AMTCLAB: A MATLAB®-based program for traveltime analysis and velocity tuning in 2D elliptical anisotropic media

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ABSTRACT

In this paper we present the program AMTCLAB, a MATLAB®-based computer code that analyzes the traveltime distribution and performs quality analysis at the pre-inversion stage for elliptically anisotropic media explored via 2D transmission experiments. This software generalizes the program MTCLAB presented in the past for the case of layered isotropic media, and makes use of traditional and robust traveltime distribution descriptors (mean, standard deviation, median, lower and upper quartiles, inter-quartile range and minimum absolute deviation), which are valid for all kinds of recording geometries. A guided user interface leads the modeller through the algorithm steps using the same data MTCLAB-structures. This methodology offers better understanding of the data variability prior to inversion, and provides the geophysicist with a macroscopic elliptical anisotropic velocity model, which is valid at the experiment scale, and matches the experimental mean traveltime distribution. To solve the inverse problems involved, program AMTCLAB uses the particle swarm optimisation algorithm, which allows the use of different norms and sampling the region of equivalent anisotropic velocity models in order to perform posterior sample statistics in each individual model parameter. The approximated velocity model issued from this analysis can serve in the traveltime inverse problem as an initial guess, or as a reference model in the subsequent inversion.

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1. Introduction

Transmission seismic tomography methods are aimed to infer the velocity distribution of a real geological medium by means of the inversion of the measured seismic traveltime data acquired from their boundaries. The tomographic inverse problem is ill posed, so, it is crucial to have at disposal methodologies to analyze the traveltime distribution, to identify and filter possible errors, and to infer prior velocity information to add stability at inversion. Mean traveltime curves (MTC) describe the variation of the main statistical parameters of the traveltime distribution for the different gathering subsets, as a function of the gather index (Fernández Martínez et al., 2006a). These curves constitute a simple methodology to accomplish a guided structured analysis of the data variability before the inversion, which helps to discriminate the contribution of data errors from that of geological heterogeneities.

This methodology was first applied to layered isotropic media, and has given birth to the program MTCLAB (Fernández Martínez et al., 2008). This program analyzes at the pre-inversion stage the sources of data variability, being able to infer from data prior velocity information, which is of great importance for the tomographic inversion.

Experimental results in hydrocarbon exploration show that anisotropy with angular dependence of velocity is the most common form of anisotropy found in seismic experiments (Upadhyay, 2004; Tsvankin, 2005). Thomsen (1986) also noted that in most cases the anisotropy is weak and developed the theory of weak anisotropy starting from the theory of transversely isotropic media. Elliptical anisotropy thereby stems as a particular case.

Clays and fine layering are mentioned in the bibliography among the main causes of seismic anisotropy in sedimentary rocks (Wang, 2002). Studies in clays also have shown that velocity anisotropy is influenced by the content of organic matter and the interaction with pore fluids (Vernik and Liu, 1997). Macroscopically, anisotropy occurs as a result of the natural fractures of rocks (Schoenberg and Sayers, 1995).

Seismic anisotropy has been taken into account in seismic traveltime inversion through different kinds of numerical algorithms (Byun and Corrigan, 1990; Carrion et al., 1992; Pratt and Chapman, 1992; Williamson et al., 1993; Watanabe et al., 1996), and still is an important field of research in geophysics (see for instance Tsvankin and Grechka, 2006).
Considering anisotropy in tomographic inversion techniques introduces the need of estimating the anisotropic model parameters. In some numerical algorithms, these parameters are taken as unknowns in the inversion problem (Pratt and Chapman, 1992; Williamson et al., 1993), but in other cases, these parameters are fed into the inverse problem, being previously estimated by different geophysical and numerical techniques (see for instance, Van der Baan and Kendall, 2002; Xiao et al., 2004).

