3D Refraction Statics Integrated with Surface-Consistent First-Break Picking, Iterative Inversion, and 3D Visualization

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Summary

A new environment for integrated first-break travel-time analysis and refraction statics inversion was developed. By utilizing reciprocal travel times, reliable and consistent manual and automatic travel-time picking is achieved. Iterative model-base inversion is performed using an extension of the GLI scheme. Three- and two-dimensional interactive visualization is used at all stages of data analysis and inversion. The implementation is based on a large geophysical data processing system and allows broad customization of the refraction statics analysis and incorporation of other data.

Introduction

Analysis of refraction statics is a key step of seismic data processing strongly influencing quality of the final image. Its purpose is in removal of the effects of shallow subsurface by deriving vertical P- and/or S-wave travel times (“statics”) from first-arrival travel times. Although approximate solutions can be obtained by manipulating the travel-times themselves (such as in the plus-minus method by Hagedoorn, 1959), the most accurate solutions require a model-based inversion for the subsurface structure.

Iterative linearized inversion is an efficient approach to solving large travel-time problems which gained popularity owing to its use in GLI3D software by Hampson and Russell (1984). Although the name of GLI (Generalized Linear Inverse) does not strictly apply to this iterative, and therefore non-linear algorithm, it has become generally associated with inversion based on realistic forward modeling of first-arrival travel times (e.g., Yilmaz, p. 228). In this sense, the description of GLI can be applied to our method as well.

Why making yet another “GLI3D”? The approach presented here differs strongly from the existing software by its concept, functionality, flexibility, and technical implementation. Firstly, we analyse and improve pre-inversion consistency of the data by utilizing the reciprocity condition during travel-time picking. This condition allows straightforward detection of errors and enables reliable manual and automatic picking without employing delicate algorithms such as Artificial

Neural Networks. Secondly, we use three-dimensional visualization to provide a number of interactive displays facilitating consistent time picking and model analysis. In the inversion algorithm, we employ midpoint travel times and the tau-p method to automatically generate starting velocity models. We also provide additional quality control tools, such as the standard checkerboard resolution test and chi-squared statistics for assessment of data fit. Finally, instead of a traditional "program," we developed a modular software that allows creating multiple tools tailored for the specifics of the project at hand. This allows integration of the refraction statics inversion with travel-time picking, seismic processing, and also analysis of nearly any other data.

Below, we overview this integrated refraction statics approach while focusing on consistent manual and automatic picking and quality control by using the new 3D visualization capabilities. The inversion method is generally similar to that of Hampson and Russell (1984) and is not discussed here.

Method

The refraction statics problem is posed as follows. In a layered medium, source-receiver travel times of refracted arrivals t_{SR} can be modelled by head-wave ray tracing (e.g., Hampson and Russell, 1984). With receivers located at the surface, surface-consistent travel times between locations $\mathbf{x}_S$ and $\mathbf{x}_R$ can be defined:

$$t(\mathbf{x}_S, \mathbf{x}_R) = t_{SR} + t_u + t_S , \tag{1}$$

where t_u is the shot uphole time, and t_S is a shot time correction in order to compensate any additional shot time variations that are not accounted for in t_u. Regardless of the velocity model, these travel-time data should be internally self-consistent; otherwise any residual error is driven into the velocity model. The following procedure outlines the data consistency tests and corrections.

Travel-time reciprocity. For any subsurface model, refracted travel times (1) between any two points on the surface must satisfy the reciprocity condition:

$$t(\mathbf{x}_S, \mathbf{x}_R) = t(\mathbf{x}_R, \mathbf{x}_S). \tag{2}$$

This condition should be tested and corrected prior to inversion. In our approach, we calculate the reciprocal time misfits between all shot locations Si and Sj with reciprocal (reversed) recording:

