An improved attenuation tomography method based on ambient noise cross-correlation

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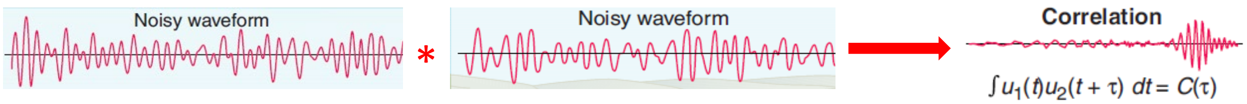
Outlines

- Introduction
- Noise-based attenuation tomography method
- Case 1： Yellowstone National Park (US)
- Case 2： Northeast China
- Discussion and Summary

Introduction

Theoretical basis



On the amplitudes of correlations and the inference of attenuations, specific intensities and site factors from ambient noise

Sur l'amplitude des corrélations et la récupération d'atténuations, d'intensités spécifiques et de facteurs de site à partir du bruit ambiant

Richard L. Weaver

Department of Physics, University of Illinois, Urbana, Illinois 61801, United States

(Weaver, 2011)

Site amplification term

attenuation coefficient

Amplitudes of Cross-correlations

$$X_{i\to j} = s_i s_j B_i(n_{i\to j})\exp\left(-\int_{r_j}^{r_i} \alpha\, dx\right)$$

noise intensity at i from i->j direction

Condition：

（1）The noise intensity varies smoothly (non-abrupt change) with location and direction

（2）The "relative amplitudes" between different station pairs are preserved during preprocessing

Introduction

Numerical simulations

On the retrieval of attenuation and site amplifications from ambient noise on linear arrays: further numerical simulations

Richard L. Weaver

Department of Physics, University of Illinois, Urbana, IL 61801, USA. E-mail: r-weaver@illinois.edu

(Weaver, 2013)

One dimensional array

Results

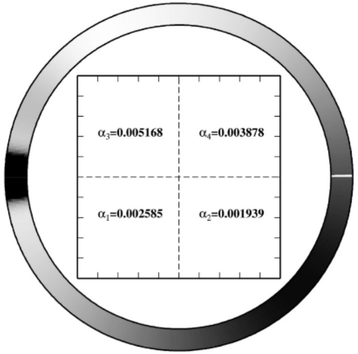
Table 6. Site amplifications and attenuations retrieved from simulation F, with eight stations, variable attenuation and constant site amplification.

Station number	log s Actual	log s Retrieved	$a_{\mathrm{actual}} = \int_{x_i}^{x_{i+1}} \alpha(x)\mathrm{d}x$	a Retrieved
1	0	−0.00387 ± 0.00404	0.04803	0.05008 ± 0.00638
2	0	−0.00570 ± 0.00389	0.04002	0.03724 ± 0.00595
3	0	−0.00244 ± 0.00384	0.05123	0.05067 ± 0.00612
4	0	−0.00286 ± 0.00426	0.03234	0.02094 ± 0.00701
5	0	0.00518 ± 0.00475	0.02978	0.03853 ± 0.00794
6	0	0.00149 ± 0.00541	0.02113	0.01688 ± 0.00930
7	0	0.00253 ± 0.00611	0.03458	0.03871 ± 0.01185

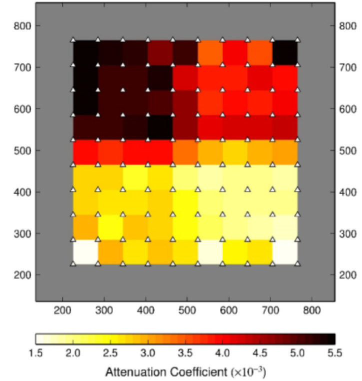
(Weaver, 2013)

Two dimensional array

Model Setting



Results



(Zhou, 2016)

Introduction

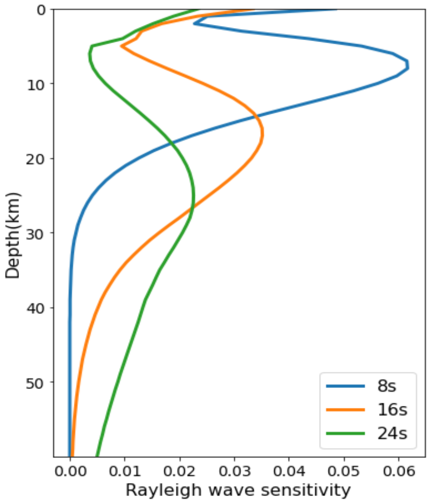
Ambient noise vs. Earthquake surface wave

Dominant periods:

