Redshift of Earthquakes via Focused Blind Deconvolution of Teleseisms

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Collaborators: Chunfang Meng, Michael Fehler, Laurent Demanet and Aimé Fournier

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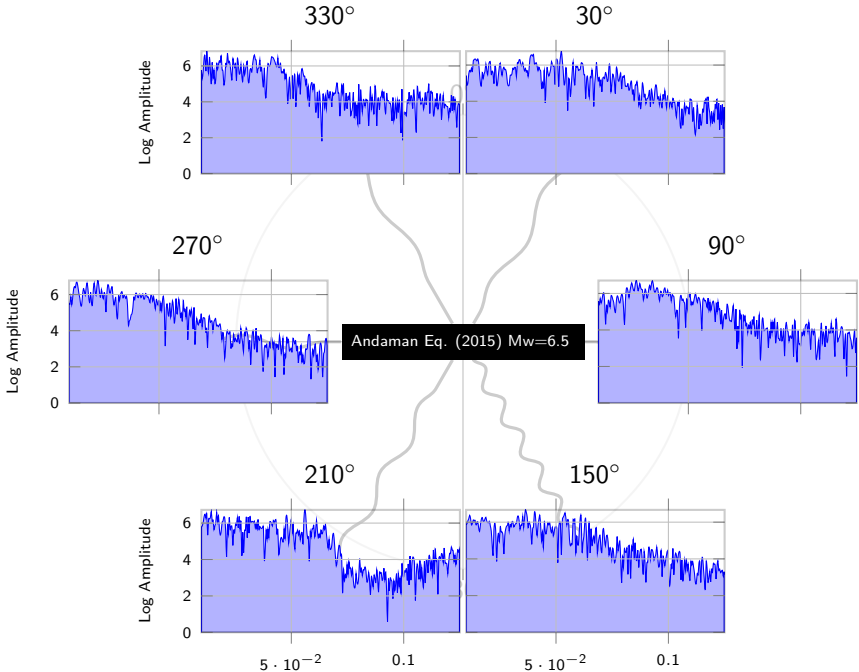
330°
30°
270°
90°
210°
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Log Amplitude
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2
4
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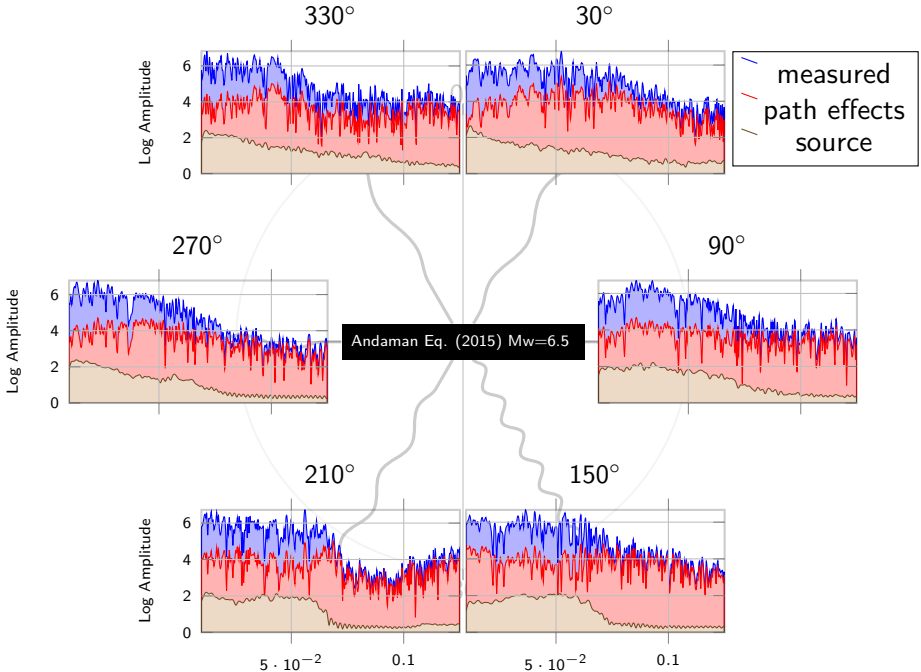
Andaman Eq. (2015) Mw=6.5
$5 \cdot 10^{-2}$
0.1


330°
30°
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Log Amplitude
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path effects
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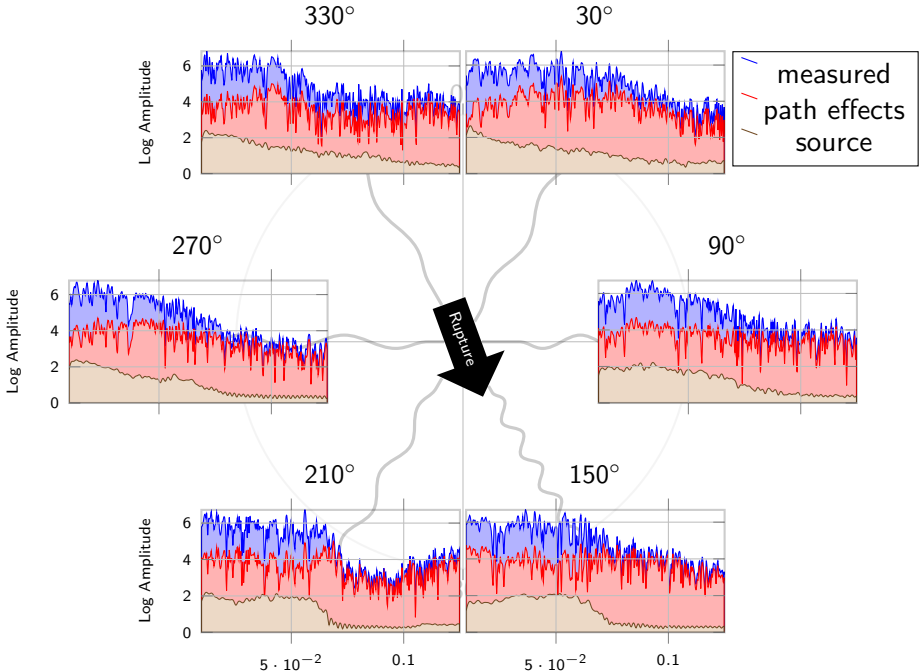
0.1