In this paper, we present the AMTCLAB program, a generalization of MTCLAB for the case of elliptical anisotropic media explored via an arbitrary recording geometry (Fernández Martínez et al., 2006b). This program makes use of the traditional mean traveltime curves (Fernández Martínez et al., 2006a), and of the robust traveltime descriptors: median, lower and upper quartiles, inter-quartile range, and the minimum absolute deviation. This last feature is an addition to AMTCLAB which was not present in MTCLAB.

This methodology helps to grasp a better understanding of the data variability (before) prior to the inversion, and provides the geophysicist with a macroscopic elliptical anisotropic velocity model, which is valid at the experiment scale, and is able to match the experimental mean traveltime distribution. The knowledge issued from this analysis is very important since elliptical anisotropy can be considered as a first step while analyzing anisotropy in real traveltime data. Finally, the use of particle swarm to solve the identification problems involved allows the sampling of the region of equivalent anisotropic velocity models in order to perform posterior sample statistics in each individual model parameter.

2. The AMTCLAB program

The main feature of MTCLAB program (Fernández Martínez et al., 2008) was the introduction of the mean traveltime curves analysis to infer the best homogeneous velocity model in each zone of analysis of the medium. Moreover, the inspection of traveltime residuals between the theoretical and empirical curves, checking for the existence of jumps, discontinuities, sharp oscillations, systematic bias or any other misfit pattern, might allow the modeller to unravel the presence of data errors, and/or medium heterogeneities. In addition, comparison of estimated velocities in the source gather domain with those in the receiver gather helps to classify the causes of traveltime anomalies (Fernández Martínez et al., 2006a).

In this section, we briefly present the main features of the mean traveltime curves (robust and non-robust descriptors) for elliptical anisotropic media (Fernández Martínez et al., 2006b).

2.1. Mean traveltime curves in elliptical anisotropic media

Let us suppose that the recording geometry is rectangular, and assume that the velocity model describing the inspected geological medium has elliptical form (Fig. 1) given by the following parameters: the maximum velocity \((V_{\text{max}})\), the direction of the elliptical anisotropy \((\alpha)\), and the ratio of anisotropy \((\lambda = V_{\min}/V_{\text{max}})\). In this case, the traveltime corresponding to a seismic ray with a direction with angle \(\beta\), measured counter-clockwise with respect to the \(V_{\text{max}}\) direction, satisfies the relation

\[
t_f(\beta) = \frac{d_{\beta}}{v_{\beta}} = \frac{\sqrt{A^2 + \xi^2}}{v_{\beta}},
\]

where \(d_{\beta}\) is the distance between the source and the receiver (defining this direction.), \(A\) is the minimum distance between the source and the line of receivers, \(\xi\) is the distance between the hypothetical receiver located at the perpendicular line to the considered source and the receiver where the seismic ray arrives, and, \(v_{\beta}\) is the velocity in the \(\beta\) direction.

Furthermore, \(v_{\beta}\) can be written in terms of the anisotropic parameters as follows:

\[
v_{\beta} = \sqrt{\frac{\lambda^2(\lambda^2 + \xi^2)(1 + \tan^2 \alpha) + (\lambda^2\xi^2 + \xi^2)\tan^2 \alpha + (\lambda^2\xi^2 + \xi^2)}{2\lambda A \tan \alpha(\lambda^2 - 1) + (\lambda^2\xi^2 + \xi^2)\tan^2 \alpha + (\lambda^2\xi^2 + \xi^2)\tan^2 \alpha}},\]

and, thus,

\[
t_f(\beta) = \sqrt{\frac{(1 + \lambda^2 \tan^2 \alpha)\xi^2 + 2\lambda A \tan \alpha(\lambda^2 - 1)\xi + \lambda^2(\lambda^2 + \xi^2)\tan^2 \alpha}{\lambda^2(1 + \tan^2 \alpha) V_{\text{max}}^2} + \frac{\lambda^2\xi^2}{V_{\text{max}}^2}}.
\]

