VS30.IT

SMARTTOMO USER MANUAL

2027.0.0

MANUAL VERSION 12

Table of contents

Table of contents **1**

Introduction **4**

Tomographic inversion *4*

Seismic attenuation and Q-factor tomography *6*

Generalized Reciprocal Method (GRM) in smartTomo *8*

Integrated artificial intelligence (MjolNET) *9*

Optimal seismic spread geometry **10**

Layout for refraction processing 11

Using smartTomo **12**

First start of the program *12*

Box – License activation 12

Software settings. *13*

Creating and processing a new project *16*

Box - Customizing the spread geometry. 16

Box - Using shot CSV files 17

Box - Quick guide to excluding a channel from the tomographic inversion 18

Box - Guide to the tomographic processing of linked lines 20

Box - Cell and number of nodes 22

Management of geotechnical boreholes 24

Georeferencing of the seismic line. 27

Signal filtering and cleaning 28

Autopicking 29

Magnifier for manual picking 30

Viewing and editing first-arrival times 30

Enabling seismic attenuation tomography and sampling attenuation data 31

Box - Garbage in, garbage out warning 31

Running the tomography 33

Box – Smoothing types 35

Box – Advice on tomography parameters 36

Refraction processing with the reciprocal method (GRM) 36

RMSE – Root Mean Square Error and maximum error 41

Opening and editing an existing project *46*

Editing the spread geometry 46
Editing the shot positions 46
Importing traveltimes from other software *47*
Display options *51*
Products of the tomographic inversion 51
Vertical gradient, weighted vertical gradient, Laplacian 53
Vertical gradient 54
Normalized vertical gradient 54
Laplacian 54
Information density 55
Color palette management 56
Box – Notes on color palettes 57
Contour line display 58
Project title 59
Show grid lines 60
Refractor color and style management 60
Exporting the results *60*
Exporting the velocity grid. 60
Export in GRD format 61
Exporting the average vertical velocity profile. 61
Exporting images (png). 61
Export to a document (PDF/ODT) 62
Export in KML format 63
Export in DXF format 63
Export in SVG format 63
What's new in version 2027.0 63
Print layout editor *64*
Graphical interface 64
Page management 64
Inserting and arranging elements 65
Element properties 65
Page setup 67
Layout templates 67
Export 67
Units and display options *69*

Graphical interface **69**

Menu *69*

Toolbar *71*

Dialogs *73*

Main window *80*

List of figures **83**

INTRODUCTION

Seismic refraction surveying is an indirect method that uses velocity contrasts of seismic waves. The velocity of seismic waves depends on the density and stiffness of the material crossed. These properties relate to the lithological characteristics of the investigated substrate. The propagation of waves at depth follows Snell's law. This gives rise to refraction and reflection.

The test consists of generating a seismic wave (shot) and recording its arrival at geophones placed in a line at known intervals. The interpretation of the recorded data is based on the time the wave takes to reach each geophone. To reconstruct the lateral variation of seismic velocity in the subsurface and reduce the ambiguity of the solution, several shots at different positions are needed.

Measurements made with the refraction technique can be processed with the tomographic procedure. This highlights local velocity variations in detail.

Tomographic inversion

The tomographic technique creates a synthetic model of the subsurface and perturbs it. The goal is to find the minimum misfit between the field measurements and the “virtual” measurements recorded on the synthetic model. This is done with an iterative procedure that alternates the following two phases:

- *In the “forward” phase,* the arrival times of the seismic pulse are calculated on the synthetic model (smartTomo is based on the work of Moser, T. J. "Shortest path calculation of seismic rays." Geophysics 56.1 (1991): 59-67). The initial velocity model is divided into a grid. Each cell has an initial velocity value. The sides of the cell carry several nodes (the number is chosen by the user). These nodes form the network of hypothetical seismic rays that connect all sources and all receivers, which are also nodes. Each node is connected to the nodes of the adjacent cells.

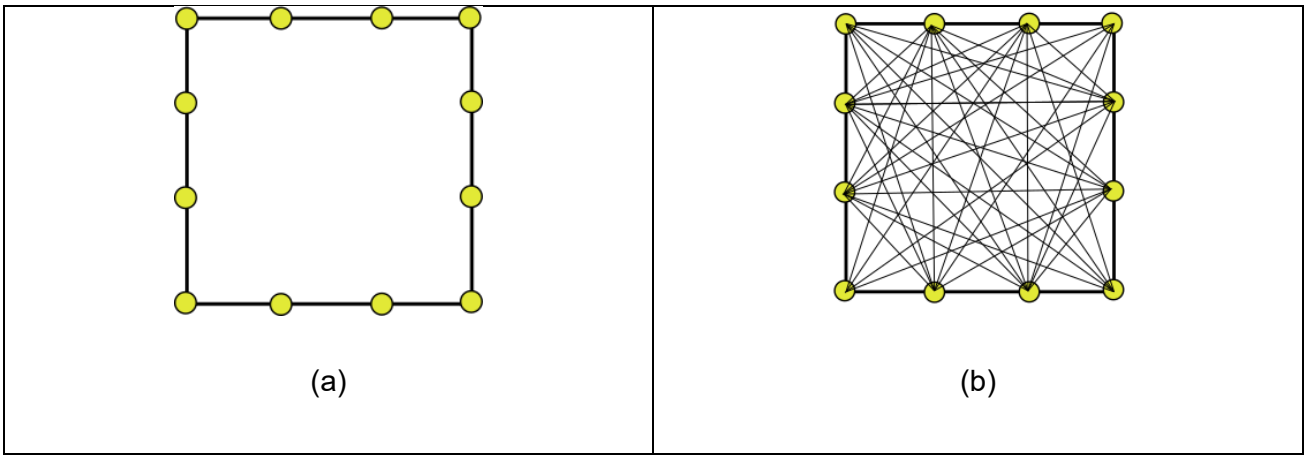


Figure 1 (a) Example of a cell with 4 nodes; (b) display of the possible seismic rays that join the nodes of the cell. Increasing the number of nodes increases the detail and accuracy of the ray paths. It also increases memory use.

The path of the refracted waves is the path along the seismic rays that takes the least time to travel from the source to the receiver.

- In the "inverse" phase, the synthetic times computed in the "forward" step are compared with the measured times. The differences between the two times are used to update the synthetic model (smartTomo uses an algorithm of the Simultaneous Iterative Reconstruction Technique family). In this method, velocity is replaced by its inverse, the slowness *S*. Consider a generic seismic ray *j* between the source and the receiver. The average slowness can be expressed as:

$$S_j = \frac{t_{0j}}{l_j}$$

where t_{oj} is the time measured between the source and the receiver and l_j is the length of the *j-th seismic ray*. Therefore, knowing the measured and computed traveltimes t_m and t_c for the *j-th ray* , the traveltime residual can be calculated:

$$\Delta t_j = t_{mj} - t_{cj}$$

The traveltime residual can be projected onto each cell *k* , where the slowness correction factor can also be calculated:

$$\Delta S_k = \frac{\sum \Delta t_{ik}}{\sum \Delta l_{ik}}$$

The index *i* indicates each seismic ray crossing the *k-th cell.* The slowness correction factor is used to update the velocity model at the end of each iteration of the solution cycle.

This procedure produces a model with continuous velocity variations, not necessarily constrained by the presence of refractors.

Seismic attenuation and Q-factor tomography

Seismic signal propagation in the ground involves several forms of energy dissipation (geometric spreading, absorption). Geometric loss is due to the spreading of the pulse in space. For body waves produced by a point source, the pulse expands along a spherical front. In this way, the energy decreases in proportion to the distance from the source (or from the reference station). Absorption loss depends on the materials crossed and is related to the ability of the medium to transmit the elastic wave. This component of attenuation is the most relevant because it is linked to the properties of the investigated material.

The decay of the signal amplitude has been observed to be exponential. Therefore we can write:

$A = A_0 e^{-\eta x}$

where A is the amplitude of the signal measured at distance x from the reference station, where the amplitude A_o is measured, and η is the absorption coefficient.

Signal attenuation can also be expressed as a function of time, that is:

$A = A_0 e^{-ht} cos(2\pi vt)$ where h is the damping factor. The attenuation factor δ can be expressed in terms of amplitude as $\delta = log\left(\frac{A}{Aunciclodopo}\right)$ but it can also be expressed as a function of the damping factor h: $\delta = hT = 2\pi\, h/\omega$ where T is the period.

The Quality factor Q is defined as $Q = 2\pi \frac{E}{\Delta E} = 2\pi \frac{E}{energiapersaperciclo}$; since energy is proportional to the square of the amplitude, we can write $E = E_0 e^{-2ht}$ that is $\Delta E/E = 2h\Delta t$Setting $\Delta t = T$ equal to one period, it can be rewritten as:

$\frac{\Delta E}{E} = 2hT = 2\delta$ and consequently $Q = 2\pi \frac{E}{\Delta E} = 2\pi \frac{f}{Attenuation \cdot v}$

In smartTomo, the amplitude of the refracted signal is calculated by sampling a portion of the signal around the first arrival and measuring the maximum amplitude in the frequency/amplitude domain. The frequency corresponding to the maximum amplitude is used to calculate the Q-factor. The logarithmic attenuation factor δ becomes the target value in the computation of the attenuation tomographic profile. The process keeps the seismic rays computed in the velocity tomography. The attenuation values are updated to fit the δ values measured on the seismograms, using a SIRT-type algorithm.

Attenuation tomography and Q-factor tomography are inversely correlated, apart from the constant π and the wave propagation velocity in the medium. Low Q values correspond to the highest attenuation, and generally also to lower velocities.

The following table gives indicative values of the attenuation parameters and of the Q-factor for some lithologies.

Rock type	**Q-Factor**	**δ = η * ƛ (dB)**

Sedimentary rocks	20-200	0,16 – 0,02
Sandstone	70-130	0,04 – 0,02
Argillite	20-70	0,16 – 0,05
Limestone	50-200	0,06 – 0,02
Gypsum	135	0,02
Dolomite	190	0,02
Gas-saturated sedimentary rocks	5-50	0,63 – 0,06
Metamorphic rocks	200-400	0,02-0,01
Igneous rocks	75-300	0,04-0,01
First 3 meters of coastal sediments of the Persian Gulf (Tullos and Reid 1969)	0,24	13

References

Sheriff, Robert E., and Lloyd P. Geldart. *Exploration seismology*. Cambridge university press, 1995.

Generalized Reciprocal Method (GRM) in smartTomo

From version 2020.0, smartTomo can also process the survey with the GRM method (Palmer 1980). (https://library.seg.org/doi/book/10.1190/1.9781560802426).

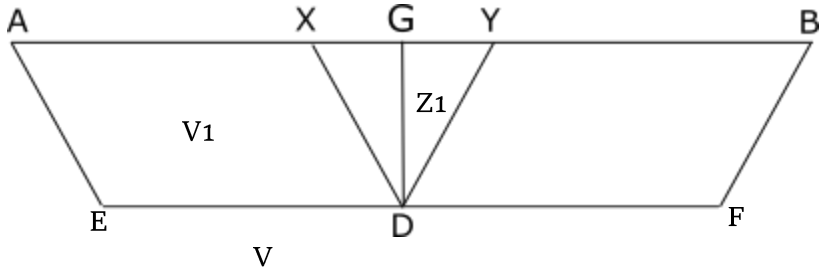


Figure 2 Geometric scheme of the Generalized Reciprocal Method (GRM). A and B are shot points, G, X, Y are geophones. D is the projection of geophone G onto the refractor. V1<V2

GRM processing requires two reciprocal shot points where the refractor is visible. For each geophone G, the traveltimes T_{AEDY}, T_{BFDX} and T_{AEDFB} (the reciprocal time) are calculated.

To calculate the refractor velocity, the function Tv is defined:

$$t_v = T_{AEDY} - T_{BFDX} + T_{AEDFB}$$

It is calculated for each geophone. The derivative of t_v with respect to x gives the refractor velocity.

The refractor depth is calculated in two steps. First, the function t_G is calculated. It represents a profile in which depth is still expressed as traveltime. Then t_g is converted into a depth value by applying a parameter proportional to the layer velocities.

$$t_G = \frac{1}{2}(TAEDY + TBFDX - TAEDFB - XY/V_n)$$

And, for the first refractor:

$$Z_1 = T_{G1}\frac{V_2 V_1}{\sqrt{V_2^2 - V_1^2}}$$

For refractors below the first, the depth is calculated by removing from the function TG the contributions of the overlying layers.

smartTomo is designed to consider a maximum of two refractors.

Integrated artificial intelligence (MjolNET)

smartTomo integrates two proprietary neural networks, developed under the name MjolNET. They are dedicated to automatic first-arrival picking (MjolNET M1) and to post-filtering of the tomographic model (MjolNET M3). Both networks are embedded in the executable. They run entirely locally on the user's computer through the ONNX Runtime inference engine. No seismic data, geometry or result is sent to external servers. No internet connection is required for their operation.

The full architecture and the training data of the two networks are confidential and are not disclosed. Only the operating principles relevant to the use of the software are described below.

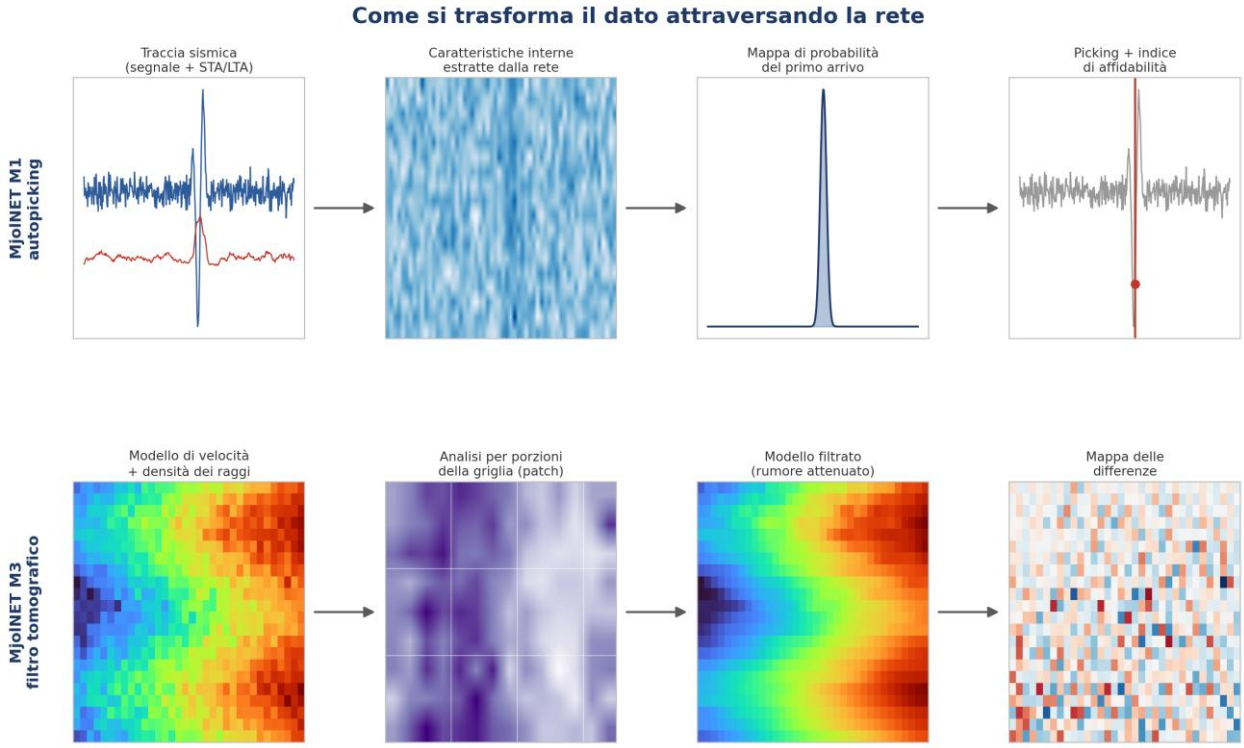


Figure 3 Data transformation along the network, for MjolNET M1 (top) and MjolNET M3 (bottom): from the raw input data to the internal features extracted by the network, up to the final result.

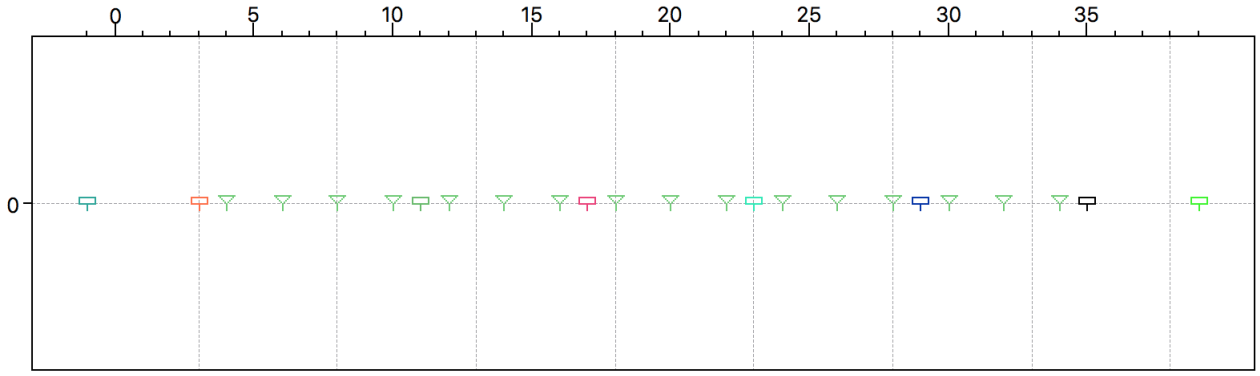
MjolNET M1 is a convolutional neural network trained to recognize the first-arrival waveform. It analyzes the trace with sliding windows of 256 samples and two input channels: the normalized signal and its STA/LTA ratio. For each window it produces a first-arrival probability map and a reliability score. The windows are then reassembled into a single map along the whole trace, weighted by reliability. The final pick is the point of maximum probability of this map.

If the reliability or the sharpness of the peak is low, the model does not force a value. It flags the uncertainty and leaves the trace to be completed manually.

MjolNET M3 is a convolutional encoder-decoder network (U-Net architecture), designed for post-filtering of the velocity model. It works on portions of the tomographic grid, which are then reassembled into the complete model. Its input is not only the velocity field but also a ray density indicator for each cell. This indicator measures how well the acquired data actually constrain that zone of the model. It allows the network to distinguish inversion noise from real structures. The network acts with more caution where ray coverage is poor.

OPTIMAL SEISMIC SPREAD GEOMETRY

The numerical solution of the tomography is iterative. It searches for the solution that reduces the difference between measured and computed times. The number of available measured source-receiver traveltimes, and therefore the number of seismic rays, is much lower than the number of unknowns of the system to be solved. To have enough data, plan the seismic survey with a high number of shots (about one shot every three geophones). The following figure shows an example scheme of an acquisition line.



The shots do not need to be symmetric. In the proposed scheme, the shots are placed inside the line every three geophones, except in the first interval, where four receivers were skipped. In this example, the shots were made midway between two receivers. They can also be made at the receiver positions.

We recommend at least one shot on each side outside the receiver line, at a distance equal to half the geophone spacing. This configuration is essential for interpretation with the GRM method.

The maximum investigation depth depends on the geological conditions of the site. On average, the survey reaches a depth of about 1/3 of the spread length. If the survey has a specific target, place the seismic line so that the target is in the central zone of the spread, at a depth not greater than ¼ of the spread length.

Different seismic spreads can be joined and processed together. This method gives longer spreads with a high geophone density. If the spreads share common shot points, greater depths are reached than with a single acquisition spread.

Layout for refraction processing

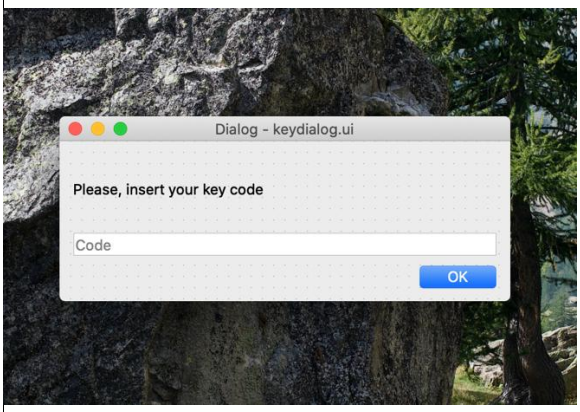
Refraction processing requires shots at both ends of the geophone line. A classic layout has two external shots at each end of the spread, placed at different distances, for example at half and at 4-5 geophone spacings. In addition to the four external shots, we recommend at least one shot at the center of the line. A layout with more shots, as used in a tomographic survey, is also suitable for reciprocal processing.

When choosing where to place the shots, try to predict how the different levels will be represented by the traveltime curves. Each investigated layer must be identified by both the direct and the reverse shots. It is better to make some extra shots than to find later that the collected data are not enough to define the seismic layers.

USING SMARTTOMO

First start of the program

BOX – LICENSE ACTIVATION



When the software starts, or when a new protection key is inserted, the program asks for the activation code. The code belongs to the activation key and is sent by email together with the download link.

The USB key must stay inserted while the software is in use.

At the first start, the software opens the window for setting the user interface language. Confirm the choice with the Ok button.

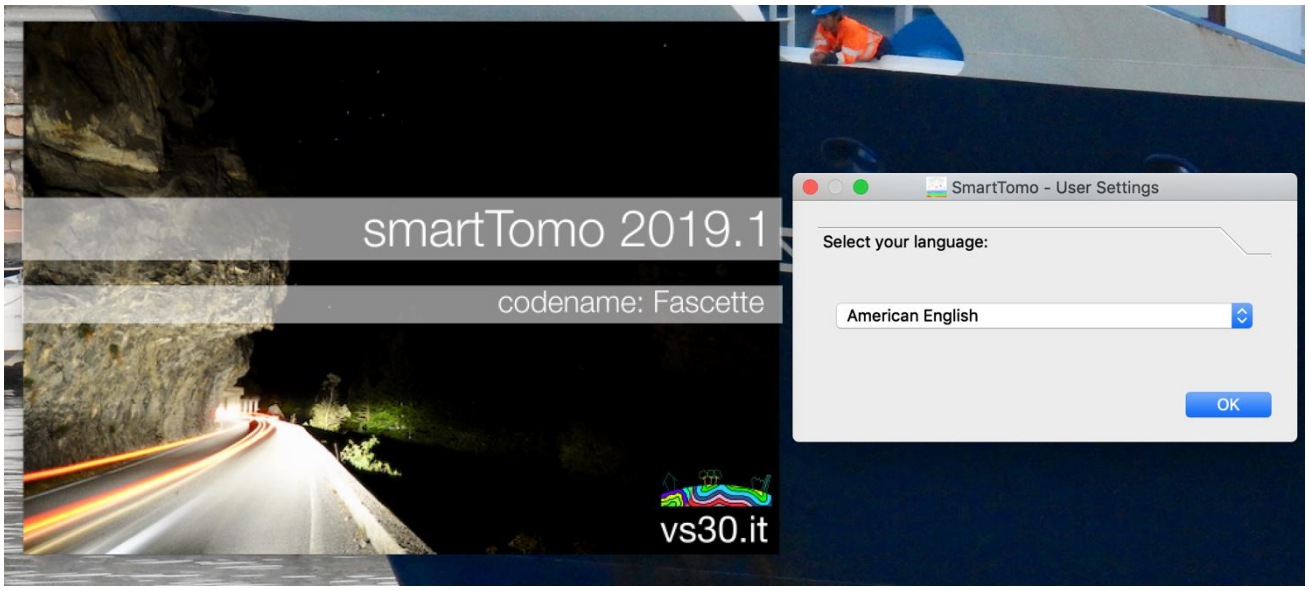
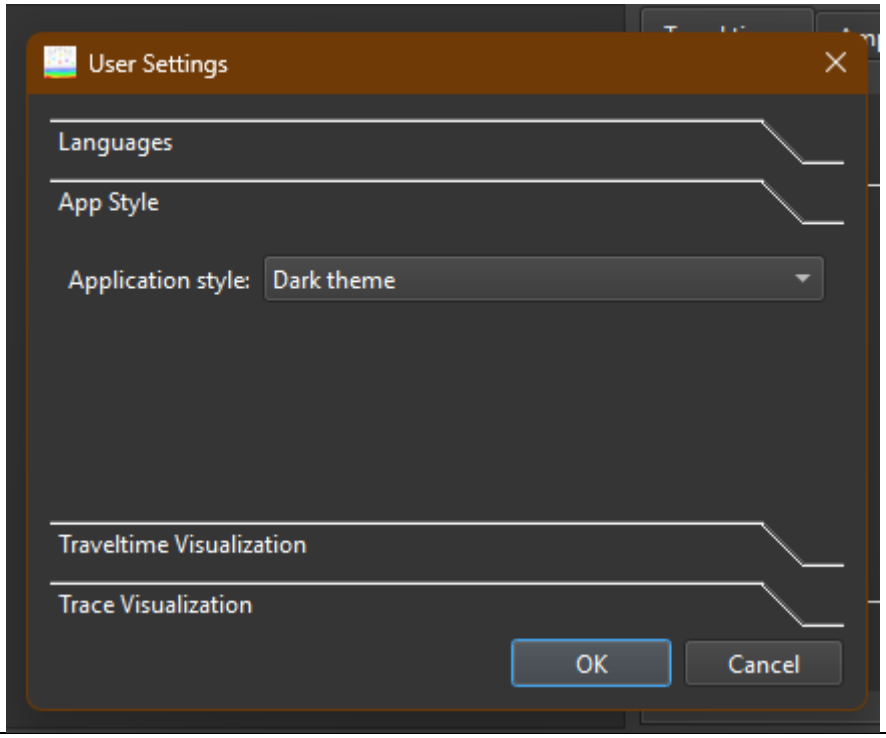


Figure 4 Splash screen with the language selection dialog

You can change the language later in the settings dialog.

Software settings.