330°
30°
270°
90°
210°
150°
Log Amplitude
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2
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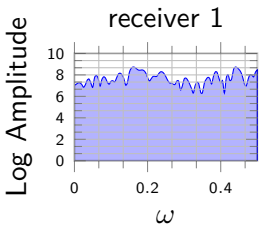
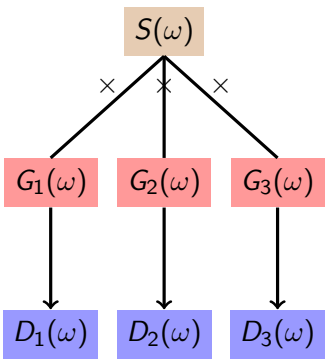
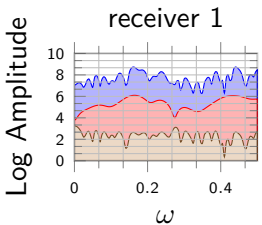
measured
path effects
source
Rupture
$5 \cdot 10^{-2}$
0.1

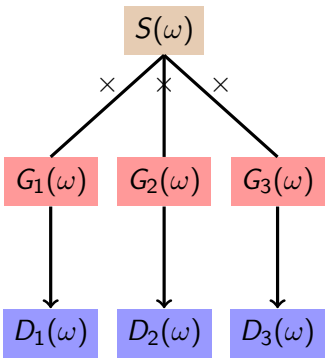
Thought Experiment: Multichannel Spectral Factorization





Thought Experiment: Multichannel Spectral Factorization





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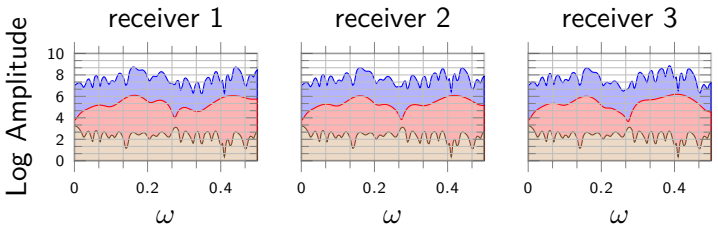

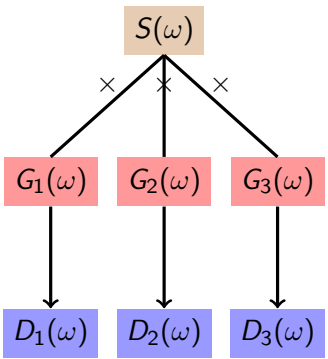

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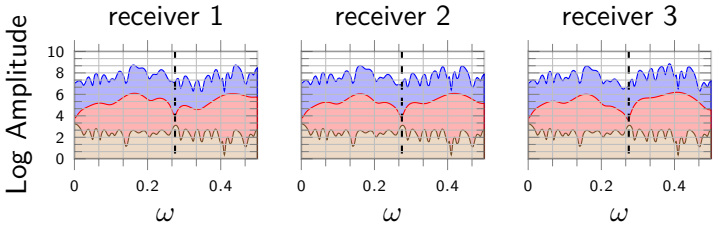
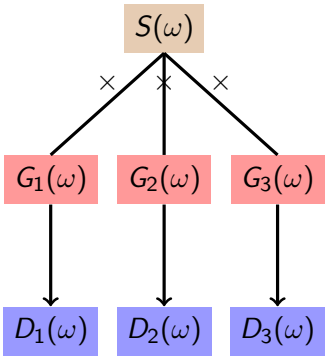
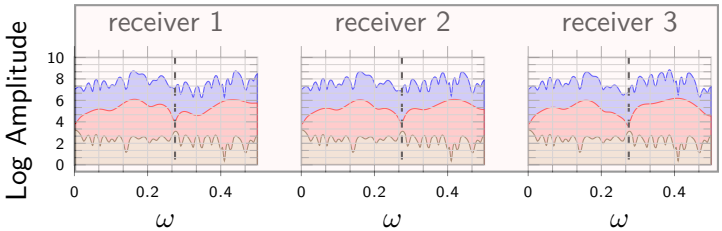
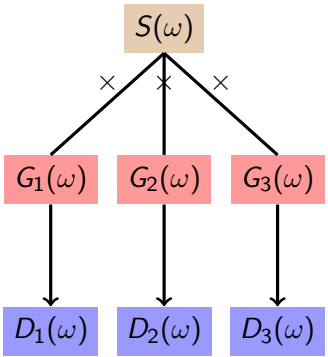




Thought Experiment: Multichannel Spectral Factorization

rejected as $G_i(\omega)$ are *similar*





Thought Experiment: Multichannel Spectral Factorization

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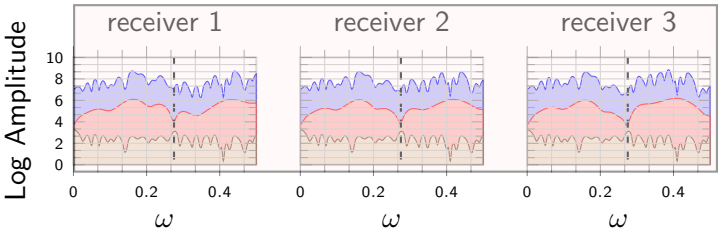
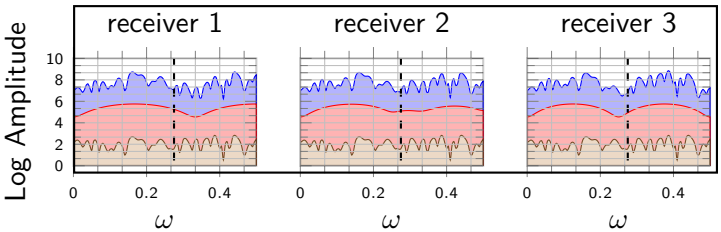
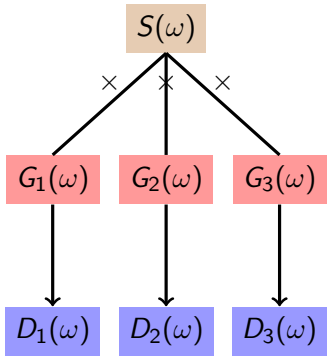


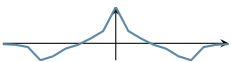
$\cdots$ until *dissimilar* $G_i(\omega)$ (this talk)



