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Timothé Perdrizet, Delphine Sinoquet

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Adaptive model parameterization designed for reflection tomography

Timothée Perdrizet and Delphine Sinoquet, Institut Français du Pétrole

Summary

Reflection tomography determines a subsurface velocity model that best fits the traveltime data associated with the main reflections picked on the seismic sections. A careful choice of the model representation has to be done: a blocky model representation based on regular gridded b-spline functions has been proposed. This parameterization allows accurate and robust inversion but can lead to a large number of parameters. An adaptive parameterization that enables to account for local complexities and inhomogeneous ray coverage is considered. Applications on two synthetic models show encouraging results.

Introduction

Reflection tomography allows to determine a subsurface velocity model from the traveltimes associated with the main reflections of the seismic waves. Solving the forward and inverse problems requires a careful choice of the model parameterization: it affects the calculation cost for the ray tracing and has a strong impact on the robustness of the inversion. The KIM consortium proposed a blocky model representation (Clarke, 1996) based on b-spline functions: it has proven its effectiveness on several applications on complex data (Ehinger et al., 2001). Nevertheless, using regular grids to define b-spline functions leads often to the inversion of useless parameters, especially in case of models with local complexities or with inhomogeneous ray coverage. Several authors have developed adaptive model parameterizations for inverse problems, for instance, Ben Ameur et al. (1999) in hydrogeology. Böhm et al. (2000) and Cox and Verschuur (2001) have proposed automatic data-driven adjustments of Delaunay triangle parameterization in tomography. The purpose of our work is to provide an adaptive model parameterization, based on b-spline functions, in order to limit the number of inverted parameters and consequently to make the inversion more efficient.

We first describe the tomography method developed in the KIM consortium and in particular the chosen model representation and argue the need for an adaptive parameterization. In a second part, we propose a method to reduce the number of parameters to be inverted and illustrate its efficiency on two applications on synthetic data.

Formulation of reflection tomography

Solution of forward and inverse problems

The forward problem of our reflection tomography (Jurado et al., 1996) is a two-point ray tracing based on a bending method: it furnishes, for a given acquisition survey and for a given model, the traveltimes associated with the interpreted reflections. The inverse problem consists in the minimization of

$$C(m) = \left\| T^{cal}(m) - T^{obs} \right\|^2 + \varepsilon \left\| D^2 (m - m^{prior}) \right\|^2 \qquad (1)$$

where $T^{cal}(m)$ represents the calculated traveltimes for the model m, and T^{obs} denotes the observed traveltimes picked on the seismic sections. $\left\| D^2 (m - m^{priori}) \right\|^2$ is a regularization term, composed of the sum of second derivatives of the interface depths and velocity variations. This penalization term is necessary to stabilize the inversion and allows the introduction of a priori information.

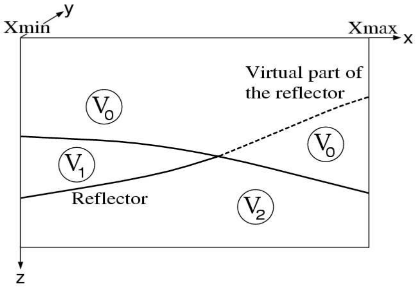

Figure 1: Blocky model representation where the b-spline functions describing the interfaces and the velocities are defined on the whole definition domain of the model.

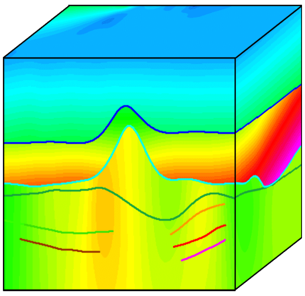

Figure 2: An example of 3D model determined by reflection tomography. It shows the hybrid character of this representation where an interface can delimit a velocity block (as for the two shallowest layers) or can be embedded in a smooth velocity (as for the deeper layer).

