Submission code: QJRAB97XVP

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Kirchhoff migration with compact Green's functions: RTM quality at a lower cost

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Summary

Kirchhoff migration is usually a 2-step algorithm. First a table of travel-times from surface to all the points in subsurface in the aperture must be computed. Then, this table is used to migrate seismic data to subsurface. In this paper we compute these travel-times using a finite difference algorithm to propagate the source field in subsurface and collect up to the first three most energetic arrivals together with their amplitudes. This ensemble of travel-times and amplitudes is called Compact Green Functions (CGFs).

In addition, the propagated source field is separated into its down-going and up-going components and it is possible to migrate using imaging conditions using several combinations of these fields for the source and receiver. In this paper we will show only the migration using the down-going part of the source and up-going part of the receiver.

The computation of the travel-times using a finite difference algorithm makes the Kirchhoff migrated image much more similar to the one obtained using an RTM algorithm. And as a 21 Hz source wavelet is used, the cost of propagation is significantly lower than that used in the majority of RTM applications. Besides, as this is Kirchhoff migration its cost is not directly associated with the frequency, allowing for much higher resolution than RTM, at a fraction of the cost.

A series of synthetic seismic migrated data is presented here to demonstrate the method.

Introduction

The Kirchhoff and Reverse Time Migrations (RTM) are two well-established methods for imaging seismic data. The Kirchhoff imaging is usually defined in common-offset domain, whereas RTM is defined in either common-shot domain for streamer data, or common-receiver domain for ocean-bottom data.

The Kirchhoff method normally uses a numerical solution of asymptotic ray theory, such as ray tracing or the eikonal equation, to compute Green's functions. It is also possible to use numerical solutions of the one-way wave equation to generate travel-time and amplitude tables.

Two-way wave equation methods for computing Green's functions have been introduced to develop RTM-like Kirchhoff migrations (Andrade et al., 2015; Cunha et al., 2019; Jin and Etgen, 2020; Pu et al., 2021). While the formulations present in these papers do not limit the number of energetic events captured to produce compact versions of Green's functions, their examples are restricted to a single event (arrival).

We derive (Cunha et al., 2024) a common framework for RTM and Kirchhoff migration using compact representations of Green's functions. These CGFs are 3D volumes containing travel-times and amplitudes for the N most representative events in the up-going/down-going decomposed 4D wavefields originating from a point source.

Theory

In high-contrast velocity models, the wavefield becomes complex, and many events in the modeled wavefields mostly contribute as noise to Kirchhoff imaging. In such cases, wavefield decomposition into up-going and down-going propagation is advisable before collecting energetic events to create compact Green's functions (CGFs) for Kirchhoff migration.

This new approach produces up to four complementary imaging volumes (different combinations of source and receiver decomposed wavefields) with computational effort less than 15% that of RTM algorithms (with equivalent spectral resolution).

The Kirchhoff method can be expressed in a general integral form (Cunha et al., 2024):

$$I(\boldsymbol{x},\boldsymbol{h}) = \int\int\int G(\boldsymbol{\xi}_M - \boldsymbol{h}, z_s, \boldsymbol{x}, t_s)\frac{\partial D(\boldsymbol{\xi}_M, \boldsymbol{h}, t)}{\partial t}\, G(\boldsymbol{\xi}_M + \boldsymbol{h}, z_R, \boldsymbol{x}, t - t_s)\, dt dt_s d\boldsymbol{\xi}_M,$$

where:

$\boldsymbol{x} = (x, y, z)$ are the coordinates of the (stacked) image volume $I(\boldsymbol{x})$, $\boldsymbol{h}$ is the horizontal half-offset vector, $\boldsymbol{\xi}_M = (x_M, y_M)$ are the coordinates for the midpoints between source and receiver positions, respectively, along the two acquisition surfaces $z_S = z_S(x_S, y_S)$ and $z_R = z_R(x_R, y_R)$ where the source and receivers are deployed;

t_S is the travel-time from the source to an image point x; t is the recording time;

D is the recorded data; G represents the Green's function (the first associated with the source and the second associated with the receiver).

The standard implementations of Kirchhoff migration drastically reduce the cost of this equation by representing each Green's function as a single event for each subsurface position:

$$G(\boldsymbol{\xi}_M - \boldsymbol{h}, z_S, \boldsymbol{x}, t_S) = A_S(\boldsymbol{\xi}_M - \boldsymbol{h}, z_S, \boldsymbol{x})\delta(t_s - \tau_S(\boldsymbol{\xi}_M - \boldsymbol{h}, z_S, \boldsymbol{x}))$$
$$G(\boldsymbol{\xi}_M + \boldsymbol{h}, z_R, \boldsymbol{x}, t - t_S) = A_R(\boldsymbol{\xi}_M - \boldsymbol{h}, z_R, \boldsymbol{x})\delta(t - t_s - \tau_R(\boldsymbol{\xi}_M - \boldsymbol{h}, z_R, \boldsymbol{x}))$$

where A_S and A_R and τ_S and τ_R are the amplitude and travel-time volumes, respectively, associated with each source/receiver position. These are usually computed by numerical solutions of asymptotic ray theory.

In our work, we extract the travel-times and amplitudes from the source propagated field using a finite difference algorithm, the same one we use to perform RTM. At regular intervals of the propagation time steps, the time and amplitude of the most energetic events are collected for every point in the grid. Note that, unlike ray methods which usually track first arrivals, our method generates most energetic arrivals, which are more appropriate to complex geological settings.

We can collect the first three most energetic arrivals, thus generating three separate sets of time and amplitudes tables.

Our finite difference algorithm separates up-going and down-going wavefields, so we can collect each event separately in each field. In total, we can generate 6 sets of time and amplitude tables or CGFs.