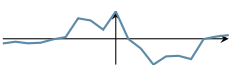


· · · Interferometric Problem in Time Domain

$\{d_1 \otimes d_1\}(\tau)$



$\{d_1 \otimes d_2\}(\tau)$



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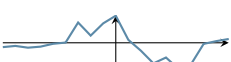
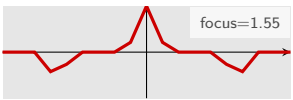


$\{g_1 \otimes g_1\}(\tau)$



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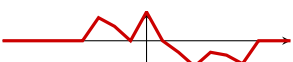
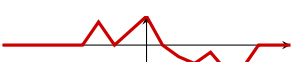
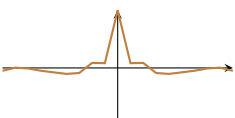


$\{g_1 \otimes g_3\}(\tau)$

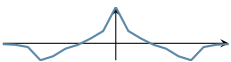


$\{s \otimes s\}(\tau)$

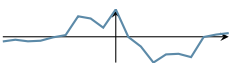


Undesired Factorization 1: Defocused $g_i \otimes g_i$

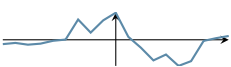
$\{d_1 \otimes d_1\}(\tau)$



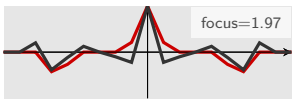
$\{d_1 \otimes d_2\}(\tau)$



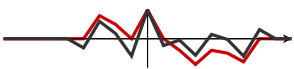
$\{d_1 \otimes d_3\}(\tau)$



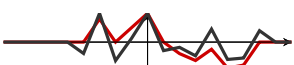
$\{g_1 \otimes g_1\}(\tau)$



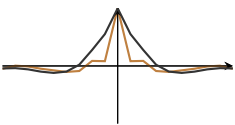
$\{g_1 \otimes g_2\}(\tau)$



$\{g_1 \otimes g_3\}(\tau)$

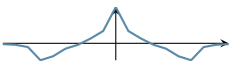


$\{s \otimes s\}(\tau)$

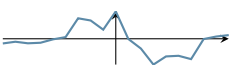


Undesired Factorization 2: Defocused $g_i \otimes g_i$

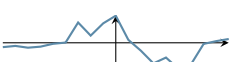
$\{d_1 \otimes d_1\}(\tau)$



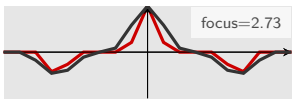
$\{d_1 \otimes d_2\}(\tau)$



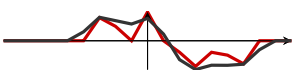
$\{d_1 \otimes d_3\}(\tau)$



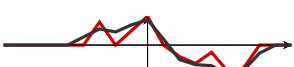
$\{g_1 \otimes g_1\}(\tau)$



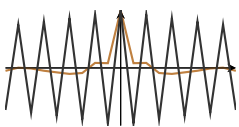
$\{g_1 \otimes g_2\}(\tau)$



$\{g_1 \otimes g_3\}(\tau)$



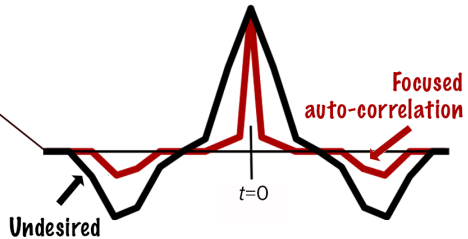
$\{s \otimes s\}(\tau)$



Novel Idea: Focusing[1] in Deconvolution Promotes Dissimilar Path Effects

Maximally White Green's Function

Energy focusing in FBD near the zero lag of the auto-correlated Green's function results in a sparse recovery.



[1] Bharadwaj, Demanet & Fournier 2018, Focused Blind Deconvolution, IEEE Trans. on Signal Processing

Focused Interferometric Blind Deconvolution[2]

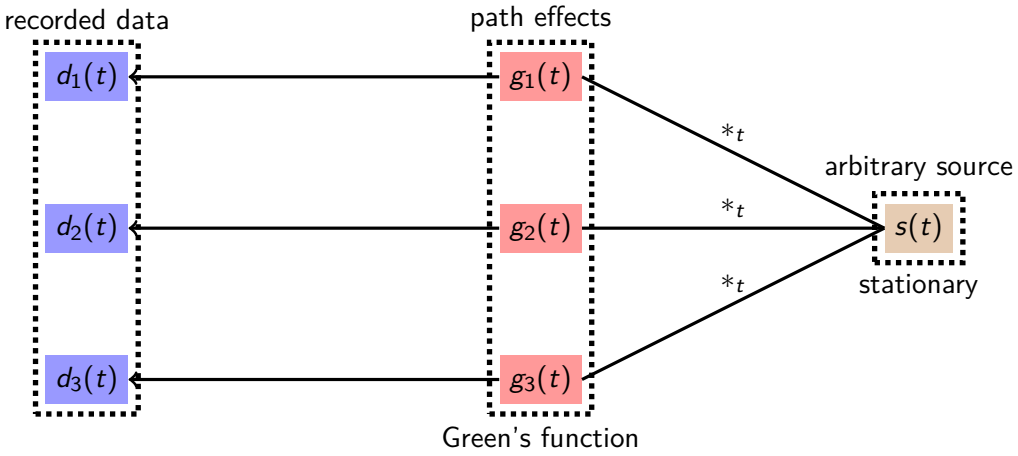
Definition

$$\arg\min \sum_{k,l} \sum_{\tau} \{\{d_k \otimes d_l\}(\tau) - \{\{s \otimes s\} * \{g_k \otimes g_l\}\}(\tau)\}^2 + \alpha \underbrace{\sum_{k} \sum_{\tau} t^2 \{g_k \otimes g_k\}^2(\tau)}_{\text{Maximally White}}$$

[2]Bharadwaj, Demanet & Fournier 2018, Focused Blind Deconvolution, IEEE Trans. on Signal Processing