Model parameterization

In our approach, the subsurface velocity is represented by a blocky model with interfaces described by 2D explicit b-spline functions ((Z(x,y), X(y,z), Y(x,z)) and layer velocities described by 2D or 3D explicit b-spline functions (V(x,y)+k.z, or V(x,y,z)). The regularity of the b-spline functions (twice differentiable) allows an exact calculation of the derivatives needed to solve the forward and inverse problems. The choice of explicit functions and regular discretization grids is crucial to fasten the ray tracing. In order to easily handle the model changes during the inversion process, we define the interfaces and the velocities on the whole definition domain of the model (see figure 1). Indeed, the domain of definition of a layer velocity has to cover completely the associated block and the blocks have to remain closed when the geometry of the interfaces delimiting the blocks changes during the tomographic inversion. Note also that this parameterization can be used to represent hybrid model with simple velocity blocks and varying velocities with embedded reflectors (see figure 2).

A realistic 3D model may require up to 50000 b-spline parameters. Delbos et al. (2001) have developed sophisticated optimization techniques for the inversion of big models which allow introduction of linear constraints on the model. Another way to improve the efficiency of the inversion of such models is to work on the parameterization itself to limit the number of parameters. This is the subject of the next section.

The need for an adaptive parameterization

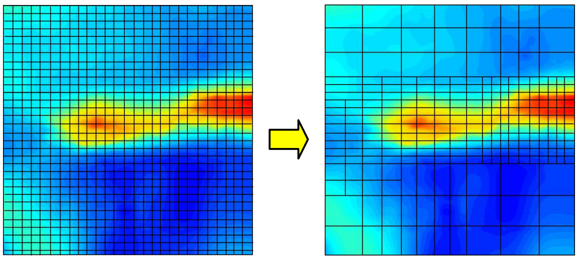

Figure 3: Regular versus irregular parameterization of an interface with local complexities. Many parameters on the left are useless and are not worth to be inverted.

The parameterization described above requires the a priori choice of a discretization step for the b-spline functions. To illustrate this, let us consider an example. The discretization step of the interface represented on figure 3 is chosen fine enough to fit local complexities roughly located in the central region of the model (figure 3 on the left). However we have introduced a lot of useless parameters in the simple regions. This problem can be solved by using an irregular adaptive parameterization (figure 3 on the right), dense in the complex zones and sparse in the simple areas. Such a parameterization allows to drastically reduce the number of parameters used to describe the interface. This case is nevertheless not the only one that involves useless parameters. Generally speaking, our approach aims at reducing the inverted model size by removing from the inversion the useless, that is to say the non-physical (e.g. associated with virtual parts of reflectors (figure 1)), non-illuminated, or redundant b-spline parameters to reduce both memory use and computation costs.

Macro-parameter methodology

To reach these objectives, we introduce, through a general formalism, new parameters called macro-parameters, which are linear combinations of model parameters. Defining macro-parameters results in replacing many useless parameters (non-physical, non-illuminated, or redundant information in simple areas) by few macro-parameters to obtain a reduced sized model, the macro-model, which is then a mix of b-spline coefficients and macro-parameters.

In this way, an irregular parameterization can be obtained from the dense discretization (figure 3, left) by replacing one or several groups of parameters in one of their embedded b-spline parameterization, or even in basic macro-parameters as constant values or planes (i.e. constant or linear extrapolation to deal with virtual parts of the model or unilluminated areas).

The choice whether to replace a group of parameters in a macro-parameter or not, must be carried out periodically in the inversion procedure to take into account model variations that can be severe especially during the first iterations of tomography. It can be done automatically through the computation of update indicators. These indicators estimate the coarser b-spline discretization that best explains the data complexity. It is classically based on the analysis of the resolution matrix, or some related approaches, which are often expensive and a posteriori methods (Böhm et Al., 2000 and Cox and Verschuur, 2001). We are currently developing a cheaper indicator based on the gradients, that gives the optimal a priori b-spline discretization to fit the data (as illustrated in the next sections).