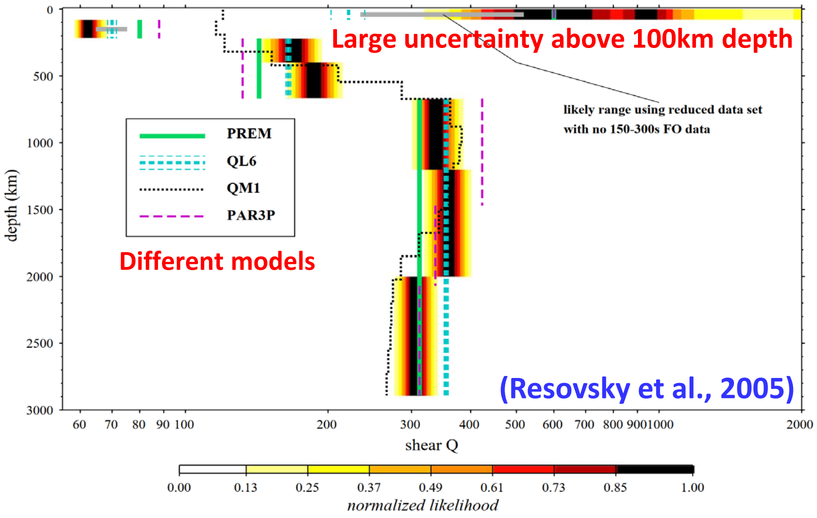
Earthquake surface wave： 20s+

Ambient noise： 6s~22s

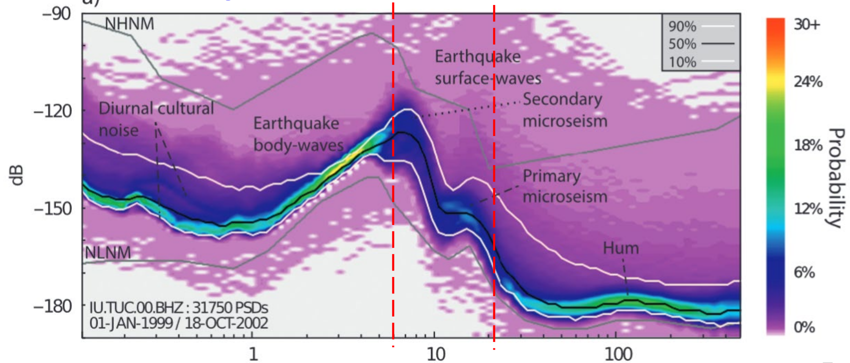
Higher sensitivity
to middle and upper crust structures



Comparison between different radial Q models



Spectrum of ambient noise



(Nakata, et al., 2019)

Introduction

Difficulties for ambient noise attenuation tomography:

(1) For preprocessing:

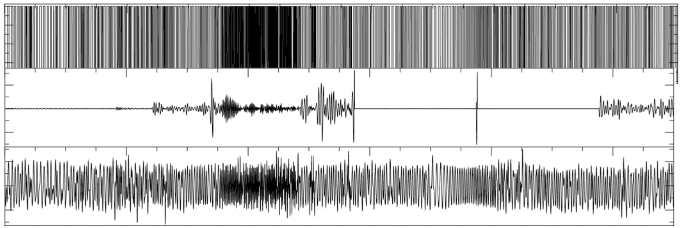
Need to preserve "relative amplitudes"

→Data from different station pairs should be treated equally

→One-bit, spectral whitening etc. are unable to use

→Retrieval of cross-correlation functions with high SNRs is more difficult

standard preprocessing method



【"relative amplitudes" are distorted】 （Bensen et al., 2007）

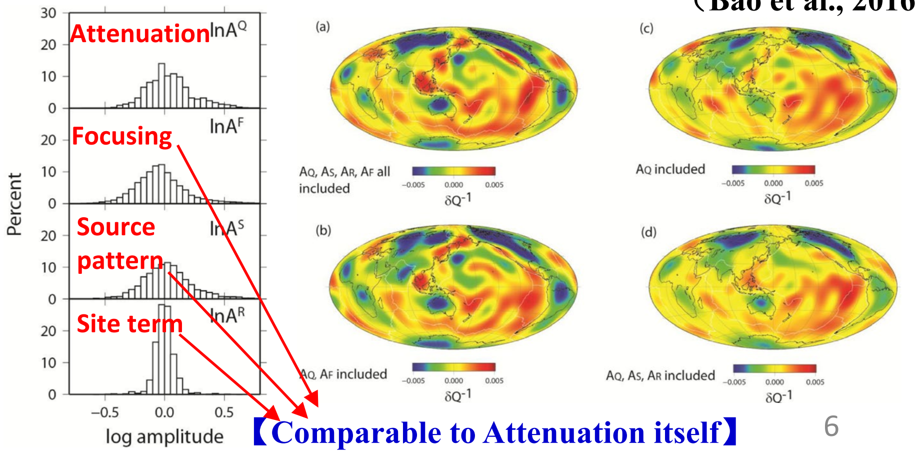
(2) For attenuation tomography

Need to consider other factors' effects on amplitudes

→Many factors (e.g., source term, site term, geometrical spreading, focusing and defocusing, attenuation) affect amplitudes