Mean traveltime curves are obtained by inserting the former expression (1) in the mean and standard deviation definitions

\[
\bar{t}(x) = \frac{1}{T} \int_{-x}^{x} \sqrt{A^2 + \xi^2} d\xi,\]

\[
\sigma^2(t) = \frac{1}{T} \int_{-x}^{x} (t_f(x) - \bar{t})^2 d\xi.
\]

Anisotropic mean traveltime curves have several interesting properties (Fernández Martínez and Pedruelo González, 2008). In particular, the degree of asymmetry of the anisotropic mean traveltime curves (displacement \(\bar{\epsilon}_{\min}\) of the mean time and standard deviation minima from the middle of the gathering line) is related to the ratio and direction of anisotropy as follows:

\[
\bar{\epsilon}_{\min} = \frac{A}{\lambda} (1 - \lambda^2) \tan \alpha \frac{\lambda^2}{(\lambda^2 + 1)}.
\]

Then, the approximate direction of anisotropy, \(\alpha\), can be visually estimated (northeast or northwest) by the displacement of the minimum of these curves with respect to the middle point of the gather line, \(\bar{\epsilon}_{\min}\). Also, the least squares fit of the empirical mean traveltime curves provides a simple methodology to estimate at the pre-inversion step a macroscopic elliptical anisotropic model which is able to match the empirical traveltime distribution. MTC analysis can be considered as a linear tomography method, since it uses straight approximation of seismic ray-paths.
Fig. 2. (a, b) Influence of anisotropic ratio on shape of the mean and standard deviation curves. Direction of anisotropy is in this case N45°E, maximum velocity \( V_{\text{max}} = 5.4 \text{ km/s} \). (c, d) Same curves for anisotropic ratio varying between 0.95 and 1 (isotropic case).

Fig. 2 shows an example of mean traveltime curves (mean and standard deviation) for an anisotropic medium explored via a rectangular recording geometry, having the source line placed left with respect to the receiver line, as shown in Fig. 1. Both boreholes are set 75 m apart. The direction of anisotropy is in this case N45°E \((\alpha = 45^\circ)\) and the maximum velocity is 5.4 km/s. Mean traveltime curves (mean and standard deviation) are asymmetric and have their minimum placed towards the left with respect to the middle of the gather line, as it should be the case for a NE anisotropy direction. Also, as the ratio \( \lambda = V_{\text{min}}/V_{\text{max}} \) increases the curve becomes more symmetric tending to the isotropic case when \( \lambda = 1 \).

2.2. The robust mean traveltime descriptors

The so-called robust mean traveltime curves refer to the variation of the different percentiles and other related measures of dispersion (inter-quartile range and minimum absolute deviation) for the traveltime distribution of the gathering subsets mentioned above.

In this section we first illustrate the methodology for the simplest case: a homogeneous and isotropic domain explored by means of a rectangular recording geometry. These concepts are extended in AMTCLAB for the elliptical anisotropic case. MTCLAB did not incorporate the robust traveltime descriptors, since these curves are a very recent theoretical development.

2.3. Percentiles

The \( p \)-percentiles, \( m_p \), describing the traveltime statistical distribution for the different gathering subsets fulfil

\[
P(t(\xi; x_s) < m_p) = p \in [0, 1].
\]

Considering that \( \xi \) is uniformly distributed in the interval \((0, L)\), this probability is

\[
P(t(\xi; x_s) < m_p) = P(x_1 < \xi < x_2) = \int_{x_1}^{x_2} \frac{1}{L} \, dx.
\]

\[
x_1 = \max(0, x_s - \sqrt{(m_p^2 - t_0^2)V}),
\]

\[
x_2 = \min(L, x_s + \sqrt{(m_p^2 - t_0^2)V}).
\]

In this calculation, three cases arise:

1. \( 0 < x_s < \frac{pl}{2} \Rightarrow m_p(x_s) = \sqrt{t_0^2 + \left(\frac{pl - x_s}{V}\right)^2} \).
2. \( \frac{pL}{2} < x_s < \frac{L}{2} \Rightarrow m_p(x_s) = \sqrt{t_s^2 + \frac{(pL)^2}{4V^2}} \)

3. \( \frac{pL}{2} < x_s < L - \frac{pL}{2} \Rightarrow m_p(x_s) = \sqrt{t_s^2 + \frac{(p - 1)L + x_s)^2}{V^2}} \).

