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A New Random Boundary Condition for Reverse Time Wave Reconstruction

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Abstract Summary

We propose a Random Boundary Condition for wavefield reconstruction, designed to suppress boundary reflections through physics-informed randomness. Grain structures are generated using Poisson disk sampling and modulated by local velocity and frequency, introducing Gaussian perturbations. The method enhances energy dissipation and coherence loss at model edges. Synthetic tests, including Marmousi2, demonstrate improved image quality using a boundary size of four wavelengths. The approach is efficient, tunable, and extendable to 3D and elastic simulations.

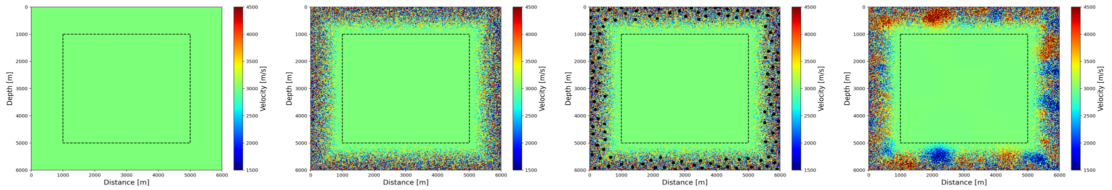
Introduction

The Random Boundary Condition (RBC), originally proposed by Clapp (2009), provides an efficient strategy for reducing memory usage and data transfer in Reverse Time Migration (RTM) by introducing randomized perturbations to suppress boundary reflections during seismic wave simulations. This allows for wavefield reconstruction during imaging procedures such as cross-correlation or gradient computation in Full Waveform Inversion (FWI) (Shen and Clapp, 2015). The method's effectiveness depends on the concept of grain size, introduced by Shen and Clapp (2011), which relates the spatial scale of randomization to model parameters like velocity and frequency. RBC has since been extended to elastic media (Clapp and Alves, 2016) and its ability to attenuate boundary-related noise has been validated in recent studies (Xu and He, 2022). In this study, we present an implementation of RBC for acoustic RTM using cross-correlation imaging. Grain locations are computed via Poisson disk sampling (Wei, 2008), with sizes determined by dominant frequency and mean velocity, followed by Gaussian perturbations to enhance wavefield scattering. Synthetic experiments confirm the influence of boundary size and demonstrate the RBC's effectiveness in improving migration image quality.

Methodology

A boundary delimitation function is defined to smoothly transition from zero at the model edges to one within the boundary region. This function modulates a linear scaling factor that controls the degree of randomization as the wave moves away from the computational domain. A maximum velocity perturbation is specified, and a normal distribution is applied where the mean corresponds to the local model velocity and the standard deviation is scaled by the boundary function. This results in background noise that is smooth near the edges and becomes progressively more variable farther from the domain. Following this, a sampling ratio is computed based on the dominant frequency and mean velocity, ensuring adherence to Poisson disk sampling criteria. Sampling points are distributed over half of the boundary region. Each point is assigned a Gaussian perturbation with a random standard deviation, a random amplitude within the defined velocity variation limits, and a random polarity to further disrupt coherent wave fronts.

Figure 1 illustrates each step in constructing the RBC, using a model with dimensions of 6 km $\times$ 6 km, a spatial discretization of 20 m, and a boundary width of 1 km. In the results section, we first analyze the energy decay in the Fourier spectrum using this homogeneous model. Next, a boundary size study is conducted, using a diffractor point model, to determine the minimum boundary width that begins to improve the migrated image. Finally, a synthetic migration of the Marmousi2 model is carried out to assess the impact of the RBC on the final image quality.



(a) (b) (c) (d)

Figure 1: Example of boundary construction using the same dimensions as in Shen and Clapp (2015). (a) boundary delineation, (b) addition of background noise, (c) Poisson disk sampling, and (d) application of Gaussian functions with random polarity and standard deviations.

Results

Figure 2 presents the energy dissipation test, using the configurations illustrated in Figure 1. A maximum velocity variation of 1.5 km/s is applied, with a maximum point spacing (ratio) of 300 m, corresponding to the wavelength at the dominant frequency of 10 Hz. A single shot without the RBC results in maximum energy retention. When the RBC is applied to a single shot, noticeable energy dissipation occurs. With a mean of 16 shots superimposed (Fig. 2(c)), the residual energy approaches zero, demonstrating the effectiveness of the RBC in attenuating wave energy.

