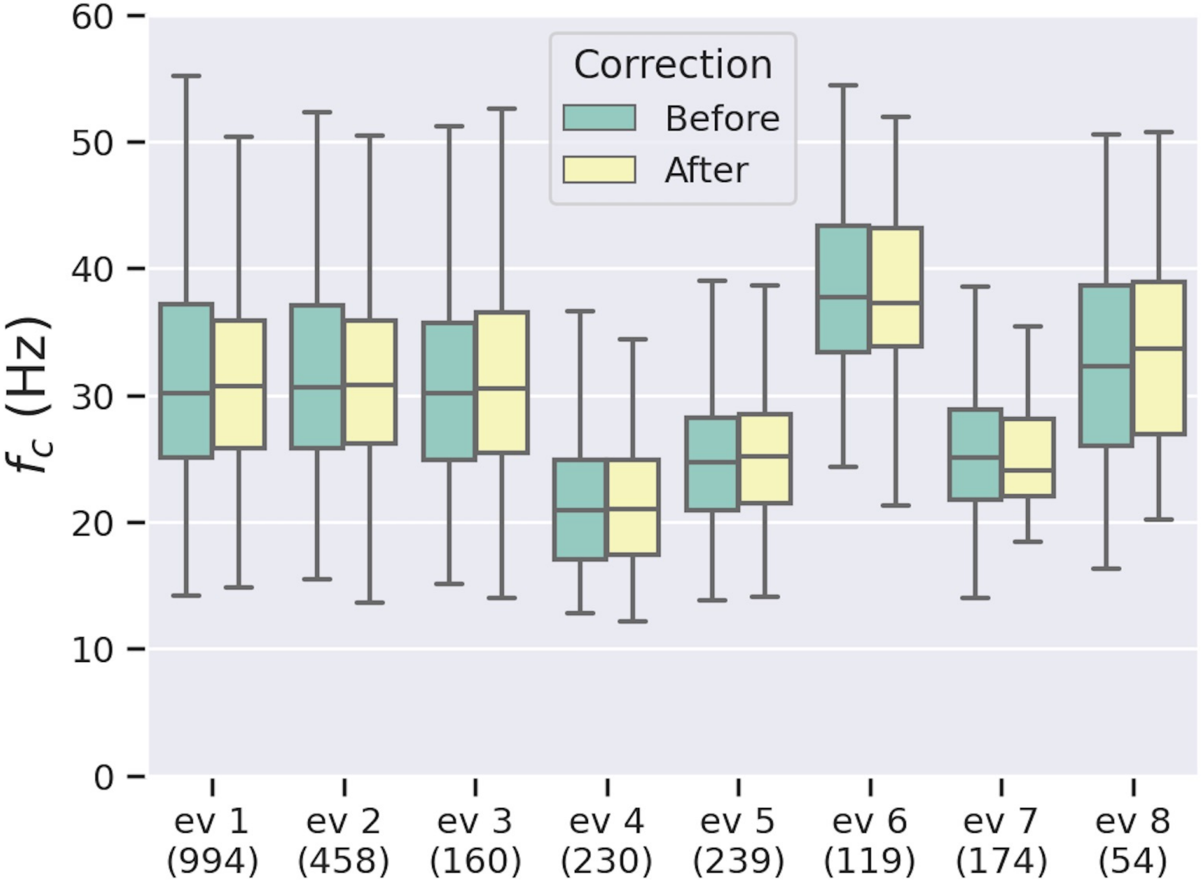
14%

8%

11%

The spatial variabilities due to site-effect are small.

8 example events in Kemna et al. (2020)



Event # (number of stations)

