Scalable one-way wave propagation methods for seismic imaging on heterogeneous supercomputers

Submitted by

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Abstract

One-way wave propagation algorithms, an active area of research, are at the heart of many modern seismic imaging and inversion processes, such as the Full Wavefield Migration (FWM) and Joint Migration Inversion (JMI). These processes are used in large seismic surveys as mechanisms for the construction of images that allow accurate representations of the subsurface structures. However, this comes at a very high computational cost due to the large volume of data that needs to be processed. To a large extent, computation time of FWM and JMI are determined by forward and backward in-time propagation of wavefields using one-way wave methods. Commonly used algorithms are the phase-shift plus interpolation, and the method of explicit $x-\omega$ convolution filters in the *frequency-space* domain. One aspect of the proposed PhD project is to analyze the computational complexity of these methods and develop efficient implementations for CPUs and GPUs. In addition, it aims to extend the method of convolution operators, such that the accuracy of modeling in inhomogeneous media with strong velocity variations is improved. The final objective is to incorporate in the FWM and JMI processes the implementation key-decisions and optimizations that were developed, thereby enabling the applications to realistic scale seismic data.

Contents

1 Background - Literature review

1.1 A general overview of seismic imaging and inversion

Seismic imaging plays an important role in exploration of structures hidden in the subsurface of the Earth. Such applications involve exploration of hydrocarbons such as oil and gas reservoirs, the characterization of the near-surface area for engineering applications, activities concerned with geothermal technology etc. Seismic imaging constitutes a specific part of the broader domain called acoustical imaging. Acoustical imaging covers a range of applications concerned with waves of a large spectrum of frequencies. From as low as 1 Hz in earth-crust imaging (depths > 50 km), up to several MHz in medical diagnostics and material inspection (depth $\rightarrow$ few centimeters). Seismic imaging falls in the category of acoustic waves with frequencies 10-100 Hz, concerning usually depths 3-15 km [Gisolf and Verschuur, 2010].

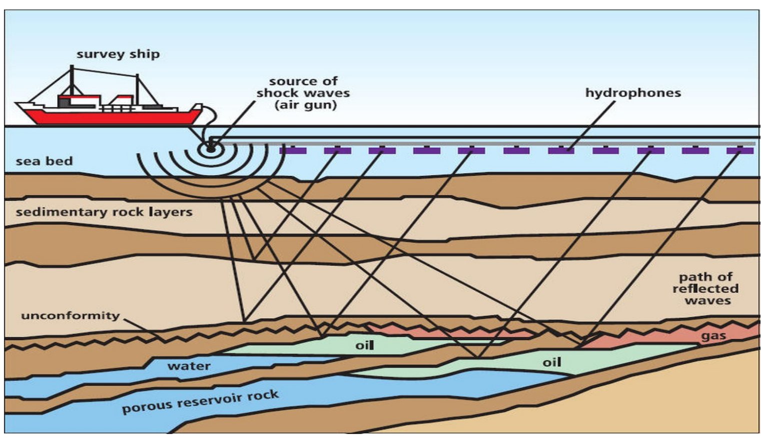


Figure 1: Illustration of a realistic seismic survey.

Figure 1 shows an example of a seismic survey, where sources (air guns) and receivers (hydrophones) are placed on the surface of the under-survey area. Waves generated from the sources will propagate though the complex geology, reflect at the interfaces, and return back to surface where receivers will record them as time-signals (traces). Using the source and receiver positions, the recorded seismic-data, and a good assumption of the velocity profile we can estimate the geometric location of the reflective boundaries that generated the recorded events/data. This process is commonly called migration, and constitutes one of the standard data processing techniques used in reflection-based seismic imaging.