Focused Blind Deconvolution

Factorize Measurements Into Source and Path Effects



Focused Blind Deconvolution

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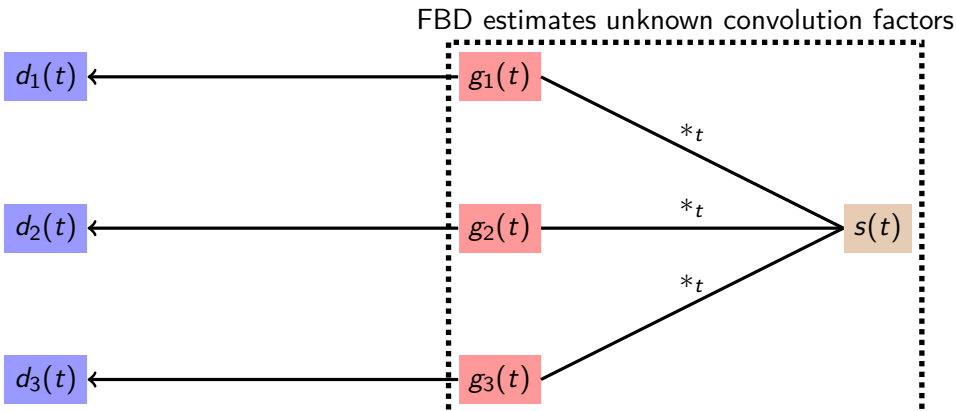
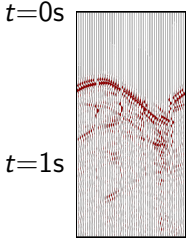


Focused Blind Deconvolution

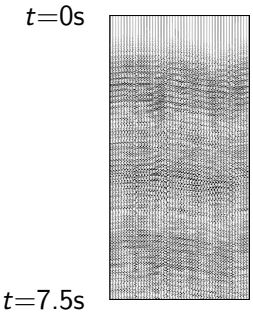
Data-Driven Green's Function Retrieval from the Multi-Channel Seismic Data of a Noisy Source

Marmousi Model

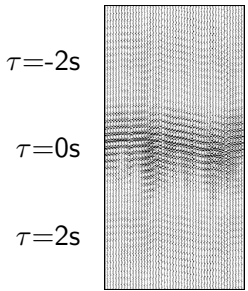
Green's Function



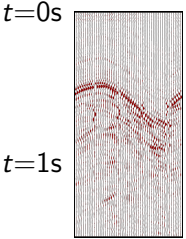
Recorded Noise



Cross-correlation
With Pilot Record

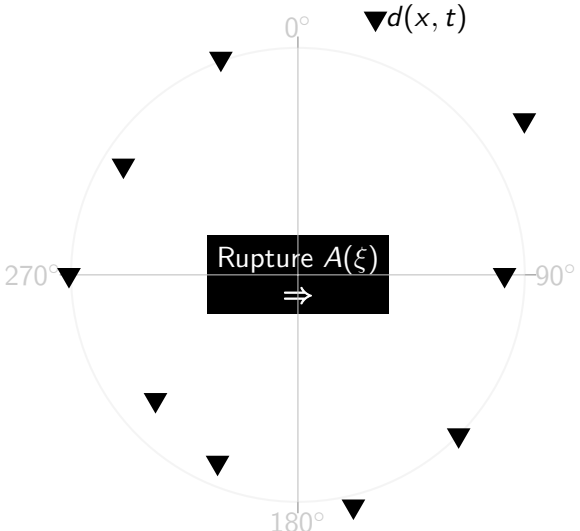


FBD of Noise



Next Section

Redshift in an Earthquake Spectrum



For a single fault with moment density tensor m, assuming instantaneous slip at ξ:

$$d^i(x,\xi;t) \approx A(\xi) \sum_{j,k} g^{ij,k}(x,\xi;t)\, m^{jk}.$$

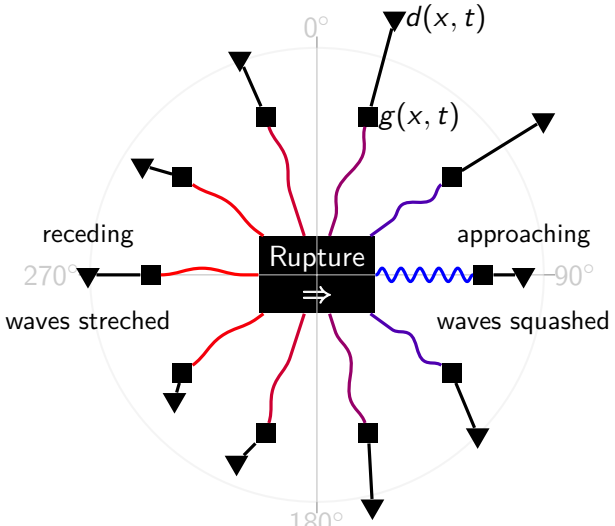
↓ Fraunhofer approx. summing over ξ

$$d(x,t) \approx s\left(\frac{c_r t}{\gamma}\right) *_t g(x,t)$$

$$\gamma = 1 - \frac{c_r}{c}\cos(\theta - 90)$$

The apparent source pulse emitted at a given direction θ is given by s, depending on the rupture velocity c_r.

Redshift in an Earthquake Spectrum



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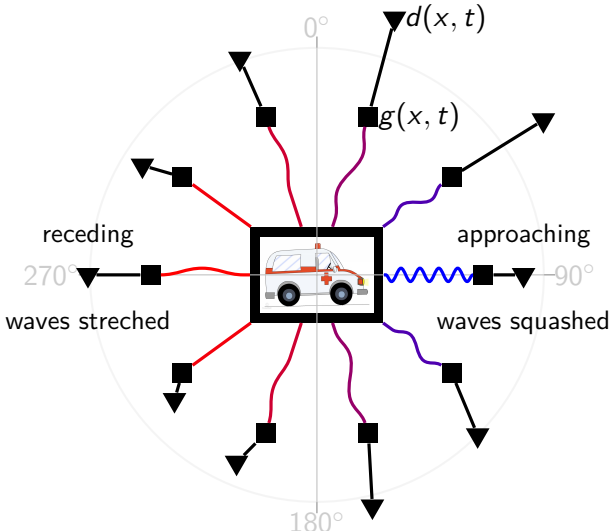
Redshift in an Earthquake Spectrum