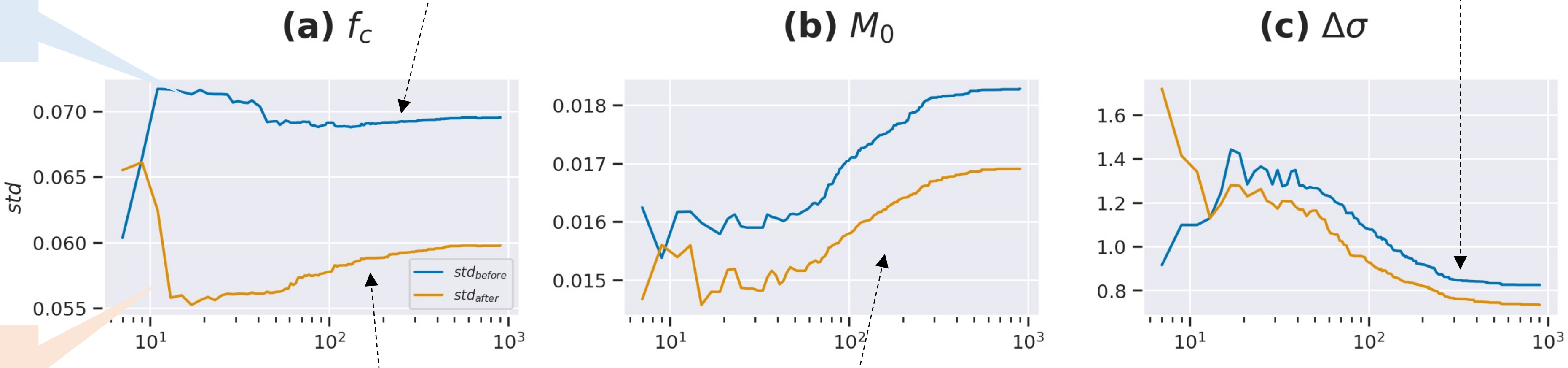
Corrections perform well when > 15 stations.

Using more stations can reduce small amount of site variability.

More stations → More stable

std **before** correction

std **after** correction



Station number

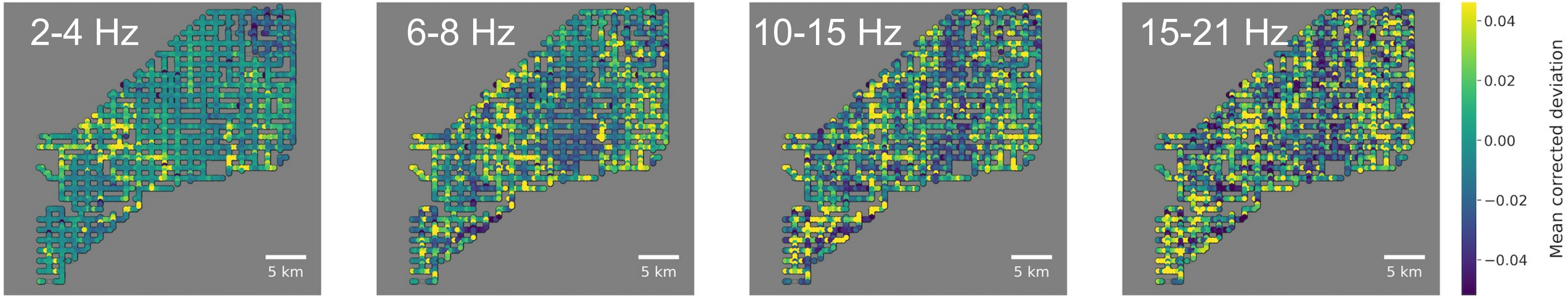
Source or path effect appears after correction.

Summary

- We investigate the **spatial variability of earthquake ground motion**
  - Radiation pattern (P wave and lower f)
  - Surface geology (S wave or higher f)

Site-effect proxy

- Single-spectrum results show systematic bias related to site-effect while the spectral ratio method effectively reduce the bias.
- The **biases are small (fc: 14%, M0: 8%, $\Delta\sigma$: 11%) but consistent**.
- The frequency dependent ground motions and correction amounts might be related to thickness of sediment.