Application to realistic synthetic data

The method described in the previous section is here applied on a model composed of 8 interfaces and 3 velocities, including a smooth (3D) velocity located under the second interface (figure 5).

The six deepest interfaces (3024 parameters) and the 3D velocity (6000 parameters) are inverted simultaneously with the classic and macro-parameter version of the inversion software.

The weak complexity of both interfaces and velocities does not require the introduction of varying b-spline discretization step.

However, the deepest interfaces are only partly illuminated and we replace the many b-spline parameters in the non-illuminated zones by macro-parameters describing simple planes. Practically speaking, we introduce for the 6 inverted interfaces 9 rectangular zones containing 56 parameters each and we compute the illumination in each one (figure 4). If a threshold of illumination is not reached (figure 4, hatched areas), the b-spline parameters included in these zones are replaced by linear (plane) macro-parameters. Besides, the 3D velocity is defined all over the model, (i.e. from z = 0 to 6 kilometers) even if it only applies to the volume located under the second interface. Moreover, it is not illuminated under the deepest interface. We thus replace the b-spline parameters located above 1 km and below 4 kms by constant macro-parameters.

The inversion with macro-parameters furnishes (figure 5) very satisfactory results (RMS = 0.8 ms), with a reduced number of model parameters (figure 6). These results are equivalent to the one obtained with the classic version, but with significant benefits (table 1): the macro-parameter version requires less memory, and is significantly faster (25%). Moreover, the tuning of the regularization weights is considerably simplified, because of the introduction, via macro-parameters, of hard constraints in the areas of poor ray coverage, which may be seen as an induced (model intrinsic) regularization.

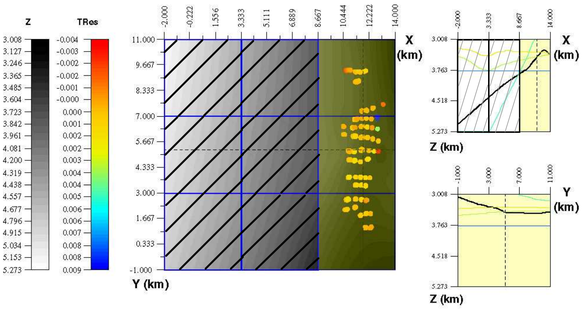

Figure 4: Map of a partly illuminated interface (hatched areas are not illuminated). It is described by 186 parameters instead of 504.

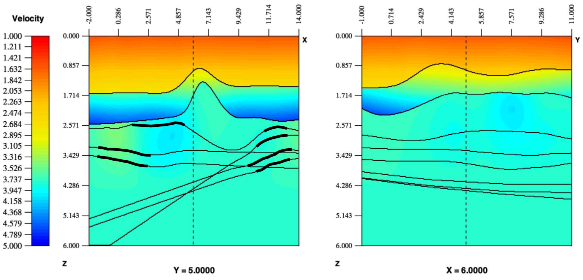

Figure 5: Solution model obtained by the macro-parameter version. In the deepest layer, he bold lines correspond to the illuminated parts of the interfaces.

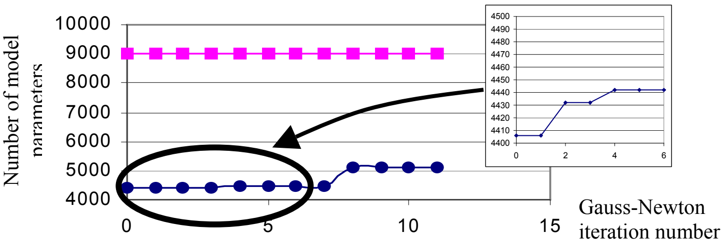

Figure 6: Inverted model size for the macro-parameter (circles) and classic (squares) versions as a function of tomography iterations.

	RAM use (Mbytes)	CPU time (s)
Macro-parameter version	137	321
Classic version	160	431

Table 1 : Inversion statistics for 2 tomography iterations on a Sun Blade 2000 workstation.

