2D Non-Linear Refraction Tomography for Velocity Model Building and Statics Correction

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Abstract

The present work applies a methodology for 2D near-surface velocity model building and statics correction for land seismic data using shallow refraction information. A synthetic seismic data was generated and then an initial interpretation, modeling and inversion was performed using a 2D non-linear ray tomography algorithm to minimize first arrival traveltimes, inverting both the seismic velocities as the vertical position of the refractor. The results obtained were compared with a linearized refraction tomography algorithm, commonly used in the seismic processing workflow. It was observed that the nonlinear algorithm obtained the smallest relative errors in most of the parameters of the model.

Introduction

In many onshore exploration areas, the land surface is covered with a relatively thin layer of material of low seismic velocity (commonly called LVL, or low velocity layer). It is generally related to aerated material above the water table or to geologically recent unconsolidated sediments on a substratum of harder consolidated rocks. Variations in the physical properties of this upper layer can cause a dramatic deterioration in the quality of land seismic data. Static corrections are most important in the processing of land data because they lead to improved quality in subsequent processing steps which, in turn, impact the integrity, quality, and resolution of the imaged section. There are refraction-based techniques which use the first break information in a deterministic way to estimate the near-surface model from which the static corrections are computed. An approach to the computation of statics is to assume a model, compute the first breaks by ray tracing through the model, and then modify the model in order to minimize the differences between observed and modeled first breaks. Such is the tomographic approach (Marsden, 1993).

Amorim et al., (1987) used a one-layer model in a tomographic approach which they called *numerical equivalent*. This algorithm uses a linear approximation, since there is no ray tracing itself, but an approximation through straight rays. The model is parameterized in vertical prisms (cells) and only inverts the velocity of LVL. Among the limitations of the algorithm is not to allow the inversion of more than one refractor (can interpret another refractor, but all enter as only one LVL and the last refractor is considered), not to invert either the thickness of LVL and velocity of the refractor.

Other approach for calculating static correlations is the *turning-ray tomography*, also known as diving-wave tomography or *tomostatics* (Zhu *et al*, 1992; Stefani, 1995). This method have advantages in regions where no refractors can be easily identified, have hidden layer or the lack of smooth velocity structure such that conventional refraction statics usually fail due to continuously refracted rays. The method uses a parameterization of the model through a finely uniform grid and does not work with surfaces, only velocity values in the grids. This limitation can make the result highly unstable, being sensitive to picks and initial model.

In order to determine the velocity model and crustal structure, a non-linear tomographic inversion algorithm was introduced by Zelt and Ellis (1988) and Zelt and Smith (1992). This algorithm called Rayinvr uses an interface model, which forms segmented layers in trapezoids. The velocity values in the vertices are used to interpolate the velocity within each trapezoid, allowing the continuous propagation of rays. In this way, the algorithm allows lateral and vertical velocity variation. The computational cost is low because it does not use uniform grid, and the use of interfaces allows flexibility in the construction of the model, since the vertices of the trapezoids do not need regular sampling.

In this work we use the Rayinvr algorithm in a seismic reflection data for determination of the near-surface velocity model. The estimated velocity model is used for static corrections, removing temporal variations from medium to long wavelengths, caused by variations of topography and LVL. We performed the first tests on synthetic data and presented the preliminary results.

Method

Zelt and Smith (1992) developed a technique for inverting traveltimes to obtain 2D velocity and interface structure simultaneously, in which the model parameterization and method of ray-tracing are suited to the forward step of an inversion algorithm. The method is applicable to any set of traveltimes for which forward modeling is possible, regardless of the shot-receiver geometry or data quality, since the forward step is equivalent to trial-and-error forward modeling. The non-linearity of traveltime inversion makes a starting model and iterative approach necessary, thus requiring a practical and efficient forward step.

The parameterization of the model consists of interfaces of fragmented layers in an irregular network of trapezoids, each with upper and lower boundary layers and left and right vertical sides. The velocities at the four corners of the trapezoid are used to interpolate a velocity field within the trapezoid so that velocity varies linearly along its four sides. Therefore, horizontal and vertical velocity gradients may exist within a trapezoid. The number and position of the model parameters (velocity and interface nodes), which specify each layer, can be completely general and therefore adapted to the resolution of the subsurface data. The algorithm also allows variations of topography and near-surface velocity to be incorporated into the model.