A common approach to migration is wave-equation migration (WEM) [Biondi, 2006], which is based on one-way wave propagation methods [Berkhout, 1982, Claerbout, 1985]. In the early 2000's this approach has been mostly replaced by the so-called reverse-time migration (RTM), based on solving wave propagation via two-way finite difference modeling [Baysal et al., 1983], mainly because of the limitations of the one-way wave equation to image steep structures and turning waves. However, the WEM method using the one-way wavefield extrapolation method is known to be more accurate for high-frequencies and also less computationally expensive than RTM. For the purpose of imaging multiples – and especially for the extension to include internal multiples - this process has been adopted for the so-called Full Wavefield Migration (FWM) method as described by [Berkhout, 2014b, Davydenko and Verschuur, 2017].

One step further is seismic inversion, where the difference with migration is that inversion denotes a process that attempts to minimize the difference between the recorded seismic data (observed data) and the acoustic response (modeled data) produced by the predicted subsurface model. However, inversion is an ill-posed problem and is not always guaranteed to converge. If it does, the advantage over migration is that the reconstructed subsurface is given in terms of its properties, unlike migration that only yields image amplitudes (reflection boundaries) which do not provide information of the acoustic properties.

Full Waveform Inversion (FWI) [Tarantola, 1984] is a common approach to seismic inversion. Typically, involves wavefield propagation based on finite-difference modeling (two-way equation) of the acoustic wave equation with constant density, meaning that velocity is the only variable to estimate. Another strategy to inversion is Joint Migration Inversion (JMI) [Berkhout, 2014c, Verschuur et al., 2016]. Unlike FWI, the JMI algorithm relies on one-way wave propagation methods, and in extension to FWM, it includes a velocity updating component. The modeling engine in both FWM and JMI is called Full Wavefield Modeling

(FWMod) [Berkhout, 2014a], and serves as the method to model primary and higher-order scattering reflections. The fundamental difference between the two inversion algorithms FWI and JMI, is that in the former, the velocity model generates scattering and can naturally deal with multiple scattering (two-way wave propagation), whereas in JMI the velocity model only affects the kinematics and the reflectivity model only affects the reflections. This decoupling makes JMI more robust compared to FWI because it avoids the nonlinearities introduced by the dual role of the velocity model.

The core mechanism behind the modeling engine FWMod, and subsequently FWM and JMI that are built on-top-of this, is one-way wavefield propagation. During the past 50 years, numerous one-way wave propagators have been developed. Some involve propagation in the real space-time (XT) domain, others in the frequency-space (WX) domain, and others in the frequency-wavenumber (WK) domain.

1.2 One-way wave propagation

Wave propagation in acoustic media is described by the wave equation

$$\frac{1}{c^2}\frac{\partial^2 p(\vec{r},t)}{\partial t^2} = \frac{\partial^2 p(\vec{r},t)}{\partial x^2} + \frac{\partial^2 p(\vec{r},t)}{\partial y^2} + \frac{\partial^2 p(\vec{r},t)}{\partial z^2} \ , \tag{1}$$

where $p(\vec{r},t)$ represents the wave-pressure at position $\vec{r} = x\ \hat{e_x} + y\ \hat{e_y} + z\ \hat{e_z}$ in three-dimensional space, at time point t. In the special case of a homogeneous medium, the velocity c is constant at all positions in the space and the propagation becomes trivial if we transform equation (1) in the *frequency-wavenumber* (FK) domain. To do so, we perform successive Fourier transformations over x, y, and t and we obtain equation

$$\frac{\partial^2 \tilde{P}(z,k_x,k_y;\omega)}{\partial z^2} + k_z^2\ \tilde{P}(z,k_x,k_y;\omega) = 0 \ . \tag{2}$$

In here, $k_z = \pm\sqrt{\frac{\omega^2}{c^2} - k_x^2 - k_y^2}$ is the phase-shift operator, ω is the frequency of a monochromatic plane wave, and k_x, k_y are the wavenumbers in x, y spatial directions respectively.

The solutions of (2) in closed-form are

$$\tilde{P}(z+\Delta z, k_x, k_y; \omega) = \tilde{P}(z, k_x, k_y; \omega)\ exp(\pm i k_z \Delta z)\ , \tag{3}$$

which incorporate forward and backward in-time propagation, both of them are important for seismic imaging applications.