→For tomography, all those factors should be considered

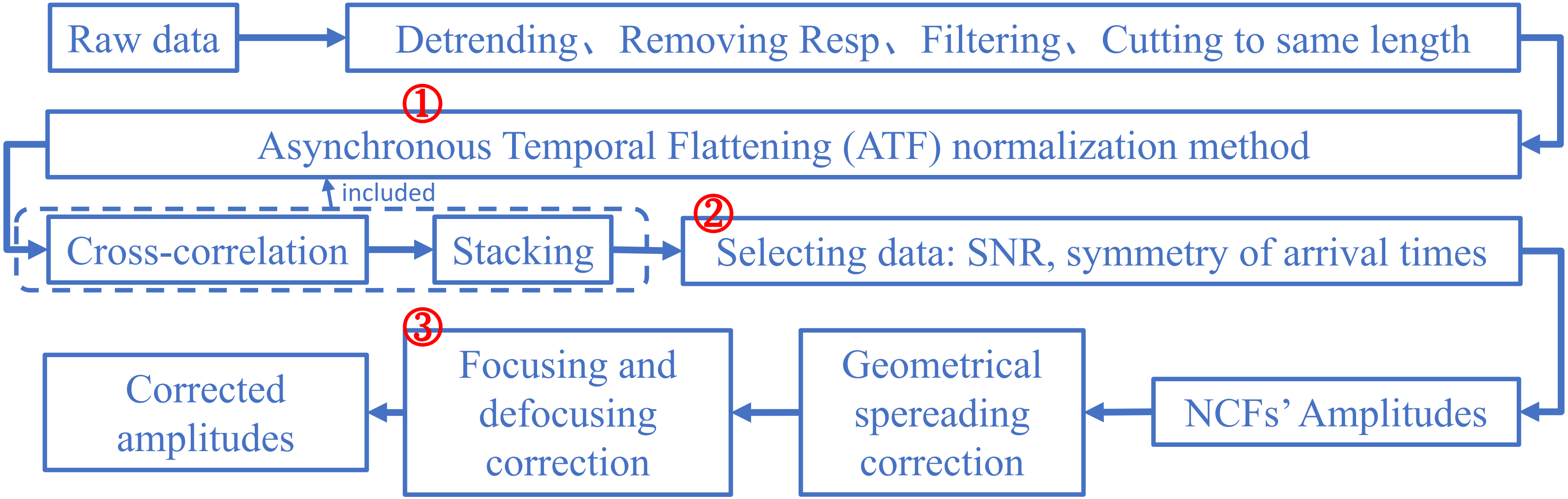
Results of global attenuation tomography: （Bao et al., 2016）



【Comparable to Attenuation itself】

Preprocessing method

Workflow： ①,②,③: major differences from standard methods (for velocity tomography)



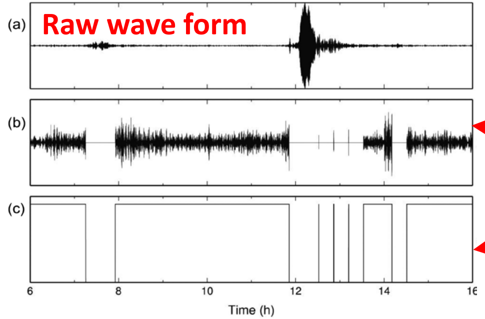
(Peng and Li, CGU 2022)

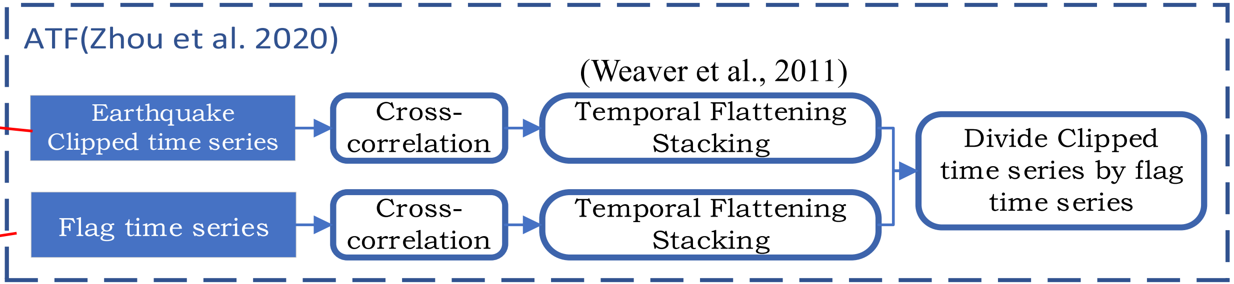
Keep balance between presperving "relative amplitude" and retriving high quality cross-correlation functions