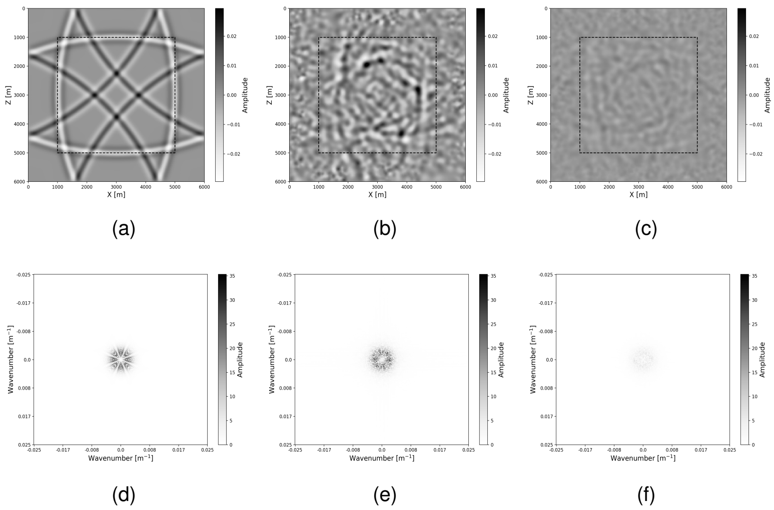


Figure 2: Energy test proposed in Shen and Clapp (2015). (a) and (d) are snapshot and Fourier transform for one shot without RBC. (b) and (e) are snapshot and Fourier transform for one shot with RBC. (c) and (f) are snapshot at time 2 s and the Fourier transform for 16 shots summed with RBC.

Figure 3 summarizes the test conducted to evaluate the effectiveness of the RBC as a function of boundary size, expressed in meters. We perform RTM in a diffractor point model with 500 m/s of velocity contrast positioned at 3.8 km in depth. Each maximum frequency tested corresponds to a specific dominant frequency, estimated as 30% of the maximum frequency. Using the relation $\lambda = v/f$, where v is velocity and f is dominant frequency, we define the sampling ratio and construct a matrix of scenarios: one column without RBC, and additional columns with boundary sizes equal to two, three, and four times the ratio, respectively. The boundary sized at four times the sampling ratio yielded the best results, producing cleaner migrated images in this test with only three shots.