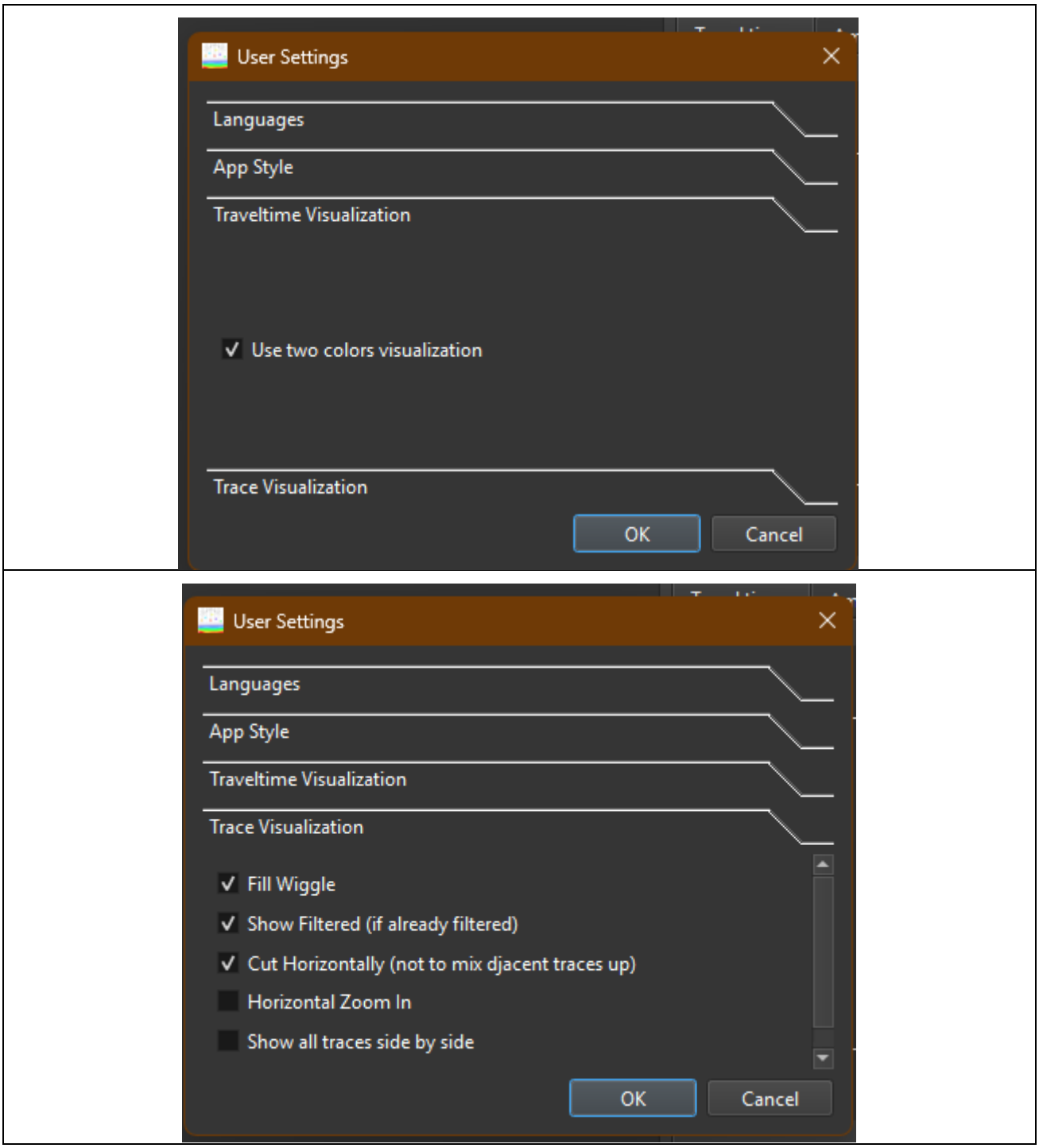


Figure 5 Dialog for setting the preferences;

From the menu **File/Settings** you can set the software language or some trace display parameters. You can:

- enable/disable the fill of the half-wave;
- enable/disable the automatic display of filtered traces, when available;
- enable/disable the overlap between adjacent traces at high zoom levels;
- enable/disable the horizontal zoom of the trace display window;

- enable/disable the display of all traces side by side;

You can also set the light or dark mode of the software, manually or automatically, to match the style of the operating system.

Creating and processing a new project

To start a new project, click the menu File/New. The dialog for selecting the files that contain the seismic traces opens (SEG2 format and, experimentally, SEGY).

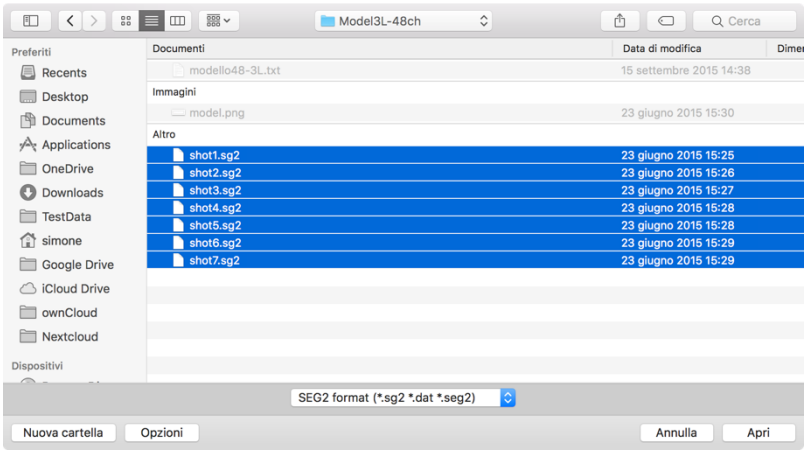


Figure 6 Seismic file selection window

After you select the files, the window for checking and setting the geometry of the shots and geophones opens.

In this dialog you can change the position of each shot, enter the elevation and define the geometry of the seismic spread used during acquisition. If the imported files already contain the correct geometry information, this dialog only serves to check that the import was correct. To add more files, press the *Add* button on the left.

Right-click on the geometry plot to export the image.

BOX - CUSTOMIZING THE SPREAD GEOMETRY

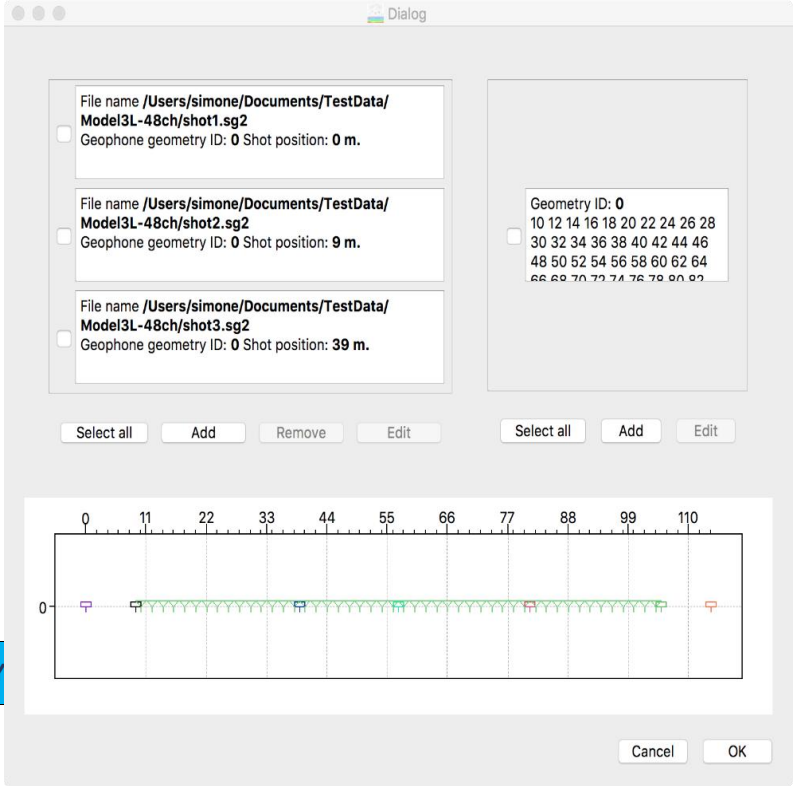


Figure 7 Editing window for the seismic line geometry

If the files do not contain information on the survey geometry, you can customize it by following the instructions in:

- Editing the spread geometry

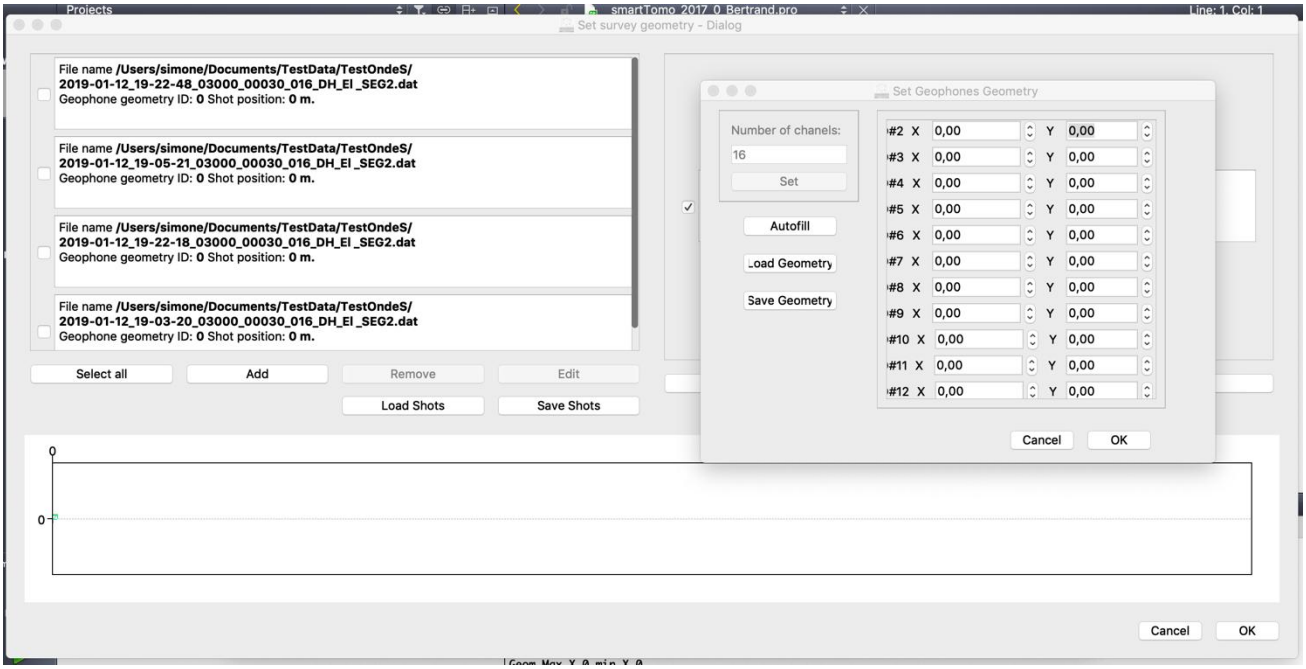


Figure 8 Geometry setting window with the options for loading from file.

Both the shot positions and the geophone positions can be imported from a CSV file. This solution can be useful in several cases:

- Recurring geometries: create the files only once and reload them later to save time;
- Irregularly spaced positions: it is easier to fill in a table in a spreadsheet than to fill in many text boxes.
- Import of positions acquired by topographic survey.

BOX - USING SHOT CSV FILES

The shot CSV file also contains the file name, for example:

```
shot1.dat;0;0
```

The file name is only a placeholder for the user. The software ignores the file name and uses only the geometry columns (X;Z). The first coordinate pair is assigned to the first loaded file, the second pair to the second file, and so on.

The seismic files may not be loaded in alphabetical order. Therefore it is recommended to:

- Load the seismic files;
- Export the shot coordinates;
- Edit the coordinates with an external editor without changing the order of the rows;
- Import the coordinates again.

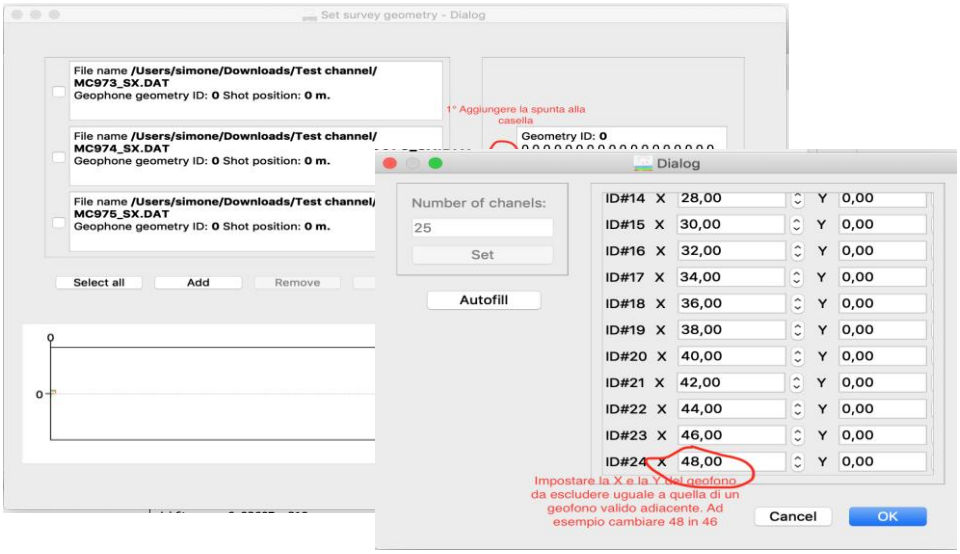
BOX - QUICK GUIDE TO EXCLUDING A CHANNEL FROM THE TOMOGRAPHIC INVERSION

Step 1 - set the spread geometry

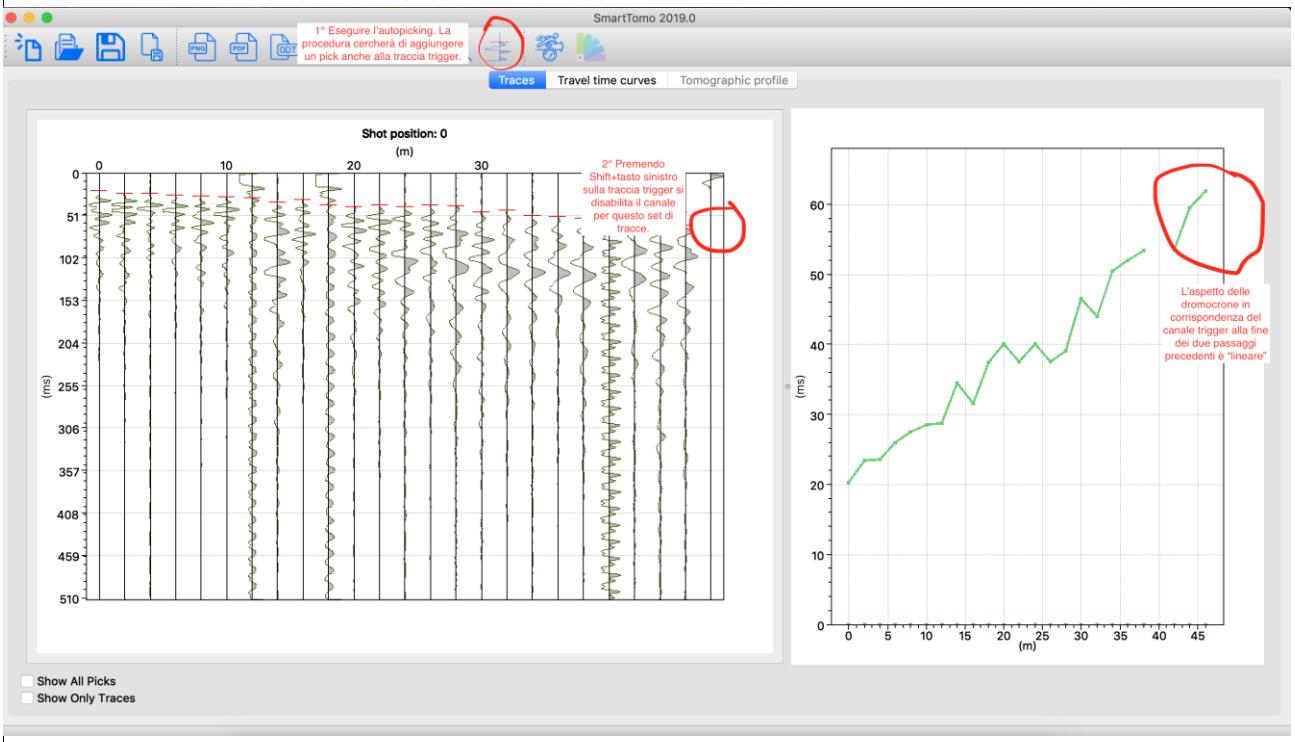
This guide applies when a seismic file (seg2) contains a channel that must never be used in the whole processing, for example when the trigger channel is recorded in the file like the other channels.

Assume 24 channels (geophones) + 1 trigger channel. The file then has 25 traces, 24 of which are used in the tomographic process.

When setting the spread geometry, note that geophone numbering starts from 0. The 25th geophone is indicated as ID#24.



If the trigger channel coincides with a valid channel, the calculation grid is not affected by the extra, always disabled channel. For example, set the coordinates of the trigger channel equal to those of the last geophone (in the example window the trigger channel corresponds to ID#24 and is given the same coordinates as channel ID#23). This creates a grid in which the trigger channel does not affect the processing, because it coincides with a valid channel.



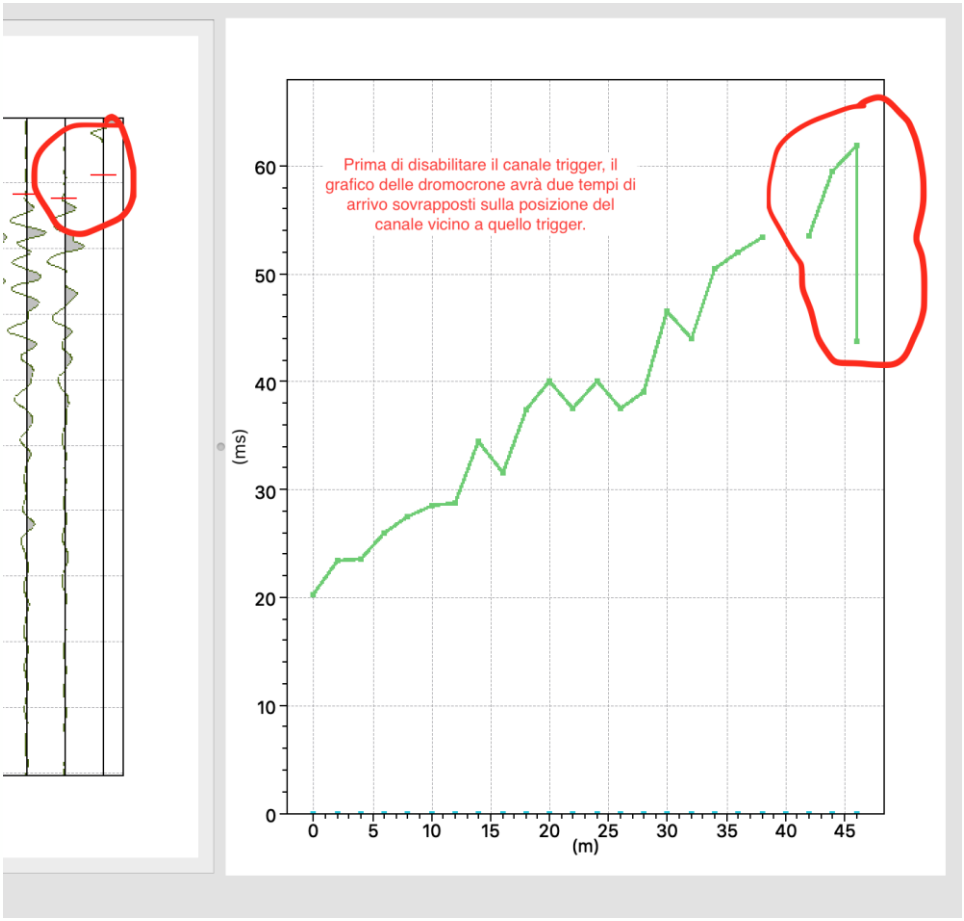
Step 2 - Delete the arrivals of the geophone to be disabled

For each shot, perform the procedures listed below to disable the trigger channel in every set of traces.

Ideally, do this after using autopicking, because the automatic first-arrival search procedure places a pick on the trigger channel even if it is already disabled.

It is recommended to perform the steps in this order:

I. Autopicking
II. Manual refinement of the picking
III. Disabling of traces that are too noisy and/or of the trigger channel.



BOX - GUIDE TO THE TOMOGRAPHIC PROCESSING OF LINKED LINES

SmartTomo can process several acquisition lines linked together and aligned along the same profile (not in 3D). To link the lines effectively, shots made at the same position must exist for all the lines to be processed. If there are no common shots, the different lines can be processed in a single project but independently of each other. SmartTomo reads the geometry from the seismic files (seg2, sgy, su) and sets up the project for linked lines automatically, without user intervention. For this reason it is important to prepare the seismic files in the field with all the necessary information, to make the processing much easier.

If the geometry could not be entered in the seismic files beforehand, it can be edited in SmartTomo during project creation.

First, load into the new project all the seismic files of all the linked acquisition lines. In the geometry setting window, all the files are listed in the left column and a single group of geophones is present in the right column (Figure 9).

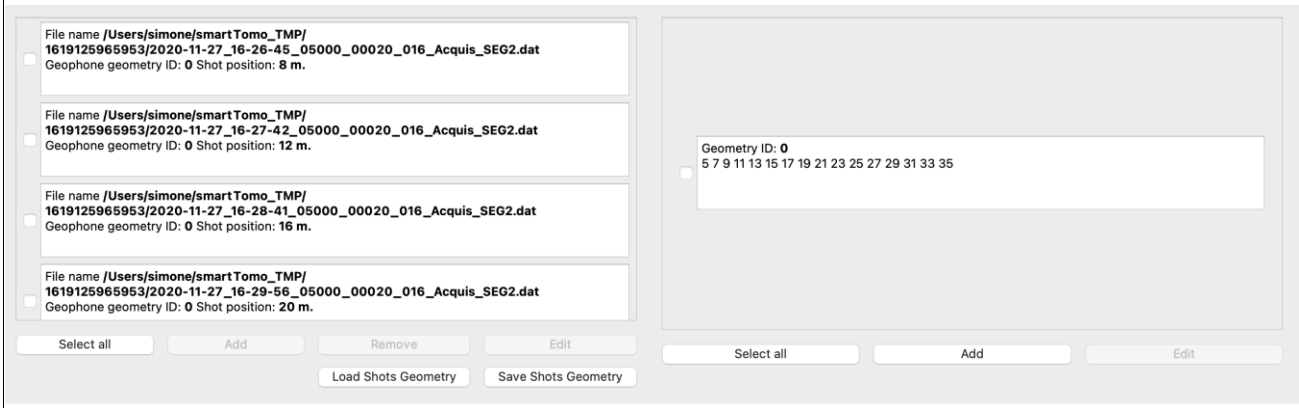


Figure 9 Geometry setting. A single line of geophones is listed on the right

With Add, you can add a further line of geophones by setting its correct number and geometry. There are then 2 groups of geophones, as shown in the following image (Figure 10).

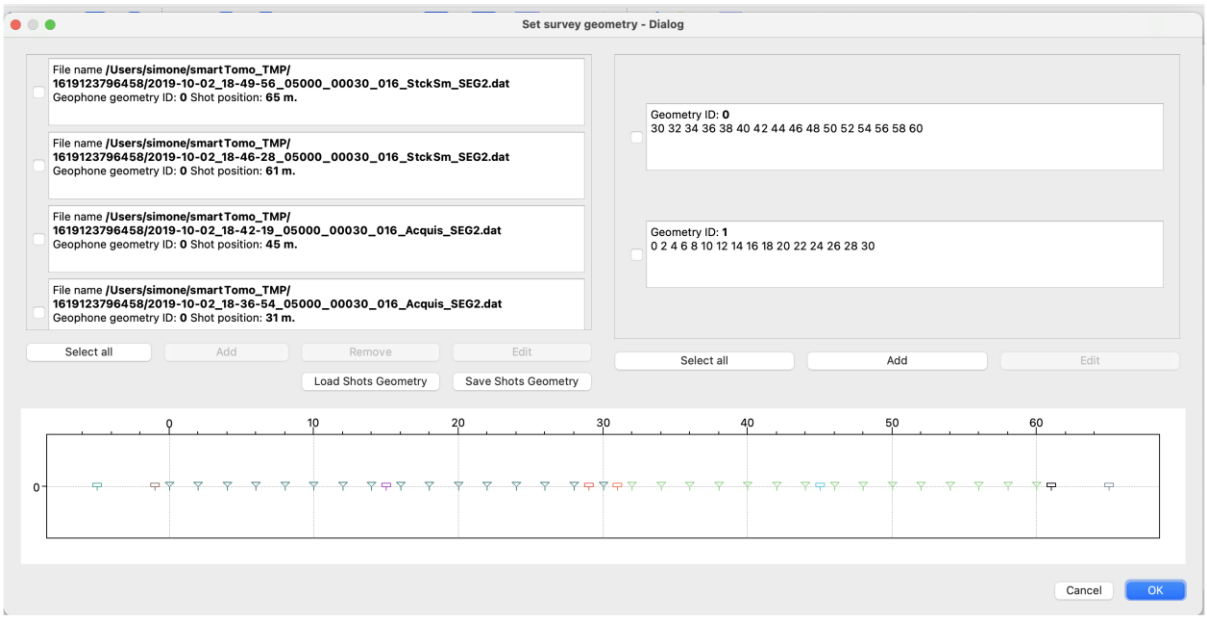


Figure 10 The geophone box contains 2 groups of geophones. The first (ID 0) has coordinates from 30 to 60 and the second (ID 1) from 0 to 30.

The last step is to assign each shot to the correct group of geophones. This operation links the geophone geometry with the traces and with the shot position. To assign the recordings to the geophones, select the file(s) in the left column with the checkbox and press Edit in the lower part. The window shown below opens (Figure 11). In it, a drop-down menu lets you choose the

group of geophones to which the recording refers. After this step, you can continue as usual with the choice of the grid parameters and the processing of the survey.

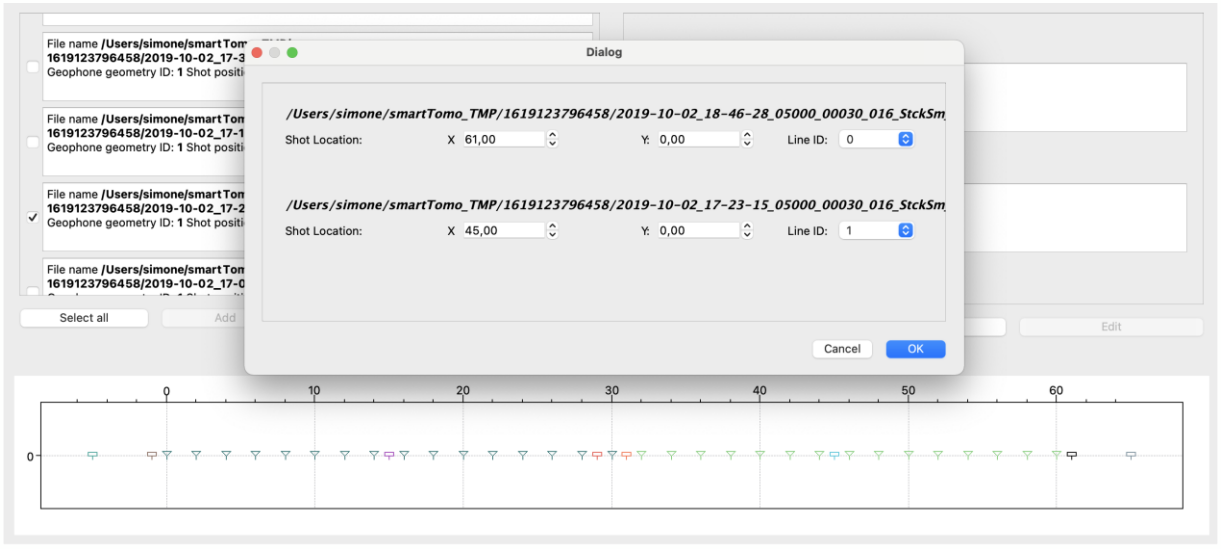


Figure 11 Dialog in which you can set the shot geometry and the geophone line to which the acquisition refers.

After confirming the geometry with the OK button, a new dialog opens to set the parameters of the calculation grid. The default parameters can be kept unchanged. Check that the cell size (*Cell size*) is at least one quarter of the geophone spacing. Increasing the number of nodes per cell improves the accuracy of the traveltime computation but also increases memory use.

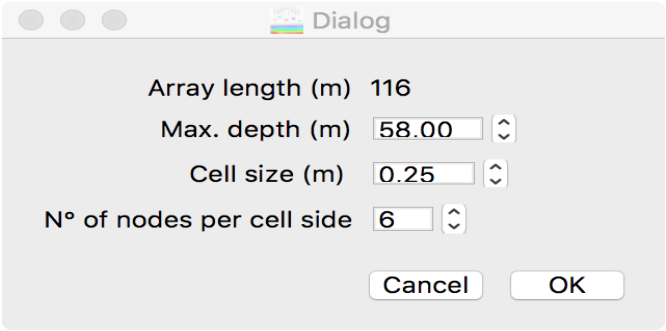


Figure 12 Grid parameters

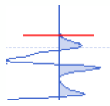
BOX - CELL AND NUMBER OF NODES

The cell size is the side length of a calculation cell in which the seismic velocity is considered constant. By default, this parameter is set to one quarter of the geophone spacing. Alternatively, a fixed value can be used, for example 0.25 m or 0.50 m. Previous versions used 0.25 m by default.