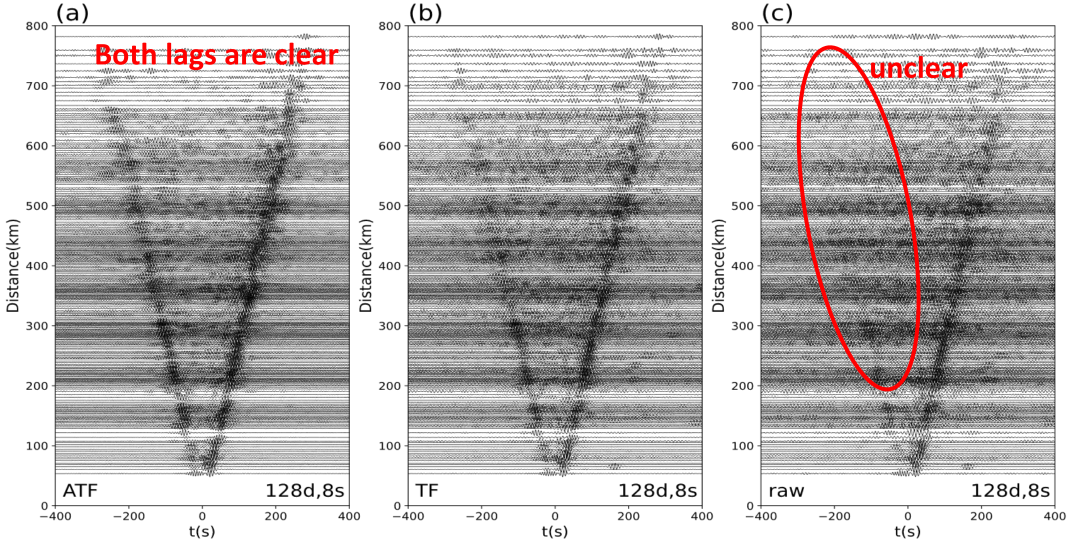
Preprocessing method

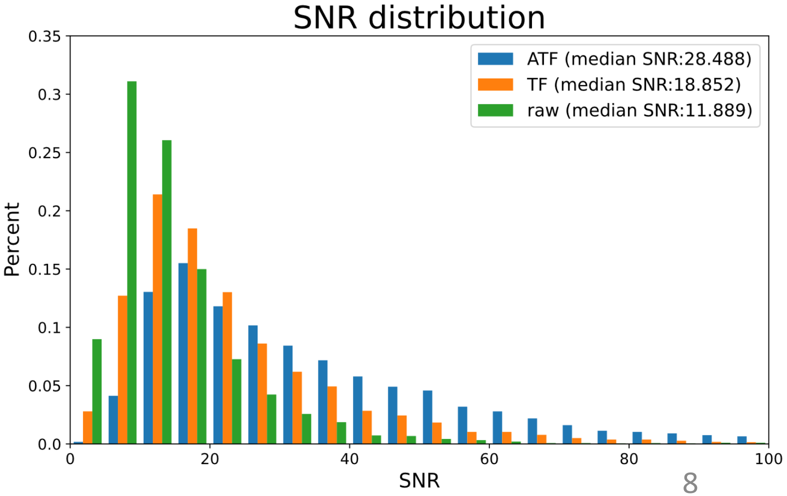
① Asynchronous Temporal Flattening

Improve SNRs, while preserving "relative amplitudes"









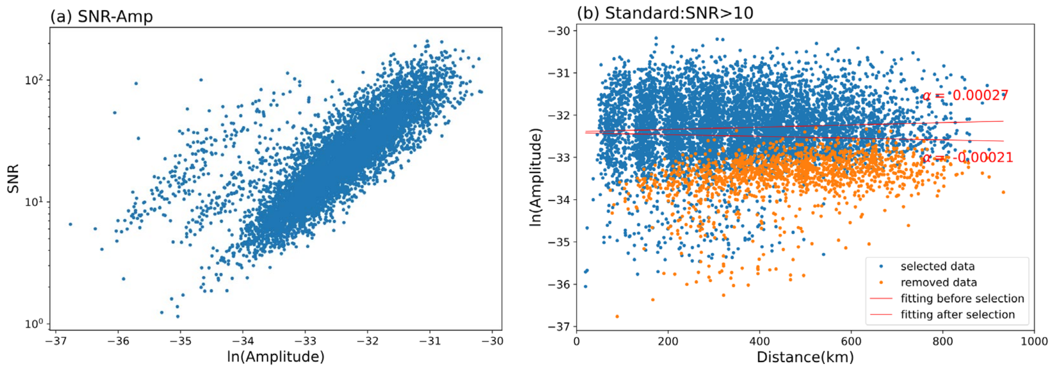
Preprocessing method

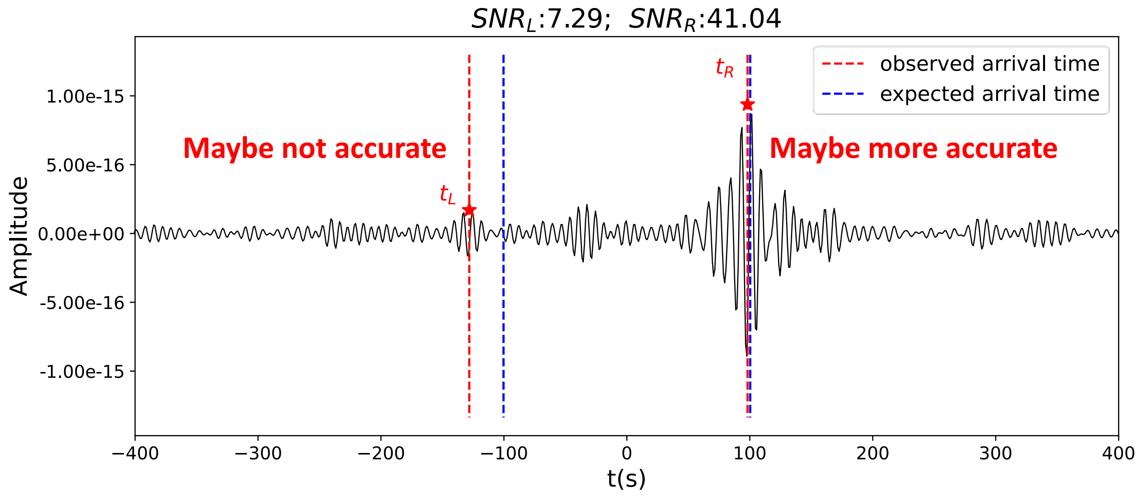
② t-symmetry criteria

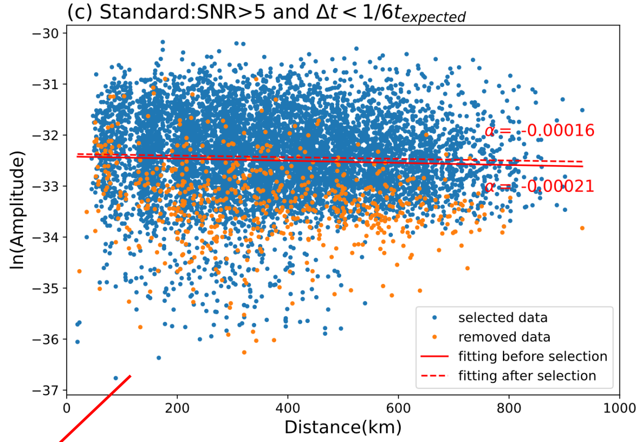
Idea: Good Cross-correlation

have similar arrival time in two lags

Setting a too high SNR threshold, will change the Amplitude-Distance relation







Selecting data with proper SNR and t-symmetry threshods, won't bias Amplitude distribution