Although it is trivial to perform wave propagation in homogeneous media using a simple phase-shift operation for an arbitrary large propagation length Δz, this is not the case for inhomogeneous media, especially for media with lateral velocity variations. For such media, the phase-shift operator is not sufficient by itself and several methods have been developed over the years to overcome this and yet keep the computational complexity to a minimum. A method that although is not rigorously defined for inhomogeneous media however in practise works very well, is the phase-shift plus interpolation (PSPI) method [Gazdag and Sguazzero, 1984], [Bonomi et al., 1998]. This method assumes that extrapolation from a depth level z to $z + \Delta z$ is governed by a set of dominant (reference) propagation velocities and a spatial interpolation mechanism through which the next-depth wavefield is calculated at each spatial position x, y from contributions of the reference wavefields. Alternative methods use the inverse-Fourier transformation (over x, y) of relation (3) to perform wavefield propagation in the *frequency-space* (XW) domain using convolution integrals of the form

$$P(z+\Delta z, x, y; \omega) = \int_{-X_o}^{+X_o} dh_x \int_{-Y_o}^{+Y_o} dh_y\ W(z, x, y, h_x, h_y; \omega)\ P(z, x, y; \omega)\ , \tag{4}$$

where W is a space-variant convolution operator, or generally, a finite-impulse response (FIR) filter as described in [Berkhout, 1982], [Holberg, 1988] and [Blacquiere et al., 1989].

It is accepted that PSPI is probably the most efficient algorithm for the general case of inhomogeneities, however for strongly laterally varying media the convolution-based approach can be more accurate upon a good choice of operators. Several methods have been developed over the years and are still under research, with emphasis on the shortage of the operator's spatial-length to a minimum, while they still preserve a set of desired properties such as stability and accuracy at high propagation angles ($> 80^o$). Some of these include the weighted least-squares (WLSQ) approximation [Thorbecke et al., 2004], the projections-onto-convex-sets (POCS) method [Mousa et al., 2009], an iterative reweighted least-squares (IRLS) method [Mousa, 2018], a method for designing homotopy-based FIR filters [Mousa and Al-Battal, 2020] etc.

One of the limitations of both the PSPI and XW approaches is that both methods assume a local laterally homogeneus medium, such that within the length of the operator aperture there is no strong medium variation. The Earth is heterogeneous, so this assumption will often not be met. One of the reason to keep working on the XW approach is that this method allows to use more dedicated convolutional operators that include more of the lateral variations of the medium and are, thereby, no longer symmetric in space anymore. In [Op 't Root and Stolk, 2010] such an approach is described based on assuming a lateral linear gradient in velocity, while [Hammad and Verschuur, 2016] showed a method to determine the operators more accurately by an (expensive) eigen-operator decomposition process. This work needs further investigation in order to find a suitable method for determining accurate, but still affordable, convolution operators in heterogeneous media.

1.3 Shot-profile depth migration

If we follow a shot-profile migration approach as shown in algorithm (1), the process involves backward-in-time downward (in depth) propagation of a set of shot-records $P_j(x, y; \omega)$ in an assumed velocity model, forward-in-time downward propagation of a set of equivalent source-responses $S_j(x, y; \omega)$ in the same velocity model, and finally a method that captures the image in a layer-by-layer fashion, called the imaging condition [Schleicher et al., 2008]. Each pair of shot-records and source-responses j corresponds to a different experiment that was fired from a different source position.