The "number of nodes" parameter is the number of nodes placed on each side of the cell for the reconstruction of the seismic rays. The default is 6. In a standard case (side 0.25 m and 6 nodes) a node is placed every 5 cm on all the sides of the cells.

Increasing the number of nodes:	• Higher memory use • Higher accuracy in the reconstruction of the seismic rays (but is it necessary?)
Increasing the cell side:	• Lower memory use • Lower accuracy in the reconstruction of the seismic rays • Higher calculation stability • Smoother seismic profile

When the parameters are accepted (OK), the seismic traces open in the main window. In the *Traces* tab, the traces of the currently displayed shot are shown on the left. On the right, a window shows the traveltime curves. You can overlay the traveltime curves already picked on the currently displayed traces, to preview the work done so far.

Autopicking of first arrivals		
From the menu: **Traces/AutoPick**	From the keyboard: **Ctrl+A**	From the toolbar: 
First arrivals can be picked manually by clicking on the trace with the mouse. Since version 2019.2, you can hold down the left mouse button and drag to pick several arrivals at once.		
The **removal** of a wrong or doubtful first arrival is done by pressing **shift+click** on the first arrival to be deleted.		

Disable a channel		
From the menu: -	From the keyboard: **Shift – left button**	From the toolbar: -

Management of geotechnical boreholes

A new module has been introduced for importing and managing geotechnical boreholes and vertical tests. It is useful for comparing the velocity model with the known stratigraphy. The module includes an import window for files, a window for manual management, and the commands for displaying the tomographic section.

Import from file

File/Import boreholes... opens the import window. It accepts CSV/TXT, XLSX, ODS and AGS4 files. For tabular files (CSV, TXT, XLSX, ODS) the procedure is:

1. select the file with Browse...;
2. choose the content type, Stratigraphic layers or Numeric log (SPT, CPT, MASW...), the delimiter (automatic, semicolon, comma, tab or space) and whether the first row is a header;
3. map the file columns to the required fields: borehole ID, X along the spread and elevation of the borehole head are common to both content types. For stratigraphy, add layer top, base and description. For a numeric log, add sample depth and value;
4. for a numeric log, also set the name, the unit of measure and the display style (histogram or line);
5. set the default values (ID and X) used for rows where the ID or the position is not mapped, and if needed enable the calculation of elevation from the spread topography;
6. check the preview of the data read from the file and confirm with OK.

For AGS4 files the window shows instead a table with one borehole per row. The AGS4 format does not record the position along the spread. Therefore the X of each borehole must be set manually in the table. Unwanted boreholes can be excluded from the import with the Import checkbox. The option to calculate the elevation from the spread topography is also available here.

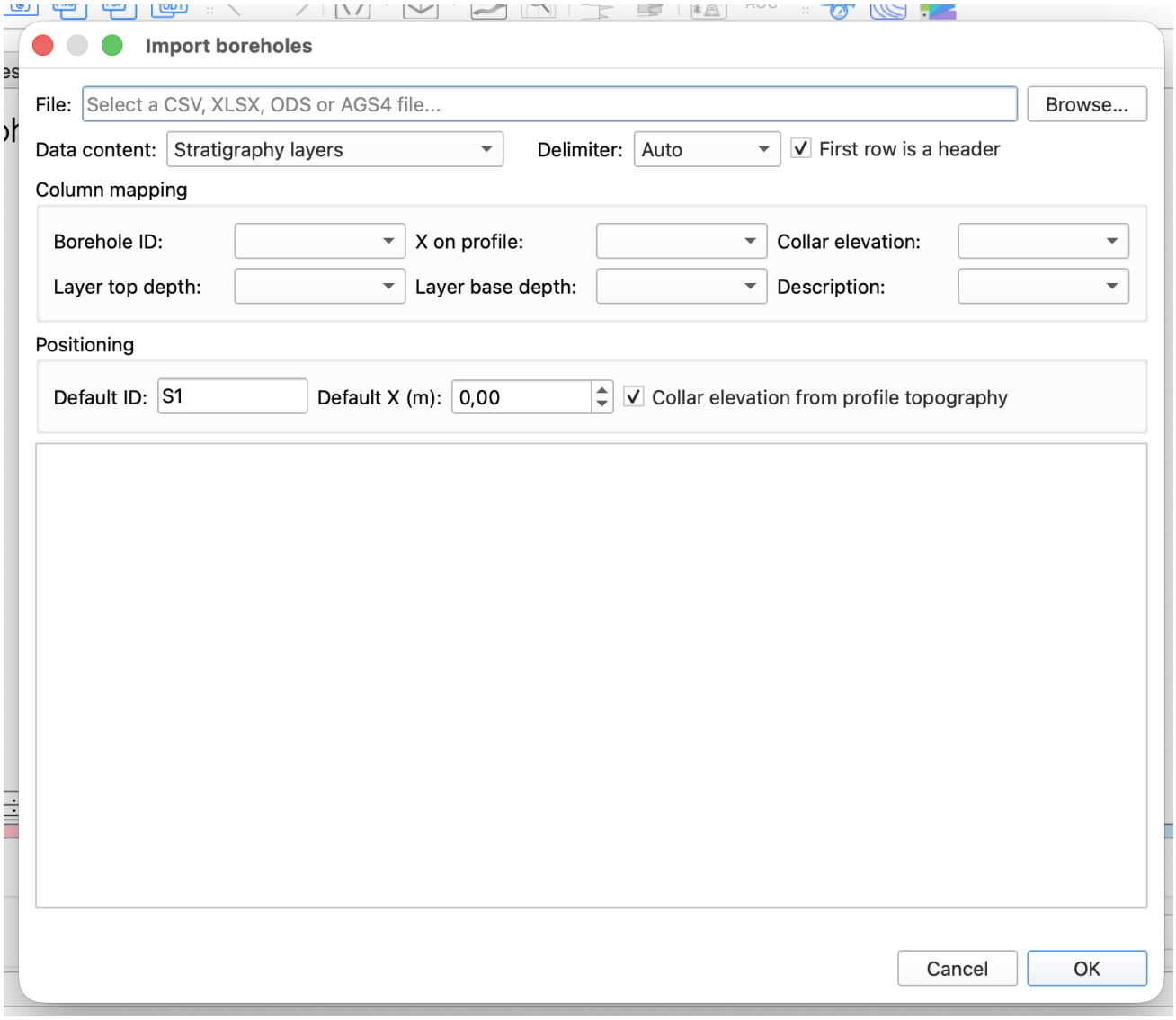


Figure 13 borehole import window with column mapping and data preview

Manual entry and editing

Project/Boreholes... opens the management window. On the left it lists all the boreholes of the project, with the commands Add borehole, Import..., Export... and Remove. On the right you edit the position and appearance of the selected borehole and its stratigraphy or logs:

1. select a borehole from the list, or create a new one with Add borehole;
2. set ID, X coordinate along the spread, elevation, depth and width of the borehole in the Borehole box, and if needed turn off its visibility;
3. in the Stratigraphy tab, enter the layers with Add layer. For each layer, set top, base, description, color and hatch pattern. Double-clicking the color or hatch pattern cell opens the selection. If the top or base of a layer is inconsistent, or two layers overlap, the table shows a warning. At the end, a window summarizes the conflicts and asks whether to keep them or go back and correct them;

4. in the Logs tab, add numeric logs with Add log, setting name, unit, style, color, width and full scale (0 = automatic scale). The individual depth/value samples are edited with Edit samples...;
5. if useful, enable Show stratigraphy legend to include the legend of colors and hatch patterns in the display;
6. confirm with OK, or export the whole set of boreholes to CSV or AGS4 with Export...

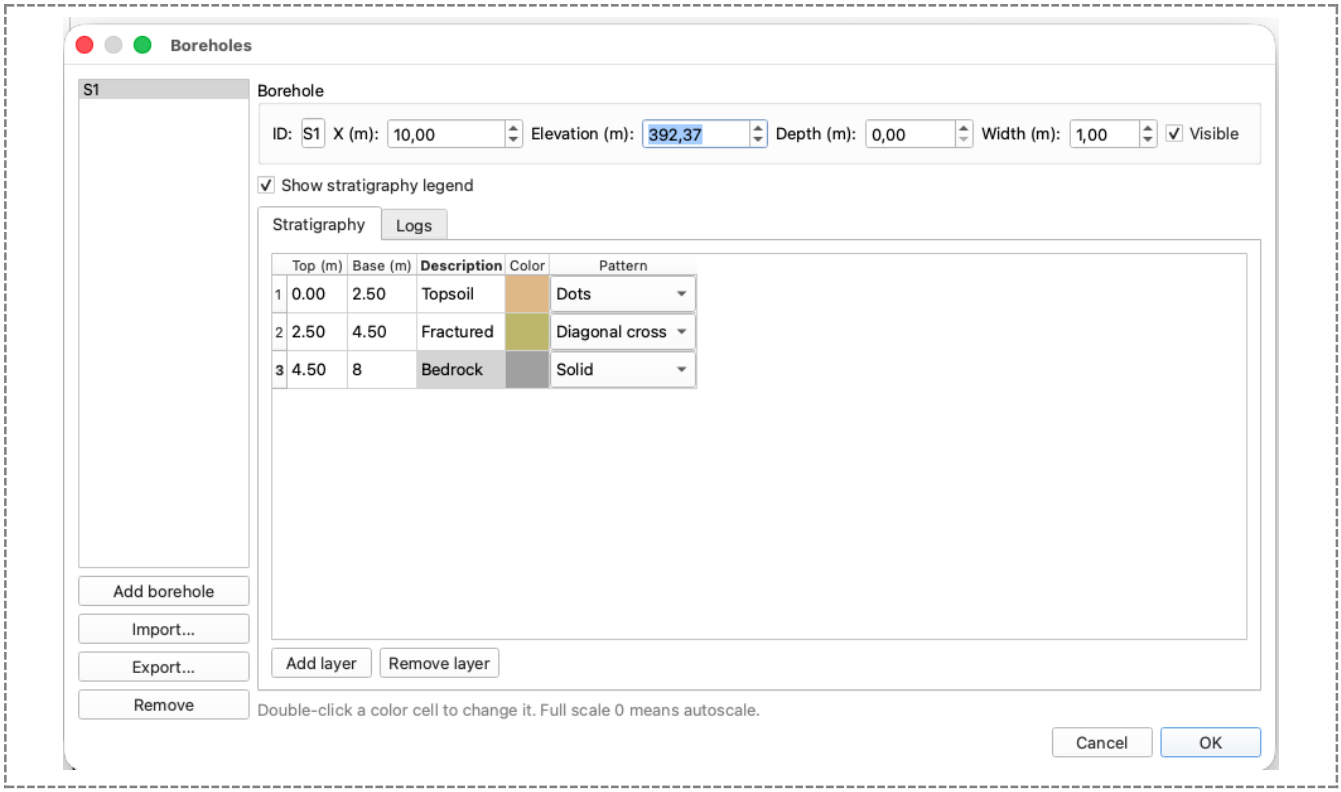


Figure 14 borehole management window with the stratigraphy and logs of the borehole

Display

Boreholes that are imported or entered manually are automatically overlaid on the tomographic section. Their visibility and that of the legend are controlled from View/Show boreholes and View/Show borehole stratigraphy legend. The same boreholes also appear in the GRM refraction processing window, for direct comparison between the known stratigraphic model and the tomography results.

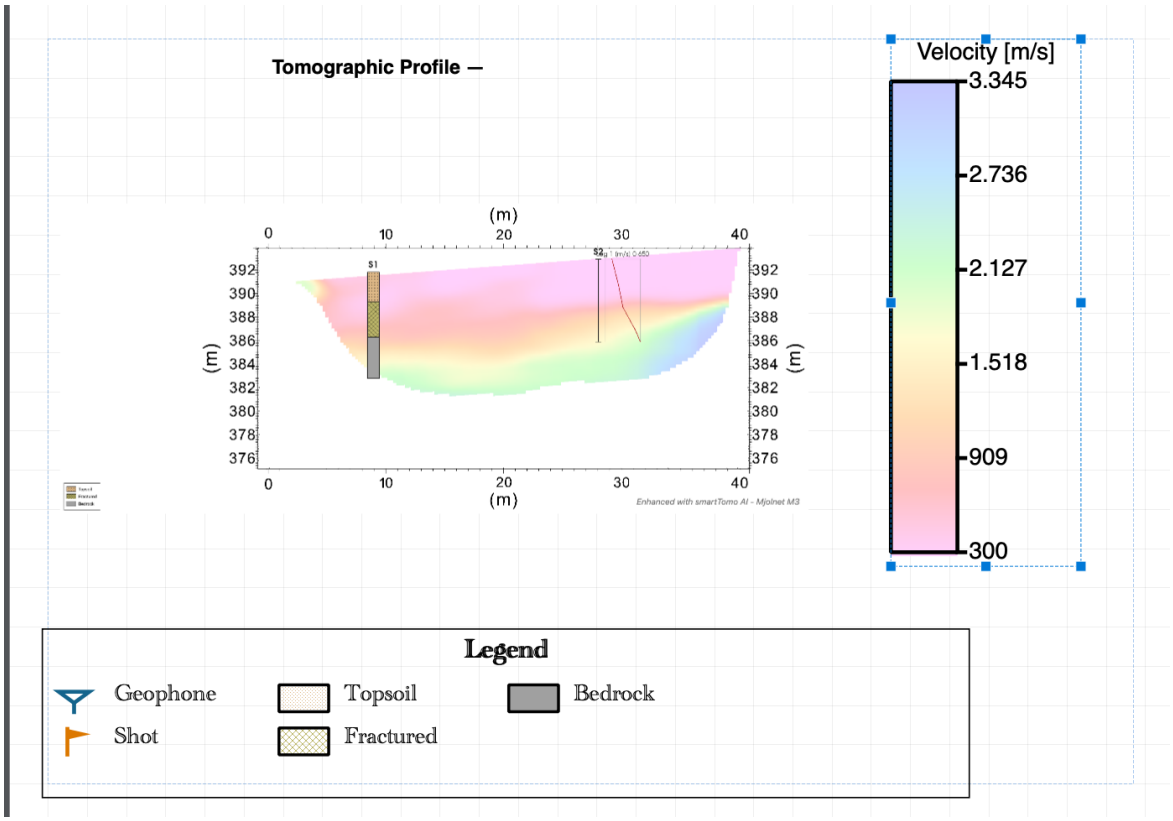


Figure 15 tomographic section with overlaid borehole and stratigraphic legend

Georeferencing of the seismic line.

The seismic line can be georeferenced. The menu *Project/Set geography coordinates* opens the dedicated dialog (Figure 16). You can enter the coordinates of the first and last geophone of the spread in a metric projected coordinate system (for example UTM, Gauss-Boaga (EPSG:3003)). The position of the geophones other than the first is calculated from the geophone geometry set previously. This ensures that the geophone spacing is the one defined. The EPSG code identifies the reference system used. The EPSG parameter is important to export the profile to a KML file, for example to view it in Google Earth.

At this link https://spatialreference.org/ you can find the list of EPSG codes.

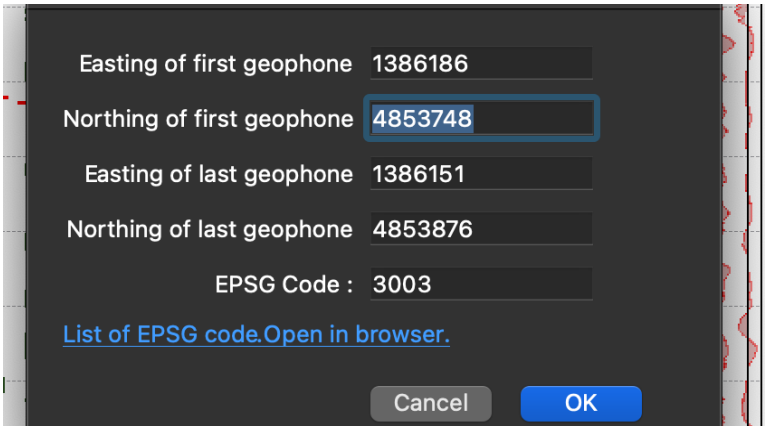


Figure 16 Dialog to set the coordinates of the ends of the spread

Signal filtering and cleaning

SmartTomo provides two tools to apply filters to the signal. The menu **Traces/Filters** opens the window to apply band-pass filters to the signal manually and to display the spectrum. The dialog shows the spectrum of the original and of the filtered signal. At the same time, you can choose whether to display the traces before or after the filters are applied.

The AGC filter can be applied to the traces from the menu item and from the corresponding toolbar button.

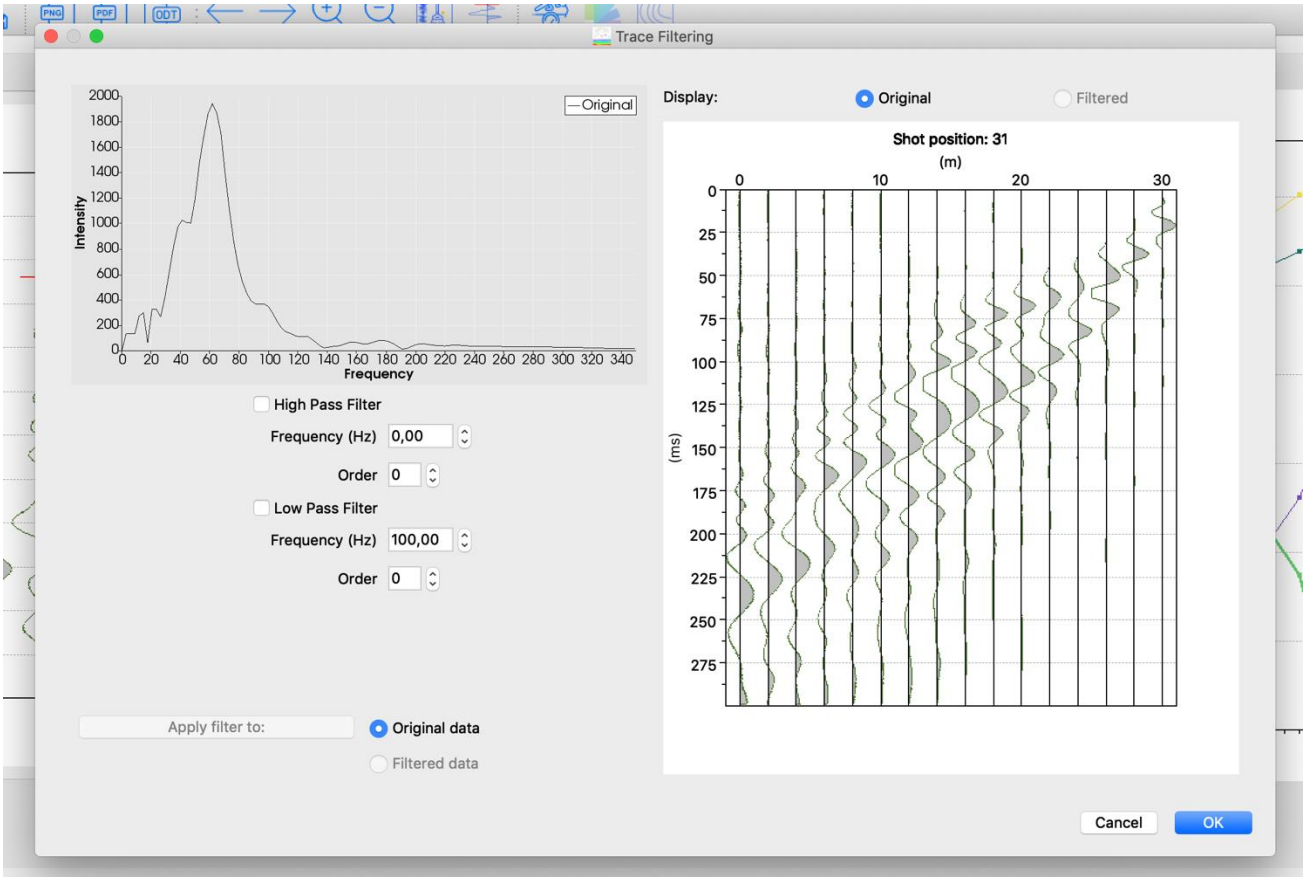
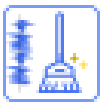


Figure 17 Filter window. If both the high-pass and the low-pass filter are selected, a band-pass filter is applied.

An automatic filter is also available (menu **Traces/Apply NoRe**). Its purpose is to enhance the useful signal for first-arrival picking. NoRe, Noise Reduction tool for seismic refraction, works as an adaptive-band band-pass filter.

AutoPick can be applied to both the original and the filtered traces, because it works on the traces displayed at that moment.

Automatic noise removal (NoRe – The Noise Reduction tool for seismic refraction)		
From the menu: **Traces/Apply NoRe**	From the keyboard: -	From the toolbar: 

Autopicking

smartTomo provides an automatic procedure for picking first arrivals. The method is based on the signal energy ratio. It is stable in the presence of noise (especially high-frequency noise), but wrong first arrivals can still be picked. Since version 2019.2, a *first break rejection* procedure also filters the first arrivals and keeps the most plausible picks. For this reason, some traces may be disabled after autopicking.

Since version 2027.0, AI-assisted autopicking is also available (MjolNET M1 model). It works alongside the energy ratio method described above. The model architecture is described in the Introduction chapter, section Integrated artificial intelligence (MjolNET).

Activation, and optional automatic execution on new projects, are set from the File/Settings menu, Picking tab.

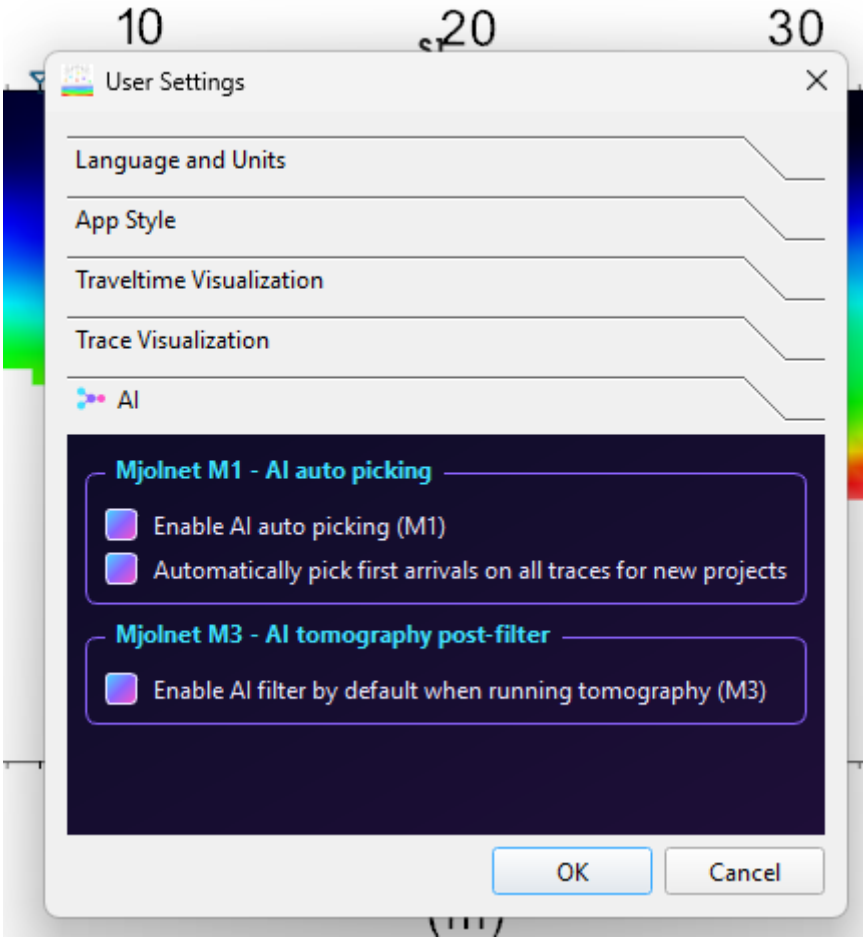


Figure 18 Picking tab of the Settings with the AI-assisted autopicking options (MjolNET M1)

After picking the first arrivals of all shots, the arrival times can be checked in the *Traveltime curves*. This tab shows the traveltime curves picked by the user as continuous lines. The curves calculated during the tomographic inversion are drawn as dashed lines.

Magnifier for manual picking

During manual picking, a floating magnifier is available. It shows an enlarged view of the trace portion under the cursor. This helps to pick the first arrival precisely.

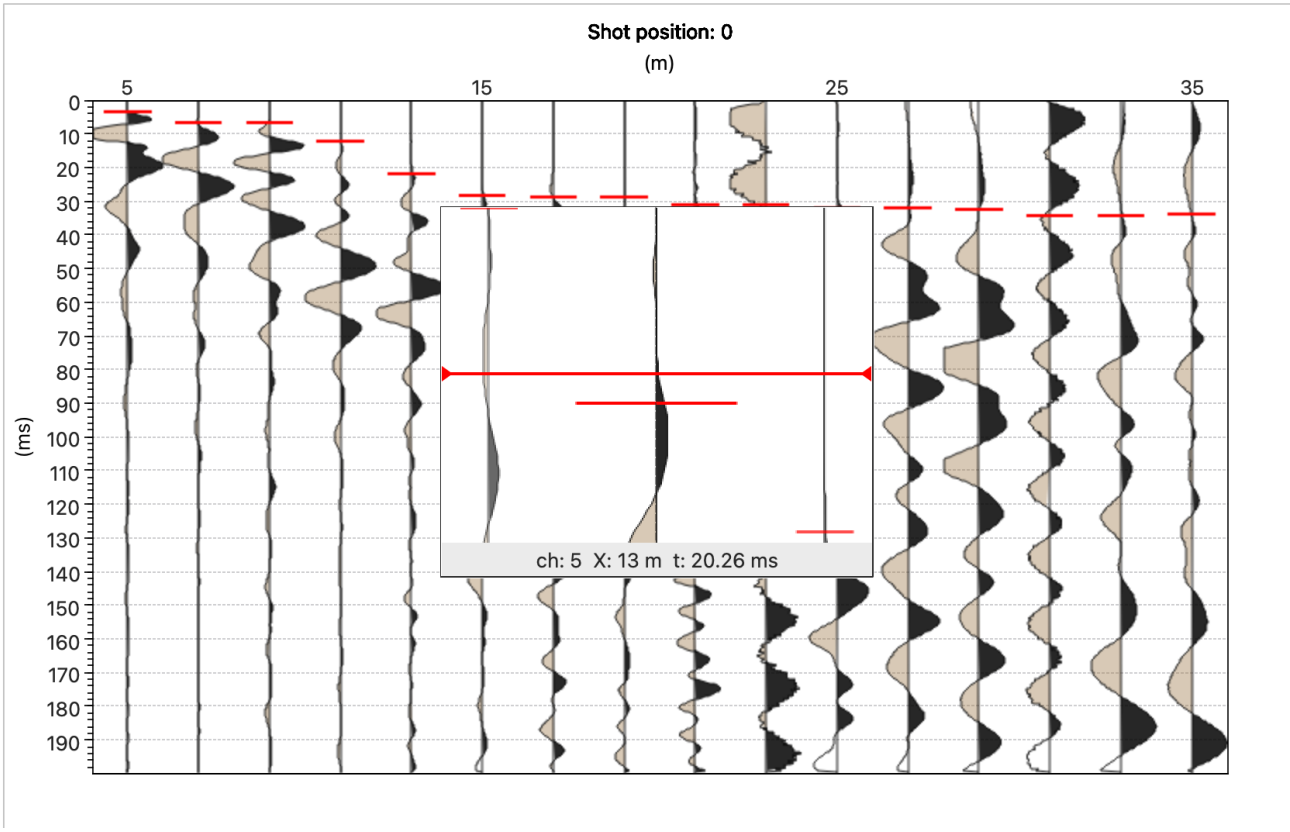


Figure 19 Magnifier active during manual picking of a trace

Viewing and editing first-arrival times

From the menu *Project/Arrival times table* a window opens with the table of arrival times. The table has geophones in the rows and shots in the columns. The Load... button loads arrival times from a csv file. The user can choose the field separator character.