The method of raytracing is coupled to an automatic determination of ray take-off angles by an efficient numerical solution of the 2D ray-tracing equations. Applying a smooth layer boundary simulation reduces the instability associated with a blocky model parameterization. The first step of the inversion is the analytic calculation of partial derivatives of traveltime with respect to the model velocities and the vertical position of boundary nodes. These partial derivatives are calculated during ray-tracing and may correspond to any arrival identified in the observed seismic traveltime data (i.e., refractions, reflections, head-waves, multiples, etc.). Traveltimes and partial derivatives are interpolated across ray endpoints to the receiver locations, avoiding the need for two point ray-tracing. Damped least-square inversion is used to determine the updated model parameters of those selected for adjusting both velocities and boundary nodes simultaneously.

The Zelt's algorithm, called Rayinvr, was initially designed to work with wide-angle seismic and crustal modeling, and is largely used to date in the literature. It has limitations, but with due consideration, it allows to work with shallow refractions from seismic reflection data.

Application

We constructed a synthetic model based on a velocity model of the Parnaiba Basin, with nine layers of constant velocities (figure 01). In the shallow part of the model, that we are interessed, the *Low Velocity Layer* (LVL) have velocity of 1500 m/s (called V0), the second layer, refered as a refractor, have velocity of 2500 m/s (called V1) with a depth structure called Z.

The synthetic modeling used a finite difference algorithm with the following acquisition parameters: 101 shots, spaced 80 meters, 200 channels, spaced 20 meters, in a split-spread arrangement. A Ricker pulse of central frequency 40 Hz was used. With the synthetic data, the first breaks picking were carried out then, a methodology was developed to construct the initial model to find V0, V1 and Z.

Initially the *crossover points* were interpreted for each arm of the synthetic data. From origin of a T-X graph until these points, the slopes (and its inverse, the velocity) were calculated for each separate spread (right and left side). The final V0 value in the shot was found using a mean between them these two values. To find V1, the principle of reciprocity was applied. Direct and reverse shots were used, then the slopes and velocities of each were calculated (Vd for direct shot and Vr for reverse shot). To overcome the problem of apparent velocities, a corrected velocity Vf was used, based on the following relation Vf = (2*Vd*Vr)/(Vd+Vr). For each direct and reverse shot Vf was calculated over the stations that cover both spread. Following, a mean of Vf was made, finding only one value in the station and calling it V1. With initial V0 and V1, the thickness Z was found using *Delay time method* (Barry, 1967), constructed in a scheme of linear equations and solved by the least squares method. We used 101 points to define V0, V1 and Z (localized in the shot points).

With the determined initial model (V0, V1 and Z), the modeling and tomography inversion in Rayinvr program was used (the possibility of vertical gradient was not considered). Initially, a smoothing filter was done using a three-point filter, performed five times, for velocities V0 and V1 to remove anomalous values. For the tomographic inversion, the following parameters were used: estimated uncertainty traveltime pick 5 ms, model velocity uncertainty 20 m/s, model boundary position uncertainty 1 m. The RMS traveltime residual was 12.56 ms for initial model and 7.96 ms for inverted model. The normalized chi-squared was 6.31 for initial model and 2.53 for the final inverted model.

Finally, we compare the result of Rayinvr with the Refratom software, owned by Petrobras. This program uses linear refraction tomography based on the algorithm of Amorim *et al* (1987), as previously described.

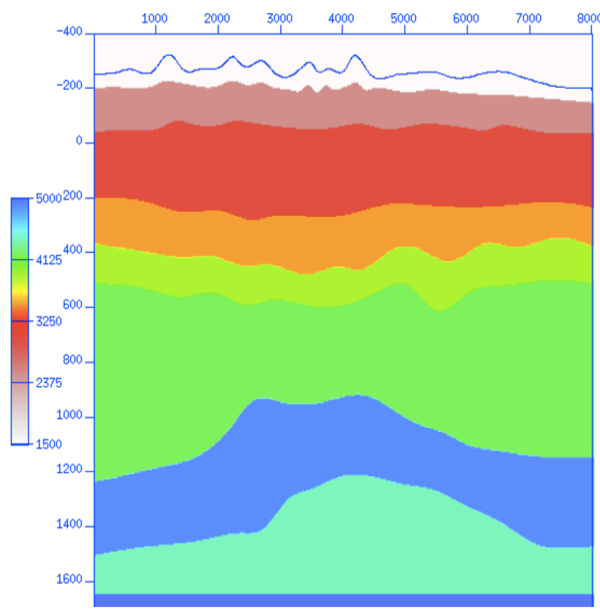

Figure 01: *Velocity model used to produce syntethic data.*

Results

Figure 02 shows, at the top, interfaces of the model, with the elevation and depth of the refractor for real model, initial model, inverted by Rayinvr and results from Refratom. The base of figure 01 shows velocity curves of V0 and V1 for initial model, initial smoothed model (used in Rayinvr), inverted by Rayinvr and results from Refratom. Remembering that Rayinvr inverts all three parameters simultaneously (V0, V1 and Z), while Refratom just velocity V0 (because the problem is linearized).