Although more arrivals can be incorporated, we show (Cunha et al., 2024) that three arrivals are sufficient to represent complex wavefields, and these CGFs are used to implement Kirchhoff migration and RTM.

For more information, please refer to Cunha et al., 2024.

Results

As our current Kirchhoff algorithm is capable of dealing with only one arrival, we developed an entirely new one, explicitly taking into account that it will use up to 12 travel-time or amplitude tables. It is optimized to run in CPU only.

In figure 1, we show Kirchhoff migrated sections of the Marmousi synthetic data with the four different combinations of imaging conditions for source and receiver, downgoing-upgoing, upgoing-downgoing, downgoing-downgoing, upgoing-upgoing. In figure 2 the same combinations of imaging conditions are presented for the RTM migrated sections.

Our preliminary measurements with real 3D data show that our new implementation of the Kirchhoff migration, CPU only, runs 4 to 6 times slower than our current production program, which uses GPU's to accelerate computations, depending on the data and migration parameters. This is a promising performance, given the current differences in prices of a CPU node versus a GPU one. Anyway, the new program is still in development, and we are looking for new opportunities to enhance its performance.

Conclusions

We successfully implemented a new version of the Kirchhoff algorithm taking advantage of the travel-time and amplitude tables generated by a finite difference wave-field propagation algorithm. The travel-time and amplitude tables are generated by the same algorithm used to propagate the source field in RTM, but with a 21 Hz wavelet, thus reducing significantly their cost. And the migration is performed in a CPU cluster, which is significantly cheaper than a GPU one.

Acknowledgments

We thank Petrobras for permission to present this work.

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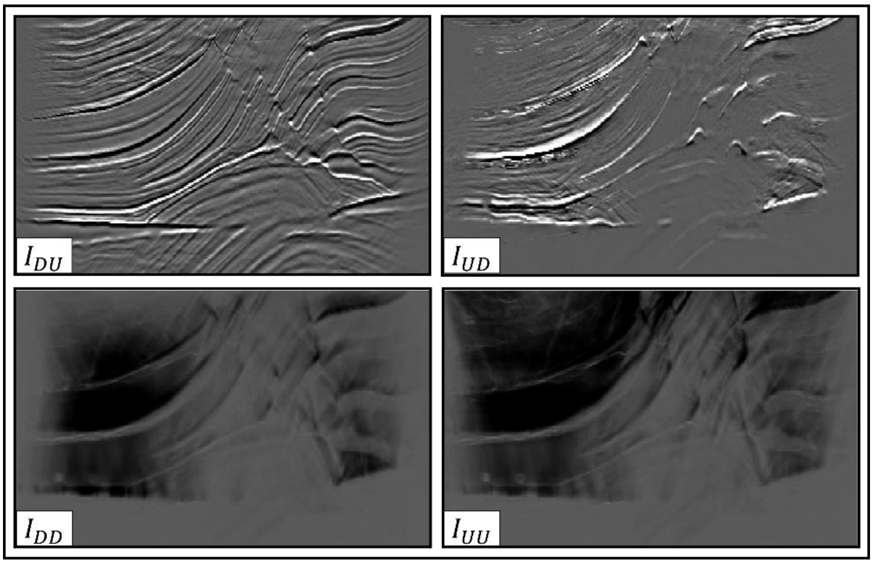

Figure 1: Kirchhoff migration using different combinations of upgoing and downgoing wavefields for source and receiver. I_{DU} (downgoing source, upgoing receiver), I_{UD} (upgoing source, downgoing receiver), I_{DD} (downgoing source, downgoing receiver), I_{UU} (upgoing source, upgoing receiver)

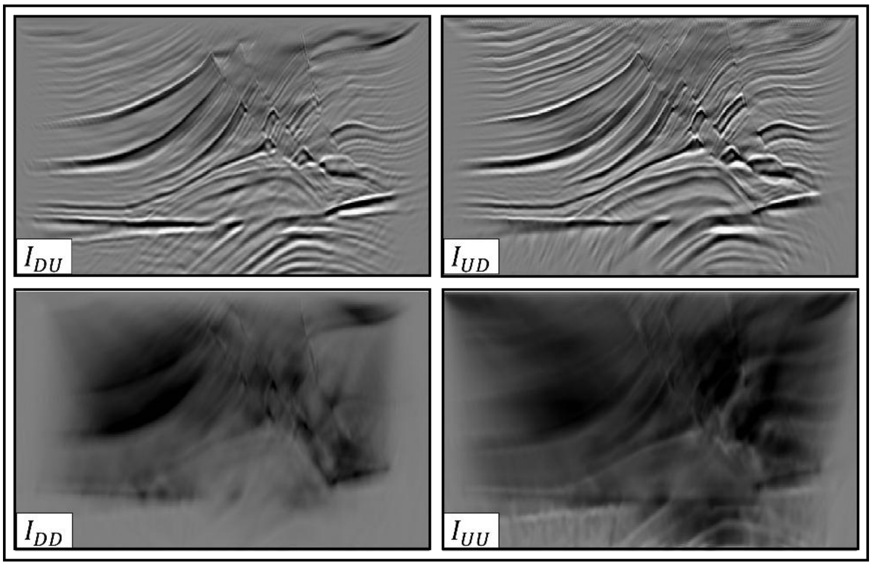

Figure 2: RTM migration using different combinations of upgoing and downgoing wavefields for source and receiver. I_{DU} (downgoing source, upgoing receiver), I_{UD} (upgoing source, downgoing receiver), I_{DD} (downgoing source, downgoing receiver), I_{UU} (upgoing source, upgoing receiver)