Table cells can be selected with the mouse. Values can be copied and pasted with the commands **ctrl+c** and **ctrl+v**. The size of the pasted data must match the size of the table. An error is shown if the sizes differ.

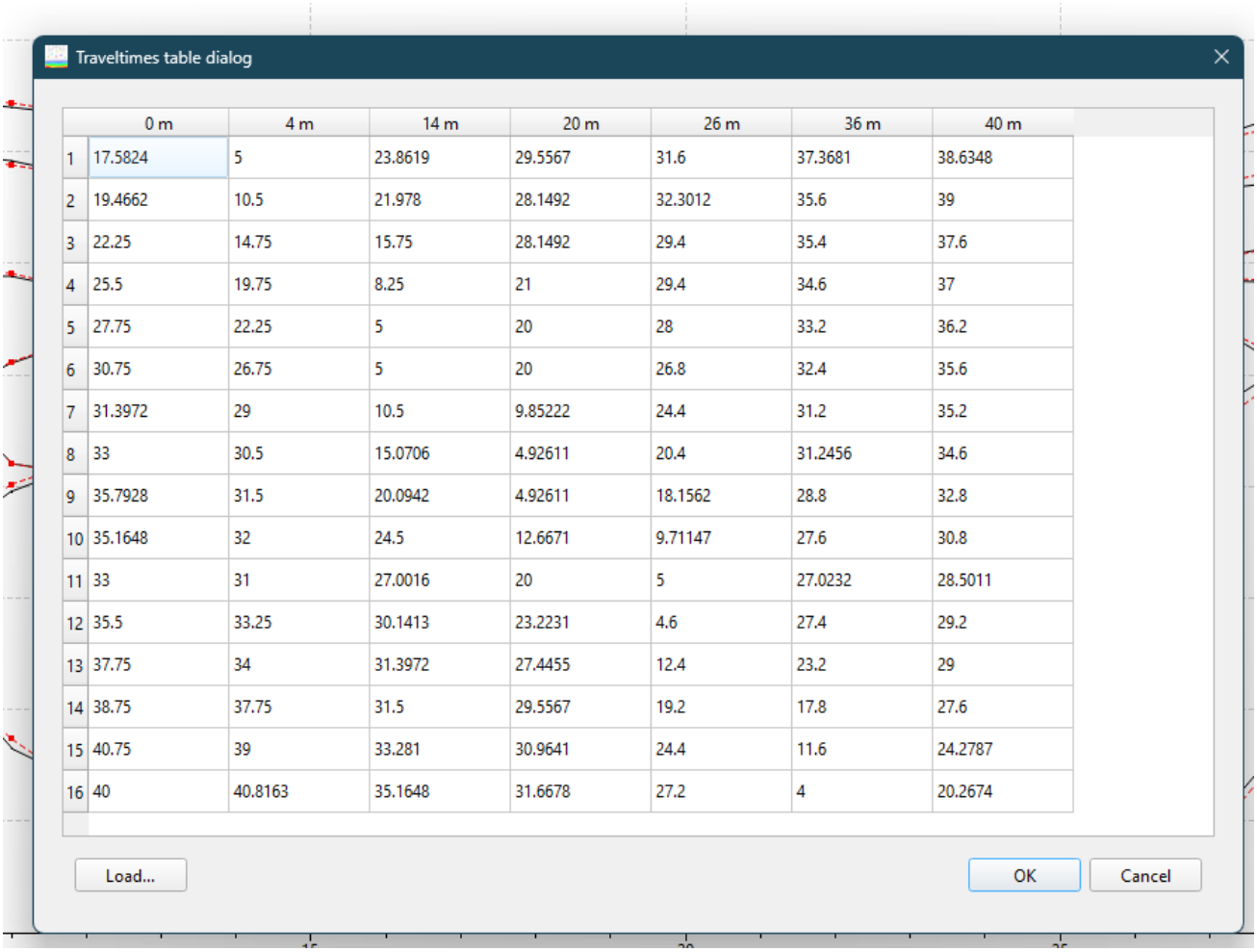


Figure 20 Dialog window to view and edit arrival times

Enabling seismic attenuation tomography and sampling attenuation data

BOX - GARBAGE IN, GARBAGE OUT WARNING

Seismic attenuation tomography uses the amplitude of the refracted seismic wave in the frequency/intensity domain as observed data. It is difficult to assess the quality of the acquired data during analysis. Field operations must therefore be carried out carefully, so that the intensity of the recorded signal is not altered.

Check that:

- The geophones are placed as specified by the manufacturer, for example vertically.
- The geophones are not placed in different ways, some on base plates and others planted in the ground. The signal is filtered in some way by the presence or absence of the base plate.
- The geophone/cable connectors are all in the same condition, with no moisture.
- The geophones are all of the same type in terms of response to the input.
- Avoid all local, surface conditions that can change the intensity of the recorded signal.

Enabling attenuation tomography		
From the menu: **Project/Enable attenuation tomography**	From the keyboard: **-**	From the toolbar:
Attenuation sampling window		
From the menu: **Traces/Attenuation sampling**	From the keyboard: **-**	From the toolbar:

When a new project is created, attenuation tomography is disabled by default. When the function is enabled, the user is asked (see Figure 21) to enter the size, in milliseconds, of the signal window used to calculate the signal intensity. The window size is defined starting from the first arrival.

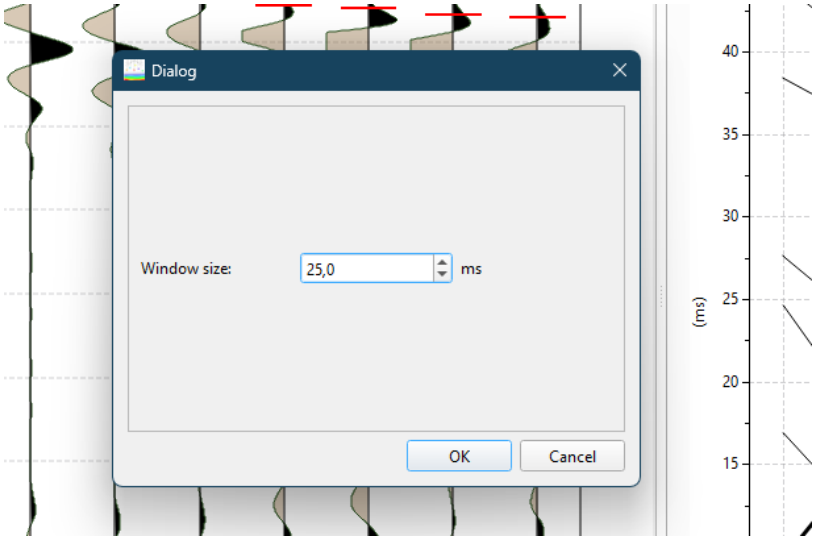
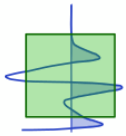


Figure 21 Dialog window to set the size of the sampling window for the signal intensity

The signal inside the window (see Figure 22) is analyzed in the frequency/intensity domain, trace by trace. The attenuation plot is then built. It can be displayed in the side view in place of the traveltime curves.

The size of the sampling window can be defined trace by trace by enabling the function from the menu or the toolbar. While this function is active, the first arrival cannot be edited. The lower end of the sampling window (green) can be positioned with a left mouse click. As in first-arrival picking, sampling can be disabled for a trace by clicking with **shift+left button**. A trace with sampling disabled no longer shows the green window that marks the sampled portion of the signal.

Manual selection of the attenuation sampling window		
From the menu: **Traces/Attenuation sampling**	From the keyboard: **-**	From the toolbar: 

In general, the sampling window can be wider with increasing distance from the source. As a guide, take a cable or a crest in the signal as a reference. Look for the corresponding feature in the neighboring traces. In this way the same portion of the signal is sampled in each trace.

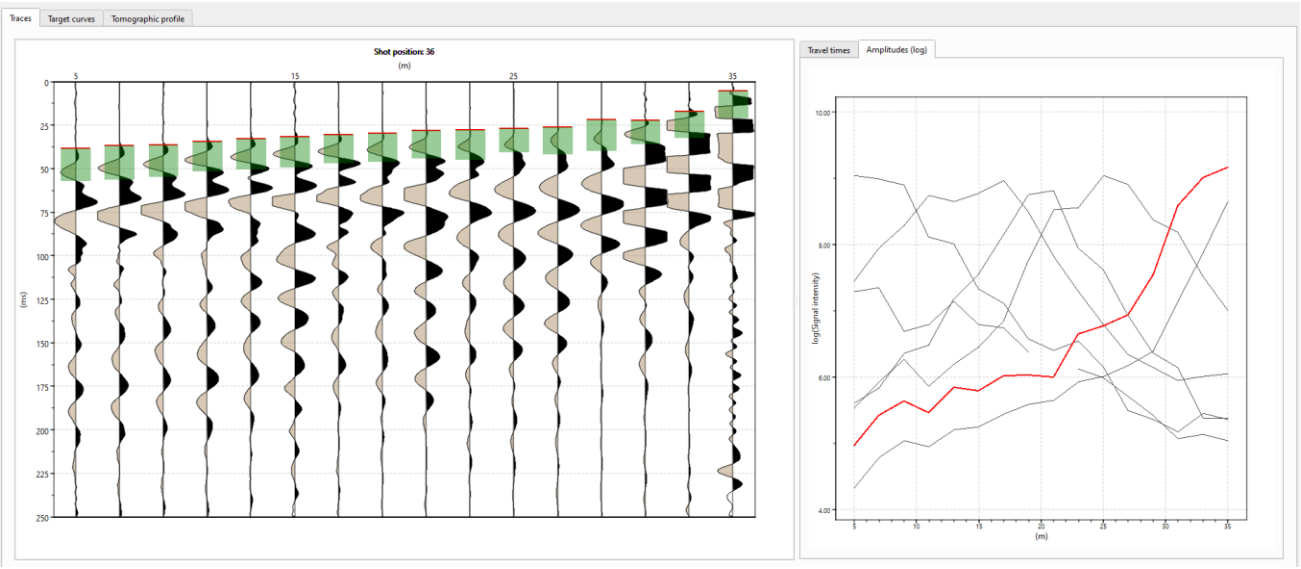


Figure 22 On the left: sampling windows (highlighted in green) of the signal used to calculate the intensity. On the right: intensity plot against geophone position.

The frequency associated with the maximum detected intensity is used in the QFactor tomography calculation. The automatically determined value can be changed manually in the dialog window opened from:

Manual selection of the frequency		
From the menu: **Processing/Set frequency**	From the keyboard: **-**	From the toolbar: **-**

The frequency value does not affect the resolution of the velocity and attenuation tomography.

Running the tomography

Running the tomography		
From the menu: **Processing/Run tomography**	From the keyboard: **-**	From the toolbar:

Running the tomography		
		

The tomographic inversion can be started from Processing/Run tomography. A dialog window opens to set the run parameters.

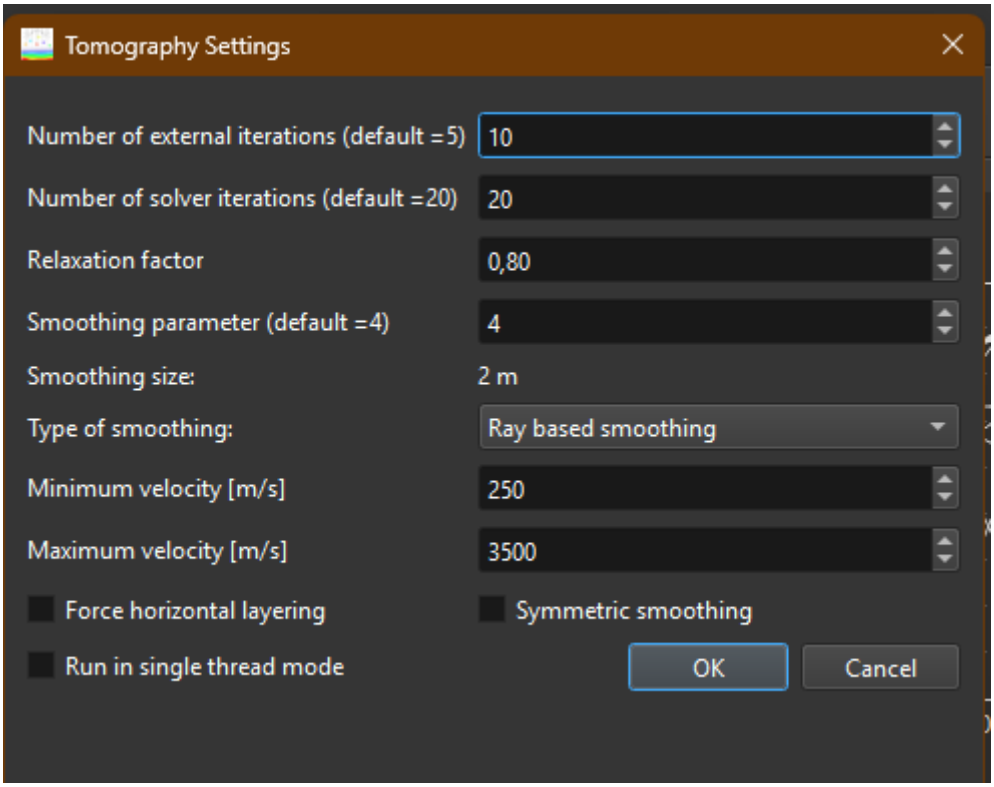


Figure 23 Settings of the tomography run parameters

The parameter with the largest influence on the result is the smoothing parameter. Low values make the update of the velocity model very local. The result can then show strong velocity contrasts. High smoothing values make the velocity model more homogeneous and continuous. Run the inversion several times with different values to find the best value for the modeled case. Since version 2024, the smoothing parameter is also shown in meters. This gives a reference that is easy to relate to the scale of the survey.

Different types of smoothing functions are available. *Uniform weighted smoothing* (uniform smoothing) corresponds to the method implemented as default in previous versions.

BOX – SMOOTHING TYPES

Type	Weight distribution
Uniform smoothing	1 1 1 1 1 1 1 1 1 1 1 1 **1** 1 1 1 1 1 1 1 1 1 1 1 1
Linear smoothing	0,35 0,45 0,5 0,45 0,35 0,45 0,71 1 0,71 0,45 0,5 1 **1** 1 0,5 0,45 0,71 1 0,71 0,45 0,35 0,45 0,5 0,45 0,35
Gaussian smoothing	0,73 0,82 0,85 0,82 0,73 0,82 0,92 0,96 0,92 0,82 0,85 0,96 **1** 0,96 0,85 0,82 0,92 0,96 0,92 0,82 0,73 0,82 0,85 0,82 0,73
Ray-based smoothing (*Default since version 2022.0*)	The weights vary inversely with the distance between the rays and the cell to be updated. They also depend on the cell velocity: faster cells contribute to a smoother result.

The tomographic problem is solved with two nested calculation loops. The inner loop optimizes the velocity model without recalculating the ray paths. In the outer loop, smoothing is applied and the ray paths are recalculated. In the default configuration, the outer loop is repeated 10 times and the inner loop 20 times. For each outer iteration, the inner loop is repeated 20 times.

The Relaxation Factor parameter can vary between 0 and 1. It can be considered a scale factor for the velocity model update between one iteration and the next. The value 0 cancels the update. The value 1 gives an unscaled update.

The result of the processing is shown in the *Tomographic profile* tab of the main window. Display customization is described in the dedicated section (see Display options).

The initial view shows the tomographic section with the seismic rays drawn over it.

BOX – ADVICE ON TOMOGRAPHY PARAMETERS
• The outer loop is the step that requires the most processing time. • The inner loop optimizes the model. To force the model update further, try values of 30 or even 50 iterations. • To make the tomography result less homogeneous, keep the smoothing values around 2-3. Values of 7-10 give a smoother result. • Uniform smoothing produces the smoothest results. Linear smoothing gives more weight to the central cells of the moving window and produces the coarsest results. Gaussian smoothing is intermediate between uniform and linear smoothing. Ray-based smoothing gives a smoother result for the higher velocities. It does not consider cells without rays in the calculation. • After the first tomography run, the inversion can be repeated. The result of the previous tomography is the starting model of the new run. In this way the progress of the processing can be evaluated. • After each inversion, check in the traveltime curves tab the overlap between the calculated curves (dashed line) and the measured curves (continuous line). If the measured curves are very irregular, low smoothing levels can be useful.

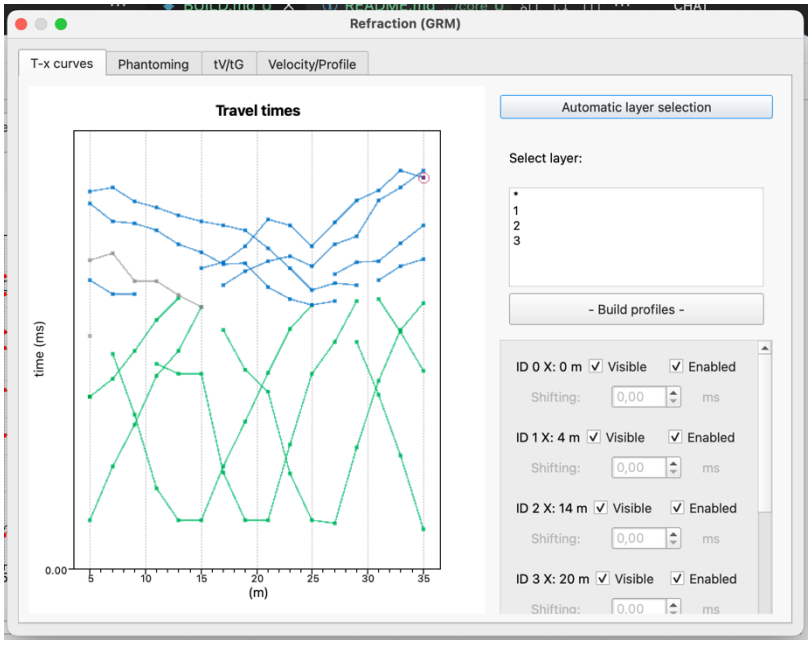
Refraction processing with the reciprocal method (GRM)

smartTomo includes a procedure to process the data with a layered model, implementing the Generalized Reciprocal Method, GRM.

Running GRM refraction		
From the menu: **Processing/Refraction**	From the keyboard: **-**	From the toolbar: -

The processing and display of the results are designed mainly for display overlaid on the tomography. The refraction processing can also be exported separately as an image.

The seismic test processing window has four tabs.



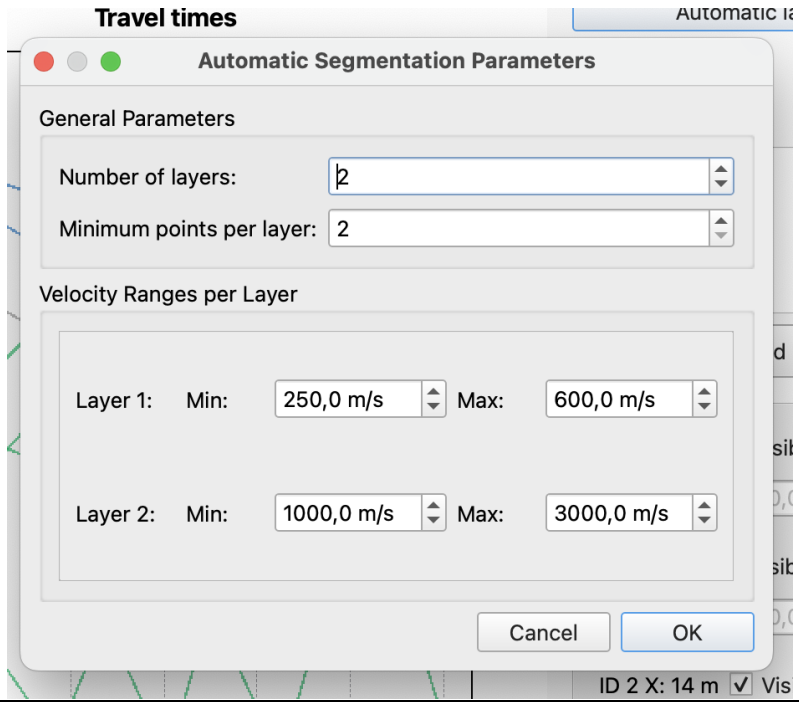
In this tab the user must assign the traveltime curves to the seismic layers.

Choose the seismic layer to which the arrival is assigned from the list at the top right. To assign the arrival time to the layer, click on the first point. Then move to the last point of that layer and click again.

The list at the bottom right shows the sequence of shots. It allows showing and disabling them.

The *Automatic layer selection* button opens the window for the parameters used to segment the traveltime curves into segments corresponding to the layers, based on increasing velocity intervals.

The *Build profiles* button automatically calculates the refraction section



The automatic segmentation of the traveltime curves assigns the seismic layers to segments of the curves automatically.
The curves are progressively approximated with a number of straight lines equal to the number of layers. If the calculated apparent velocity falls within the velocity range of the layer, the corresponding curve segment is assigned to that layer. The result can be corrected manually.

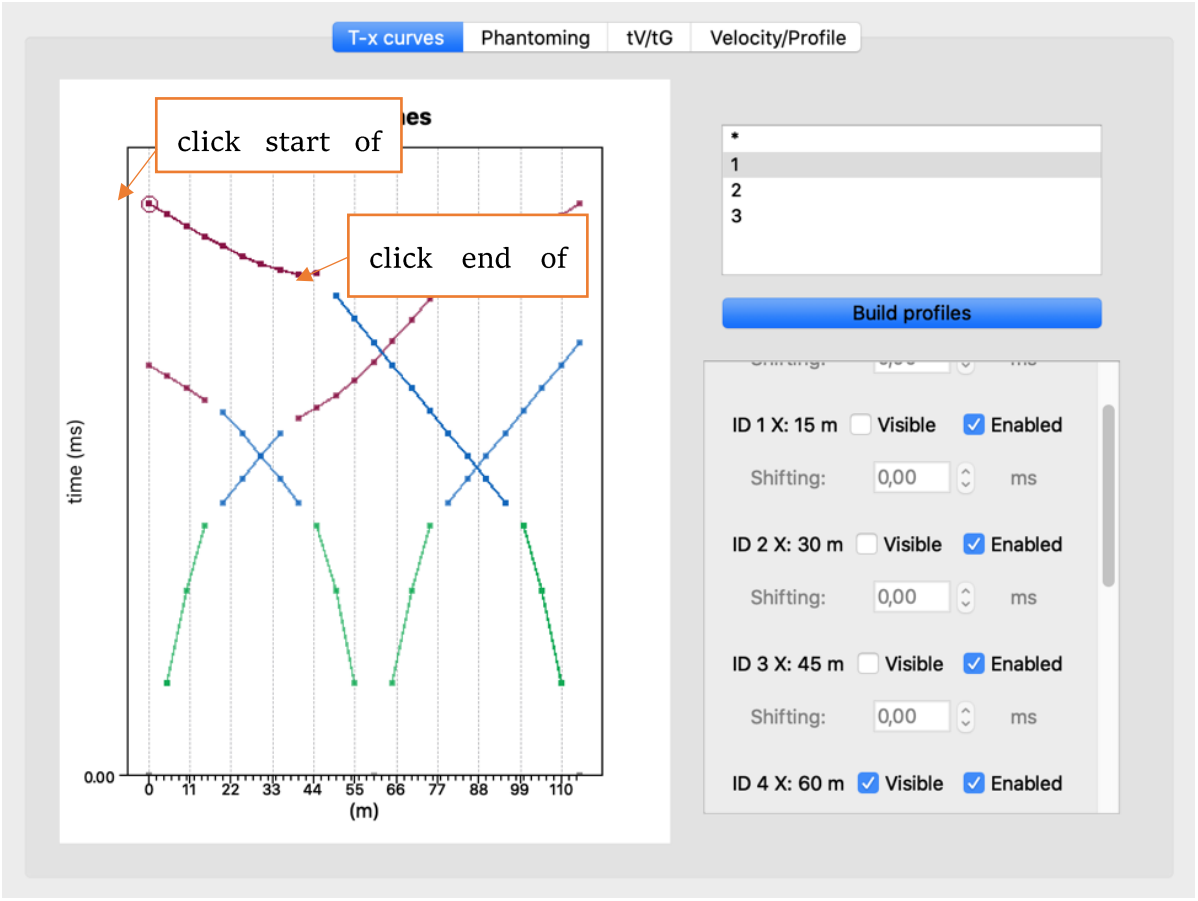
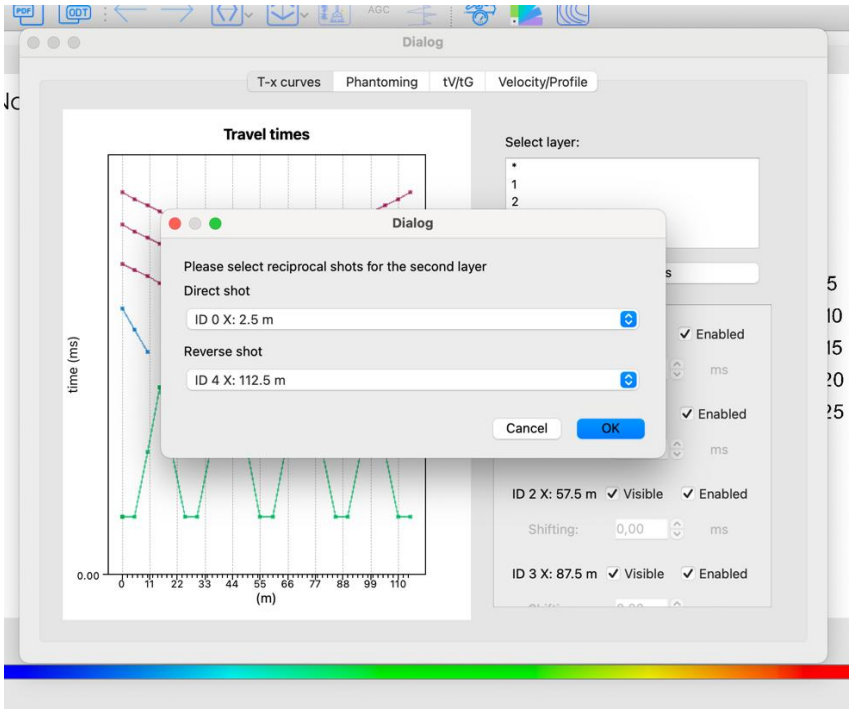
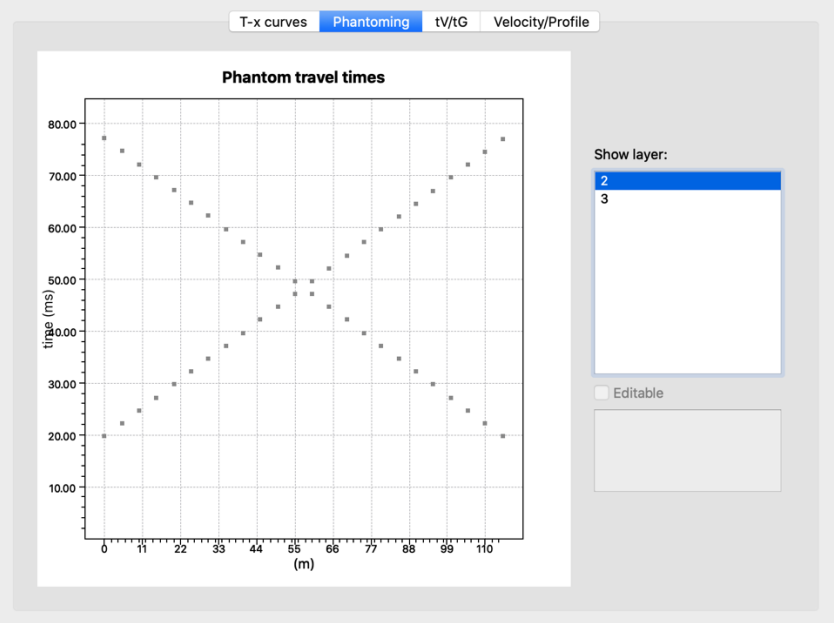


Figure 24 Example of manual assignment of the seismic layers to the first arrivals in a refraction processing

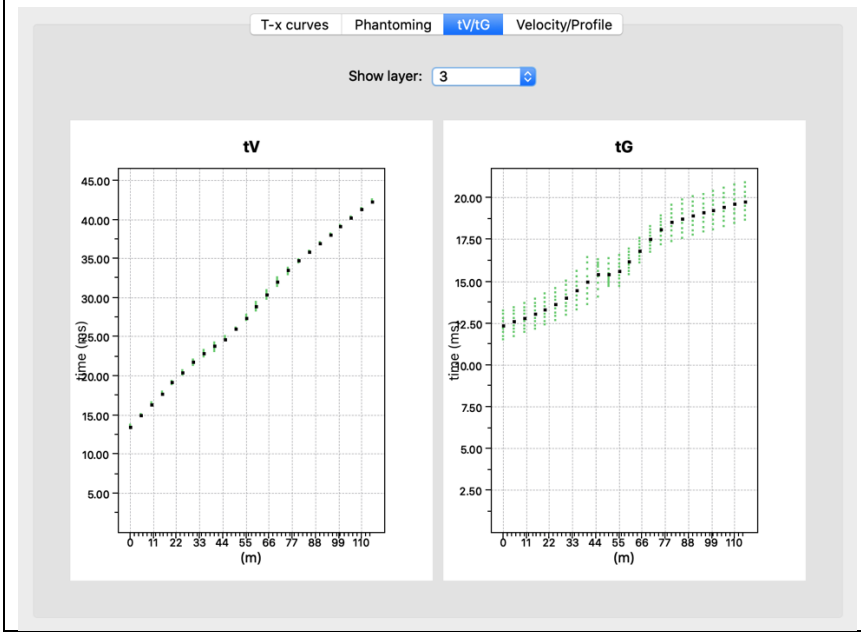


If the software cannot identify the reciprocal shots, this interface is proposed to select them. Inconsistent choices will obviously lead to inaccurate solutions.