Preprocessing method

③ Correction of focusing and defocusing

Focusing and defocusing：

Wave filed energy distribution change caused by lateral inhomogeneity of velocity

Estimation of focusing and defocusing

- Ambient noise data → Noise cross-correlation (Bensen et al. 2007) → Dispersion curves
- Dispersion curves → Surface wave tomography (Yanovskaya et al. 2007) → Velocity model → Estimation of focusing by 2D sensitivity kernel (Zhou et al. 2004)

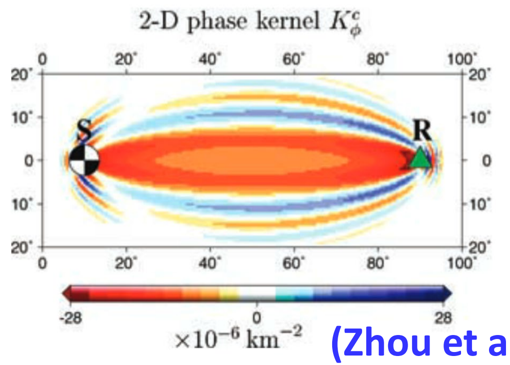
Focusing and defocusing

$$\delta d(\omega) = \int\int_{\Omega} K_d^c(\hat{\mathbf{r}}, \omega)\left(\frac{\delta c}{c}\right) d\Omega,$$

$$K_\phi^c(\hat{\mathbf{r}}, \omega) = \mathrm{Im}\left(\frac{2k^2 \mathcal{S}'\mathcal{R}'' e^{-i[k(\Delta' + \Delta'' - \Delta) - (n' + n'' - n)\pi/2 + \pi/4]}}{\mathcal{S}\mathcal{R}\sqrt{8\pi k(|\sin\Delta'||\sin\Delta''|/|\sin\Delta|)}}\right),$$

(Zhou et al., 2004; Bao et al., 2016)

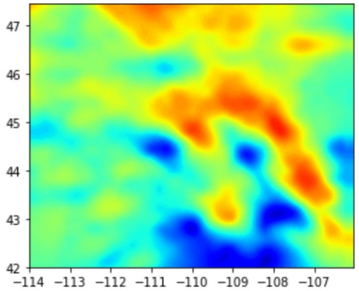
finite-frequency theory (FFT) method



(Zhou et al., 2004)

+

Phase velocity model



→ **Estimation of focusing and defocuisng**

Inversion method

$$B_i(n_{i\to j}) = B_o(\theta)\exp\left(-\int_{r_i}^{r_o} 2\alpha dx\right)$$

Obey the radiative transfer equation

（**Weaver, 2011**）

Design：

$$X_{i\to j} = s_i s_j B_i(n_{i\to j})\exp\left(-\int_{r_j}^{r_i}\alpha dx\right) \qquad (1)$$

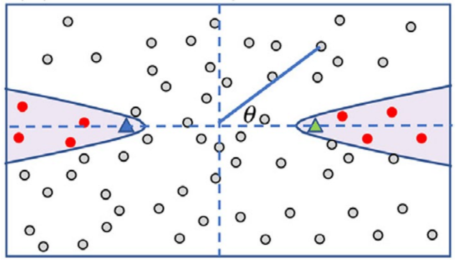
Take ln() on both sides

$$\ln(A_{ij}) = \ln(s_i) + \ln(s_j) + \ln(B_o(\theta)) - \int_{r_i}^{r_o} 2\alpha dx - \int_{r_j}^{r_i}\alpha dx + C \qquad (2)$$

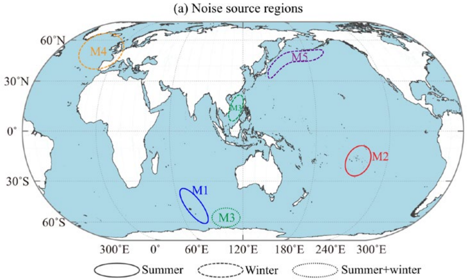
(A linear inversion system)

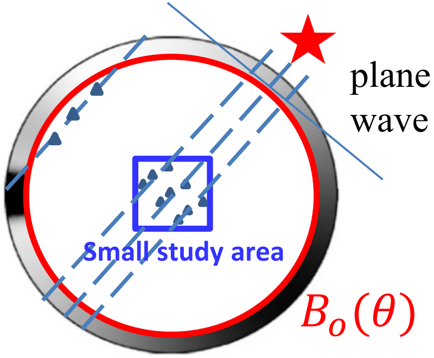
Noise intensity's variation with azimuths：

(1) cross-correlation amplitude is affected mostly by noise sources along the interstation direction



(2) Most ambient noise energy come form oceanic sources (approximate to plane waves)