As a main conclusion, the \( p \)-percentile curves are symmetric with respect to the middle of the gather line, \( x_s = \frac{L}{2} \) and have a sill interval whose length is \( L(1 - p) \) of constant value, \( m_{pc} \), which is related to the isotropic velocity
\[
V = \frac{\sqrt{A^2 + (pL/2)^2}}{m_{pc}}.
\]

This formula provides a robust method to identify the isotropic velocity, \( V \), since its uses the \( p \)-percentile sill value, \( m_{pc} \), which is the traveltine at position \( x_s = x_s + (pL/2) \), and is the same for all the gathers on the interval \( [(pL/2) - L(1 - pL/2)] \).

The median curve, \( m_{p,1/2} = 1/2 \).\( m(x_s) \), provides the trajectory of the centre of the traveltine distribution as a function of the gather index, \( x_s \). This curve is symmetric, has a sill of length \( L/2 \) and constant value \( m_{1/2} \), which is related to the isotropic velocity as follows:
\[
V = \frac{\sqrt{A^2 + (L/4)^2}}{m_{1/2}}.
\]

The same way of reasoning can be applied to deduce the inter-quartile range and the minimum absolute deviation
\[
iqr(x_s) = m_{3/4}(x_s) - m_{1/4}(x_s),
\]
\[
\text{mad}(x_s) = \frac{1}{L} \int_0^L |t(x_s, \xi) - m_{1/2}(x_s)| d\xi.
\]

Both descriptors admit analytical expressions.

This theoretical development can also be generalized either for isotropic or anisotropic media explored via any arbitrary recording geometry, which is what has been implemented in AMTCLAB.

Fig. 3 shows the robust traveltime curves for a weak elliptical anisotropic medium explored via a rectangular as well as an irregular recording configuration. The irregular configuration causes asymmetry of these curves and the sill becomes a dipping straight line. Anisotropy induces an additional lateral shift of these curves, which depends on the anisotropy direction (northeast or northwest).

3. AMTCLAB program structure

Similar to MTCLAB, AMTCLAB program was conceived to take advantage of the MATLAB® array computation capabilities. In addition, the use of structure-type objects lightens the information flow through the program. A guided user interface (GUI) leads the user through all the algorithm steps. The program uses the same pre-processing structures as MTCLAB to select and read the traveltime data, the recording geometry configuration, and the zones for anisotropic MTC analysis. In this sense, both programs are data compatible. Experimental traveltime curves are then calculated and stored on the corresponding sgather and rgather structures, for sources and receivers gathers, respectively.

3.1. Inference of the elliptical anisotropic velocity parameters

The anisotropic parameters \( (\lambda, \alpha, V_{max}) \) can be inferred from the experimental mean traveltime curves. The method consists of dividing the domain into fairly homogeneous zones (isotropic or anisotropic), and reducing the misfit between the experimental traveltime curves and the theoretical predictions in each gather by solving the following optimisation problems in the source and receiver domains:
\[
(V_{max}, \alpha, \lambda)^* = \min_{(V_{max}, \alpha, \lambda) \in \mathcal{M}} \| m - m_{V_{max}, \alpha, \lambda} \|_p,
\]