It is advisable to fire at least one shot outside the line on each side.



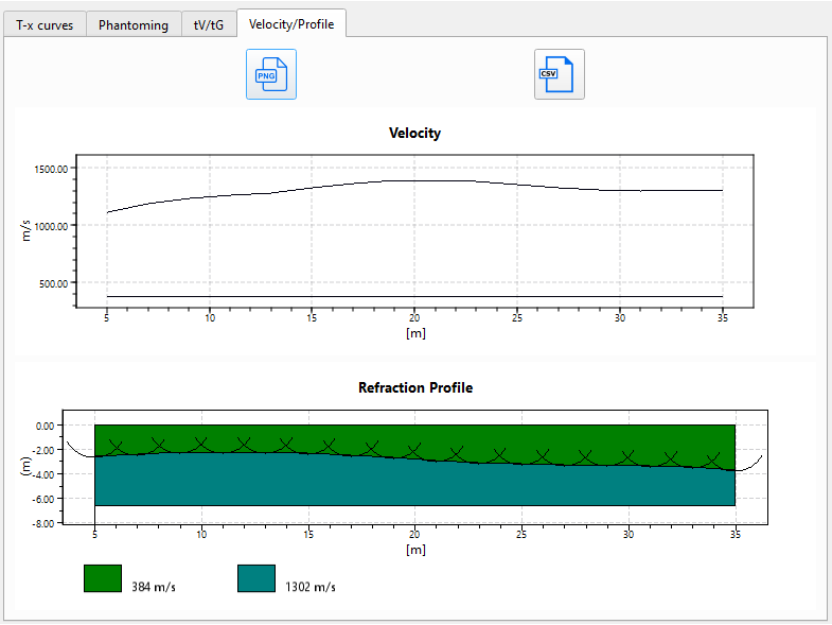
The second tab shows the reconstructed traveltime curves. This (automatic) process combines all the arrival times of a layer, sampled on several shots, to generate a continuous traveltime curve. Check that the forward and reverse travel times (reciprocal time) are approximately equal. If not, there are probably problems in the picking. In the image the reciprocal time is about 78 ms.



This tab shows the plot of the Tv and Tg functions.

The black plots correspond to the function used for the section. The green plots show the range of variability of the function values as the XY distance changes. (See:

Generalized Reciprocal Method (GRM))



The last tab shows the refraction profile (bottom) and the layer velocities (top).

The button exports the velocity and depth sections as PNG.

RMSE – Root Mean Square Error and maximum error

One way to assess the quality of seismic tomography inversion results is to evaluate the maximum error and the root mean square error (RMSE). They are calculated by comparing the fitted traveltimes with the observed ones. There is no definitive criterion to decide whether these errors are small enough to guarantee a reliable reconstruction of the subsurface structure. The user must judge case by case whether the fit is reasonable for the investigated context.

The suggested workflow is to inspect the traveltimes visually at the end of the tomographic inversion. Look for the points where the difference between calculated and measured traveltimes is largest. A large maximum error can indicate a problem in the survey geometry, for example a wrong position of shots or receivers. In the traveltime plot, an error in the shot geometry shows up when the calculated traveltimes tend to zero at a point where there is no actual shot. It is therefore important to check the quality of data acquisition and processing before running the inversion.

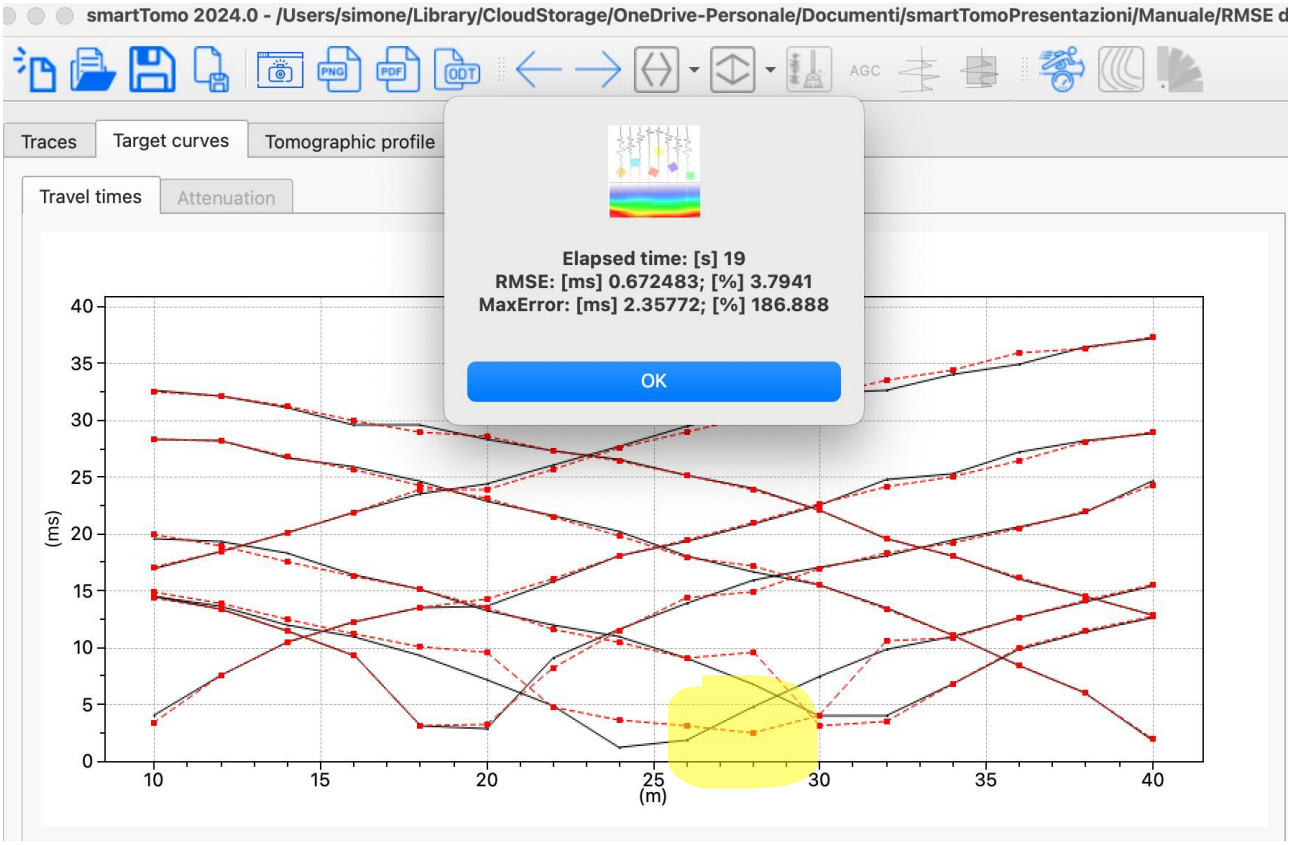


Figure 25 *The yellow spot highlights where wrong shot position is; the computed travel times (red dotted line) has a flat low value zone that does not match measured one.*

By examining both the tomographic profile and the traveltime plot, the user can identify problems related to the minimum and maximum velocity settings of the tomography.

Setting the velocity parameters in the *Run tomography* dialog to a range that is not appropriate for the geological context increases the RMSE and the maximum error.

If the minimum velocity is set too high, users can observe the following:

- The minimum velocity of the profile is close to the minimum velocity set in the dialog.
- The first-arrival times diverge near the shot points and the calculated first arrivals come too early.

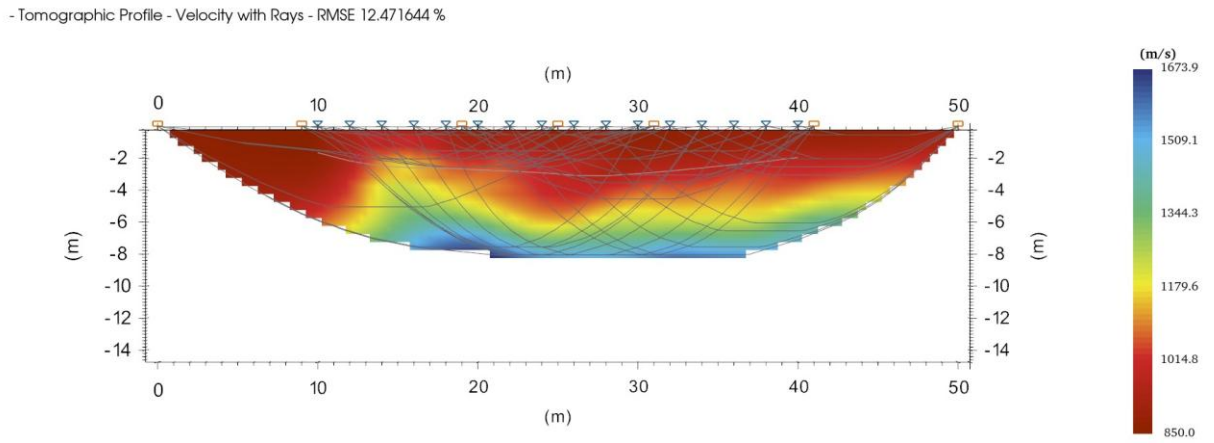


Figure 26 Tomographic profile calculated with a minimum velocity that is too high: a large part of the section is flattened at the minimum value set in the parameters.

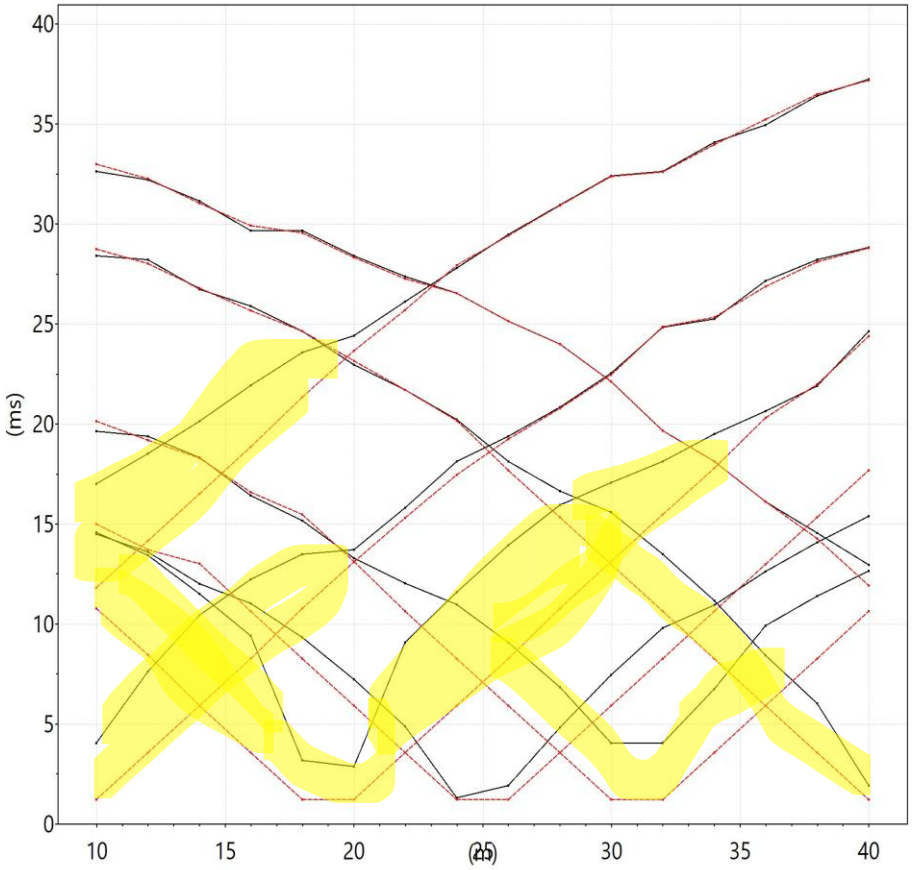


Figure 27 Traveltime curves for the profile in Figure 26. A minimum velocity that is too high produces wrongly calculated traveltime curves, especially near the shot points, with times that arrive too early.

If the maximum velocity is too low, users can observe the following:

- Tomographic profile clipped at velocities close to the maximum.
- The calculated traveltimes differ from the observed ones and arrive too late at the receivers located far from the shot points.

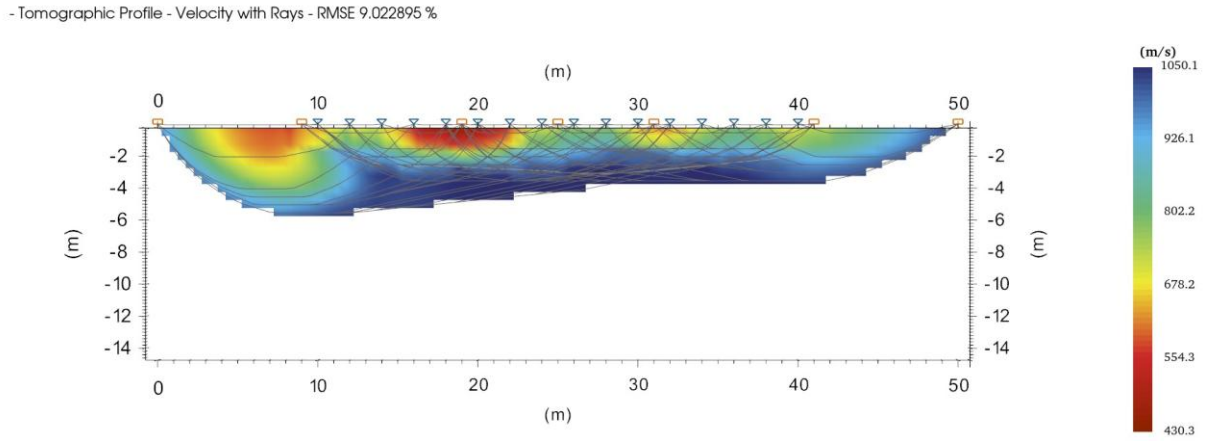


Figure 28 Seismic profile calculated with a maximum velocity that is too low.

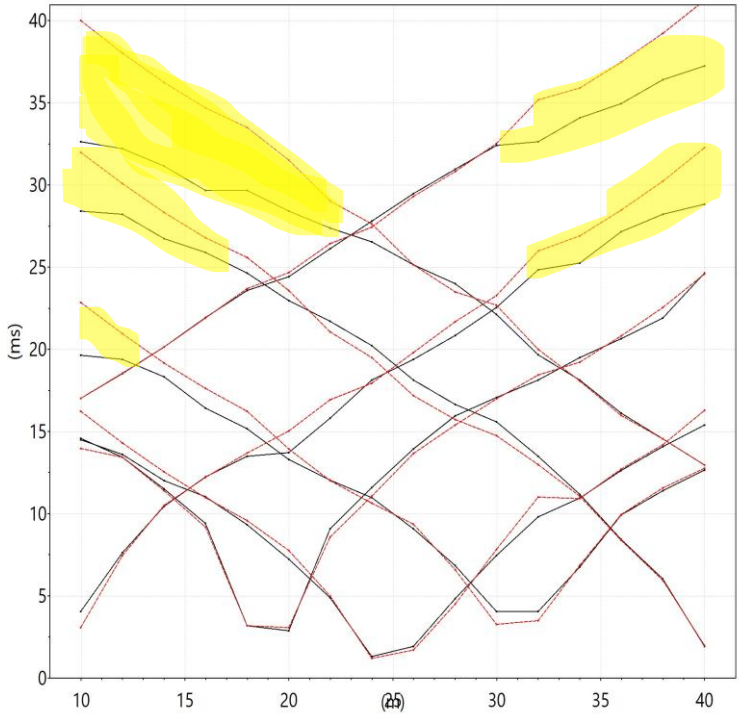


Figure 29 Traveltime curves for Figure 28 calculated with a maximum velocity that is too low. The yellow areas highlight the strong delay of the calculated curves (red) with respect to the measured ones (black).

Finally, the degree of smoothing applied in the inversion can affect the fit between observed and calculated traveltimes. A high smoothing parameter can lead to an overly smooth solution that misses the details of the heterogeneities. A low smoothing parameter can lead to a noisy solution that does not reflect the real variations of the velocity field. To find the optimal smoothing level, users must examine the trade-off between data misfit and model complexity

and choose a value that minimizes both. This gives a more accurate and robust tomographic image of the subsurface.

Opening and editing an existing project

Projects are saved in a proprietary “stomo” format that contains all the information needed to reopen the project. To open a saved project, click the icon or use the menu **File/Open.**

Once the project file is open, you can change several project properties. You can also edit the first-arrival picking and recalculate the seismic profile.

Editing the spread geometry

The geometry of the geophone spread can be edited in the project. The user can edit the geometry of an existing spread, created automatically from the metadata of the seismic files (seg2), or create a new spread to associate with the seismic files. A project can contain several geophone spreads.

In the geometry summary dialog, the geophone spread section is in the right column. Selecting the checkbox of the spread to edit opens the editing window. You can change the position both along the line (X) and in elevation (Y). Sensors cannot be placed underground.

The same editing window opens when you create a new spread. In this case you can also specify the number of geophones. The number of geophones must match the total number of geophones in the seismic files to associate with the spread.

Editing the shot positions.

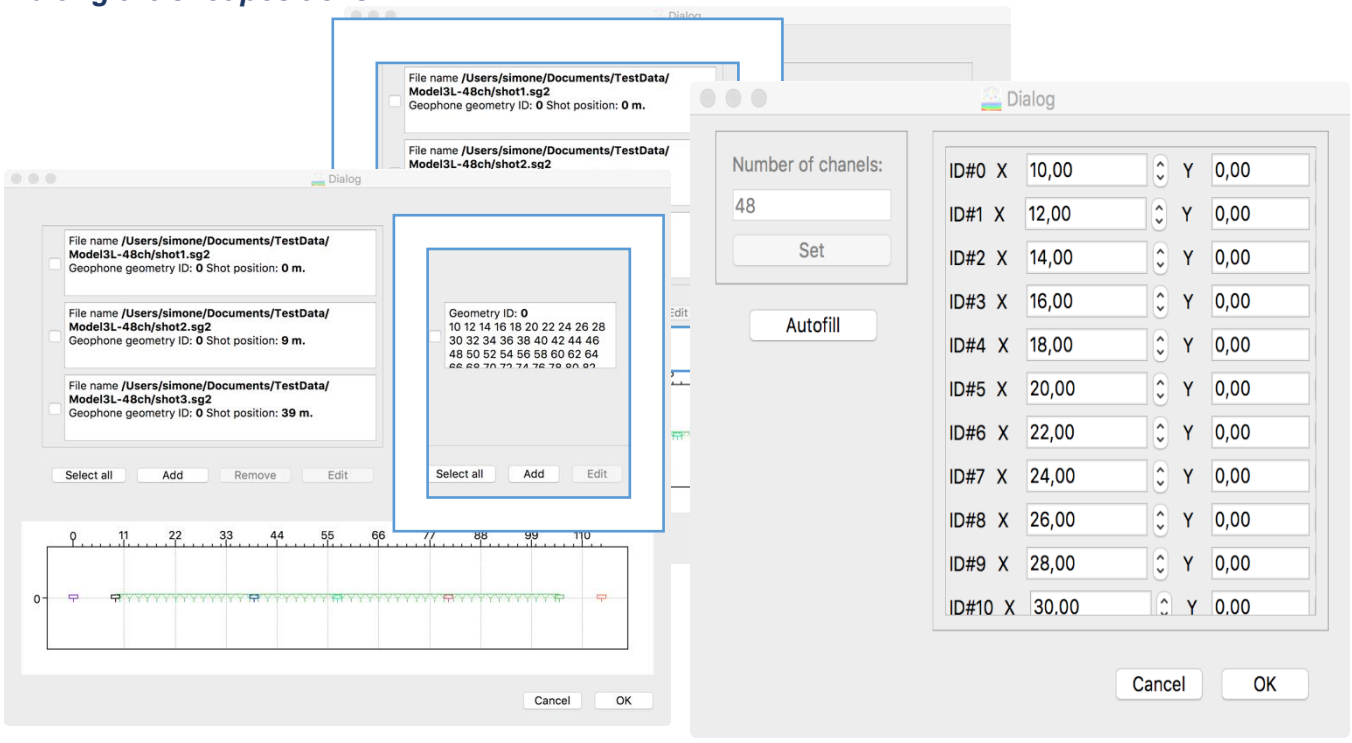


Figure 30 Setting the geophone geometry

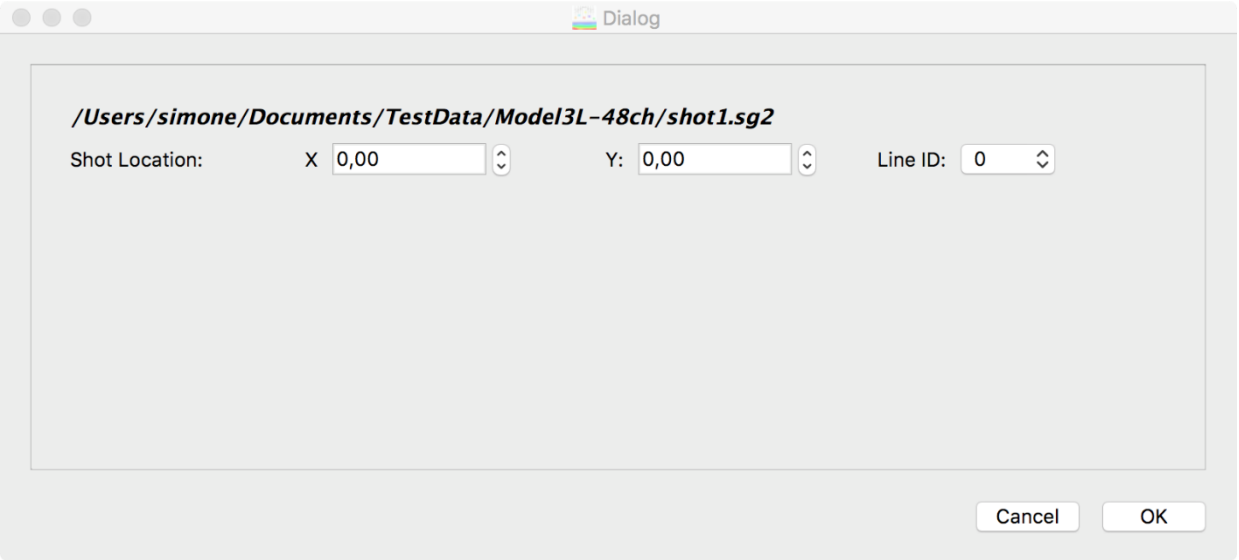


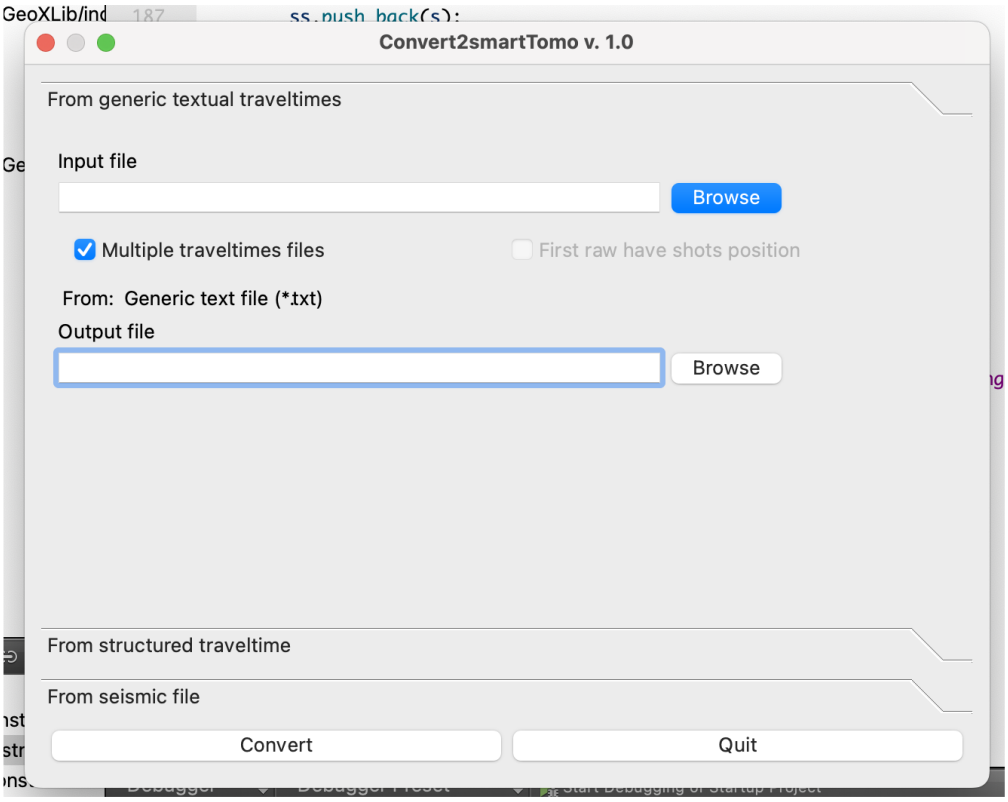
Figure 31 Editing the shot geometry settings

The shots in the project are associated with the files containing the seismic traces. In the geometry summary dialog they are in the right column. To change the position of a shot, select the corresponding file and click edit. A second dialog opens, where you can choose the position of the shot point and the associated geophone line. Shot points can only be placed at the surface. The associated geophone line corresponds to the ID of the geophone spread geometry defined in the previous section.

Importing traveltimes from other software

SmartTomo uses a structured format (OTTE – Open Travel Times Exchange) to import and export first-arrival times and the seismic spread geometry.