Algorithm 1 : Shot-profile depth migration algorithm

- prepare tables of propagation operators
- read shot records P_j and for each one prepare the corresponding source response S_j

for each *shot* j **do**

  for each *depth* z **do**

    for each *frequency* ω **do**

      - forward-in-time propagation: $S_j(z-1,x,y;\omega) \rightarrow S_j(z,x,y;\omega)$
      - backward-in-time propagation: $P_j(z-1,x,y;\omega) \rightarrow P_j(z,x,y;\omega)$

    end for // over ω

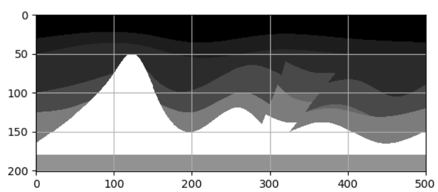
    - image depth layer z of the j^{th} shot-record: $I_j(z,x,y) = \sum_{\omega} f\Big(P_j(z,x,y;\omega), S_j(z,x,y;\omega)\Big)$

  end for // over z

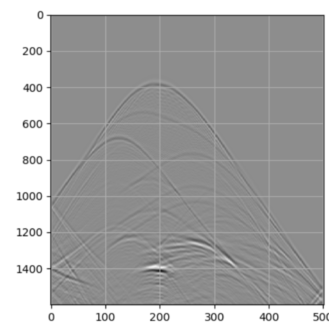
  - accumulate pixel-wise I_j to I_{final}

end for // over j

- save final image I_{final}

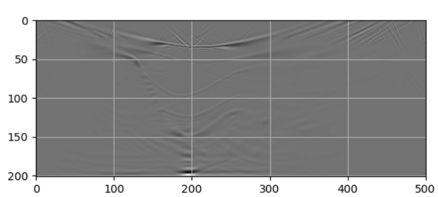


(a)

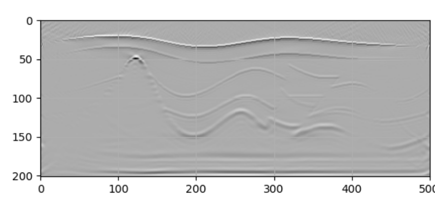


(b)

Figure 2: a) True velocity model, b) shot-record generated from source at position $x = 800$ meters.



(a)



(b)

Figure 3: a) Image obtained after migration of data in 2b, b) final image after accumulation of 85 independently constructed images.

For example, a simplified two-dimensional scenario is illustrated using synthetic data. Assuming that we have the velocity model shown in figure 2a. A shot-record generated by a source that is located in the lateral position $x = 800$ meters, is shown in figure 2b. Using the migration algorithm (1) with only one shot-record, the obtained image is shown in figure 3a. As we can see, only the area below the source position was illuminated. In order to better reconstruct the reflection interfaces in other areas we need to sample across the whole surface. Each image is constructed independently from the others. If we sample well across the whole surface, and accumulate all images pixel-wise, we obtain a better image of the subsurface 3b.

Shot-profile depth migration is a commonly used tool for imaging three-dimensional complex geological structures located in the subsurface and has only been recently a practicable approach to subsurface imaging, due to its high computational complexity. That is due to the wave propagation mechanism, the core mechanism of this process. Its computational complexity increases even more multiplicatively because it involves the propagation of a large number of wavefields, forward or backward in-time. Consequently, it is a very important aspect to consider efficient one-way wave propagation implementations, both from the mathematical and the computational perspective, in order to take advantage of the processing capabilities of modern heterogeneous supercomputers. In recent years, graphics processing units (GPUs) have improved significantly offering very high computational power, dominating in this way the nowadays supercomputers. However, general-purpose central processing units (CPUs) are still capable of performing floating-point operations (FLOPS) at a good fraction of what GPUs can [1]. Since the programming model is different on the two processing units, different computational implementations and, therefore, optimizations are required in order to achieve high performance.

Previous works ([Liu et al., 2012, wei Liu et al., 2012, Zhang et al., 2009] and [Jang and Kim, 2016]) that carried out performance experiments on CPUs and/or GPUs for

[1] Fujitsu processor A64FX: Equipped the world's fastest supercomputer in 2020, Fugaku, in Japan.