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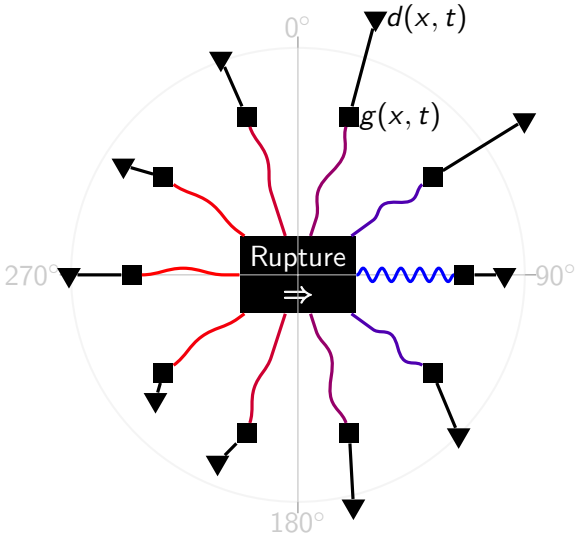
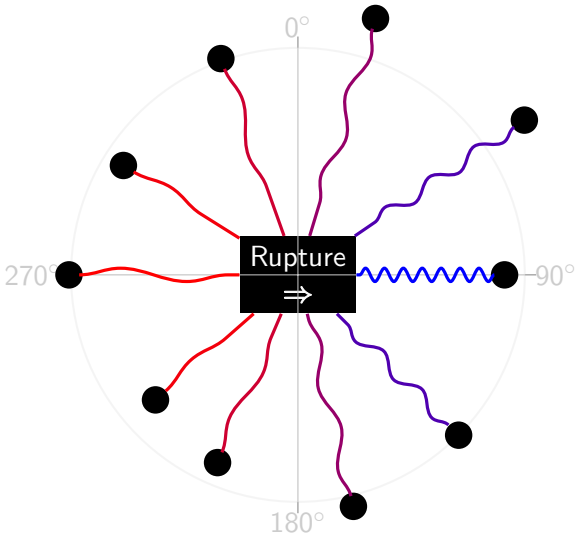


Aim: quantify the redshift to infer
a) the speed of rupture;
b) the direction of rupture propagation;
c) time duration of the apparent source function s.

Problem: propagation effects due to $g(x,t)$.

Solution: summon Focused Blind Deconvolution.

Redshift in an Earthquake Spectrum



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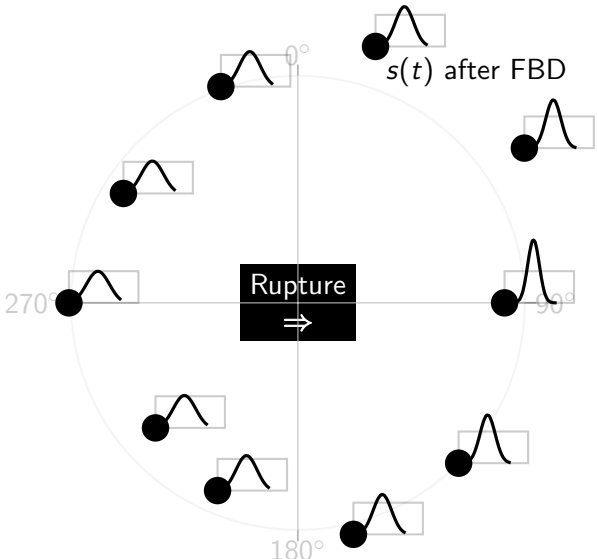
Redshift in an Earthquake Spectrum



Aim: quantify the redshift to infer
a) the speed of rupture;
b) the direction of rupture propagation;
c) time duration of the apparent source function s.

Problem: propagation effects due to $g(x, t)$.

Solution: summon Focused Blind Deconvolution.

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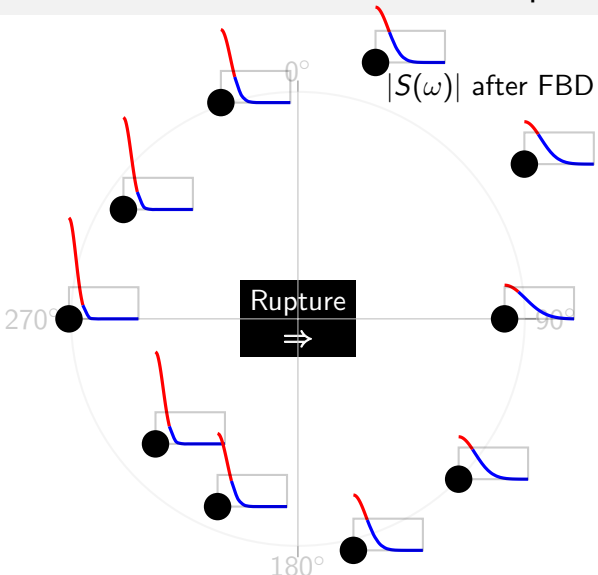

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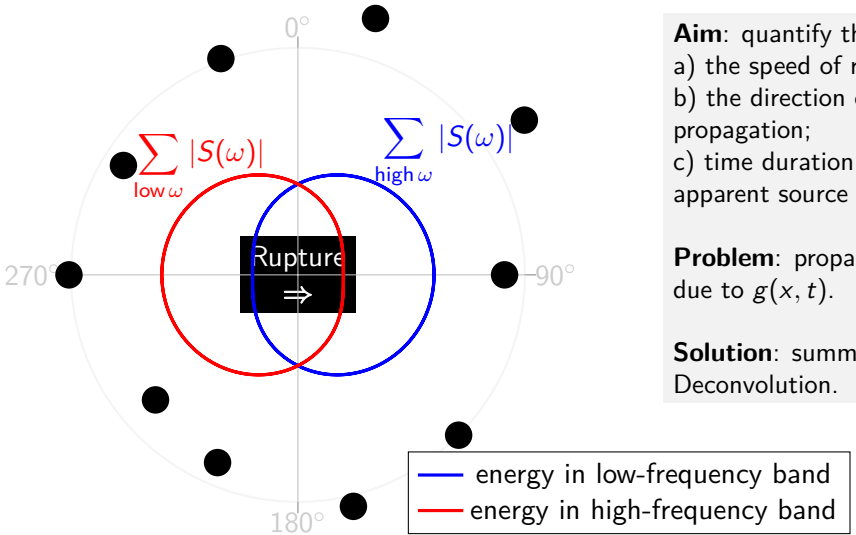

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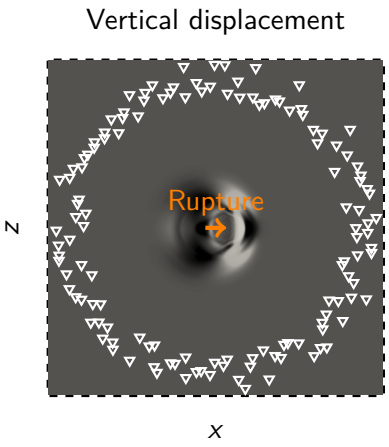
Next Section

2-D Finite Element[3] Simulation of a Rupture



[3]software: Chunfang Meng, 2019, *defmod-swpc*, A finite element and finite difference mixed code for multiphysics and multiscale crustal motions, ERL, MIT.