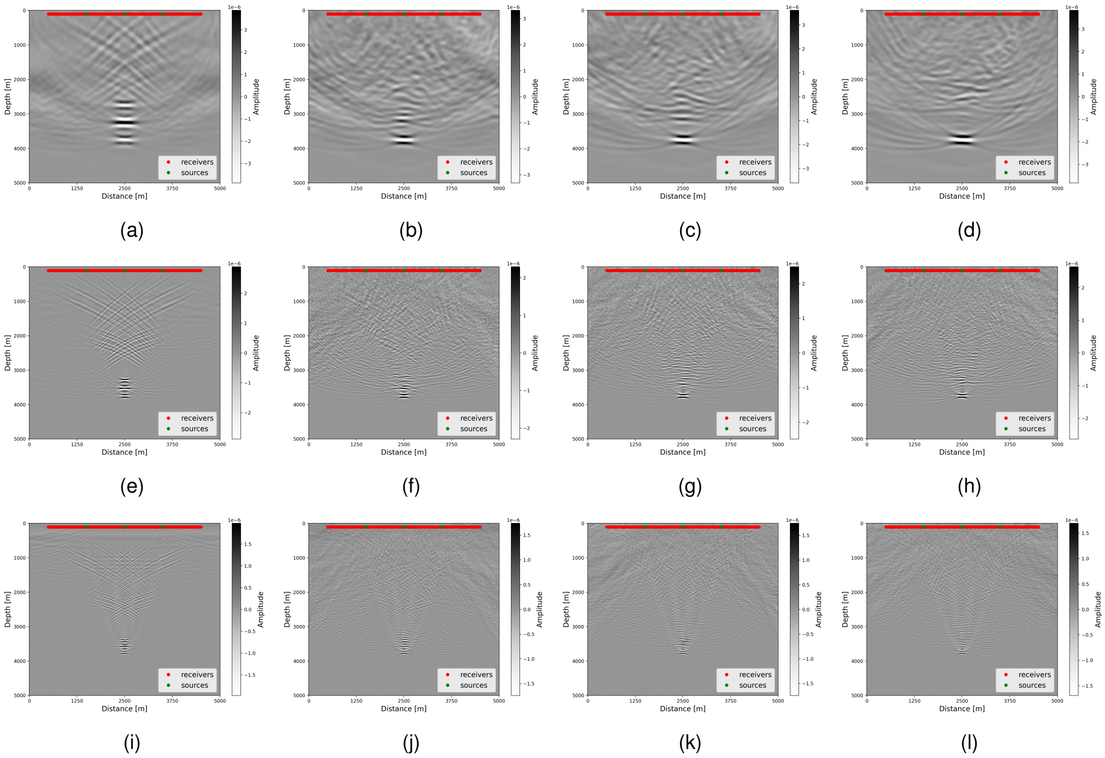


Figure 3: Boundary size test: rows indicate increasing boundary size, while columns represent frequency rising. Only three shots (in green) are considered for each migration. Maximum frequencies of 10, 30 and 50 Hz are applied. (a), (e) and (i) are migrations without RBC. For the frequency of 10 Hz the boundary sizes are (b) 430 m, (c) 645 m and (d) 860 m. For the frequency of 30 Hz: (f) 150 m, (g) 225 m, and (h) 300 m. Finally, for the frequency of 50 Hz: (j) 90 m, (k) 135 m and (l) 180 m.

Using the Marmousi2 model, we performed forward modeling, followed by the removal of direct and refracted waves from the input data. To preserve travel times, the slowness model was smoothed using a Gaussian filter with a standard deviation of $\sigma = 5$. RTM was then performed with the proposed RBC. Spatial discretization was set to 6.25 m in both depth and lateral directions, with a temporal sampling interval of 0.5 ms, 5 seconds of simulation, and a maximum frequency of 50 Hz. The acquisition geometry, based on the reciprocity principle, consists of 41 shots spaced every 500 m and located at a depth of 500 m along the water bottom. A total of 681 receivers were placed at the model surface, evenly spaced at 50 m intervals. To determine the appropriate boundary size for migration, a mean velocity of 3000 m/s and a dominant frequency of 20 Hz were considered, resulting in an average wavelength of 150 m. Using four wavelengths as the boundary width, a total boundary size of 600 m was applied, corresponding to 96 grid points dedicated to boundary sampling. Figure 4 presents the migration result, post-processed with a Laplacian filter. The final image reveals strong correlation with the main geological interfaces and highlights low-velocity anomalies in the Marmousi2.

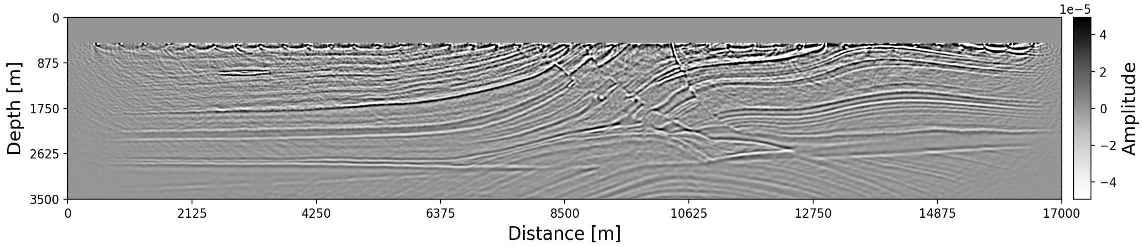


Figure 4: Migration with 50 Hz of the Marmousi2 model using the strategy proposed in this study.

Conclusions

We developed a Random Boundary Condition using a novel approach implemented on GPU, enabling instantaneous generation of the random boundary for each shot during Reverse Time Migration. This method is easily extensible to 3D imaging, Full Waveform Inversion and seismic imaging in complex media, offering high computational efficiency and flexibility. The RBC is grounded in a physics-informed design, where the grain size for Poisson disk sampling is derived from the dominant frequency and mean velocity of the model. Gaussian perturbations with randomized polarity and standard deviation are applied to destructively interfere with outgoing wave fronts in an unpredictable manner. Experimental results demonstrated that using a boundary size equal to four times the characteristic wavelength provides significant benefits, yielding small background noise migration images even with a small number of shots. In particular, the application to the Marmousi2 model confirmed the effectiveness of the proposed RBC, highlighting its potential as a robust, tunable, and computationally efficient alternative in seismic imaging workflows.

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