WEM algorithms, do not provide detailed information of the implementation decisions to justify the level of optimizations attempted in each case. Also, for the CPU case usually the experiments were carried out on single core, which makes the comparison with a GPU inadequate. Additionally, the overheads from data movements were sometimes omitted from discussion as evaluations focused only on the computations. We suggest that a more fruitful comparison would provide information of implementation decisions in all important kernels, followed by estimated performances (i.e. FLOPS rates, or effective bandwidths GB/s) per section, include data-movement overheads, and better compare fully utilized CPUs by exploiting shared memory parallelism at CPU level. That would make these analyses more insightful, since at the end of the day, what is the most important to come out with is not to proof that GPUs can carry out a workload faster than CPUs, or vice versa, rather it is to understand what it requires to write efficient applications in both units.

1.4 Imaging with multiple scattering effects: FWM & JMI

In the earlier migration surveys the multiple scattering effects were handled as noise that should be removed from the data before migration. However, it is currently understood that not only they shouldn't be removed, instead they should be processed in an analogous way since they "assist" the imaging process to better illuminate the subsurface, especially at the locations where primaries cannot reach. This processing is introduced by the Full Wavefield Modeling (FWMod) algorithm, which serves as the modeling engine in FWM and JMI processes.

Modeling multiple scattering effects though increases even more the computational complexity of an already expensive process. The higher-order scattering terms are calculated iteratively, or else, in round-trips of downward and upward wavefield continuation using one-way wave propagation and an explicit mechanism to calculate the transmitted and reflected terms from the subsurface structures. The algorithm (2) shows the main steps involved in one roundtrip of the FWMod algorithm.

Algorithm 2 : Full Wavefield Modeling - roundtrip

for each *shot* j **do**
  for each *frequency* ω **do**
    for each *depth* z (downwards - "+") **do**
      - calculate down-going scattering term: $\delta\vec{S}_j^+(z;\omega) = R\vec{P}_j^+(z;\omega) - R\vec{P}_j^-(z;\omega)$
      - include it in full wavefield: $\vec{P}_j^+(z;\omega) = \vec{P}_j^+(z;\omega) + \delta\vec{S}_j^+(z;\omega)$
      - downward propagation: $\vec{P}_j^+(z;\omega) \rightarrow \vec{P}_j^+(z+1;\omega)$
    end for // over z
    for each depth z (upwards - "$-$") **do**
      - calculate up-going scattering term: $\delta\vec{S}_j^-(z;\omega) = R\vec{P}_j^-(z;\omega) - R\vec{P}_j^+(z;\omega)$
      - include it in full wavefield: $\vec{P}_j^-(z;\omega) = \vec{P}_j^-(z;\omega) + \delta\vec{S}_j^-(z;\omega)$
      - upward propagation: $\vec{P}_j^-(z;\omega) \rightarrow \vec{P}_j^-(z-1;\omega)$
    end for // over z
  end for // over ω
end for // over j

This pseudocode demonstrates the importance of one-way wavefield propagation, as it is present in the core of this process (the computational complexity for the calculation and addition of scattering terms is typically one order of magnitude less than that of wavefield propagation). In each iteration the wavefields across all *shots* and *frequencies* are extrapolated downwards initially and upwards afterwards, in order to capture the scattering contributions from all depth levels. One new scattering order is added with each new roundtrip. This iterative modeling of total wavefields is similar to the Bremmer series following [Bremmer, 1951].

With respect to the comutational complexity in the FWM algorithm, one iteration (reflectivity update) initially involves forward modeling using the FWMod algorithm for the calculation of the modeled data. Once the modeled data are obtained, the residuals are determined from the difference between the modeled and observed data. Then, the residuals are used for the computation of the reflectivity gradient. This step involves back-propagation (downwards) of the residuals to the reflector positions for imaging by cross-correlation with the down-going wavefield (in the simplest angle-independent mode). The computed reflectivity gradients represent a direction in the conjugate-gradient scheme, however, are not at true-amplitudes. Thus, they need to be scaled with a certain value, whose calculation involves again forward propagation (upwards) of wavefields through all the depth levels. In total, each iteration in the FWM algorithm involves two downward, and two upward continuations of wavefields though all depth levels, which in principle reduce to one-way wavefield propagation. In a similar way, for the JMI algorithm the workload is typically doubled compared to FWM, since it involves apart from reflectivity, velocity updates as well. This highlights how important is the role of the adopted wave propagation method, in both processes.

