Regional Full Waveform Inversion with Source Encoding

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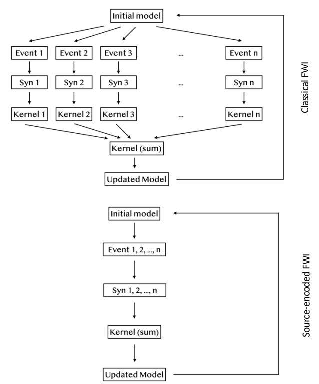
Abstract

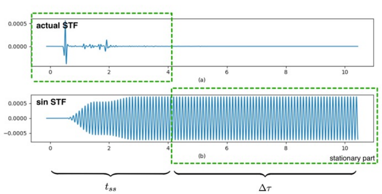
We present the results of applying source encoding technology to regional full waveform inversion (FWI). With source encoding, a kernel containing all events can be computed with only one forward and one adjoint simulation, which is a massive speedup compared to classical FWI. The region of interest spans 120 degrees, covering part of North America, Asia, and Europe. The global full waveform inversion model GLAD_M25 is used as starting model, and we selected 821,623 traces in the period band 17 s – 90 s from 786 events recorded by 11,381 stations. After 50 iterations, we see a significant data misfit reduction and sharper structural features. By comparing our new model with other existing regional and global models, we believe that source-encoded FWI has indeed moved the initial model closer to the true Earth model. Each iteration takes only ~30 minutes when running in Summit's GPU nodes, which is just a small fraction of the cost required for classical FWI. This demonstrates that source encoding can potentially bring FWI to a new level, enabling it to reach a resolution previously not computationally feasible.

Classical FWI vs source-encoded FWI



Source Encoding

Instead of using a classical source time function (STF), we assign each event with a unique frequency and run forward simulation with a monochromatic STF of that frequency. In this way, we will be able to obtain the Fourier coefficient of the seismogram at that frequency by measuring only the stationary part of the wavefield, which is also monochromatic.



When we include multiple events with evenly-spaced frequencies, we can separate individual event with an orthogonality relation:

$$\frac{1}{\Delta\tau}\int_{t_{ss}}^{t_{ss}+\Delta\tau}\cos(\omega_s t)\cos(\omega_{s'} t)\mathrm{d}t = \frac{1}{2}\delta_{ss'}$$

$$\frac{1}{\Delta\tau}\int_{t_{ss}}^{t_{ss}+\Delta\tau}\sin(\omega_s t)\sin(\omega_{s'} t)\mathrm{d}t = \frac{1}{2}\delta_{ss'}$$

$$\frac{1}{\Delta\tau}\int_{t_{ss}}^{t_{ss}+\Delta\tau}\cos(\omega_s t)\sin(\omega_{s'} t)\mathrm{d}t = 0$$

where

$$\Delta\tau = \frac{2\pi}{\Delta\omega} \quad \omega_s = \omega_0 + s\Delta\omega$$

This integration is included the expression of kernel computation, which means that the wavefields from different events in the same simulation will not affect each other during kernel computation. This also means that the kernels computed with the encoded wavefields equal the summation of individual event kernels.

Bonus: double difference measurement

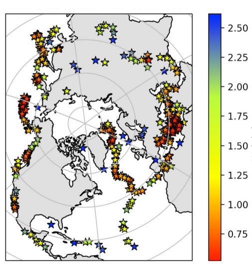
Since we are measuring only the stationary wavefield, we can cancel out the source time function term $f(x_s, \omega)$ by measuring the misfit of all station pairs.

$$s(\boldsymbol{x}, \omega) = G(\boldsymbol{x}, \boldsymbol{x}_s, \omega)\, f(\boldsymbol{x}_s, \omega)$$

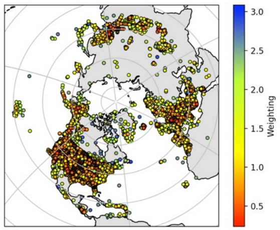
$$\frac{s_{\mathrm{obs}}(\boldsymbol{x}_B)/s_{\mathrm{syn}}(\boldsymbol{x}_B)}{s_{\mathrm{obs}}(\boldsymbol{x}_A)/s_{\mathrm{obs}}(\boldsymbol{x}_A)} = \frac{G_{\mathrm{obs}}(\boldsymbol{x}_B, x_s)/G_{\mathrm{syn}}(\boldsymbol{x}_B, x_s)}{G_{\mathrm{obs}}(\boldsymbol{x}_A, x_s)/G_{\mathrm{syn}}(\boldsymbol{x}_A, x_s)}$$

Inversion setup

We start our experiment with a regional setup because it is easier for the wavefield to reach steady state. The event and station distribution as well as their geographical weightings are shown in the figures below. The model is parameterized with transversely isotropic parameters with the assumption that anisotropy is caused only by shear wave velocity. So 4 parameters are considered: horizontal and vertical shear wave speed β_v and β_h, bulk sound speed c and dimensionless parameter η. The time to reach steady state is estimated to be 200 minutes, and we run another 288 minutes after steady state.



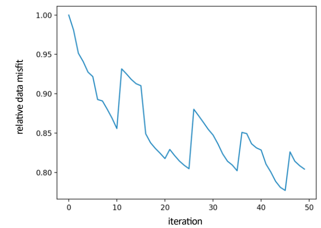
Event distribution



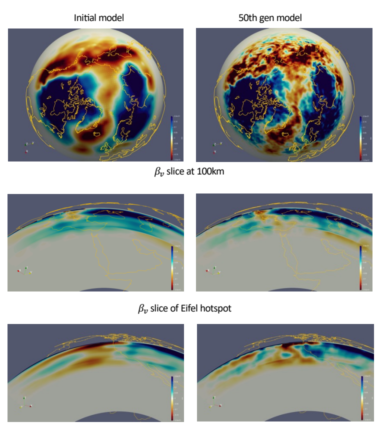
Station distribution

Data misfit

The data misfit reduction in 50 iterations is shown in the figure below. Because the frequencies are randomized every 5 iterations, we can see an increase in data misfit at these iterations which is simply caused by the change of objective function.



Model evolution



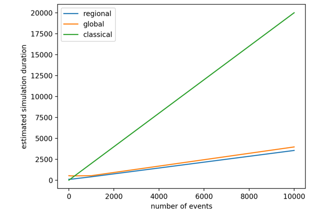
β_v slice at 100km

β_v slice of Eifel hotspot

β_v slice of Yellowstone

Computational cost

Wavefield simulation is the most expensive part of FWI. We will compare the computational cost of classical FWI and source-encoded FWI by the required duration of simulation. For classical FWI, the simulation duration for each event can be 1~2 hours. The simulation for source-encoded FWI consists of two parts: transient part, which is ~3 hours for regional model and ~12 hours for global model, and stationary part which increases linearly with the number of events. A comparison between the estimated computational cost of regional / global source-encoded FWI and classical FWI is shown below.



Conclusions

We have applied source encoding to regional full waveform inversion. After 50 iterations, there is a significant data misfit reduction and sharper structural features are revealed. This is achieved with a negligible computational cost compared to classical FWI. We are still further investigating the stability and applicability of source encoding and we are positive that source encoding could be a powerful tool to obtain high resolution Earth structure.

References

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