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Ray versus full wave velocity model building: status and challenges

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Summary

While full wave based velocity model building approaches have earned their stripes during the last decade, ray based approaches remain the working horse in industry. I review here first the successes and the limitations of both families of approaches. If it appears that ray based approaches suffer of limitations in complex media, others of their characteristics like the picking (often seen as a weakness) or the computation of Fréchet derivatives may also appear in practice as decisive advantages. I believe that these are points on which we should challenge and even inspire full wave approaches. By the end rather than opposing ray based and full wave approaches I review the various trends in terms of the combination of the tools and concepts which appear from my point of view as the most promising.

Introduction

Velocity model building is a critical step for depth imaging. While ray based approaches have continued to dominate industrial velocity model building (Woodward et al., 2008), over the last decade, full wave methods based on numerical solution of the wave equation have earned their stripes. The breakthrough came with full waveform inversion (FWI), which emerged as an unrivaled tool for high resolution velocity model building in shallow layers penetrated by diving waves (see for example Virieux and Operto (2009) for a review). Numerous works now aim at extending the applicability of conventional FWI, but despite these efforts we have to agree that ray based velocity model building is still widely used. To attribute this fact only to the conservatism of the geophysicists' community would not be fair. Much more fundamentally it should be associated to several characteristics of ray based techniques on which we should challenge the full wave approaches.

To feed the debate, I propose here to review these aspects, first addressing successes and limitations of ray based and full wave approaches, and then considering approaches and workflows where they are combined. From my point of view these combined tools and workflows are the most promising in the midterm and already a reality in many applications.

Successes and limitations of ray based approaches

Ray based tomography remains the workhorse for velocity model building. Behind a great variety of approaches and implementations these tools have in common a picking step (Travel time/slope or depth/dip picked on prestack data or migrated images) and the computation of the gradient or Fréchet derivatives of the tomographic inverse problem through ray tracing. While these approaches are now mainly disdained by academic researchers (with some exceptions like Tavakoli et al. ,2017), who have massively moved towards full wave approaches. Over the years they have been consistently improved by industry resulting in highly efficient high resolution industrial solutions (Barnes et al., 2011; Lambaré et al., 2014; Hardy, 2016). I can identify three main components explaining the successes of ray based tomography:

1) The relative linearity of the kinematic parameters with respect to the velocity model.
2) The picking step (frequently mentioned as a strong limitation of these approaches). It is my contrary point of view that this is a real strength. In fact picking aims at selecting events and characterizing their kinematics, and most of the time it is done through a systematic exploration (a global optimization) of the data space that insures the robustness of the process. The lack of a picking step in a full wave approach is a great handicap as they can easily be biased by coherent noise.
3) The computation and compact storage of Fréchet derivatives of the data with respect to model parameters (and not only the gradient of the cost function). This is a tremendous advantage for the efficiency of the resolution of the linearized inverse problem and for the balancing of the various necessary constraints (velocity model building is an ill constrained inverse problem!).

Ray based tomography methods however have limitations. Some connected to the chosen method (reflection travel time tomography, migration velocity analysis or slope tomography), some others connected to their implementation (for the ray tracing or the picking), and finally some inherently associated with the theoretical limitations of the approach. About this last point I can mention:

1) The use of ray tracing for modeling wave propagation. It has theoretical limitations (high frequency asymptotic approximation) but also practical (multi-arrival ray tracing is possible but can rapidly result into labyrinthine algorithms, especially when discontinuities are introduced).
2) The selection of the events during the picking step. Sometimes it is very difficult. From my point of view the consequence should not be to abandon the picking but to find a way to ease it (applying preprocessing, picking a more appropriate domain for it, adding prior information, …)
3) The theoretical limitation associated with the frequency content of the data which has a direct impact on the accuracy and resolution of the picking and then on the resolution and accuracy

of the inverted velocity model (Lambaré et al. (2014) mentioned a maximum resolution of 6 Hz and Hardy (2016) up to 15 Hz).

The second issue certainly remains one of the great challenges of these approaches but the first one inherently remains in the case of complex media and is from my point of view one of the main motivations for full wave approaches.