Application to a 2D model with local complexities

To illustrate the effectiveness of our update indicator, we now apply our method to synthetic data calculated on a model composed of a velocity and a locally complex interface. We compute our gradient-based indicator for the interface of the initial model[1] (figure 7) in order to determine the b-spline discretization step required to fit the data. A discretization step is eligible if its indicator is near zero. We notice that the interface is locally complex, especially from 6 to 10 kilometers where a discretization step of 78 meters is required. The classic version is consequently performed with this step, leading to the inversion of 131 b-spline parameters. However, between 0 and 6 kilometers, which is a relatively simple region, it is possible to choose a discretization step of 156 meters (312 meters is not good enough). We have run the macro-parameter version to invert the data with the chosen discretization step: 156 meters between 0 and 6 kilometers and 78 meters between 6 and 10 kilometers. The inversion is performed with 95 parameters instead of 131. The solution model (figure 8) obtained with this parameterization is equivalent to the one obtained with the classic version but with a significant gain (27%) on the number of inverted parameters.

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[1] The initial model is composed of a plane interface at z = 800 m, and a constant velocity.

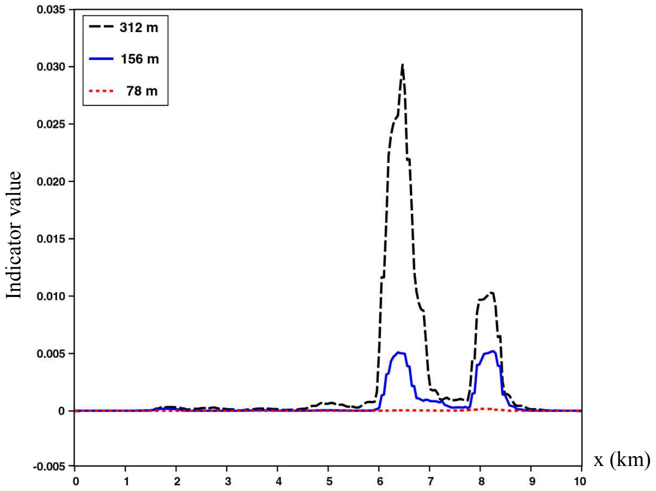

Figure 7: Update indicator. The discretization step that best fits the data gives a near-zero indicator.

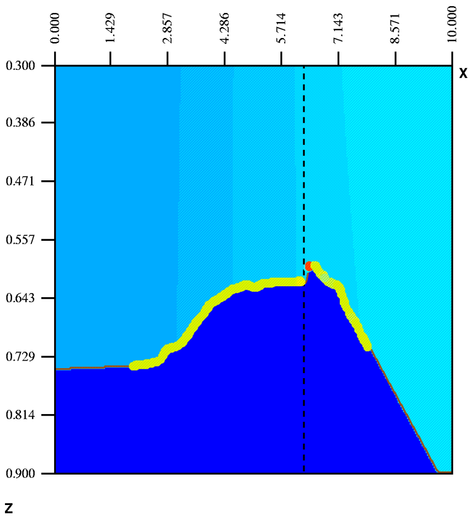

Figure 8: Solution model obtained by the macro-parameter version with two different b-spline discretization steps.

Conclusions

We have developed a new adaptive parameterization approach, based on an original formalism, that makes our reflection tomography even more efficient. Our model description now combines the efficiency of regular parameterization for ray-tracing and the flexibility of irregular grids for inversion. The results obtained with the macro-parameter approach compared to the classic version of the software show multiple benefits: the inversion is more stable and less sensitive to regularization weight tuning (this is mainly due to the model intrinsic regularization), the computing costs and memory use are significantly reduced. This method is mainly automatic thanks to the computation of appropriate update indicators. Then, macro-parameters coupled with adequate update indicators allow an adaptive parameterization for reflection tomography. This formalism may also be used for the introduction of hard a priori constraints on the model for underdetermined problems.

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