Fig. 3. (a) Robust mean traveltine curves for an anisotropic medium with \( V_{max} = 5.4 \text{ km/s}, \lambda = 0.95 \) and \( \alpha = 45^\circ \text{ (E45' N) } \) explored via a rectangular recording geometry. (b) Robust mean traveltine curves for same anisotropic medium explored via an irregular configuration geometry.
where \( m \) is one of the following experimental mean traveltime descriptors (robust and non-robust) in the considered gather (source or receiver):

\[
m \in \{ \bar{t}_{g}, \sigma_{g}, m_{0,25}, m_{0,5}, m_{0,75}, \text{mad}, \text{iqr} \},
\]

and \( m_{\text{vmodel},k} \) is the corresponding anisotropic MTC theoretical prediction for a certain set of anisotropic parameters, \( (V_{\text{max}}, L, \lambda) \), which has to be found.

\( M \) is the \( \mathbb{R}^p \) prismatic search space

\[
0.8 \leq \ell \leq 1;
-90 \leq \varphi \leq 90;
V_1 \leq V_{\text{max}} \leq V_5,
\]

and \( p \) is the norm used for optimisation. Lower and upper bounds for \( V_{\text{max}} \) and the zones of analysis can be deduced from a priori information or from the analysis of the isotropic mean traveltime curves themselves (Fernández-Martínez et al., 2006a).

Identification problems in (2) are non-linear and overdetermined. The optimisation is performed in the real study case by means of a global algorithm: particle swarm optimisation. The reasons for having adopted this global optimisation algorithm are the following:

1. The presence of different equivalent anisotropic velocity models, which are those that fit the experimental traveltime curves within the same error tolerance.
2. The low number of parameters (1), allowing to speed-up the error evaluation for a swarm of anisotropic velocity models.
3. Global heuristic algorithms allow easier solving the above-mentioned optimisation problems using different \( L^p \) norms, which obviously influence the solution found.
4. Finally, as explained in the next section, the basic PSO algorithm is very intuitive and easy to program.

All the results (velocity models) coming from the optimisation are stored in the vmodel structure.

3.2. The optimisation algorithm: particle swarm optimisation (PSO)

The particle swarm is a stochastic evolutionary computation technique (Kennedy and Eberhart, 1995) used in optimisation, which is inspired by the social behaviour of individuals (called particles) in nature, such as bird flocking and fish schooling.

An individual, or particle, is represented by a vector whose length is the number of degrees of freedom of the inverse problem. To start, a population of particles is initialized with random positions \( (x_i(0)) \) in the search space \( M \), and null velocities \( (\nu_i(0) = 0) \). An error or misfit function is evaluated for each particle (velocity model), to quantify the difference between the observed and the predicted data (experimental and theoretical MTC). As time advances, the position and velocity of each particle are updated as a function of its own history of misfits and the information about the misfit of its neighbours. In the present case, the positions are the anisotropic velocity models found, and the velocities stand for the parameter perturbations needed for these positions (anisotropic velocity models) to find the global minima of (2).

At iteration step \( k+1 \), the algorithm updates positions \( (x_i(k)) \) and velocities \( (\nu_i(k)) \) of individuals at time \( k \), as follows:

\[
\nu_i(k+1) = w \nu_i(k) + \phi_1 (x_i(k) - g(k)) + \phi_2 (x_i(k) - l_i(k)),
\]

\[
x_i(k+1) = x_i(k) + \nu_i(k+1),
\]

\[
\phi_1 = r_1 \alpha_1, \quad \phi_2 = r_2 \alpha_2, \quad r_1, r_2 \in [0,1], \quad w, \alpha_1, \alpha_2 \in \mathbb{R}.
\]

As can be seen, the velocity of each particle \( (i) \) at each iteration step \( (k+1) \) is a function of three major components:

1. The inertia term, which consists of the old velocity vector of the particle, \( \nu_i(k) \), weighted by a real constant \( w \), called inertia.
2. The social learning term, which is the difference between the global best position found thus far in the entire swarm (called \( g(k) \)) and the particle’s current position \((x_i(k))\).
3. The cognitive learning term, which is the difference between the particle’s best position so far found (called \( l_i(k) \)) and the particle current position \((x_i(k))\).