A tool called "Convert2smarttomo" is installed with smartTomo. It converts arrival times from other formats to the OTTE format, so they can be imported into smartTomo.



Convert2smartTomo main windows

The main window of the **Convert2smarttomo** application is divided into three tabs, corresponding to different types of conversion.

From a generic text file: in this tab you can convert a text file (.txt) formatted as in the following example:

```
0;0;0.008
2;0;0.013
4;0;0.026
6;0;0.037
```

Values must be separated by a semicolon (;). The columns are, in order, the X value, the geophone elevation [m] and the arrival times in seconds. Each shot must be saved in a separate file. During the conversion (click Convert) the program asks for the coordinates of each shot.

From structured travel-times: this tab converts different structured formats to the OTTE format. It can convert data from the following formats:

XYZ from Winsism;

TXT from Geogiga Refractor (not standard format);

vs from Pickwin;

From seismic file: converts SU files to SEG2 files.

OTTE Format

The Open Travel Times Exchange format is a way to share traveltime data from refraction surveys together with the geometry information. The following lines explain the meaning of the file content.

```
First line have the name of the format:
otte
number of the otte format version:
1.0
number of the dimensions of the geometry:
2
number of geophones lines:
1
X positions of geophones:
0;2;4;6;8;10;12;14;16;18;20;22;24;26;28;30;32;34;36;38;40;42;44;46;
elevations of geophones:
0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;
X of shots:
-2;50;48;31;11;19;5;25;39;
elevation of shots:
0;0;0;0;0;0;0;0;0;
beginning of travel times section;
geophones line - count starts from 0;
0
shot ID - count starts from 0
0
travel times:
4.57015;13.4674;19.0439;20.7465;22.4439;23.9927;26.6229;29.4617;31.3925;33.8248;3
4.6322;35.8949;37.2851;38.7219;39.651;40.6927;41.8419;43.0485;44.284;46.3934;47.6
834;48.3127;49.3082;50.5384;
```

```
new travel time section:
0
the follow 1 means that these travel times refers to the second shots
1
57.42;56.2144;55.0003;53.8586;53.1648;52.8585;52.0726;49.0149;46.9562;45.6532;44.
1943;42.6747;41.1;39.5558;37.9847;36.3958;34.7767;33.1356;31.7576;30.7477;28.8825
;26.4255;24.723;19.1465;
and so on.
```

A complete OTTE file is structured as in the following example:

otte

```
1.0
2
1
0;2;4;6;8;10;12;14;16;18;20;22;24;26;28;30;32;34;36;38;40;42;44;46;
0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;
-2;50;48;31;11;19;5;25;39;
0;0;0;0;0;0;0;0;0;
0
0
4.57015;13.4674;19.0439;20.7465;22.4439;23.9927;26.6229;29.4617;31.3925;33.8248;3
4.6322;35.8949;37.2851;38.7219;39.651;40.6927;41.8419;43.0485;44.284;46.3934;47.6
834;48.3127;49.3082;50.5384;
0
1
57.42;56.2144;55.0003;53.8586;53.1648;52.8585;52.0726;49.0149;46.9562;45.6532;44.
1943;42.6747;41.1;39.5558;37.9847;36.3958;34.7767;33.1356;31.7576;30.7477;28.8825
;26.4255;24.723;19.1465;
0
2
56.2169;54.9868;53.7693;52.6264;51.9326;51.6263;50.6716;47.5899;45.5249;44.1973;4
2.6737;41.1013;39.557;37.9858;36.3959;34.7767;33.1355;31.479;30.0885;29.0631;27.1
851;24.723;19.1465;10.2492;
0
3
45.6504;44.4056;43.1874;42.0416;41.3478;40.2753;37.4801;34.2777;32.1668;30.641;28
.9653;27.2768;25.5743;23.0821;14.7746;5.72389;5.72389;14.7746;23.0821;26.3338;28.
2146;29.2462;30.6477;32.3129;
0
4
29.2792;27.5767;25.8742;23.1468;14.8393;5.78863;5.78863;14.8393;23.1468;27.6028;2
9.7184;31.4209;33.1234;34.8137;36.4846;38.1289;39.7563;41.3671;42.9988;45.3317;47
.0613;48.0235;49.1873;50.637;
0
5
38.3059;36.8276;35.382;34.1007;32.6886;30.1977;27.5407;23.0821;14.7746;5.72389;5.
72389;14.7746;23.0821;25.5743;27.2768;28.9653;30.641;32.304;33.9515;36.3472;38.13
54;39.0516;40.3323;41.919;
0
6
23.0821;14.7746;5.72389;5.72389;14.7746;23.0821;26.3645;29.4761;31.9015;34.4399;3
5.2507;36.5188;37.9573;39.4639;40.9828;42.0245;43.1737;44.3803;45.6158;47.7252;49
.0152;49.6445;50.6778;51.935;
0
6
42.2185;40.7763;39.3987;38.1175;37.3562;35.3052;32.4756;29.2631;27.1396;25.5743;2
3.0821;14.7746;5.72389;5.72389;14.7746;23.0821;25.5743;27.2768;28.9653;31.4005;33
.2486;34.239;35.5876;37.1963;
```

```
0
7
51.5172;50.2724;49.0542;47.9083;47.2145;46.9082;44.8764;41.6945;39.6001;38.1566;3
6.5511;34.9243;33.2745;31.6092;29.9313;28.2405;26.538;23.2492;14.7746;5.72389;5.7
2389;14.7746;23.2492;26.538;
```

Display options

Products of the tomographic inversion

SmartTomo offers several ways to display the results:

- **Tomographic section:** display of the velocity distribution in the subsurface;
- **Vertical gradient:** representation of the velocity variation along the vertical; useful to identify discontinuities;
- **Weighted vertical gradient (new in 2022.1):** representation of the velocity variation along the vertical, weighted by depth;
- **Laplacian:** highlights the omnidirectional velocity variation;
- **Information density:** shows how significant the velocity inversion is, based on the density of seismic rays;
- **Attenuation:** represents the tendency of materials to attenuate the seismic signal. Loose soils and highly weathered rocks show higher values;
- **Q-Factor:** gives a rough indication of material quality. It is inversely proportional to attenuation and directly proportional to velocity. Higher values indicate better materials
- **AI filtered model (new in 2027.0):** velocity model processed by the MjolNET M3 network to attenuate the residual noise of the inversion;
- **AI difference map (new in 2027.0):** difference between the filtered model and the original one, useful to see where the network intervened most.

The result is available among the display options as AI filtered model and AI difference map (the latter highlights the areas where the filter changed the original model most). Views generated with the AI filter carry an “AI” watermark that the user can hide. The comparison between the original and the filtered model can be opened from the AI Filter Comparison... window.

MjolNET M3 receives as input the velocity model calculated by the tomography and the ray density per cell. As output it produces the filtered model and the difference map with respect to the original.

The network was trained on about 40,000 synthetic profiles and has about 5 million parameters. It is a lightweight model that runs quickly even on modest hardware. Like any neural network, however, it can produce hallucinations. These are structures that look plausible in the filtered model but are not actually supported by the data, especially where the ray density is low. The filtered model must therefore always be compared with the original, for example using the difference map, before it is used for geological interpretation.

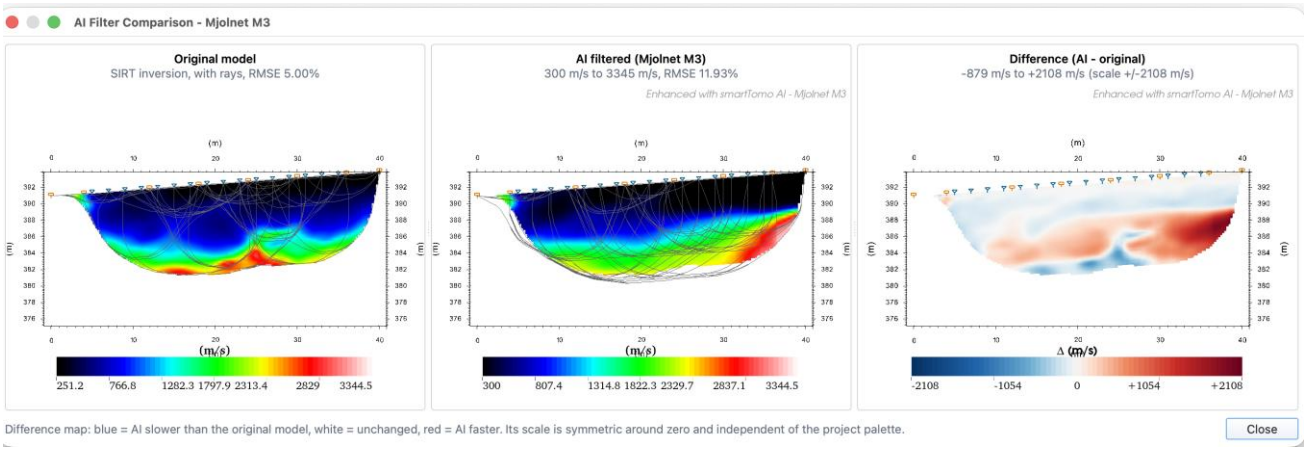
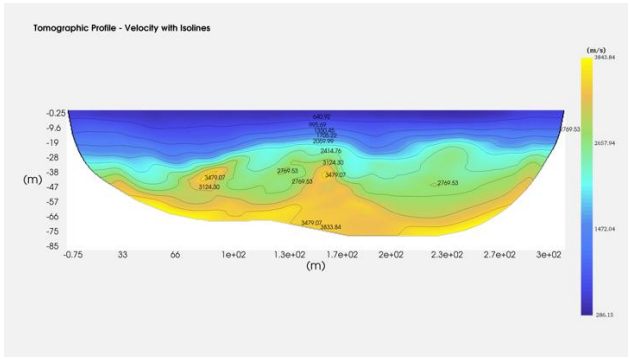
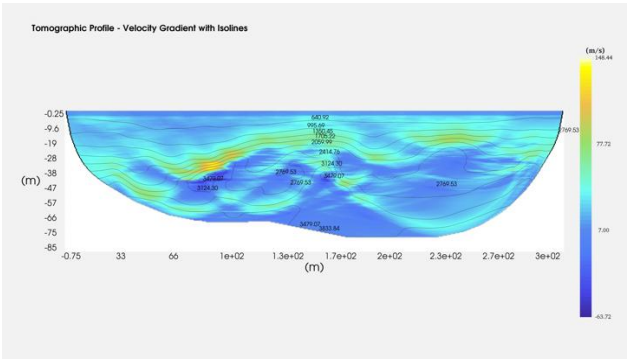
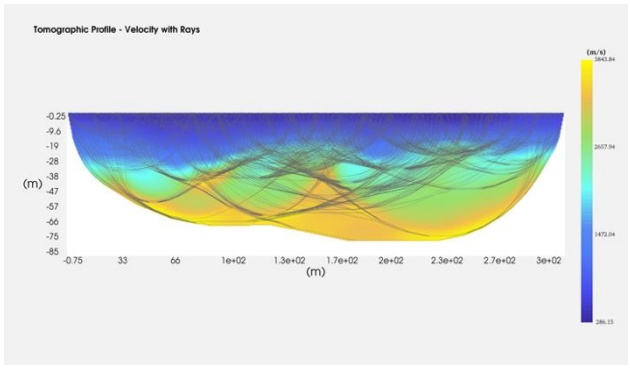
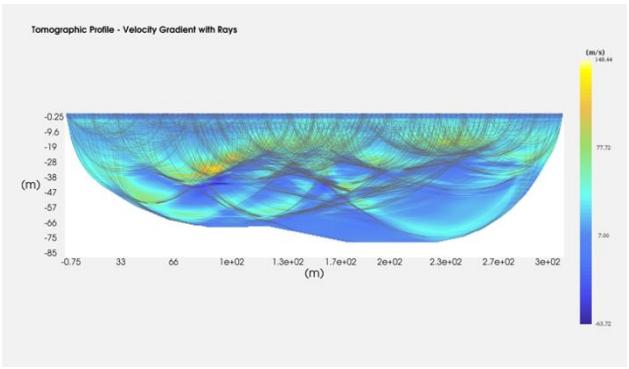
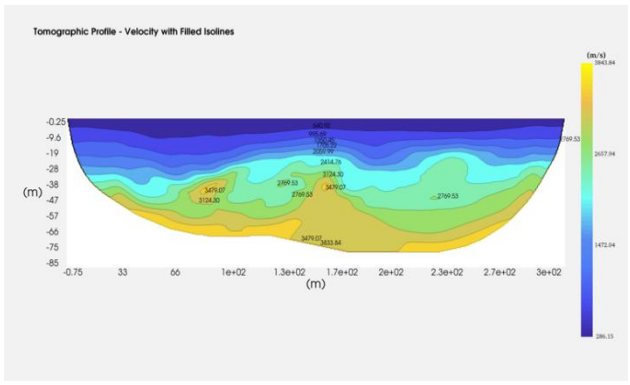


Figure 32 AI Filter Comparison window with AI filtered model and AI difference map

All displays can be shown in different styles. The following table lists the options for the velocity profile and the vertical velocity gradient.

The different display modes and options are available from the **View** menu.

Velocity profile	Vertical velocity gradient
	
Profile with isovelocity lines	**Gradient with isovelocity lines**
	
Profile with seismic rays	**Gradient with seismic rays**
	NA
Profile with isovelocity lines filled with solid fill	

Vertical gradient, weighted vertical gradient, Laplacian

SmartTomo provides three different modes to highlight the trend of seismic wave velocity in the subsurface, and in particular its anisotropies: the vertical gradient, the weighted vertical gradient and the Laplacian.

Vertical gradient.

The vertical gradient image is the graphical representation of the value of the function:

$$\nabla V_z = \frac{\delta V}{\delta z}$$

where the z direction is the depth of the tomographic section and V is the velocity field.

This view highlights the vertical velocity variations along the profile. It shows how velocity changes with depth. Positive values indicate a velocity increase with depth. Negative values indicate a velocity inversion. Three-color palettes, for example blue-white-red, help to appreciate the details expressed by the vertical gradient.

Normalized vertical gradient

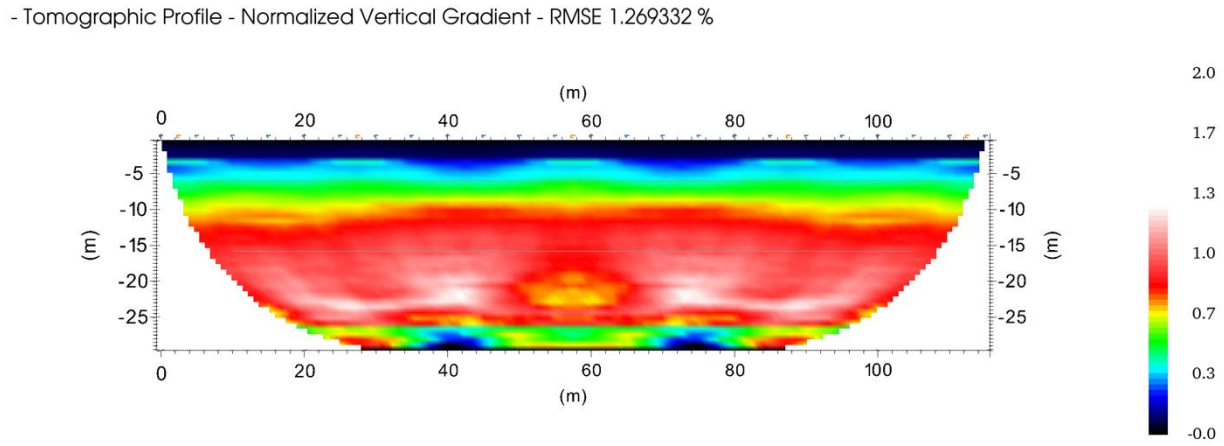


Figure 33 Normalized vertical velocity gradient profile. Higher gradient values identify the zones with a larger velocity increase.

The normalized vertical gradient view shows the graph of the following function:

$$z * \frac{\partial V}{\mathrm{V}\,\partial z}$$

where the z direction is the depth of the tomographic section and V is the velocity field.

This view is dimensionless. It highlights velocity contrasts by weighting them with depth. The transition from slow to faster materials is well identified by a sudden increase in the value of the function.

Laplacian

The Laplacian of a two-dimensional image is defined as:

$$\nabla^2 V = \frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial z^2}$$

Here V is the velocity field and z is the direction corresponding to depth in the profile.

In a discrete distribution of values, such as a tomographic image, the Laplacian is calculated from the values of the pixels adjacent to the central one, according to this scheme:

-1	-1	-1
-1	8	-1
-1	-1	-1

The Laplacian is therefore calculated by subtracting eight times the value of the central point from the sum of the values around it.

The Laplacian highlights the points with the largest velocity variation. It shows sharp velocity jumps. A grayscale palette helps to emphasize the features highlighted by the Laplacian.

Information density

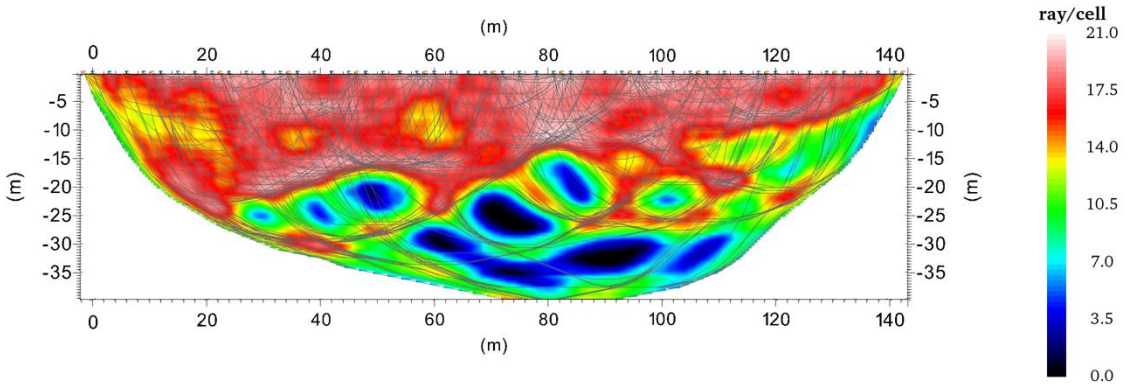


Figure 34 Example of a profile showing the information density

The information density profile shows how many seismic rays cross each cell. This information allows you to assess how much the tomographic profile is constrained by the measured data. The portions with a higher density of seismic rays are the areas where the solution was calculated with more constraints. Where the density is low or equal to zero, the resulting profile was determined with few conditions, or it corresponds to the initial model without having received any updates.

It can be displayed with the rays overlaid, or with the velocity contour lines if these are already shown on a previous view.

Color palette management

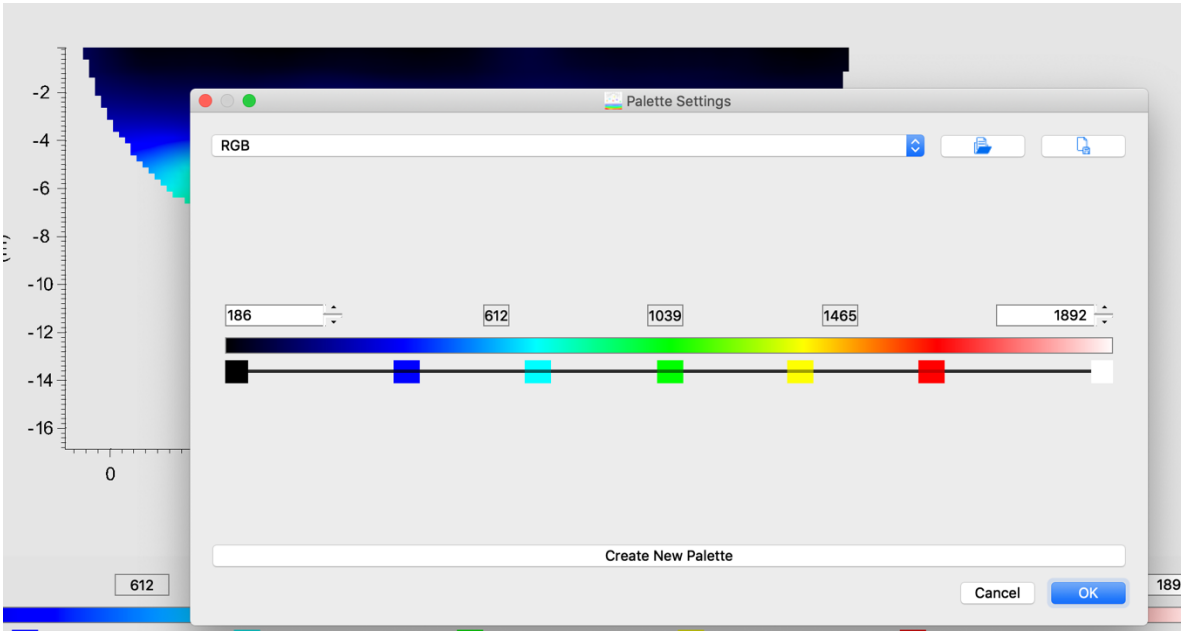


Figure 35 Dialog to choose the palette

The lower part of the tomography view contains the current color palette. Here you can manually set the maximum and minimum velocity values. If you set a minimum velocity greater than the minimum velocity of the section, all cells with a velocity lower than the set value are drawn with the minimum color.

Initially, the section is displayed with the palette called RGB. It is a color gradient from black to white, passing through blue, green and red. You can choose the palette among those already available in the software. You can also create a new one by modifying an existing one.

Edit palette		
From the menu: **View/Palette**	From the keyboard: -	From the toolbar: 

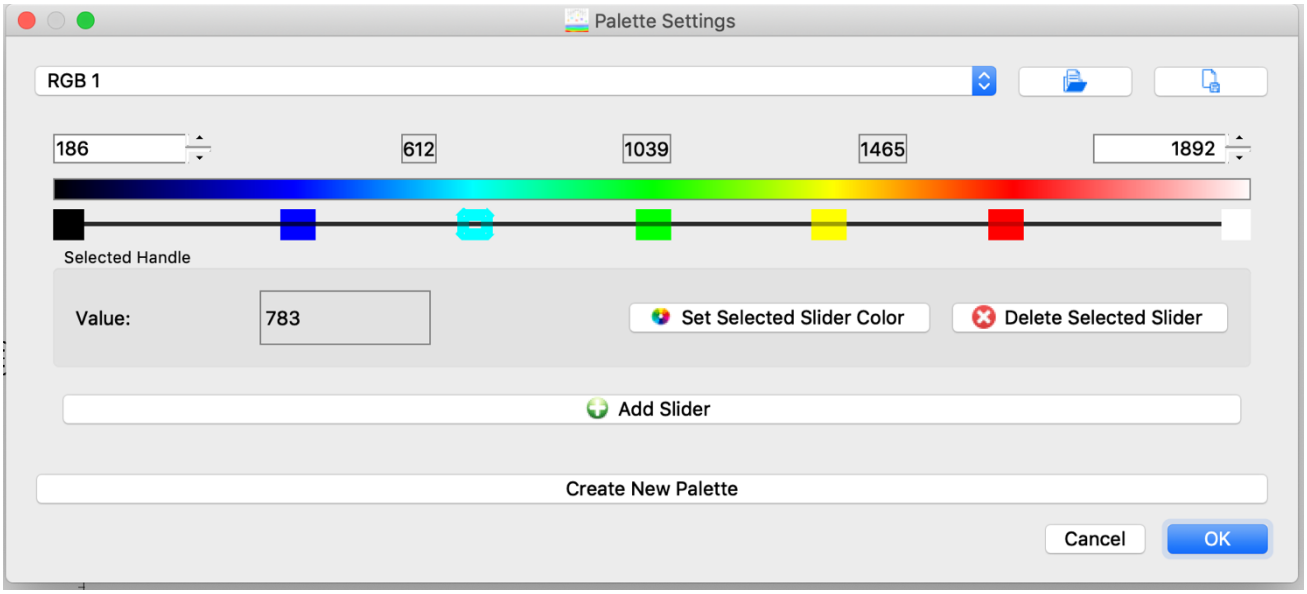


Figure 36 Palette customization. Note the two buttons to load and save a custom palette.

In the palette options dialog, click *Create new palette* to make the current palette editable. Below the color bar there is a slider with several handles. Each handle corresponds to a velocity value and a color. The resulting palette is the linear gradient of the colors associated with each handle. You can add and remove all handles except those corresponding to the minimum and maximum values.

BOX – NOTES ON COLOR PALETTES

Starting from version 2019.2, two new color palettes were introduced:

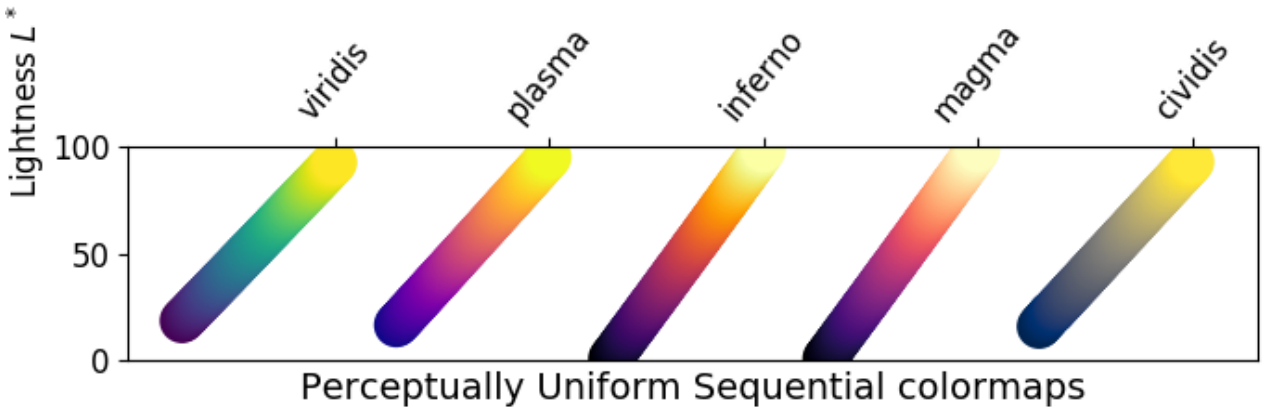
- silva viridis;



- vulcanic magma;



These two palettes come from statistical analysis and data visualization environments (R and Matplotlib). They are perceptually uniform. They have no sharp luminosity jumps that alter the perception of the data. They are accessible to color-blind people.



A good source of information on choosing a color palette is the following page, from which the previous chart was taken. (https://matplotlib.org/3.1.0/tutorials/colors/colormaps.html)

Contour line display

Show contour lines		
From the menu: **View/Show contour lines**	From the keyboard: **-**	From the toolbar: -

Selecting this item from the menu opens the dialog with the options for the display of contour lines and velocity gradient. The available options are divided into two parts. The upper part contains the contour line display options. The lower part contains the choice of the display mode.

Contour lines can be set at user-defined values (velocity or other), or at equal intervals by setting their number. The display can use a continuous color gradient, or filled contours with a solid color.