Figure 03 shows the difference curves with respect to the real model for V0, V1 and Z for the initial model, inverted by Rayinvr and results from Refratom. The improvement of the result obtained by Rayinvr in relation to the initial model and Refratom for the parameter Z is visible, mainly in the right part of the model, where was able to solve well the top of the refractor.

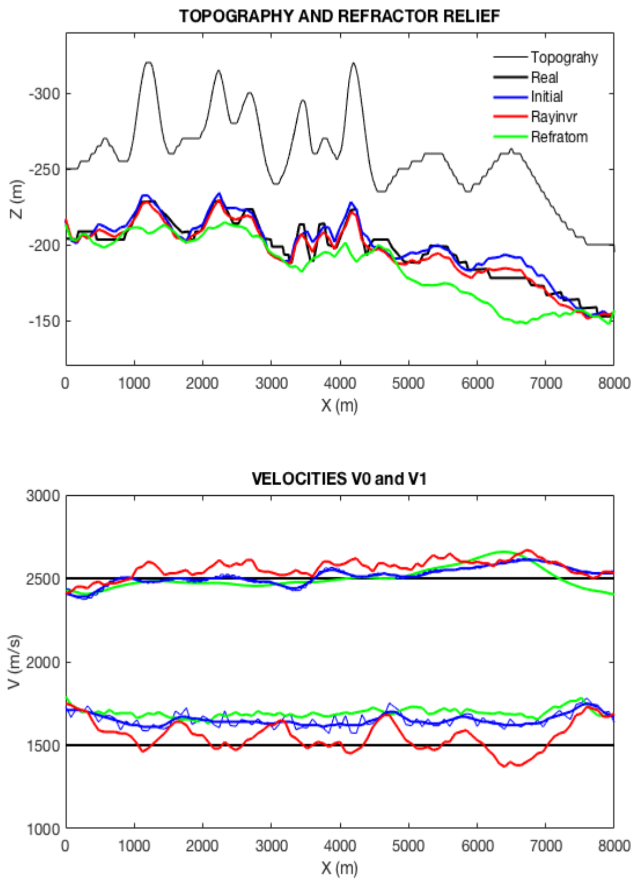

Figure 02: *Top: topography and depth of the refractor for real model, initial model, Rayinvr model and Refratom model. Base: velocity curves of V0 and V1 for initial model, initial smoothed model, Rayinvr model and Refratom model.*

For the parameter V0 it was also better, but introduced to lateral velocity variation, where it has parts that approximate the constant real velocity (1500 m/s) and other parts shifts away. Finally, for velocity V1, Rayinvr ended up getting worse than the initial model.

Figure 04 shows on top the calculated static correction, the bottom the difference in relation to the real model. Apparently the difference between the two tomography methods is very similar. For the Refratom, it is clear that the larger Z thicknesses were compensated by the larger velocity V0.

We calculate a relative RMS (*root mean square*) error using the following formula:

$$E(\%) = \left[\frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(a_i - b_i)^2}}{\frac{1}{N}\sum_{i=1}^{N} a_i} \right] x100$$

The table bellow gives a summary of relative RMS error for Z, V0, V1 and statics correction relative to real model.

Parameter	Initial	Rayinvr	Refratom
Z	3.16%	2.32%	7.49%
V0	10.58%	6.85%	13.06%
V1	2.21%	3.19%	2.61%
Statics	4.29%	2.02%	2.21%

We can see that Rayinvr have worse error for V1, but is better one for the others. The initial model of V1 has the better one. One limitation is because Rayinvr uses turning rays instead of straight rays for direct waves. Since the model has a constant velocity for the LVL, the algorithm has difficulty in drawing straight rays (because it uses shooting method based on ray-take off angles), which hinders the seismic imaging. The Rayinvr algorithm, originally proposed to solve crustal models, has some limitations for near-surface velocity building. Zelt (1999) suggests the use of minimum independent parameters and use of prior-information to avoid instability. The fewer parameter points you use, the less unstable and the more reliable the result of your inversion. In this work, we use 101 points for each parameter of the model that we inverted (one for each shot point station). This can be considered huge, and can result in poor inverted data.