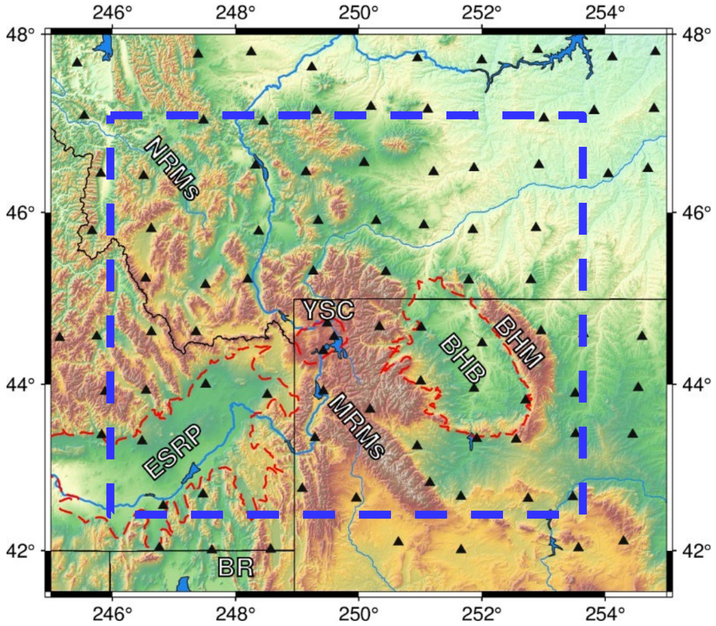




∴treat B_o as a function of azimuth θ

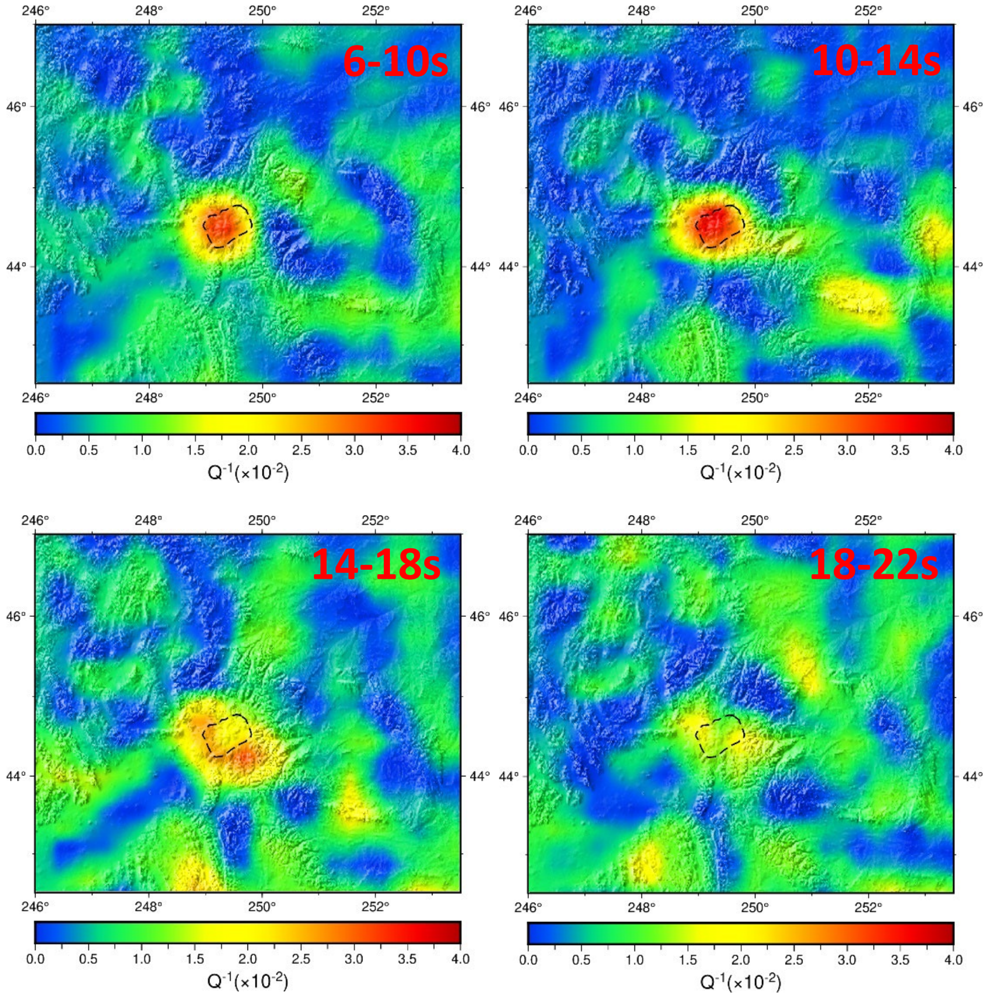
Case 1: Yellowstone

Yellowstone National park and surrounding areas：



Data set：