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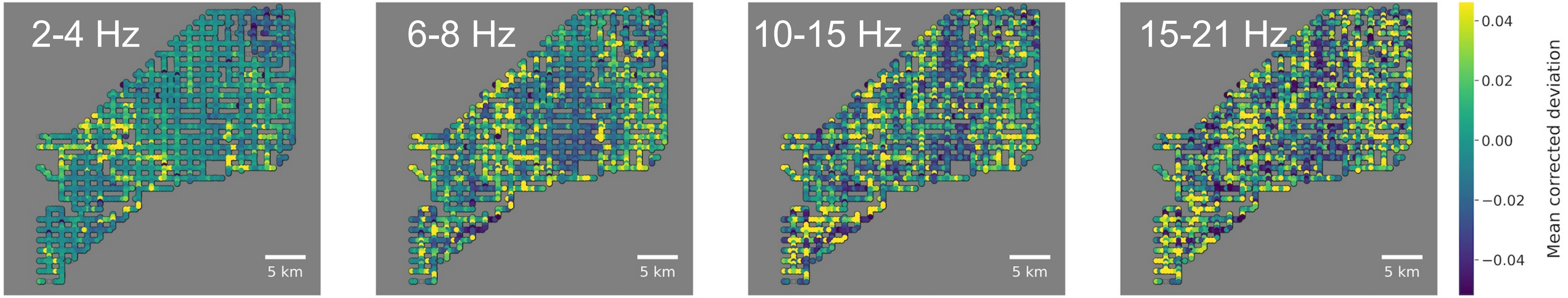
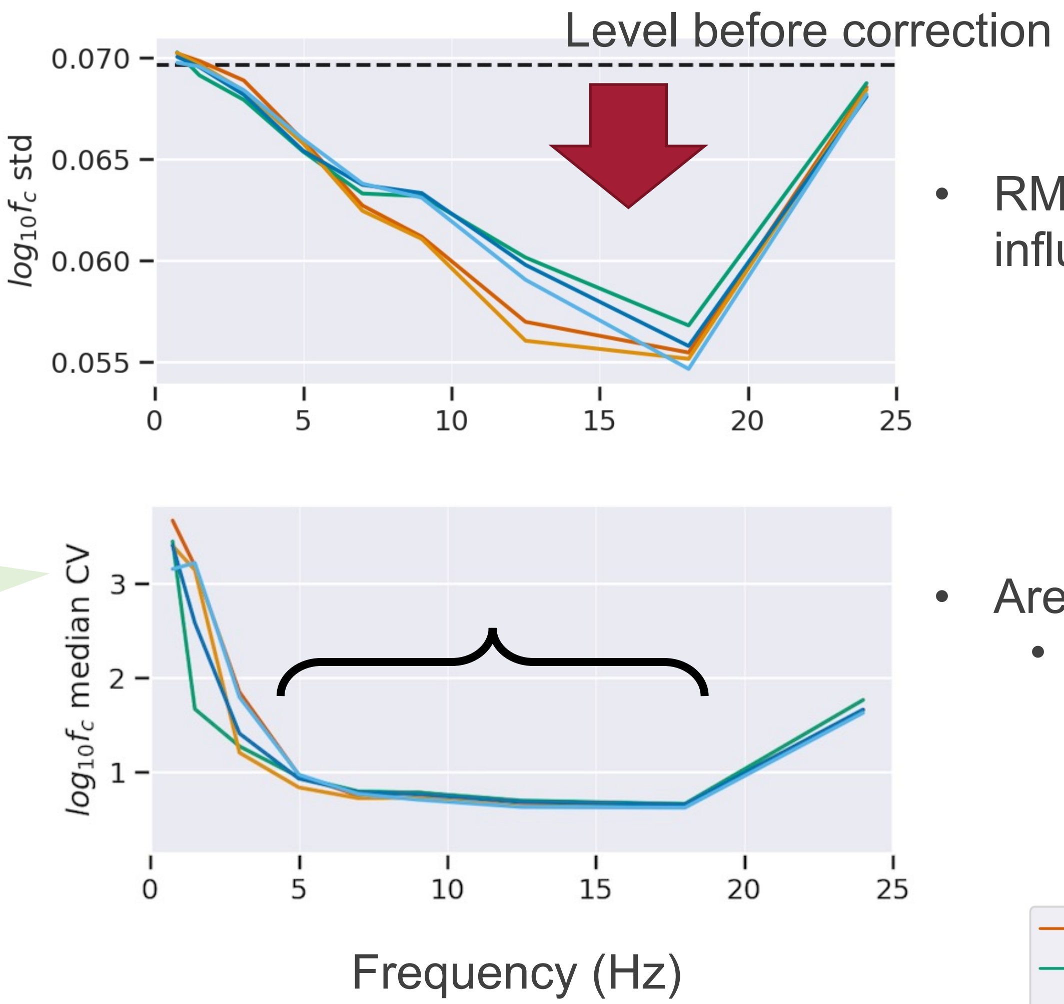
Some sites have larger corrections on average.

Mean correction of 906 events using RMS (S wave) at



RMS at 10-18 Hz is a better site-effect proxy.



CV: coefficient of variance

- RMS at 10-18 Hz show more apparent influence on fc.

- Are corrections consistent at a station?
  - Corrections are more consistent between 4-18 Hz.