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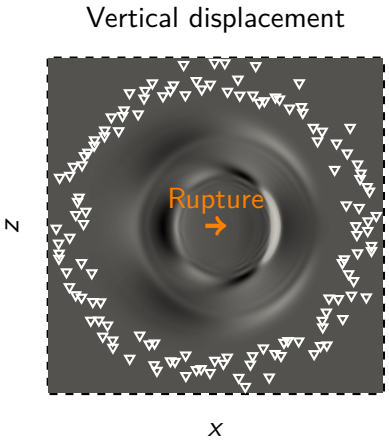

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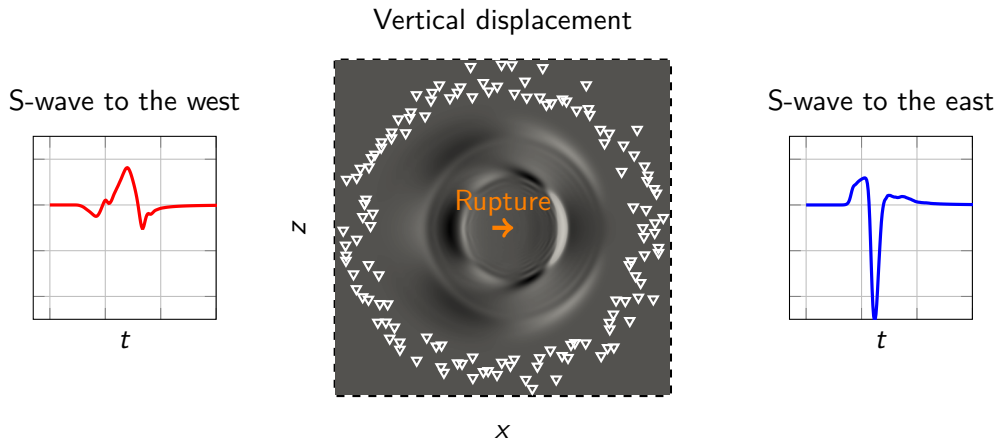

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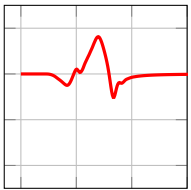
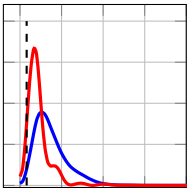
2-D Finite Element[3] Simulation of a Rupture

S-wave to the west



t

S-wave spectra



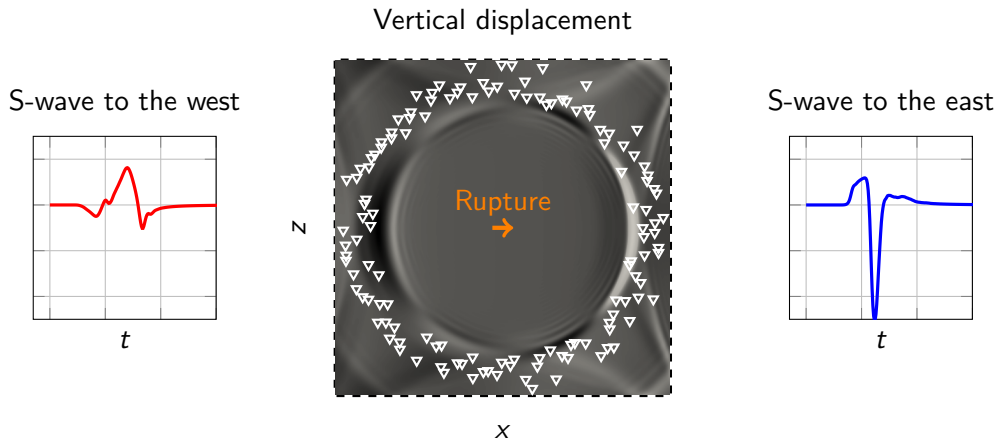
ω

S-wave to the east

t

[3]software: Chunfang Meng, 2019, *defmod-swpc*, A finite element and finite difference mixed code for multiphysics and multiscale crustal motions, ERL, MIT.

2-D Finite Element[3] Simulation of a Rupture



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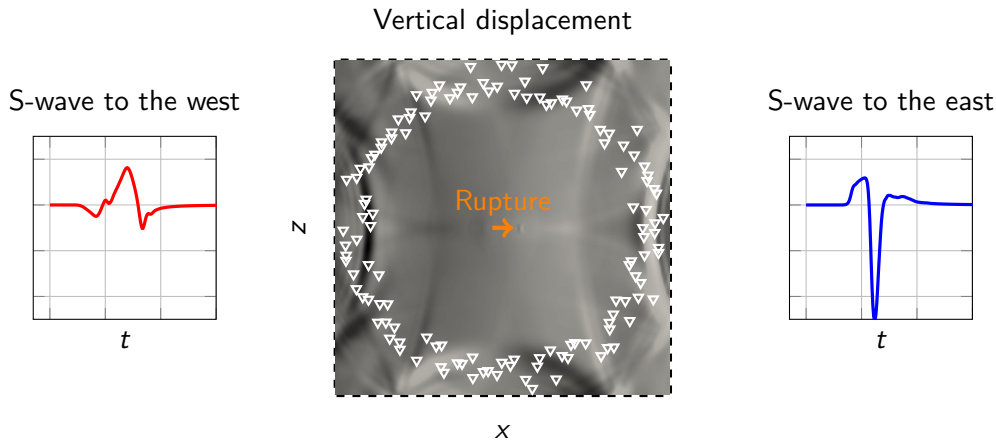