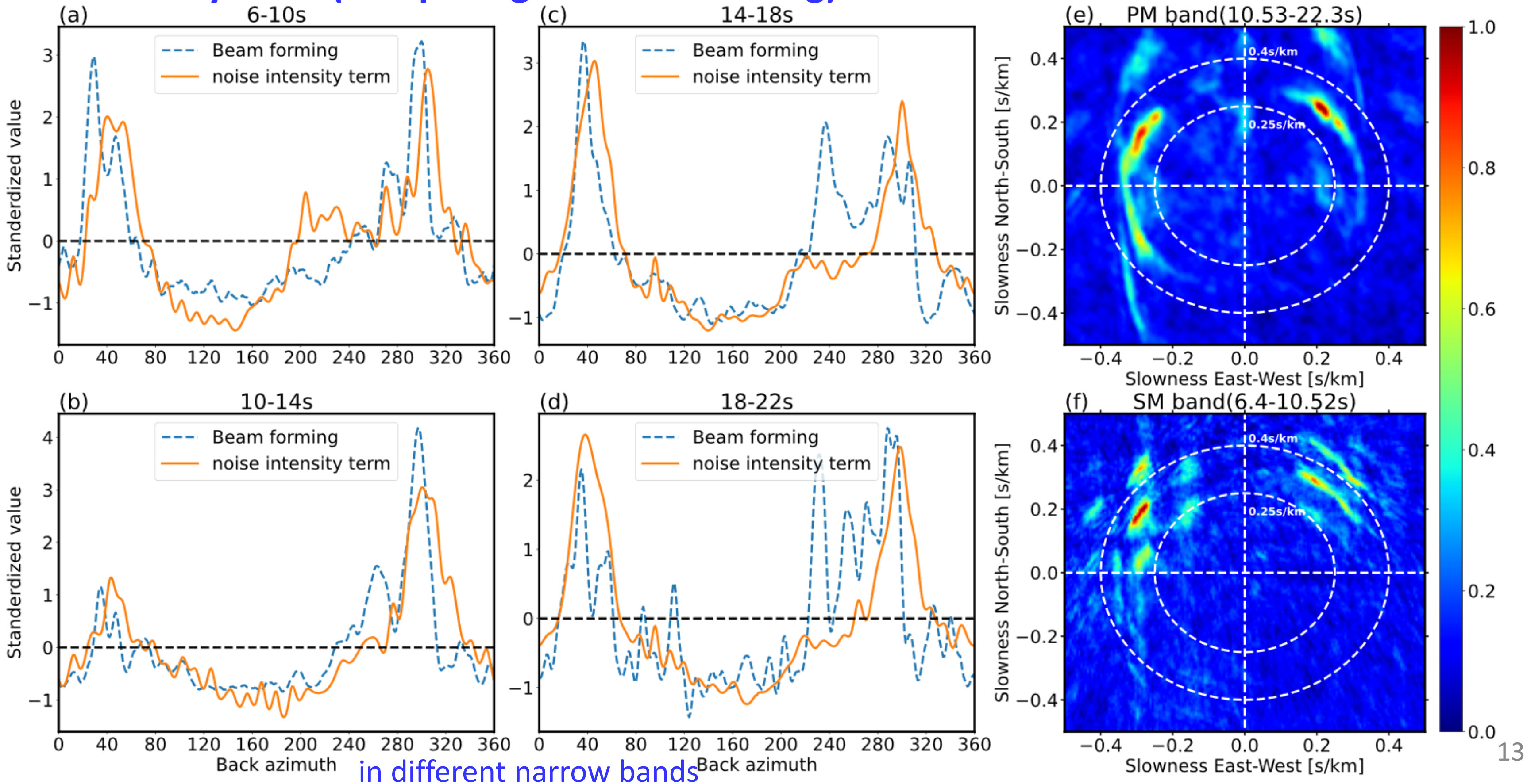
Station number： 92 stations (USArray)
Data length： about half a year
Sampling rate： 1Hz



Case 1: Yellowstone

Noise intensity term (comparing to Beamforming):