Additionally, in large three-dimensional surveys, parallelism across multiple processes is essential in order to make the migration time practically feasible. In this way, apart from the computations, which depending on the implementation can be done on CPUs and/or GPUs, global communication is another important aspect. Due to the iterative-nature of the FWM algorithm, the reflectivity model is updated in every new iteration, and for that calculation to take place global information (from all processes) is needed. Similarly in the JMI algorithm, global communication is required both for the reflectivity and velocity updating. As long as the number of processes is relatively small (several hundreds or thousands) gathering global information might not be a serious bottleneck, however for larger numbers of processes, this requires more attention otherwise that could be a performance bound. According to the dependency between the data movements and the computations, one could attempt to explore more asynchronous (for example task-based) parallelism patterns, as alternatives to the standard data-decomposition, or ways to reduce to a minimum the volume of transferred data between distant (on hardware) processes.

2 Research objectives

2.1 Objective 1: Cross-platform efficiency in one-way wave propagation

Modern supercomputers are powered mostly with CPUs and GPUs: What are the implementation key points that lead to high-performance one-way wave propagation solvers for these systems? Since, the end-goal applications are seismic imaging-inversion applications, we need a good representative application. This will serve as the application to apply our developments on, analyze the computations performance, and at the same time validate imaging correctness.

One-way wave propagation is the basic building block in many modern migration and inversion algorithms, which make use of primary and/or higher-order scattering reflections in subsurface imaging. Albeit, translating a mathematical algorithm into software is not always a trivial task, especially when high performance is an important aspect. The existence of different algorithms and the heterogeneity (in processing components) of modern supercomputers, makes the computational implementation and optimization space large, yet interesting to explore. Through selected application implementations accompanied with detailed quantitative analyses of their performance, is a concise and consistent approach to develop understanding of the key elements to high performance in larger-scale applications that are build on top of them.

Shot-profile depth migration has the same problem dimensionality as the larger modern inversion-based applications, since it involves processing data from multiple shot-records, frequencies, depths and spatial locations. In good approximation, the computational complexity in shot-profile migration is equivalent to the first iteration in FWM and JMI. Additionally, it is an application one can implement using various one-way wave methods. Since for example a PSPI-based migration is very different to implement compared to a convolution-based one, the implementation challenges and the optimization key points will be different in each case.

A meaningful analysis would reveal in a quantitative basis all optimization points addressed in each case, and furthermore since cross-platform efficiency is important, it would make comparison between the obtained performances on different processing units, justifying in each case the level of optimization(s) and the achieved performance. The scope is to implement the 3D shot-profile depth migration algorithm for CPU(s) and GPU(s), using firstly one-way wave-filed propagators based on the PSPI algorithm, and then repeat the same but instead use explicit X-W propagators. Through quantitative analyses of the performance and explanation of the major implementation decisions, we aim to understand what are the key points to high-performance in each case.

2.2 Objective 2: Improved $x-\omega$ convolution operators for strongly varying media

Current one-way wave propagators are based on the assumption of local homogeneity as a good approximation for inhomogeneous media with smooth velocity variations. However, for strongly laterally varying media this assumption is not sufficient, and thus one-way wave propagation methods should be extended in an analogous fashion, in order to handle modeling and imaging in such media more accurately.