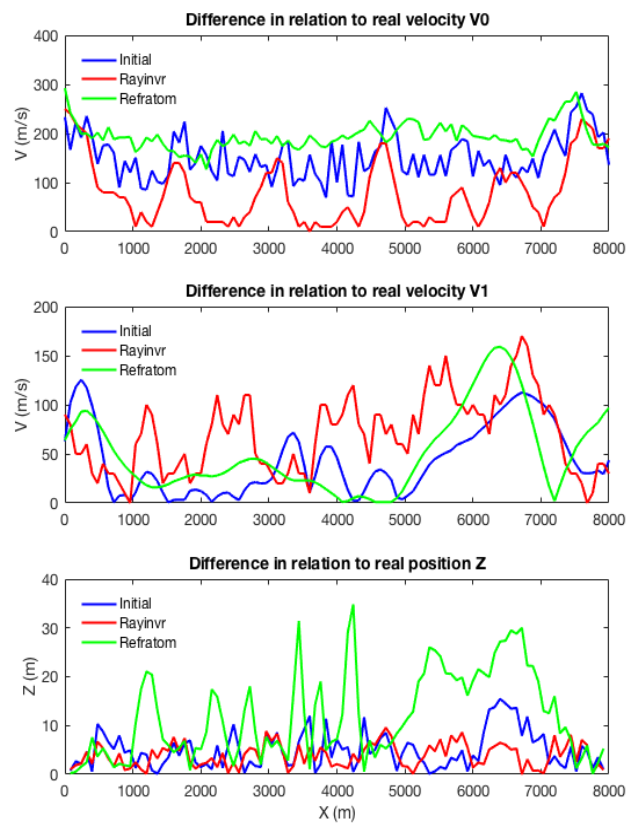

Figure 03*: Difference curves with respect to the real model for V0, V1 and Z for the initial model, Rayinvr model and Refratom model.*

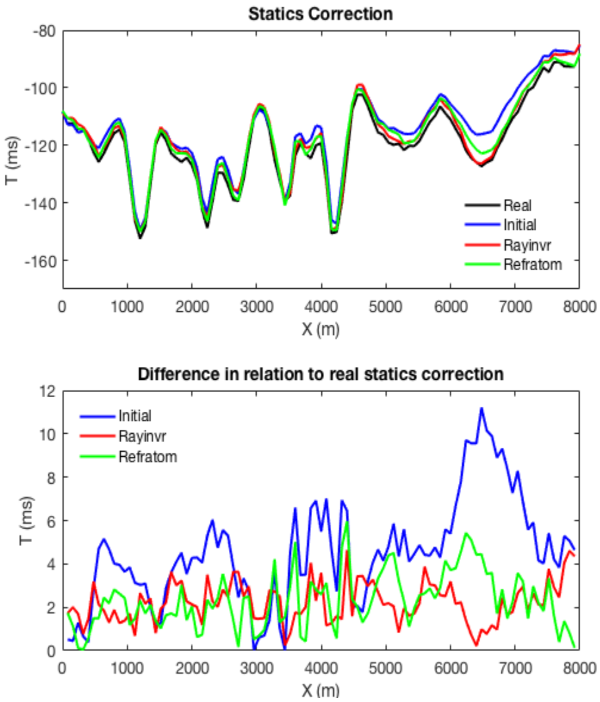

Figure 04: *Top: Calculated static correction for real model, initial model, Rayinvr model and Refratom model. Bottom - difference in relation to the real model.*

Conclusions

A 2D non-linear seismic tomography algorithm was used to invert simultaneously V0, V1 and Z in a 1-layer refraction model. The inversion obtained by was closer to the real model, with relative errors of 2.32%, 6.85% and 3.19% for V0, V1 and Z, respectively. Even tough the final static correction values are similar, in comparison with a result from linear refraction tomography, it is important to study the impact of this velocity model for seismic depth imaging.

This work is still being developed, and the authors are studying other models and characteristics of each method of tomography. In this sense, the authors are still studying the program, testing other models parametrization, use of different values of uncertainties in the picks (data) and in the velocities and boundary positions (model), all to try reducing instability.

The authors are rewriting the Rayinvr code and working to improve it. It is expected that with the resulting algorithm it will be possible to construct near-surface velocity models more reliably to geology. In later works, the authors also intend to use others models, like one two refractors, vertical velocity changes in the low velocity layer, lateral velocity changes in the refractor, and so on.

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