Constants \( w, \alpha_1, \alpha_2 \) constitute the tuning PSO parameters to achieve convergence. \( \alpha_1, \alpha_2 \) are called, respectively, the global and local accelerations, and are stochastically weighted by uniform random numbers in the interval \([0,1] \), \( r_1 \) and \( r_2 \). This stochastic effect causes each particle trajectory to oscillate at each iteration step \( k \) around the point:

\[
o_i(k) = \frac{a_l g(k) + a_g l_i(k)}{a_s + a_l}.
\]

The algorithm convergence is somehow related to the particle trajectories stability, which depends on inertia constant, \( w \), and the total mean acceleration \( \phi = \alpha_1 + \alpha_2/2 \). A complete analysis of the algorithm properties can be seen in Fernández-Martínez and García Gonzalo (2008).

As mentioned above, the PSO not only allows finding in each case the anisotropic parameters which better fit the corresponding experimental traveltime curve, but also sampling and exploring the region of equivalent anisotropic velocity models, in order to perform posterior sample statistics in each individual model parameter. The dispersions around the modes of the sample histograms serve to analyze how each anisotropic parameter is individually resolved by the mean travelttime data. Usually, the maximum velocity is the parameter that always exhibits the lowest dispersion and, thus, is better resolved or identified. Data noise produces smearing of the value of the estimated anisotropy ratio and wrong directions of anisotropy, biased towards zero degrees (Fernández-Martínez et al., 2006b).

Nevertheless, synthetic studies have shown that the mean, median and upper-quartile curves are very resistant to data noise, and thus, they are preferred to infer background velocity models, which can be taken into account in the solution of the travelttime tomographic inverse problem. Furthermore, the inverse problems involved become more stable when \( V_{\text{max}} \) is correctly identified.

In the AMTCLAB program the following parameters are user-defined:

1. The optimisation norm, \( p \). The default norm is the Euclidean.
2. The PSO parameters: swarm size, maximum number of iterations, inertia and local and global accelerations. Usually a swarm size of 100 models and 20 iterations are enough to find the region of good anisotropic models. The Carlisle and Dozier (2001) PSO point, \((w, \alpha_1, \alpha_2) = (0.729, 0.948, 2.041)\), provides a good-enough balance between convergence and exploration while solving optimisation problems (2).
3. The \( M \) search space limits. The program performs an isotropic analysis to inform the user about the value of the isotropic velocity background, and monitors the evolution of the best anisotropic parameters found through the iterations.
4. The statistical descriptors chosen to perform the MTC analysis (robust and non-robust measures): mean, standard deviation, median, minimum absolute deviation, inter-quartile range, and upper and lower quartile. It is important to note that AMTCLAB performs the source and receiver gather analysis at the same time.
Finally the program produces the graphical and alphanumeric outputs, including:

- Plot of empirical and theoretical traveltime curves in source and receiver gather for each of the selected descriptors.
- The alphanumeric results for the optimisation problems on the ascii file “amtclab.out”
- Plots of the residual traveltime maps (program aremap.m) and posterior histogram analysis (program histoparam.m) if desired. Obviously, to perform posterior analysis on a descriptor, the corresponding experimental curves have to be previously selected for optimisation.

The MATLAB command clear all is required to clean all the workspace variables (data structures) to allow for a new execution of the AMTCLAB program changing the data set, and/or the zones of analysis.

4. Tutorial example

In this section, we show as a tutorial example the application of AMTCLAB to a data set, which comes from an area with granitic geology: the Grimsel test site-field 1 (a data set acquired and kindly put at disposal by NAGRA, the Swiss National Cooperative for the disposal of Radioactive Waste). We recall that the goal of this section is to provide the user with a quick visual understanding of the main steps and potentialities of the program based on a real example, and not to perform a complete analysis of this data set. Interested readers can find more details in Fernández Martínez et al. (2006a,b).