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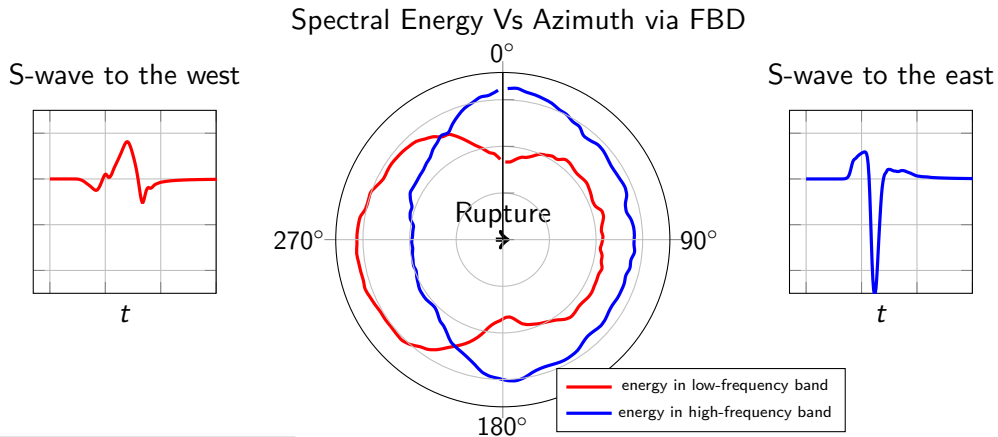

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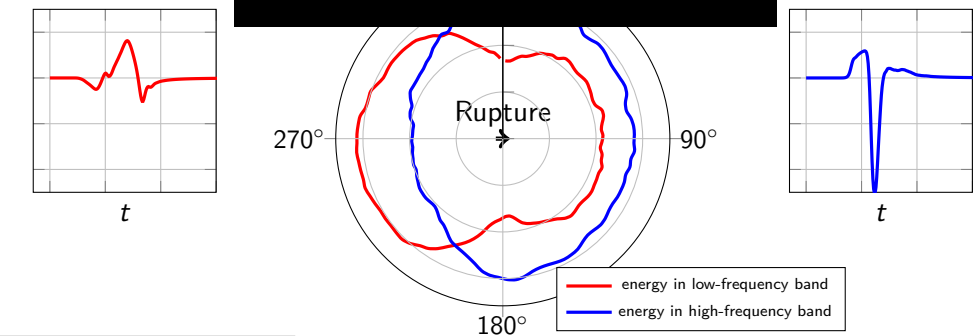
2-D Finite Element[3] Simulation of a Rupture

FBD is data-driven i.e., it doesn't demand:
→knowledge of faulting;
→synthetic Green's function modeling;
→picking phases in seismograms.

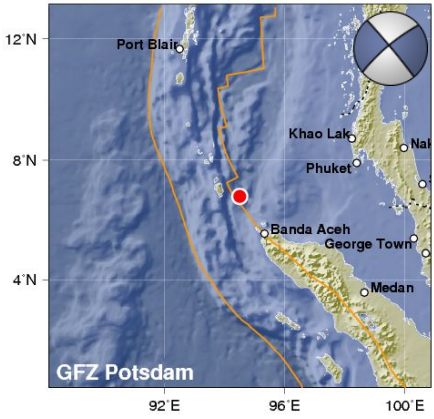


[3]software: Chunfang Meng, 2019, *defmod-swpc*, A finite element and finite difference mixed code for multiphysics and multiscale crustal motions, ERL, MIT.

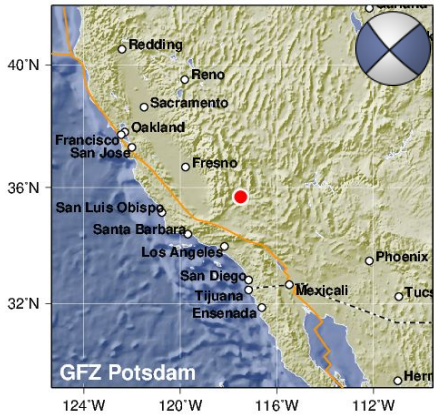
Next Section

Two Strike-Slip Earthquakes

(a) Nicobar Islands, India

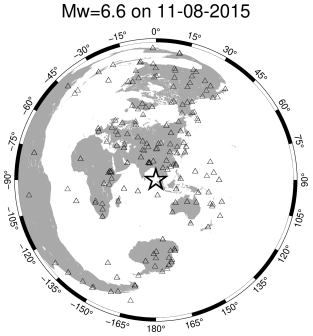


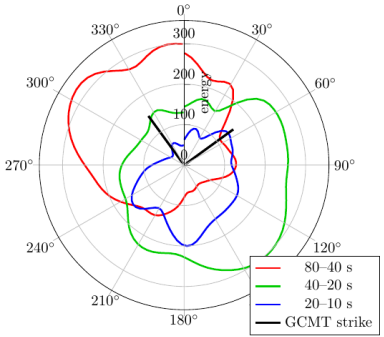
(b) California, USA



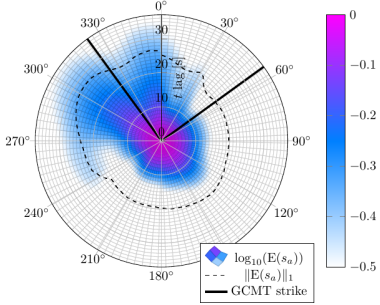
Strike-slip Earthquake in Nicobar Islands

Result:
⇒rupture velocity ≈ 2500 m/s
⇒rupture propagation direction ≈ 140°N
⇒min and max source durations: 10 & 30 seconds



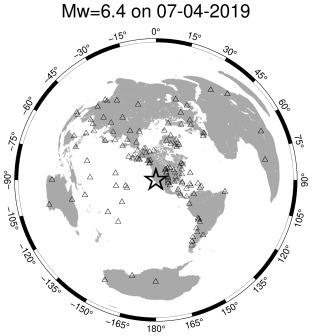


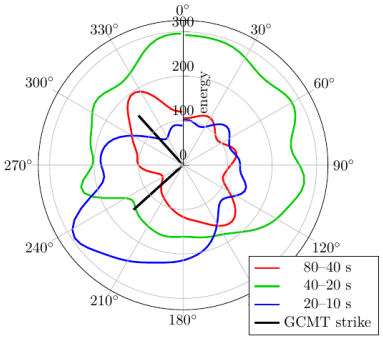
FBD estimated auto-correlated source time pulse