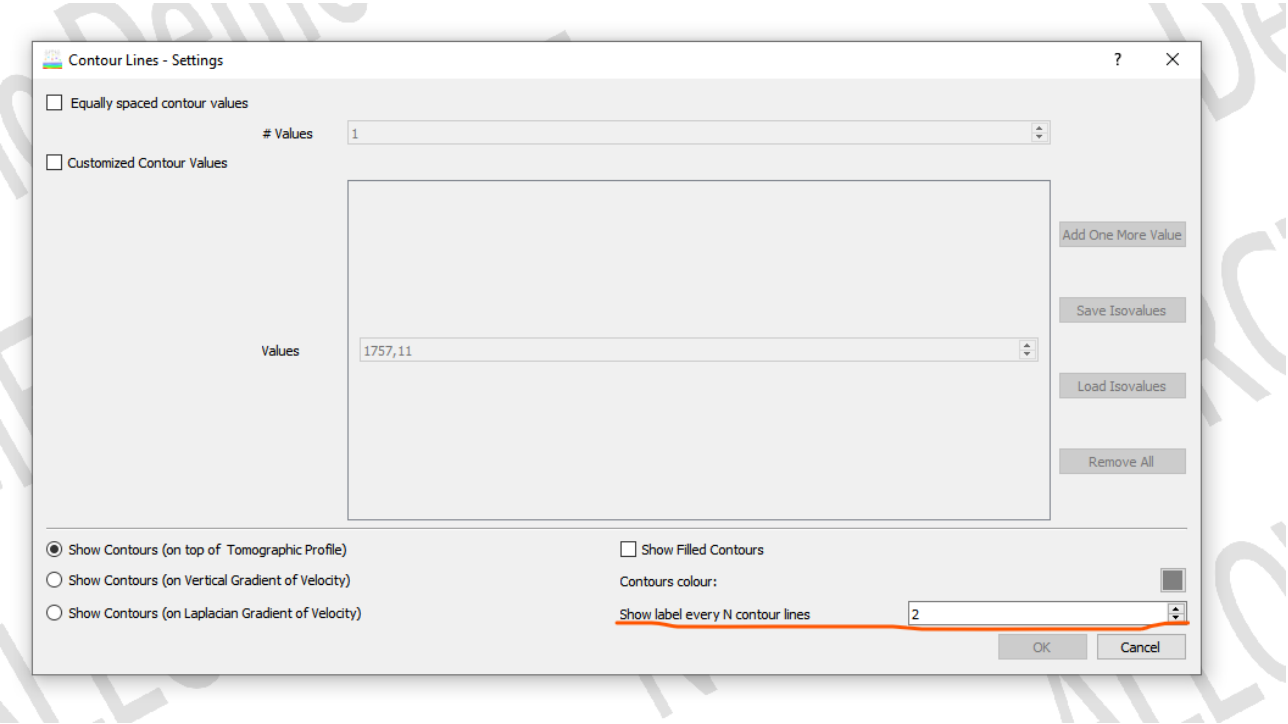


Figure 37 Dialog for contour line display. It highlights the option to choose how many contour lines have a printed value, and the font size of the label applied to the lines.

Contour lines are calculated and displayed with respect to the variable shown in the profile:

- velocity profile, vertical gradient and Laplacian: contour lines are calculated and drawn with respect to velocity;
- information density profile: contour lines represent lines of equal information density;
- attenuation profile: contour lines are calculated and drawn as lines of equal attenuation;
- Q factor profile (Q Factor): contour lines represent lines of equal Q factor.

Compared to previous versions, the displayed contour lines adapt to the type of data shown in the profile.

Project title

You can display the project title. The section title, the view name and the mean error are shown at the top of the view.

Set title		
From the menu: **Project/Set title**	From the keyboard: **ctrl + T**	From the toolbar: T

Show grid lines

From the *View* menu you can select the Show grid option. It overlays lines parallel to the axes at the major ticks.

Refractor color and style management

From the *View* menu you can overlay on the tomography the result of the seismic refraction processed with the GRM method. Refractors are drawn as lines. To make the lines visible against the chosen palette, you can change their color and thickness from the menu View/Refraction options .

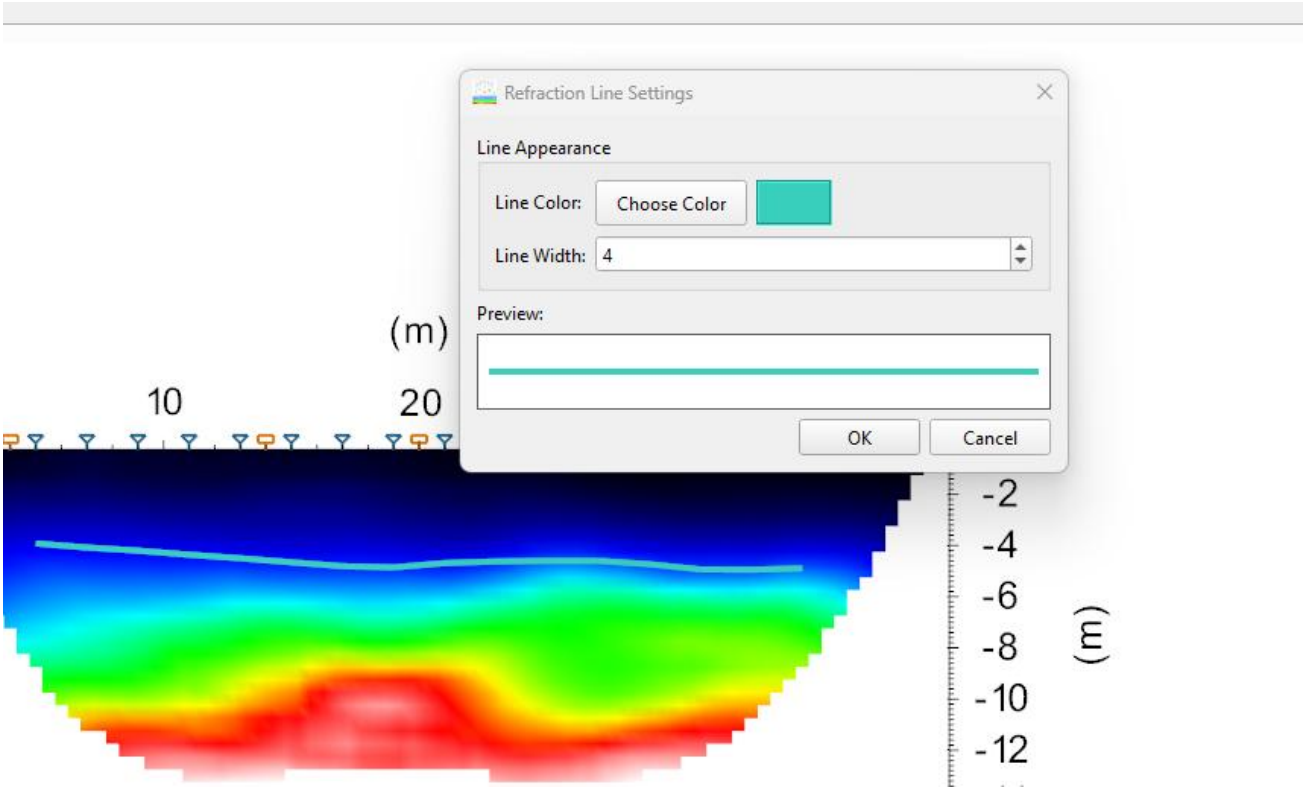


Figure 38 Dialog to set the refractor display style

Exporting the results

The processing results can be saved as a numerical grid, as documents and images, and as a KML file.

Exporting the velocity grid.

Velocity grid export		
From the menu: **File/Export velocity grid**	From the keyboard: -	From the toolbar: -

The velocity grid export saves a text file formatted in columns separated by a space. For each cell, the coordinates of the center and the velocity are saved. If the seismic section has been georeferenced, the cell center coordinates are expressed according to the coordinates entered in the spread (EPSG code). This format can be loaded in external viewers.

Export in GRD format

SmartTomo exports the tomographic profile grid in GRD format for direct import into Surfer by Golden Software.

Exporting the average vertical velocity profile.

Export of the average vertical velocity profile		
From the menu: **File/Export average velocity profile**	From the keyboard: **-**	From the toolbar: -

This function exports a vertical profile of the average velocity, with an interval equal to the cell thickness. The result is a text file with several columns: depth, average velocity, minimum and maximum.

Image export		
From the menu: **File/Export/Images**	From the keyboard: **-**	From the toolbar: -

Exporting images (png).

The image export lets you choose which object to export in the dialog. You can define a file name prefix. The prefix is placed before the name of the exported object (for example, Figure_profile.png is the name of the file containing the profile)

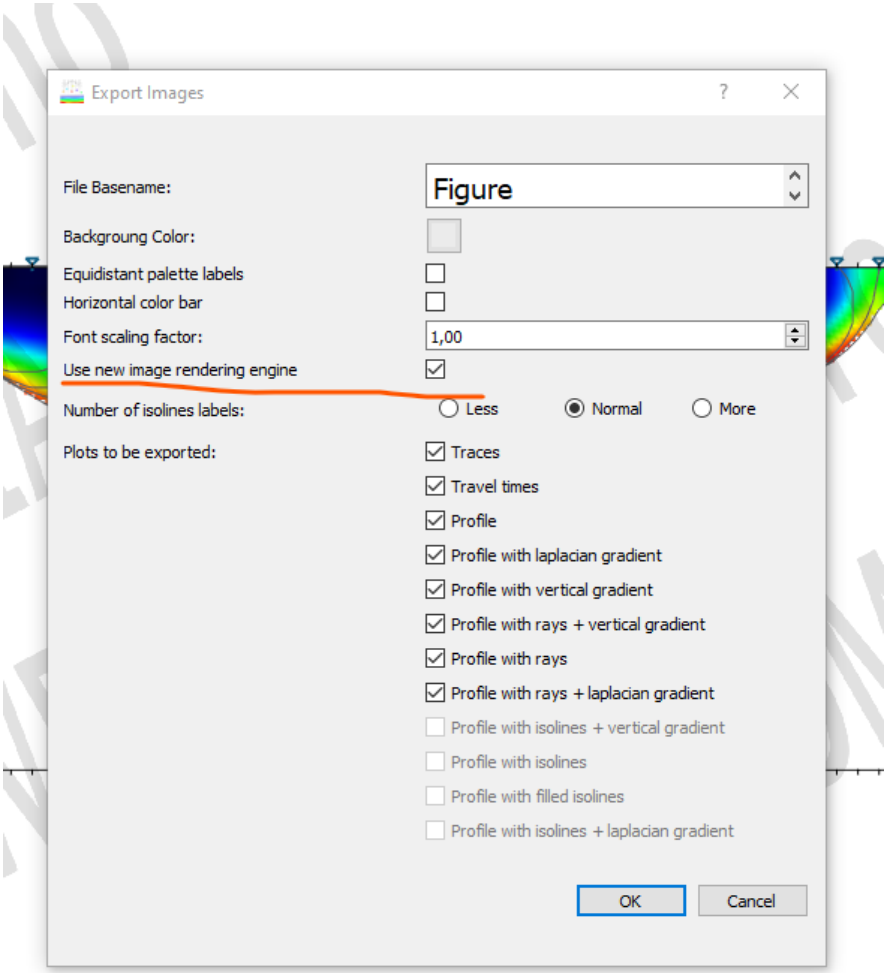


Figure 39 Image export dialog. You can choose what to export. You can also choose whether to place the color palette labels at regular intervals or at the positions of the palette handles. The font scale parameter scales the font size in the saved images.

From version 2020.0 you can choose whether to use the new graphics engine or the previous one to export images. The new graphics engine can export the maximized section. On some hardware the resolution may be low. In those cases, we recommend using the old graphics engine by disabling the option, or using the screen capture function.

We also recommend considering saving a screenshot. It gives an exact copy of what is shown on the screen. The result of the image export can vary depending on the video hardware.

Export to a document (PDF/ODT)

PDF export		
From the menu: **File/Export/PDF**	From the keyboard: **-**	From the toolbar: -

Text document export		
From the menu: **File/Export/ODT**	From the keyboard: **-**	From the toolbar: -

You can export all graphic elements to a single PDF file.

You can export all graphic outputs, laid out in an ODT document (which can be opened, for example, with the open-source software LibreOffice by The Document Foundation). The document also contains a table that summarizes all the first arrival times, both measured and reconstructed in the tomography.

Export in KML format

You can export the tomographic profile and the spread geometry to a KML file. To export to a KML file, the geographic position of the first and last geophone must be set, together with the EPSG code. (see Georeferencing of the seismic line.)

The KML file can be displayed in environments such as Google Earth. It allows you to display several seismic spreads together.

KML export		
From the menu: **File/Export/KML**	From the keyboard: **-**	From the toolbar: -

Export in DXF format

SmartTomo exports the tomographic profile in DXF format. DXF does not embed the tomographic image. The output therefore includes two image files (profile and color scale) and a DXF file that contains the references. To share the product, all three files must be transferred together.

Export in SVG format

SmartTomo can export the seismic profile in SVG graphic format. SVG is a file type based on a markup language that describes vector images. This format is widely used for technical drawings, diagrams and maps. It ensures a precise rendering that adapts to different devices.

WHAT'S NEW IN VERSION 2027.0

Version 2027.0 is an important step forward for smartTomo. The MjolNET neural networks, described in the chapter Introduction, assist the user for the first time in picking and in filtering the tomographic model. The new module for geotechnical boreholes fits into the workflow right after the spread geometry. A print layout editor for print sheets, a command-line mode to automate several projects, and various refinements in the display and export of results complete the picture. The following pages describe these new features in detail.

Print layout editor

The Layout/Print layout editor... menu opens an editor for composing print sheets on one or more pages. The editor works per project. Each sheet you create stays associated with the project and is saved with it. Sheets can also be saved as reusable templates in the layout library and exported to PDF, PNG, SVG, Word (.docx) and OpenDocument (.odt).

Graphical interface

The editor window is organized around a central area, the canvas. It shows the current page with horizontal and vertical rulers for precise placement of elements. Three panels are docked around the canvas. All of them can be moved and undocked:

- Pages (left): lists the pages of the sheet and lets you add, duplicate, delete and reorder them;
- Properties (right): shows the parameters of the element selected in the canvas; its content changes with the element type;
- Warnings (right): lists the problems detected in the sheet, for example overlapping or off-page elements.

The menu bar offers File, Insert, Edit, Arrange, Page, View and Templates. The toolbar below the menu collects the most used actions: inserting each element type, deletion, page setup, zoom fit and export. The status bar at the bottom shows a hint about the current action, for example how to move or resize an element with the selection handles.

Page management

The Pages panel contains the + Page button, to add an empty page, and + Traces, which automatically adds one page for each shot of the project (one traces sheet per shot). The Duplicate and Delete buttons duplicate or delete the current page. The arrows move it up or down in the print order. The same operations, together with page renaming, are available from the Page menu, which also opens the Page setup window described below.

An element can be set to repeat on all pages (Repeat on every page option in the Properties panel). Typical cases are title blocks, logos or headers that must appear identical on every page of the sheet without recreating them one by one.

Inserting and arranging elements

Elements are added from the Insert menu or from the corresponding toolbar buttons. The available types are:

- Tomographic profile: the tomographic section, in the same display modes available in the 3D viewer (velocity, velocity with rays, gradients, information density, attenuation, Q factor, plus the results of the MjolNET M3 AI filter);
- Refraction profile: the non-tomographic layered model, with optional proportional axes and borehole overlay;
- Traveltime curves: the diagram comparing measured arrival times with those computed by the tomography;
- Refraction arrival times: the first arrivals colored by the assigned refraction layer;
- Seismic traces: the seismogram of a shot, with a choice of data source (current shot, selected shot, specific index or, in traces sheets, the shot of the page);
- Color bar: the color legend of the palette in use, vertical or horizontal;
- Legend: the symbols used in the sheet (geophones, shots, refraction line, lithologies and borehole logs);
- Spread geometry: the layout of geophones and shots, as an image or as a table, with automatic pagination if it does not fit on one page;
- Text: a free text box, with support for dynamic placeholders (see below);
- Title block: the header of the sheet, with customizable label/value rows;
- Image: an image or logo loaded from file and embedded in the sheet;
- Shape: rectangles, ellipses or lines for separators and graphic frames.

Once inserted, elements are moved by dragging and resized with the handles on the edges. The Edit menu offers undo/redo, duplication and deletion of the selected element, selection of all elements and a change of stacking order (bring forward/send backward). The Arrange menu adds alignment (left, horizontal center, right, top, vertical center, bottom), even distribution of three or more elements along an axis, and equalization of width, height or size among selected elements.

Element properties

The Properties panel always shows two groups common to all elements, Geometry (X/Y position, width, height, rotation, Z order, visibility and repetition on every page) and Style (border, background and opacity). They are followed by a group specific to the type of the selected element:

- Tomographic profile: choice of the display mode among those available in the viewer, including the two items AI Filtered Model (MjolNET M3) and AI Difference Map

introduced in this version. The profile is captured with the same view that is active in the 3D viewer at the time of export;

- Seismic traces: data source (first available dataset, current selection or specific dataset) and dataset index;
- Refraction profile: proportional 1:1 axes without vertical exaggeration, velocity legend and borehole overlay;
- Color bar: palette, orientation, range (inherited from the palette or set manually), number of labels, title, font and title size;
- Text: content, font, size, bold, italic, color, alignment and automatic word wrap, with the list of available placeholders;
- Title block: optional heading and table of label/value rows, with buttons to add or remove rows and a common text style;
- Image: loading and removal of the file, aspect ratio lock. The image is embedded in the sheet, so it remains valid even if the original file is moved or deleted;
- Shape: type (rectangle, ellipse, line), line color and thickness, fill;
- Legend: title, items to show (geophones, shots, refraction line, lithologies and borehole logs), number of columns, symbol scale, line spacing, title alignment, font, text size and color;
- Spread geometry: title, image or table mode, items to show (geophones, shots, axes), number of columns, automatic pagination if the geometry does not fit on one page, font, text size and color.

Title block, text and legend accept dynamic placeholders such as ${project.title}, ${project.file}, ${date}, ${author}, ${profile.rmse}, ${shot.index}, ${shot.count} and similar. They are replaced automatically with the project values at display and export time. In this way the same sheet template adapts to different projects without manual editing.

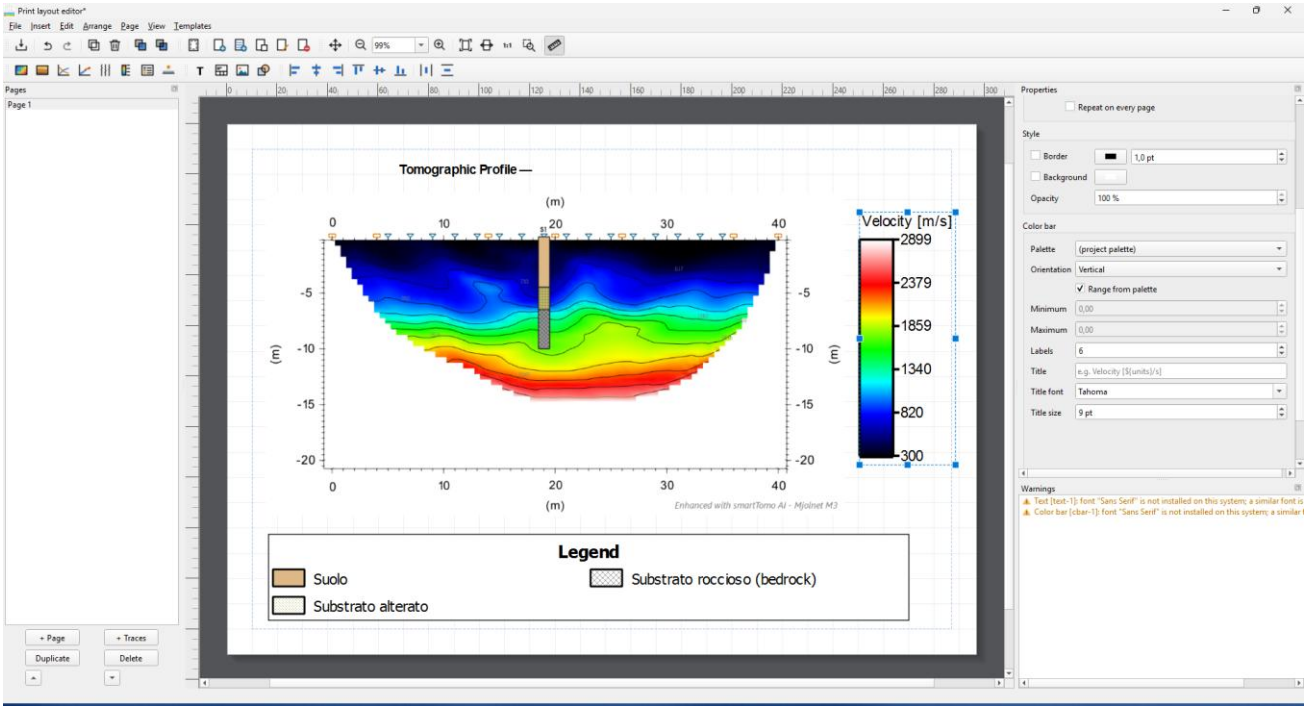


Figure 40 Properties panel with a tomographic profile selected and its parameters

Page setup

The Page setup window, available from the Page menu or the toolbar, defines the page type (normal, or traces with one shot per page, with the first and last shot to include), paper size (predefined or custom, with its dimensions), orientation, margins on each side and background color. For traces pages it also shows the list of repeated elements inherited from the other pages. This lets you check what will appear on the page in addition to the traces.

Layout templates

A composed sheet can be saved as a template with Templates/Save as template..., giving it a name. It is written to the layout library shared among projects. Templates/Manage templates... opens the library. There you can apply a template to the current layout (replacing it, after confirmation), delete it, or import or export it as a .stomolayout file to share it with other smartTomo installations.

Export

The File/Export page... menu, or the corresponding toolbar button, opens the export window. There you choose the format (PDF, PNG, SVG, Word .docx or OpenDocument .odt), the scope (current page only or all pages) and the resolution in DPI for raster formats. For multi-page PDF the Single multi-page PDF option is available. It collects all pages in one file instead of writing one file per page. PNG, SVG and single-page PDF produce one file for each exported page.

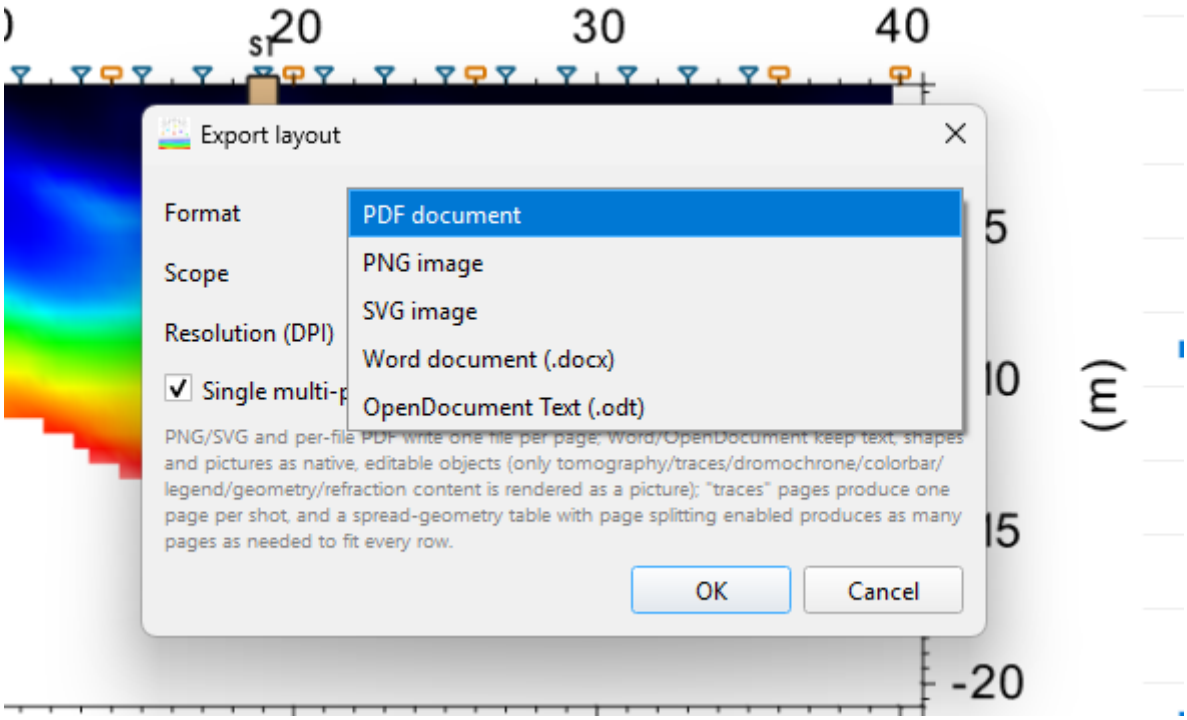


Figure 41 sheet export window with the format and resolution options

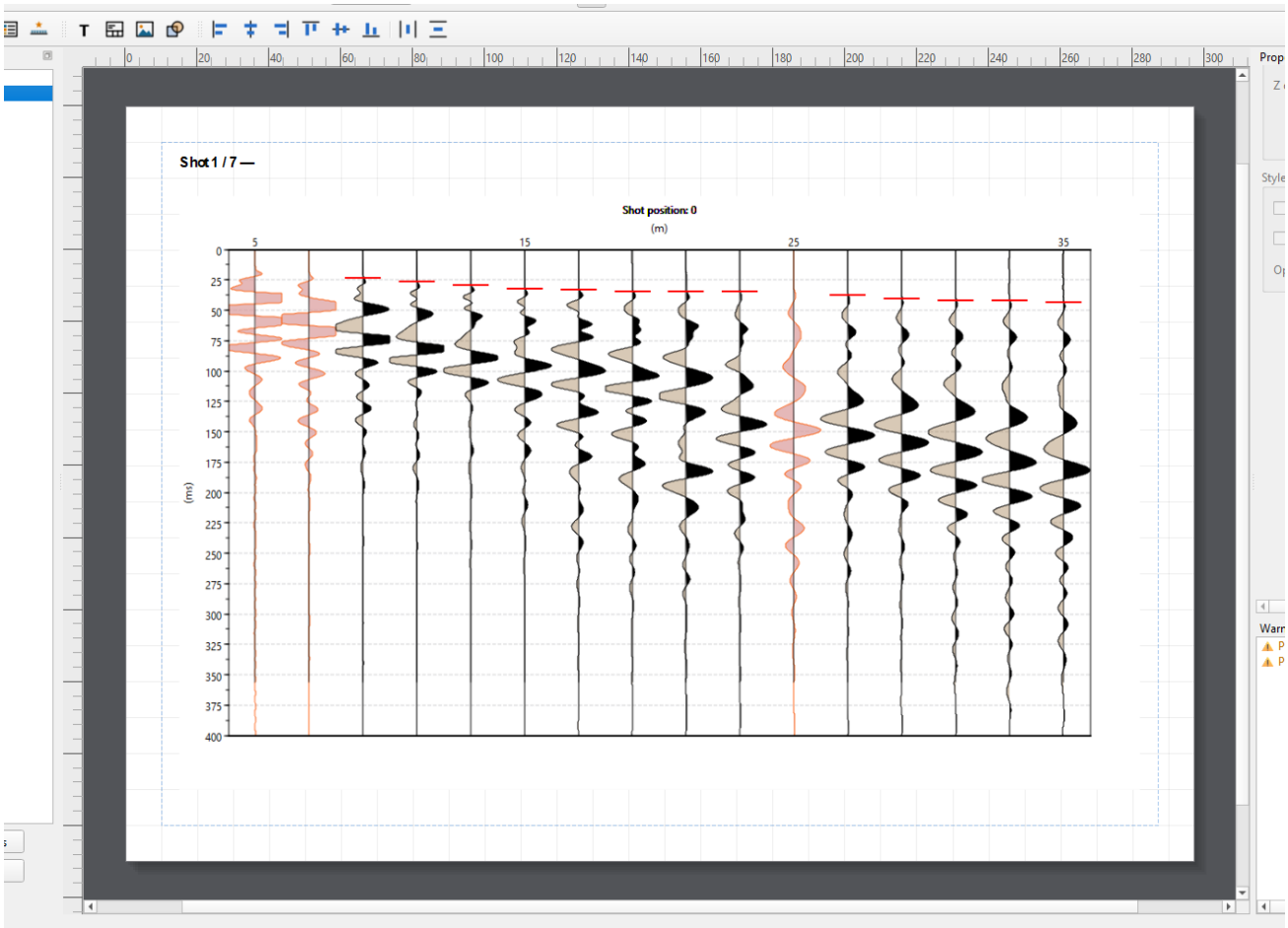


Figure 42 print layout editor with a multi-page sheet being composed

Units and display options

In the Language and units tab of Settings you can now choose to express distances in meters or feet. The choice applies to axes, annotations and measurements shown in the program. The color bar can be customized in orientation (horizontal or vertical) and in the font size of title and labels. The palette drop-down menu now also shows a graphic preview of each palette, for easier recognition. Finally, you can now show an identification label of the spread directly on the drawings.