The geometry of the survey is approximately rectangular bounded by two boreholes. The dimensions of the domain are approximately 70 × 150 m² and the distance between adjacent sources or receivers was approximately 2.5 m. The tomography is aimed at imaging the geological structure of the granitic body, specially the presence of faults and intrusions.

In this case, we show the inference of the anisotropic velocity model using the most robust descriptors: mean, median and upper-quartile. The results obtained were the following:

1. Source gather:
   - Mean: \( (V_{\text{max}}, \alpha, \lambda)^* = (5.26, 46.6, 0.97) \)
   - Median: \( (V_{\text{max}}, \alpha, \lambda)^* = (5.34, 54.6, 0.95) \)
   - Upper-quartile: \( (V_{\text{max}}, \alpha, \lambda)^* = (5.28, 73.2, 0.97) \)

2. Receiver gather:
   - Mean: \( (V_{\text{max}}, \alpha, \lambda)^* = (5.26, 53.6, 0.97) \)
   - Median: \( (V_{\text{max}}, \alpha, \lambda)^* = (5.37, 64.9, 0.95) \)
   - Upper-quartile: \( (V_{\text{max}}, \alpha, \lambda)^* = (5.25, 61.3, 0.97) \)

Fig. 4. Grimsel data set 1. Results of anisotropic MTC analysis for mean (a), median (b) and upper-quartile (c) curves.
Results are very coherent for all the selected curves in both gathers, and correspond to a weak anisotropic medium with anisotropic ratio between 0.95 and 0.97, anisotropy direction, E47–73 N, and maximum velocity between 5.26 and 5.37 km/s.

Fig. 4 shows the graphical results obtained for these analysis, both, on the source and on the receiver gathers. The theoretical predictions match reasonably well the corresponding empirical curves. Sharp zigzagging oscillations observed in all the curves for the first 10 receiver gathers are due to a lack of traveltime data caused by acquisition problems.

Fig. 5 shows the residual traveltime map obtained for example for the velocity model issued from the receiver gather mean traveltime curve. Blue and red colours indicate the zones where the geological medium exhibits a geophysical behaviour that differs from the theoretical model \((V_{\text{max}}, \lambda, \alpha) = (5.26 \text{ km/s, E53.6 } \lambda, 0.97)\). The causes of these differences can be data errors and/or geological heterogeneities.

Fig. 6 shows the posterior histogram analysis for this last model, \((V_{\text{max}}, \lambda, \alpha) = (5.26 \text{ km/s, E53.6 } \lambda, 0.97)\), in the region of 8% relative error (the relative error for the reference model was 5.6%). As expected, the histogram’s mode is close to the reference model. The lower the dispersion is around the histogram mode, the better each individual anisotropic parameter is resolved by the empirical traveltime curve under analysis.

Finally, it is important to note that this analysis can be performed in different zones of the geological medium, provided there are sufficient source/receiver gathers in each zone.
5. Conclusions

In this paper, we have presented a MATLAB®-based program to perform mean traveltime curves analysis for 2D transmission experiments in elliptical anisotropic media. This program generalizes the code MTCLAB, published in the past for layered isotropic media, providing a structured procedure to understand the causes of data variability and delivering an approximate macroscopic anisotropic velocity model, which is able to match the experimental traveltime distribution. This approximate anisotropic velocity model can be used as a reference model (regularization term) in the inverse problem thereby improving its stability. The particle swarm algorithm allows to solve the corresponding identification problems using different norms, and also performing posterior sampling in each individual anisotropic parameter. The knowledge issued from this analysis is very important since elliptical anisotropy is a first modelling step while analyzing anisotropy in real traveltime data.

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Appendix A. Supporting Information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.cageo.2008.11.013.

References