PSPI handles propagation in inhomogeneous media by selection of a set of reference velocities, which constitute good representatives of the other existing velocities in each depth level. On the other hand, symmetric $x - \omega$ convolution operators perform propagation in the XW domain assuming that the medium is locally - within the operator aperture - homogeneous. These assumptions are important as they keep the computational complexity of these methods to a minimum, while still provide sufficiently good results in smooth inhomogeneous media. One advantage of the method of explicit $x - \omega$ convolution operators, is that it is naturally more extendable to handle propagation in inhomogeneous media at different approximation levels. That is due to the approximation is expressed through the operators, which are prepared separately.

True amplitude is an important limitation in one-way wave propagation methods, and a way to improve this properly is to take into account the velocity gradients in the preparation of the operators [Op 't Root and Stolk, 2010]. Another approach to more accurate operators, is via the (considerably expensive) eigen-operator decomposition process following [Hammad and Verschuur, 2016]. However, an important drawback - with respect to the computational complexity - is introduced here, which is that the symmetric in-space shape of operators is not preserved. This is expected to affect the efficiency in implementation. Firstly, the symmetric shape of operators allowed so far to reduce the memory-size of operators and the number of FLOPS in convolution kernels. Secondly, another way to keep memory footprint low is following a table-driven extrapolation approach as described by [Blacquiere et al., 1989]. According to the operators details this approach might not be the most suitable in the case of asymmetric operators, or it could be suitable after some adaptions. These are important questions that we want to research in more detail.

2.3 Objective 3: Enhance multi-node parallelism in FWM and JMI processes

In large three-dimensional seismic imaging and inversion applications such as the FWM and JMI processes, it is essential to split the workload across different processes on multiple nodes in order to obtain the desired results in a reasonable amount of time. To this end, not only efficient computations need to account on each processing unit individually, communication of the data should be handled in an optimal way as well.

In HPC there are three main components to take into account in order to speedup the data processing in an application. These are computation, networking, and storage [Geshi, 2019, Hager and Wellein, 2010]. Each part requires special attention, and usually optimizing only one part is bounded by the limits of the other two. Although software is designed to process data that pass through all three components as a monolithic block (code), each part is optimized separately in a different way. In objective 1, we address the optimization of computations involved in one-way wave propagation methods as carried out in each individual processing unit, considering both CPUs and GPUs. Aside this, it is important as well to enhance the communications involved.

When computations are ported on GPUs, one important matter to consider is the data-movements overheads, which if not carefully implemented, they can easily bottleneck the total processing time reducing in this way the positive impact from the large compute capabilities of GPUs. Since, the computations and the communications are handled from different units on the GPU, one could use this to overlap the computations and the communications "hiding" in this way an amount of data-movements time. Also, the volume of transferred data should be reduced to the minimum necessary as another factor to reduce the CPU-GPU communication overhead. We aim to research and incorporate these aspects when porting the FWM and JMI processes to GPUs.

3 Methodology

Below is described the procedure that will be followed throughout the next years until the completion of this PhD project. The important events in the description that follows are noted as milestones, which are later on summarized in bullet-points for reference.

3.1 Procedure

During the second year the target is to implement a 3D PSPI-based shot-profile migration algorithm for CPU(s) and GPU(s), and carry out performance analyses and comparisons. To complete this first milestone, the following tasks are identified:

- Make a first CPU version and use OpenMP for full-CPU parallelism
- Use CUDA(HIP) to transfer computation on NVIDIA(AMD) GPUs
- Analysis of all important parts of code and description of implementation
- Make experiments and performance comparisons on a range of CPU and GPU-based platforms
- Publish findings

Once that first step is completed, we want to transfer optimization ideas to the PSPI version of FWM Delphi code and make a GPU version, aside the already existing CPU one. Since both FWM and JMI rely on migration principles with respect to their computational implementation, we want to apply the same ideas to JMI as well. We aim to start working on this before the end of the second year, and complete first versions somewhere close to the beginning of third year, or if possible earlier.