Successes and limitations of Full wave approaches

The full waveform inversion approach which emerged industrially with the works of Prof. Gerhard Pratt (Pratt, 1999; Sirgue et al., 2008; Plessix, 2009) is a data fitting problem. It can reach an unrivaled resolution when transmitted and reflected waves are inverted jointly. This is certainly an amazing success when we consider that:

1. The data components (reflected or transmitted, low or high frequency, short or large offsets) give information about different model components (short or long wavelengths, velocity, impedance, anisotropy, …).
2. The nature of the relation between the data and the model components strongly varies (linear or not).

When we analyze the processes involved in FWI we can clearly discriminate the behaviors of depth migration and of tomography (Virieux and Operto, 2009). For the success of the FWI applications both behaviors have to be carefully balanced to insure a convenient convergence with a local optimization process. But from the two behaviors the tomographic one is certainly the most special (it makes FWI a velocity model building method rather than a migration tool). Note that it is also the most critical as it is highly sensitive to cycle skipping. This explains the lasting efforts to remedy this through dedicated workflows or new cost functions (Jiao et al., 2015; Warner and Guasch, 2016; Métivier et al., 2016). It is interesting to see that several of the new proposed cost functions contain (explicitly or not) a kinematic parameter as used in ray based tomography (travel time, time or depth shift, slope, …).

In order to remedy the limitation to the area investigated by diving waves of conventional FWI as a velocity model building tool (i.e. solving for the long wavelength components of the velocity model), efforts have been made to extend the tomographic behavior of full wave approaches to the area investigated by reflected waves only (Albertin, 2017). This has resulted in approaches like Reflection FWI (R FWI) (Xu et al., 2013; Valensi et al., 2017; Gomes and Chazalnoel, 2017; Zhou et al., 2018), Differential Semblance Optimization (DSO) (Shen and Symes, 2008; Fei and Williamson, 2010; Biondi and Almomin, 2014; Chauris and Cocher, 2017; Shan and Wang, 2017), or other wave equation migration velocity analysis methods (Symes, 2008; Soubaras and Gratacos, 2017). In all these approaches reflected arrivals are introduced through an internal depth migration process, and they exhibit connections with ray based Migration Velocity Analysis (MVA). This is even more evident when they explicitly involve a kinematic parameter in the cost function (Ma and Hale, 2013; Vigh et al., 2017). A very important aspect of these full wave velocity model building approaches is that ray tracing has been replaced by numerical wave propagation, which can afford wave propagation in complex models. Full wave approaches appear for many as the future and even near future of velocity model building.

Combining ray based and Full wave approaches?

Following this general overview of successes and limitations of ray based and full wave velocity model building tools, it is important to consider that far from being in competition they are, for the most part, used in complementary ways and increasingly in combination. This is becoming even more crucial considering that we have moved from a mid-frequency gap (a set of mid frequency components of the velocity model was expected to be unreachable) to a spectral overlap between the resolutions of tomographic and migration behavior (Nichols, 2012). In terms of combinations, several strategies are possible and already investigated.

First, in terms of workflows, when for example ray based tomography is used for the estimation of the initial model for conventional FWI or even after conventional FWI to insure flatness of final common image gathers. Note that in this context the versatility of non-linear tomography (travel time

tomography for diving waves or slope tomography for reflected waves (Montel et al., 2009) is particularly adapted as it does not requires a new migration and picking step. Note also that a typical velocity model building workflow can often involve several loops of ray based tomography and full wave approaches to reach its final result.
Second, in terms of tools, when for example velocity model building tools combine ray based and full wave based methods and concepts. This can be done explicitly in the cost function which may contain ray based and full wave based terms. This can also be done when one solution is used to guide the other (Allemand and Lambaré, 2016). Finally this can be done when the velocity model building approach internally combines concepts and tools of both families of approaches, as for example, picking but cost function estimated by a full wave approach (Bakker et al., 2015,; Zhang et al., 2015); no picking but cost function estimated by a ray based approach (Jin and Beydoun, 2000), etc ….

I have lots of expectations with all these types of approaches because they allow us to take advantage of the existing toolboxes and workflows but also more fundamentally of the most interesting and useful concepts. Concerning this last point I have in mind the full wave modeling in complex models, the introduction of a global optimization step as inside the picking, the capability to combine efficiently various types of information and finally the physical understanding with ray tracing.
As we see, a significant part of these advantages belongs rather to the family of ray based approaches. Considering the developments, successes and limitations of full wave approaches I believe it is important to challenge them on these points.

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