Beamforming

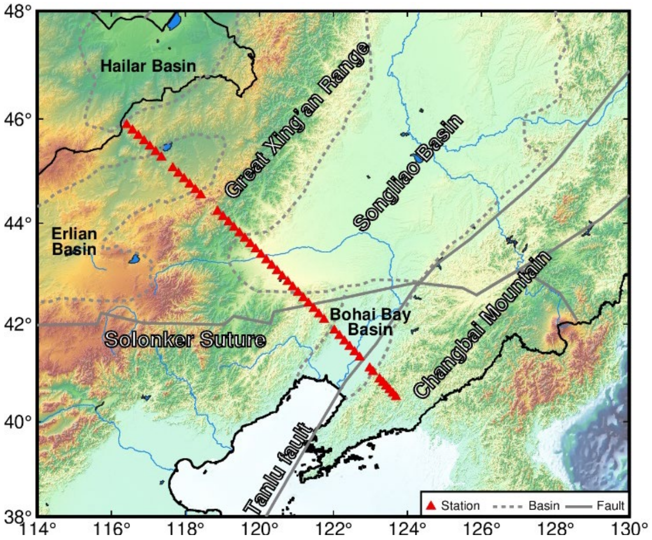


in different narrow bands

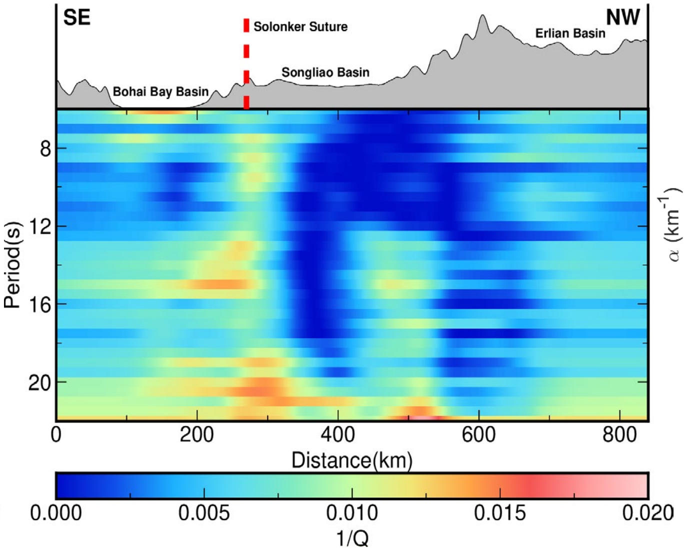
Case 2: Northeast China

$$\frac{1}{Q} = \frac{\alpha U}{\pi f}$$

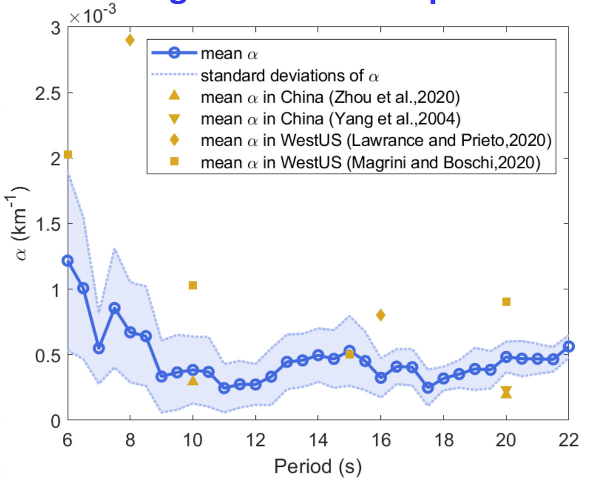
NCISP-6 array in Northeast China



1/Q in different periods



Average α in different periods



Data set:

Station number: 47 stations (from NCISP-6)
Data length: about three months
Sampling rate: 40hz downsampled to 1hz

$\alpha - period$:
fast decrease in short periods, gradual change in longer periods

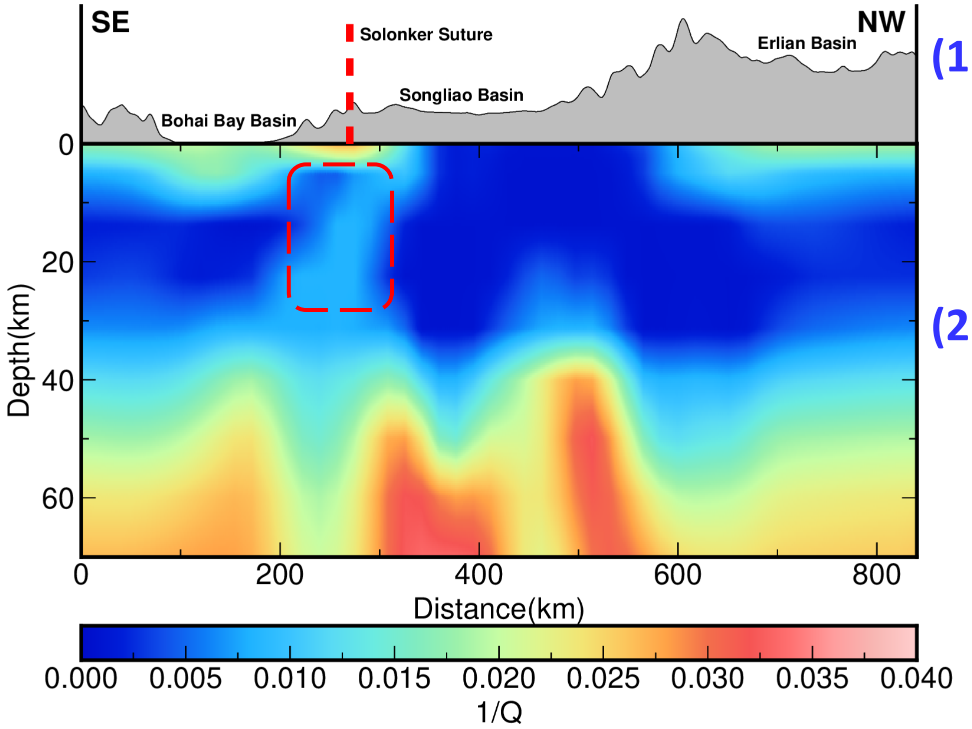
Case 2： Northeast China

Inversion to Qs in different depth:

$$Q_R^{-1} = \sum_l \left(\frac{\beta_l}{c_R} \frac{\partial c_R}{\partial \beta_l} \right) Q_{\beta l}^{-1} + \sum_l \left(\frac{\alpha_l}{c_R} \frac{\partial c_R}{\partial \alpha_l} \right) Q_{\alpha l}^{-1},$$

$\frac{\partial c_R}{\partial \alpha_l} \approx 0$

(Anderson et al., 1965)
(Liu et al., 2022)



(1) Q change markedly with depth

- **Sediment layer**: about 60~40
- **Crust**: more than 100, 350 in average
- **Upper mantle**: about 80~30

(2) Q correspond well with geological structures

- **Bohai Bay Basin, Erlian Basin**: high attenuation
- **Solonker Suture**: high attenuation in crust
- **Deeper Moho in NW**: lower attenuation to deeper layers
- (Songliao Basin did not show high attenuation, which might because this profile is near the basin’s edge)

S wave velocity model and phase velocity model are refer from（Guo et al., 2016）

Discussion and Summary

- Using proper preprocessing method, we can derive reliable amplitude information from ambient noise.
- Besides attenuation, other factors also affect wave amplitudes. It is necessary to take those factors into account before or during inversion
- Attenuation tomography based on ambient noise can give reasonable results，which correspond well with geological structure in middle and upper crust.

Thank you for your attention!

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