At the same time, from the beginning of the third year we will start working on the improvement of the accuracy of the $x - \omega$ operators, which are used in the convolution-based wave propagation mechanism. The major steps to complete this process are:

- Cover additional background material: [Op 't Root and Stolk, 2010] and [Hammad and Verschuur, 2016]

- Proof of concepts in python [2]

- Use synthetic data-sets (2D initially) to examine improvements in propagation and imaging

The findings from the last work will be submitted for publication, and that would eventually mean the reach of the second milestone! The target is to have completed this work before the end of the third year (Sep. 2022).

In the fourth year (the last one), once we complete the research for better quality operators, we want to repeat a similar performance analysis as the one we describe for the 3D PSPI-based migration process (see bullet-points in first milestone). The difference now is that we will do this analysis for the convolution-based migration process. The publication of these results would mean the achievement of the third milestone.

Transferring ideas from the shot-profile migration analyses to FWM and JMI will be an ongoing process throughout all years until the completion of this PhD project. It will be held under the RAISE and ENGAGE projects, in collaboration with other PostDoc and PhD students enrolled. Possible extensions/improvements to existing FWM/JMI software are:

- Port computation to GPUs (multi-GPU parallelism)

- Reduce volume of transferred data to enhance scalability

- Explore different parallelism patterns (i.e task-based parallelism)

- Overlap computations on GPUs with communications to reduce data-movement overheads

When improvements are applied to FWM and/or JMI codes, we would like to include demonstration of performance in large-scale experiments.

The final step is to write the thesis.

[2]Python programming language: `https://www.python.org/`

3.2 Milestones

1. Aug.-Sep. 2021: Finish work for 3D PSPI-based shot-profile migration - towards publication.

2. Sep.-Oct. 2022: Finish work for better quality $x - \omega$ operators - towards publication.

3. Feb.-Mar. 2023: Finish work for 3D convolution-based shot-profile migration - towards publication.

4. Demonstration of performance improvement in FWM (and JMI) Delphi software.

3.3 Materials and possible limitations

The essential materials for carrying out this project are not a lot! A laptop, access to literature and HPC infrastructure. Access to literature is already granted through the University of Illinois based on collaboration with the CYI. For HPC infrastructure the CYI already provides access to a range of platforms suitable for development and medium-scale experiments. Access to larger systems is provided through European projects, in which CaSToRC is involved.

Access to AMD GPUs: For the performance experiments for the 3D shot-profile migration algorithms, apart from CPUs, we aim to make comparisons on NVIDIA and AMD GPUs. The former are available at the CYI HPC facility, but not so the later. It is expected that we will have access, at least for development, however it is currently an open matter.matter

Write code both for NVIDIA and AMD GPUs: We prioritize the implementation of software for NVIDIA GPUs. However, it is also desired to do the same for AMD GPUs. The idea is that we will be able to do this by translating the existing (by that time) CUDA software into HIP. Since the two programming interfaces are very similar, we expect that the difficulty to do this will not be an issue.

4 Expected outcomes

The expected outcomes from this project include publications to recognized scientific journals and software.

- Understanding of performance optimization key points for one-way wave propagation solvers on a range of platforms including CPUs and GPUs, accompanied with publication to recognized scientific journals among *IEEE Transactions on Computational Imaging*, *Elsevier Computers & Geophysics*, *Springer Computational Geosciences* etc.

- Improve wave-field propagation in strongly laterally varying media using more accurate $x-\omega$ convolution operators. The results is expected to be published in one of following scientific journals: *Geophysical Journal International*, *Geophysical Prospecting*, *SEG Technical Program Expanded Abstracts* etc.

- Optimizations applied to the seismic imaging and inversion algorithms FWM and JMI.

Software:

- One-way wave propagation solvers for CPUs and GPUs - based on the PSPI algorithm.

- One-way wave propagation solvers for CPUs and GPUs - based on explicit $x-\omega$ convolution operators.

- Improved time-to-solution and scaling of the FWM CPU code.

- Port FWM to GPUs.

- *It is desired to do the same for JMI - according to availability of time.

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