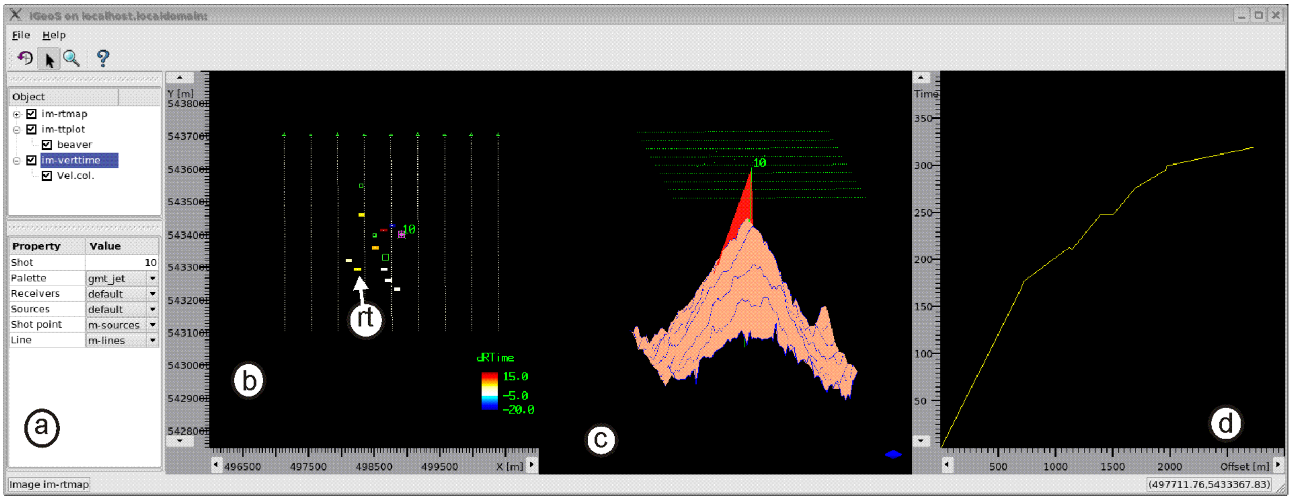
$$\delta t_{Si,Sj} = t(\mathbf{x}_{Si}, \mathbf{x}_{Sj}) - t(\mathbf{x}_{Sj}, \mathbf{x}_{Si}) = t_{ui} - t_{uj} + t_{Si} - t_{Sj} . \tag{3}$$

The system of equations (3) is strongly over-determined for typical 3D recording and can be solved for parameters t_S by using the Least Squares method. As a result, the average travel-time discrepancies between the shots become equal zero. In addition, anomalous values of t_S and $\delta t_{Si,Sj}$ can be used for identification of picking errors during the interactive quality control described below.

Interactive assessment and editing. We use interactive tools to integrate first-break picking with data quality control. For shots selected in a survey map (Figure 1b), the picked and reciprocal travel-time surfaces can be compared in 3D views (Figure 1c). This allows quick detection of geometry and picking errors. The time mismatches $\delta t_{Si,Sj}$ in eq. (3) are displayed in colour at the positions of reciprocal shots (labelled "rt" in Figure 1b). For any position within the survey, the corresponding "midpoint" first-arrival travel-time curve can also be viewed as a direct indicator of the local velocity structure (Figure 1d). Such travel-time curves are further used in the inversion.

Reciprocal time mismatches between all shots in the survey can also be summarized in a single diagram (Figure 2a). By using this diagram, shots with anomalous travel-times (e.g., caused by cycle skipping) can be quickly identified by their characteristic cross-like patterns and corrected. This diagram is also accompanied by a survey map showing the layout of the actual picks in the current shot (Figure 2b) and a travel-time picking dialogue (Figure 2c). To assess the quality of picking and inversion, the user can also apply time reduction (linear moveout corrections) and the current values of statics in this display (Figure 2c).

For guidance in picking a particular shot, travel times from previously picked reciprocal shots can be used. By taking x_R equal the positions of reciprocal shots in equation (1), one can construct a travel-time surface by interpolating between them. We use Delaunay triangulation to perform this interpolation between the source points (Figure 1c). Therefore, once several "seed" shots have been picked in the vicinity of any given shot, their travel times can be used to approximate the times of this shot with good accuracy, especially at receivers located near the reciprocal shots. These times can also be displayed during travel-picking and serve to control its consistency (Figure 2c).



Property	Value
Shot	10
Palette	gmt_jet
Receivers	default
Sources	default
Shot point	m-sources
Line	m-lines

Figure 1: Interactive travel-time analysis: a) tool Property menu, b) map of selected shot, rt) reciprocal-time mismatch indicators in eq. (3), c) 3D display of shot (tan colour) and reciprocal (red) times, d) vertical travel-time at a midpoint selected in base map b). A 10-shot data subset is used for clarity of display.