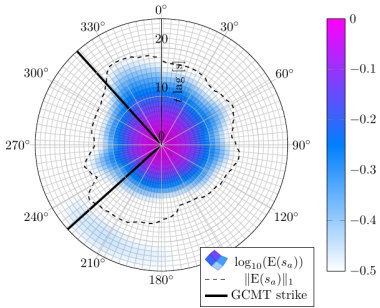
Strike-slip Earthquake — Ridgecrest Foreshock, California

Result:
⇒rupture propagation direction ≈ 230°N
⇒min and max source durations: 11 & 15 seconds



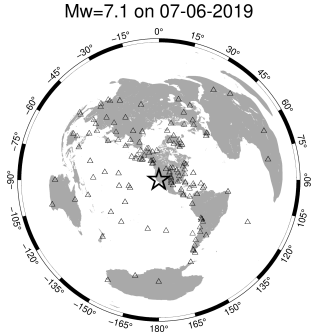


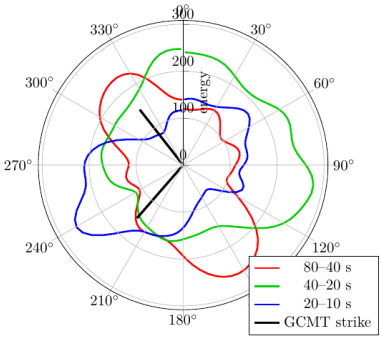
FBD estimated
auto-correlated
source time pulse



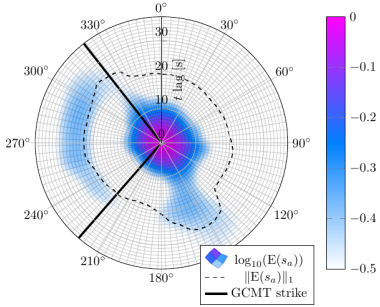
Strike-slip Earthquake — Ridgecrest Aftershock, California

Result:
⇒dominant rupture propagation direction ≈ 330°N
⇒more complicated rupture than the foreshock



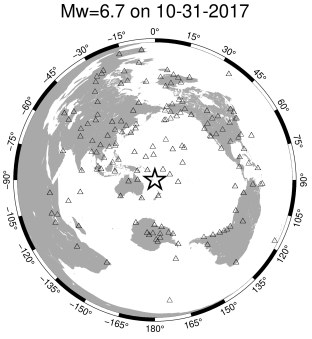


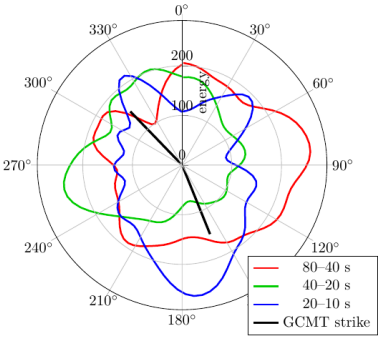
FBD estimated auto-correlated source time pulse



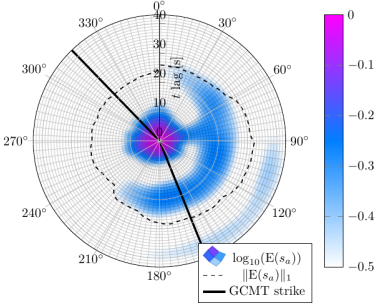
Loyalty Islands

Result:
⇒rupture halted between the first and second subevents
⇒duration of silence is about 5 seconds



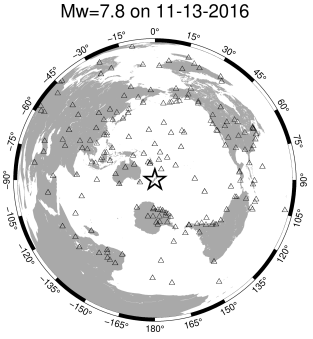


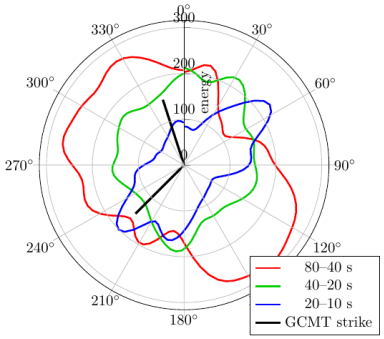
FBD estimated
auto-correlated
source time pulse



Kaikoura Earthquake in Christchurch, New Zealand

Result:
⇒multiple modes of rupture
⇒rupture halted between the first and second subevents
⇒propagating towards NNE





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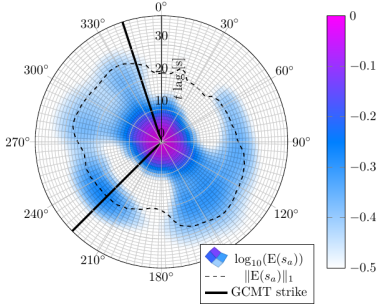

Next Section

Conclusions

Focused Blind Deconvolution (FBD):

- ➔ achieves data-driven separation of path effects from the multi-channel seismic data to infer the source characteristics,
- ➔ as it doesn't demand unrealistic assumptions either on the source mechanism or the subsurface models.

Redshift:

- ➔ it is an increase in wavelength, equivalent to a decrease in frequency, of a far-field seismic source pulse emitted due to a spreading rupture;
- ➔ we have employed FBD for its estimation and therefore accurate determination of the velocity of rupture propagation.

Acknowledgements

➔ Many thanks to Matt Li, Aurelien Mordret, Tom Herring, Hongjian Fang and Charles-Henri Clerget in MIT.

➔ This project was funded by Equinor.

Thank You! Any Questions?

Further Reading

- ➔ Bharadwaj, P., L. Demanet, and A. Fournier, 2019, Focused blind deconvolution: IEEE transactions on signal processing, vol. 67, no. 12, pp. 3168-3180.
- ➔ Robinson, E. A., and S. Treitel, 1980, Geophysical signal analysis: Prentice-Hall Englewood Cliffs, NJ, 263.
- ➔ Madariaga, Raul, Seismic source theory, Geophysics, 1989.

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