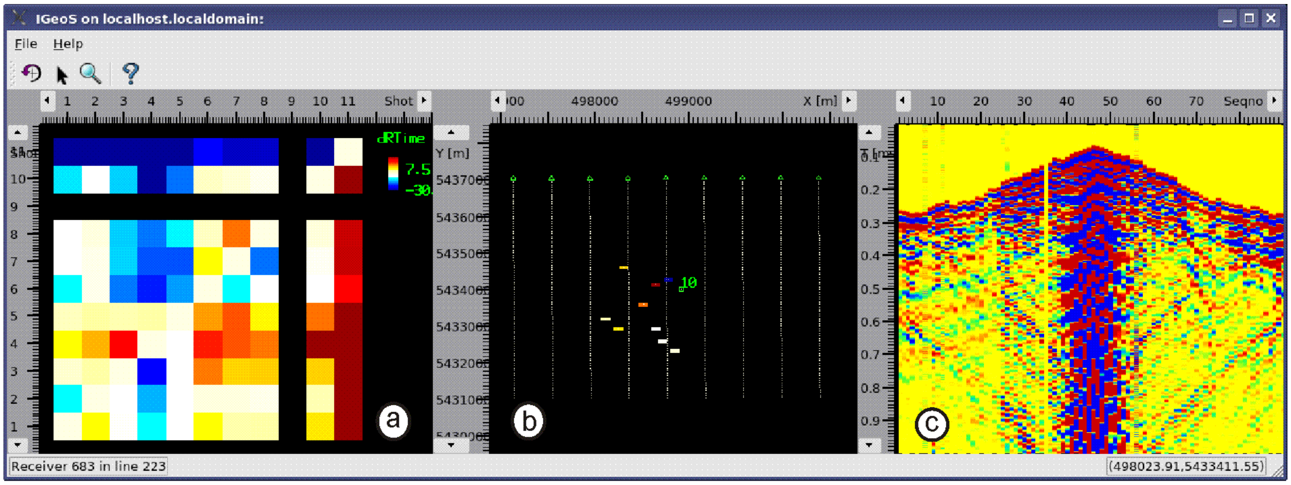


Figure 2: Interactive and automatic surface-consistent travel-time picking: a) reciprocal-time shot mismatch diagram. Colours represent the reciprocal-time misties in eq. (3), b) map of the selected shot with reciprocal-time mistie indicators as in Figure 1b; c) seismic section of the selected line for picking. Shots and lines can be selected from panels a) and b) and time reduction is applied. Reciprocal times from travel-time surfaces (Figure 1) can be used to guide picking.

Automatic picking. Notably, travel-times predicted from reciprocal shots can be sufficiently close to allow their automatic refinement by locating the peak amplitudes in their vicinities. A still better approach consists in "training" the program by interactive selection of a waveform from one shot, which is further cross-correlated with the records in the vicinities of first breaks. In other shots, this "seed" waveform is selected automatically from receivers located near shots that have already been picked. The waveforms collected from each shot record can be saved and used later, for example, for deconvolution.

Automatic surface-consistent first-break picking starts from manual picking of several shots located within one recording swath, plus maybe additionally several shots along the edges of the survey area. The program then starts picking from a shot with the best reciprocal-shot coverage and proceeds until all required records are picked and included in the travel-time dataset.

Visualization and Integration with a Processing System

Three-dimensional (3D) graphics using OpenGL opens new possibilities for improving interaction with the data, resulting in an improved efficiency of the procedure and quality of the inversion. Travel-time surfaces from different shots can be viewed and examined for consistency. Selection of shots and seismic lines for viewing and travel-time picking is performed visually from an interactive base map (Figure 2b). The images can be zoomed, paned, and rotated smoothly, as in most seismic interpretation programs. Many graphical options (colours, lines, fills, palettes) are selectable from context-sensitive goCad-like property menus (Figure 1a). Drop-down menus, status lines and tool tips improve the interpreter's experience.

The design of interactive displays is unusual and takes advantage from integration with a large data processing system (Chubak et al., 2007). The contents of the displays (such as selection of images, objects, and their options in Figures 1 and 2) is performed entirely by the user, in the form of processing flows similar, for example, to those used in ProMAX. Other objects not directly related to the refraction static problem (e.g., base maps, gravity or magnetic models, wells, or seismic cross-sections) can also be included. Note that the images shown above were constructed by the user without any “real” computer programming. The system’s Graphical User Interface can be used for maintaining and executing the flows.

In addition to customisable graphics, integration with the processing system brings other significant advantages. Data input/output, visualization, PostScript plotting, seismic and potential-field data processing is performed “on the fly” by other (currently over 200) tools. The resulting code has only to deal with the refraction statics problem and is therefore relatively compact. Software maintenance is also simplified by an automated code distribution system including tools for web-based collaboration (Morozov et al., 2007).

Conclusions

Consistent and accurate travel-time dataset is the key to refraction statics inversion. New tools utilizing travel-time reciprocity and 3D/2D visualization allow efficient manual and automatic picking and inversion of first breaks in large 3D datasets. The analysis procedure can be broadly customized for the needs of the specific projects and integrated with other types of data.

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References

Chubak, G., Morozov, I., and Blyth, S. 2007. Towards a comprehensive open-source system for geophysical data processing and interpretation, CSEG recorder, **32**, Sept. 2007, 52-61.

Hagedoorn, J. G., 1959. The plus-minus method of interpreting seismic refraction sections, Geophys. Prosp., **7**, 158-182.

Hampson, D., and Russell, B., 1984, First-break interpretation using generalized inversion, J. Can. Soc. Explor. Geophys., **20**, 40-54.

Morozov, I., Reilkoff, B., and Chubak, G. 2007 A generalized web service model for geophysical data processing and modeling, Computers & Geosciences. 32, 1403-1410, 2006.

Yilmaz, O., 1987, Seismic Data Processing: Neitzel, E. B. (Ed.), Investigations in Geophysics, vol. 2, Soc. Expl. Geophys., Tulsa, OK