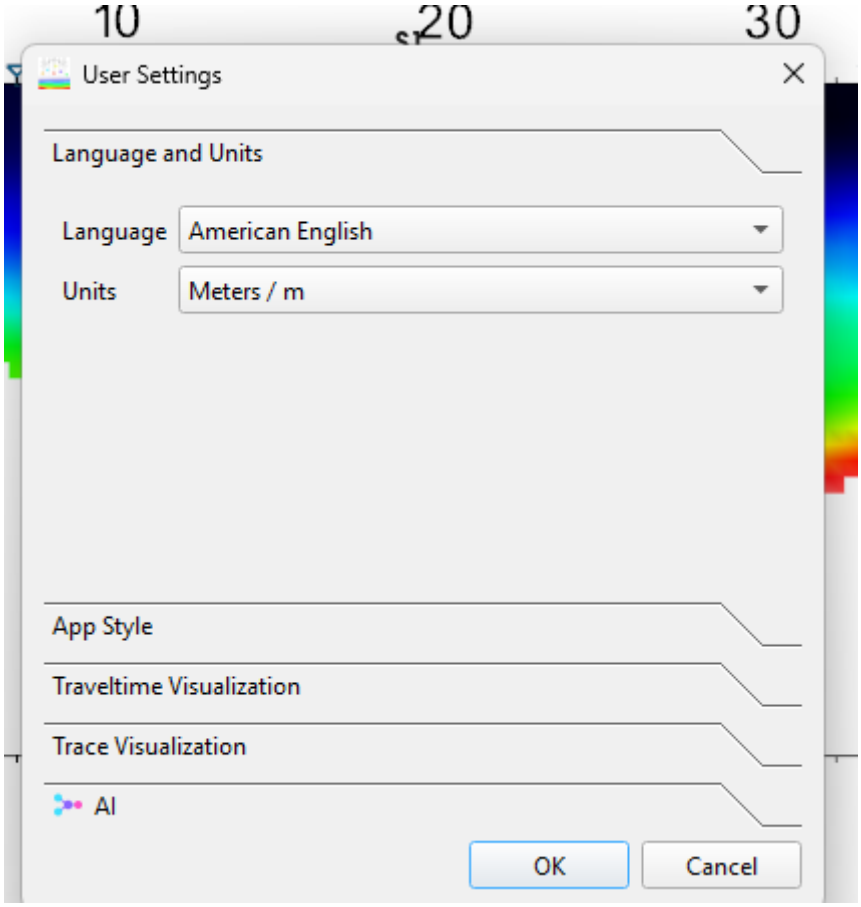


Figure 43 Settings window with the unit choice and palette previews

GRAPHICAL INTERFACE

Menu

File	
New	
Open	

File	
Import traveltimes (OTTE)	
Export traveltimes (OTTE)	
Export:	
Gridded data	
Average velocity profile	
KML: Seismic line Tomographic profile	
- Images	
- PDF	
- ODT	
- SVG	
- DXF	

Project	
Geometry and files	
Grid	
Geography coordinates	
Set title	

Traces	
Next	
Previous	
AutoPick	
Filter…	
Apply NoRe	
AGC	

Processing	
Refraction	
Define velocity model	
Run tomography	

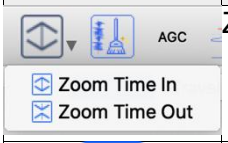
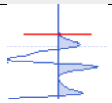
View	
Fill half-wave	
Show rays	
Show contour lines	
Show geophones (small, medium, large)	
Show refraction	
Color scale options	
Show grid lines	
Show title	

Toolbar

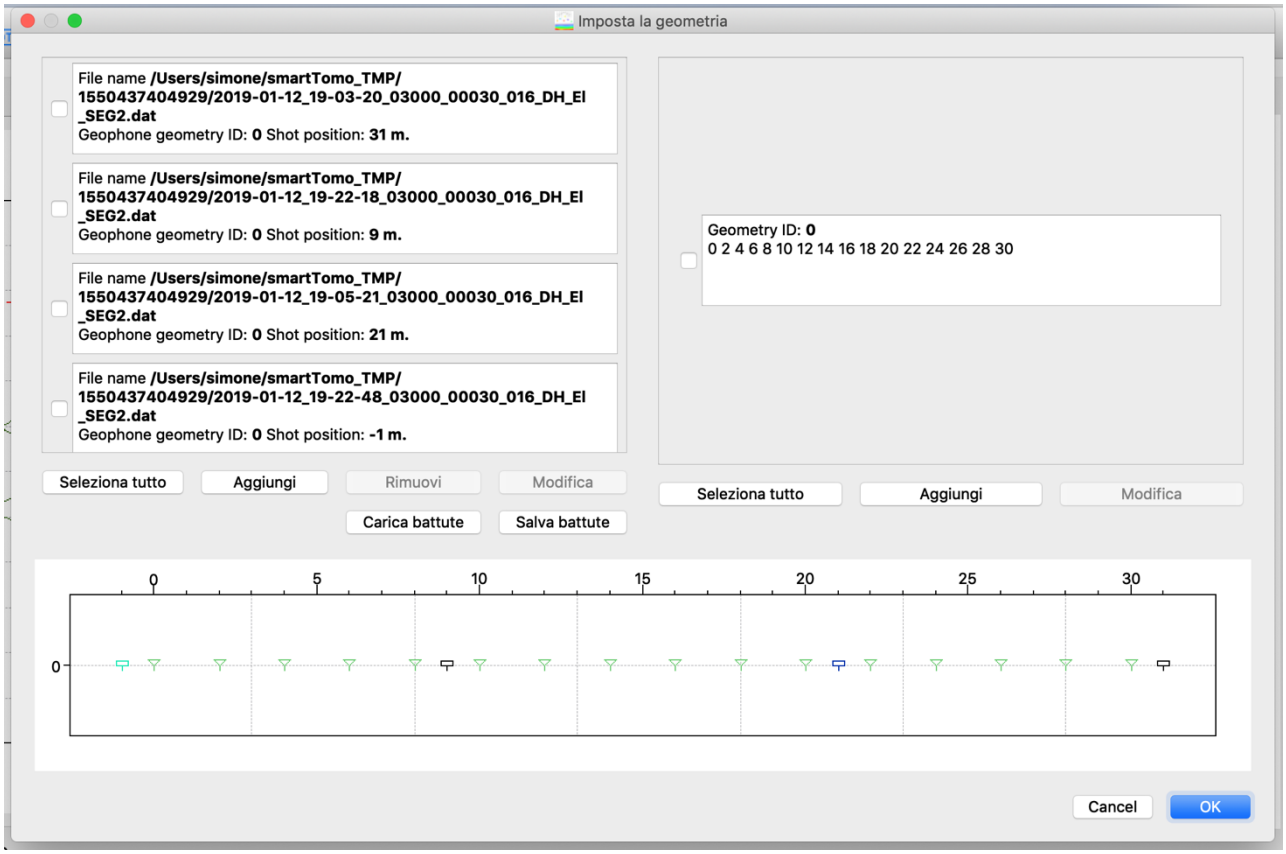
The toolbar groups the main functions of the program. These functions are also available from the menu.



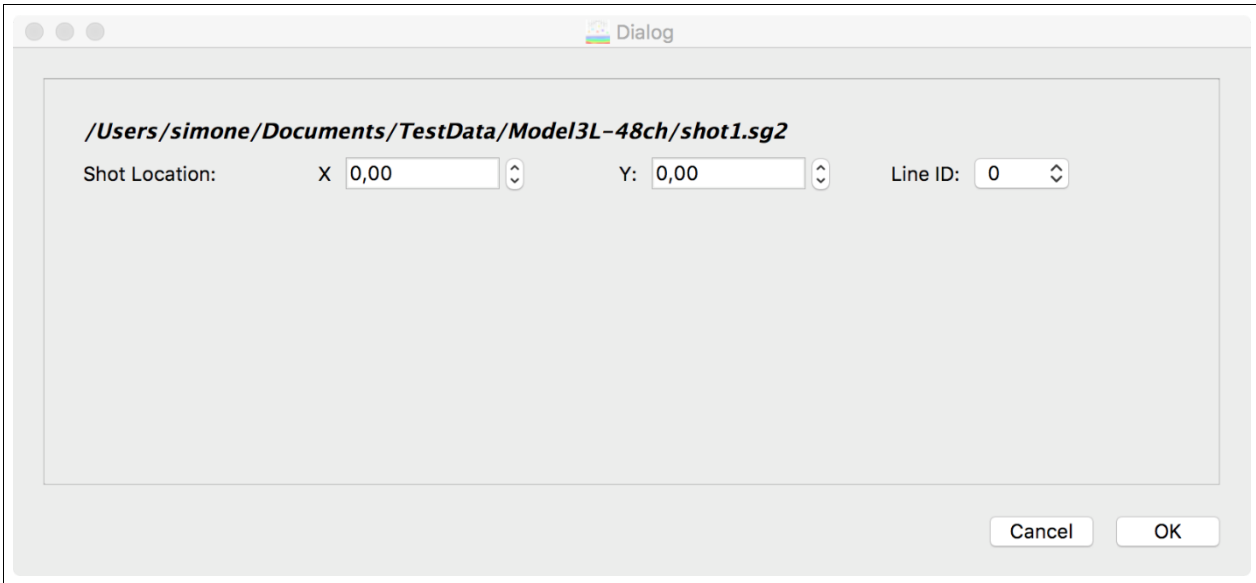
	Creates a new project. If a project is already open, it closes it and asks whether to save the changes.
	Opens a saved project. If a project is already open, it closes it and asks whether to save the changes.
	Saves the current project.

	Exports the current screen as an image (PNG).
	Exports the graphic outputs available in the current project as images (PNG). Opens a dialog where you can choose the items to save.
	Exports the graphic outputs available in the current project as a PDF.
	Exports an ODT containing the graphic outputs and a table with the summary of the traveltime curves.
	Shows the previous trace
	Shows the next trace
	Zoom – dropdown menu
	Enlarges the traces along the time axis
	Reduces the traces along the time axis
	Increases the trace amplitude
	Decreases the trace amplitude
	NoRe – Adaptive noise removal from the traces
	Runs automatic picking of the first arrivals. Existing first-arrival picks will be modified.
	Opens the dialog to start the seismic tomography.
	Opens the dialog to select the color palette used to display the tomographic section.
	Opens the dialog to display the isolines.

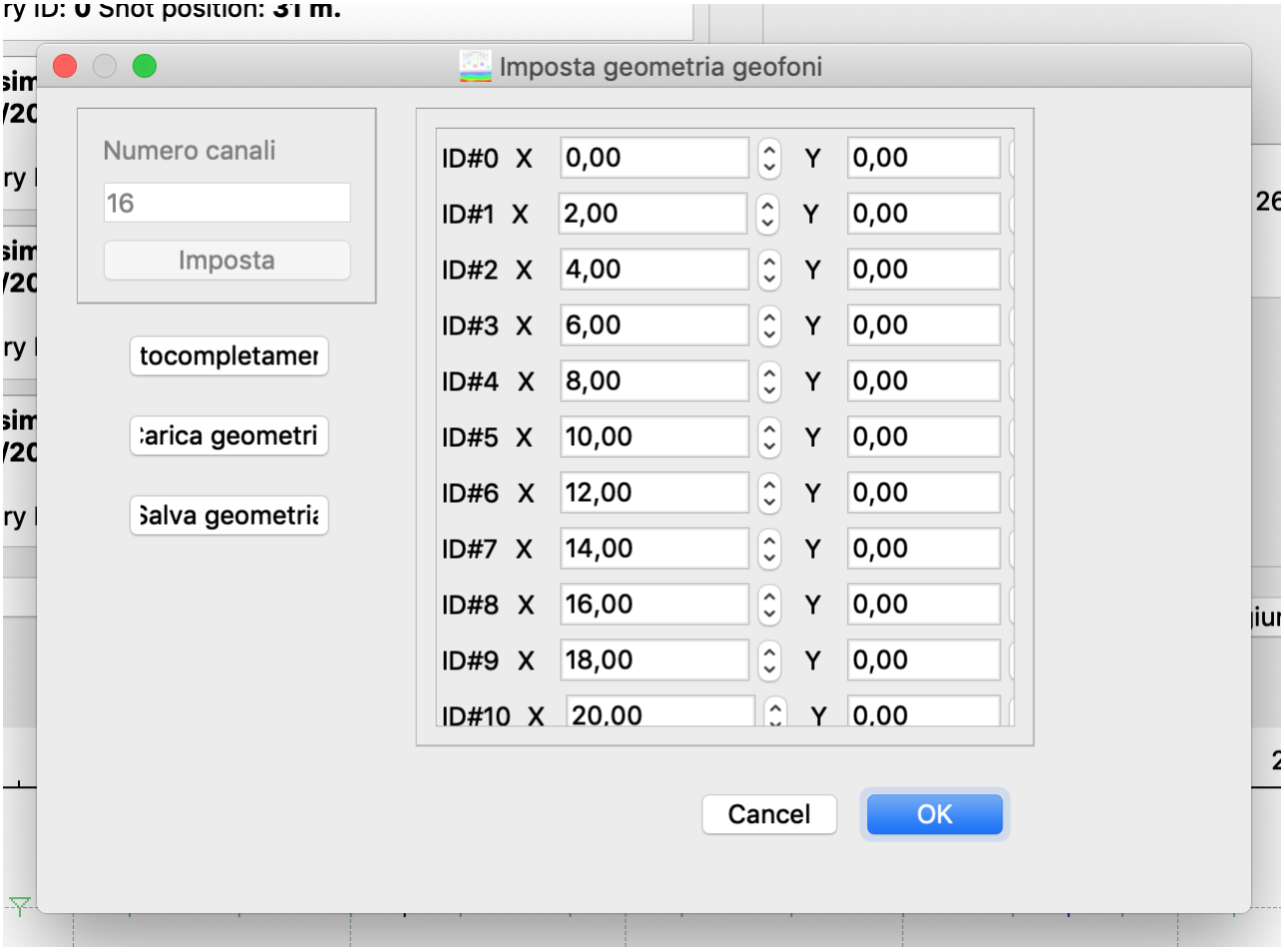
Dialogs



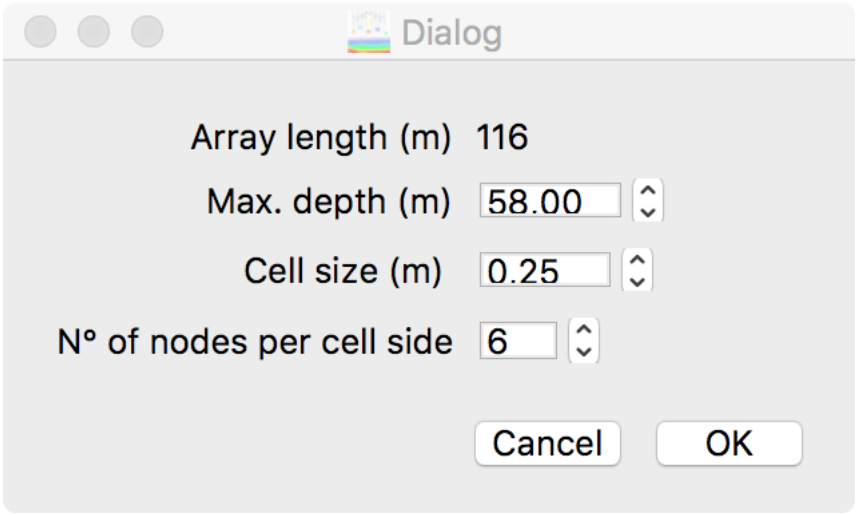
Dialog for editing the geometry of the shots and geophones, and for loading or removing seismic record files from the project. The loaded files are listed on the left. Each box shows the path of the original file, the number of the reference geometry and the position of the reference shot.



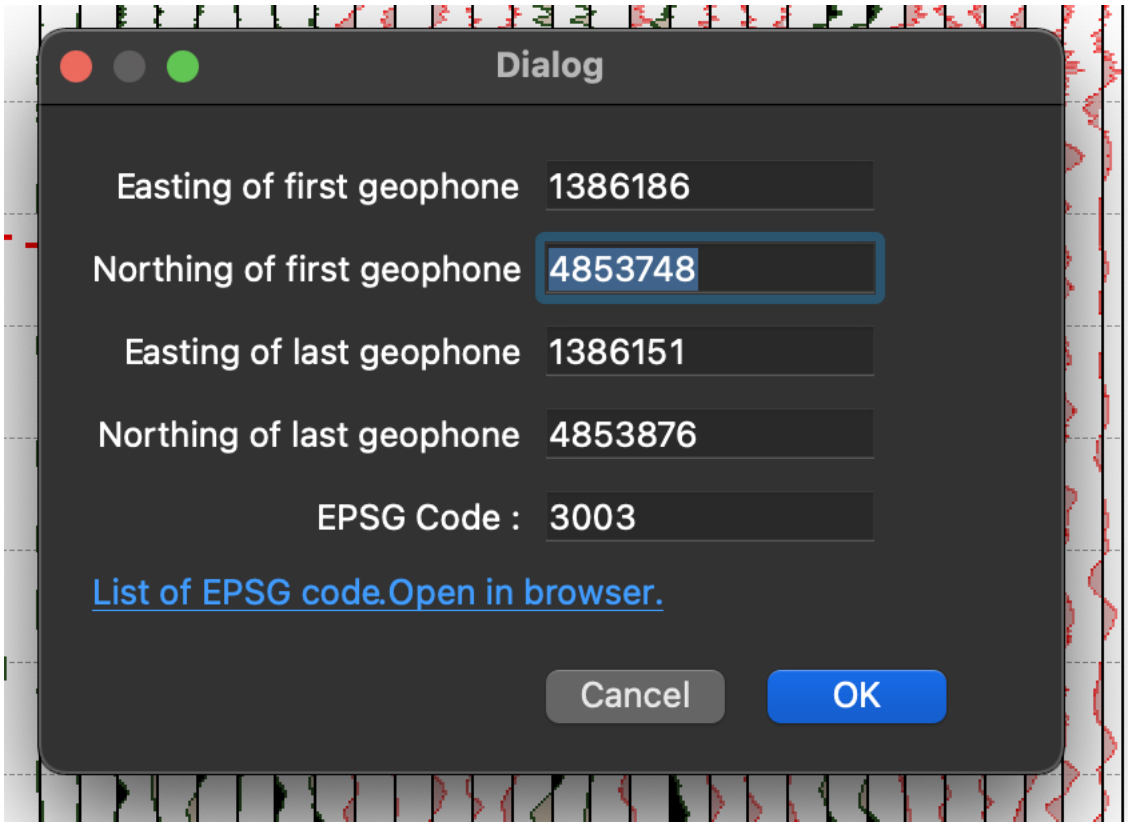
Dialog for editing the information of each seismic trace file. You can change the shot position and the reference to the geophone geometry.



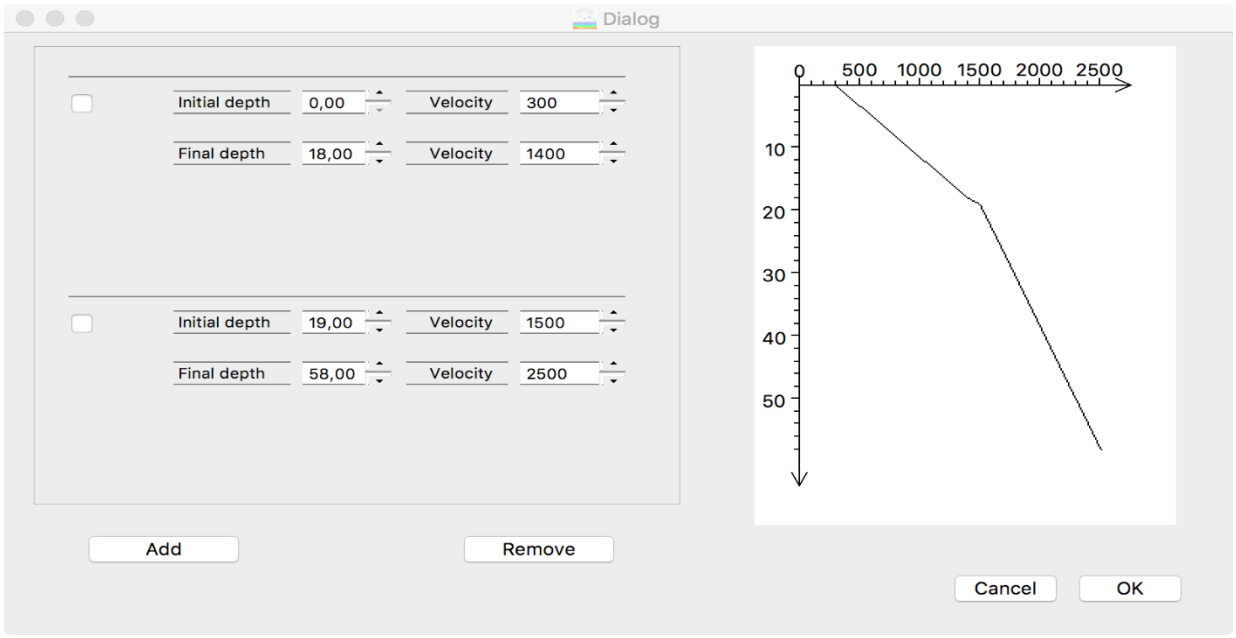
Dialog for editing the geophone positions. You can edit each value manually, or set the first two values and press **Autocomplete** to fill all the remaining fields with the same spacing as between the first two. Load and save geometry respectively read and write the geometry to a CSV file.



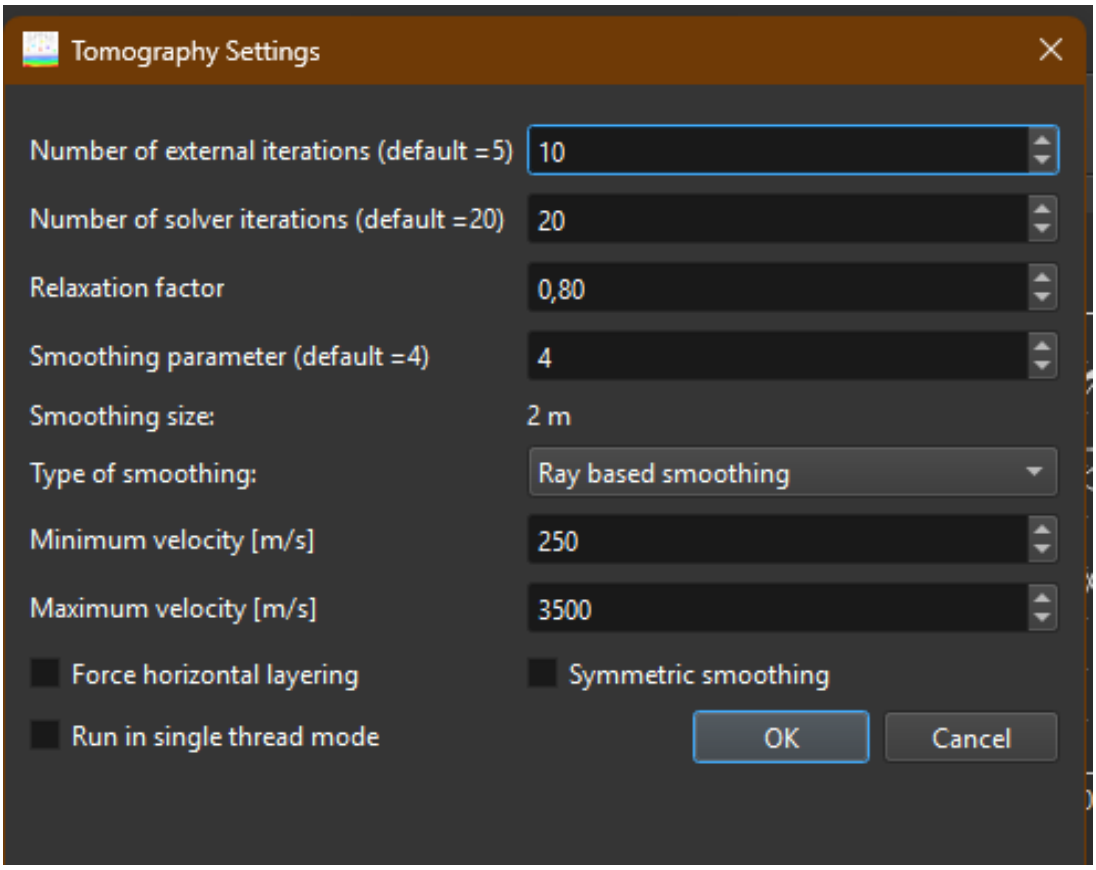
Dialog for setting the parameters of the computation grid. The maximum depth (Max. depth) is set automatically to half the length of the spread. The computation cell size (cell size) is the length of the cell side. The geophone spacing should be at least twice the cell side.



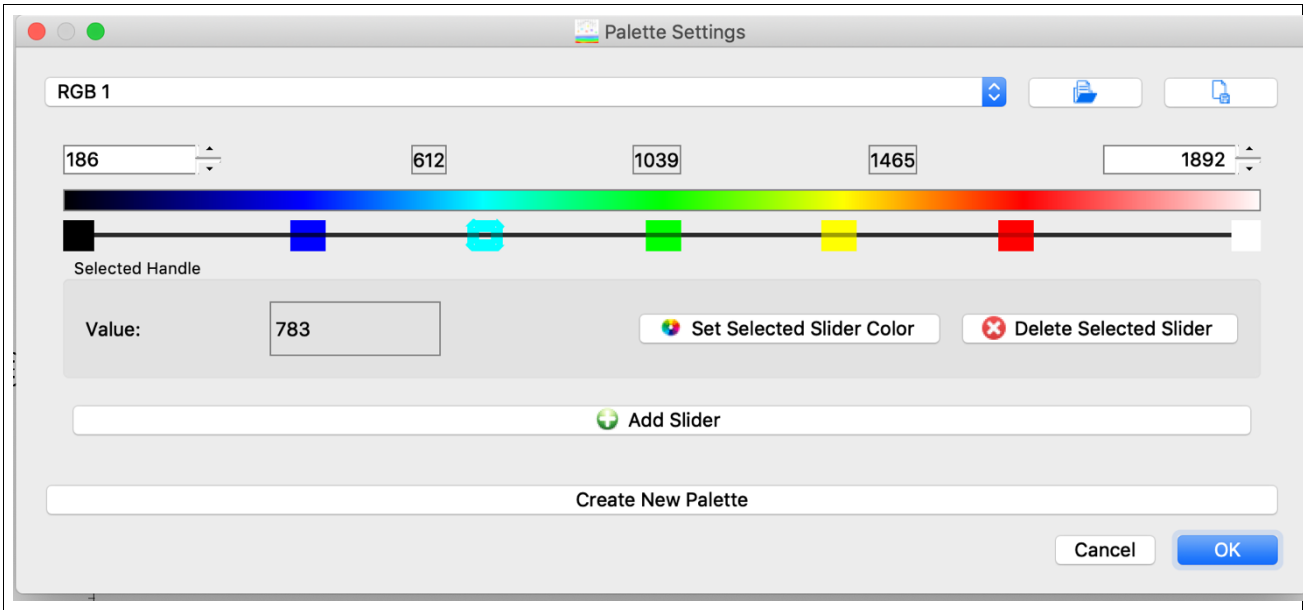
Dialog for setting the geographic coordinates of the first and last geophone. The intermediate geophones are placed along the line joining the first and the last. The EPSG code identifies the coordinate system in use. It is required to export the profile to KML.



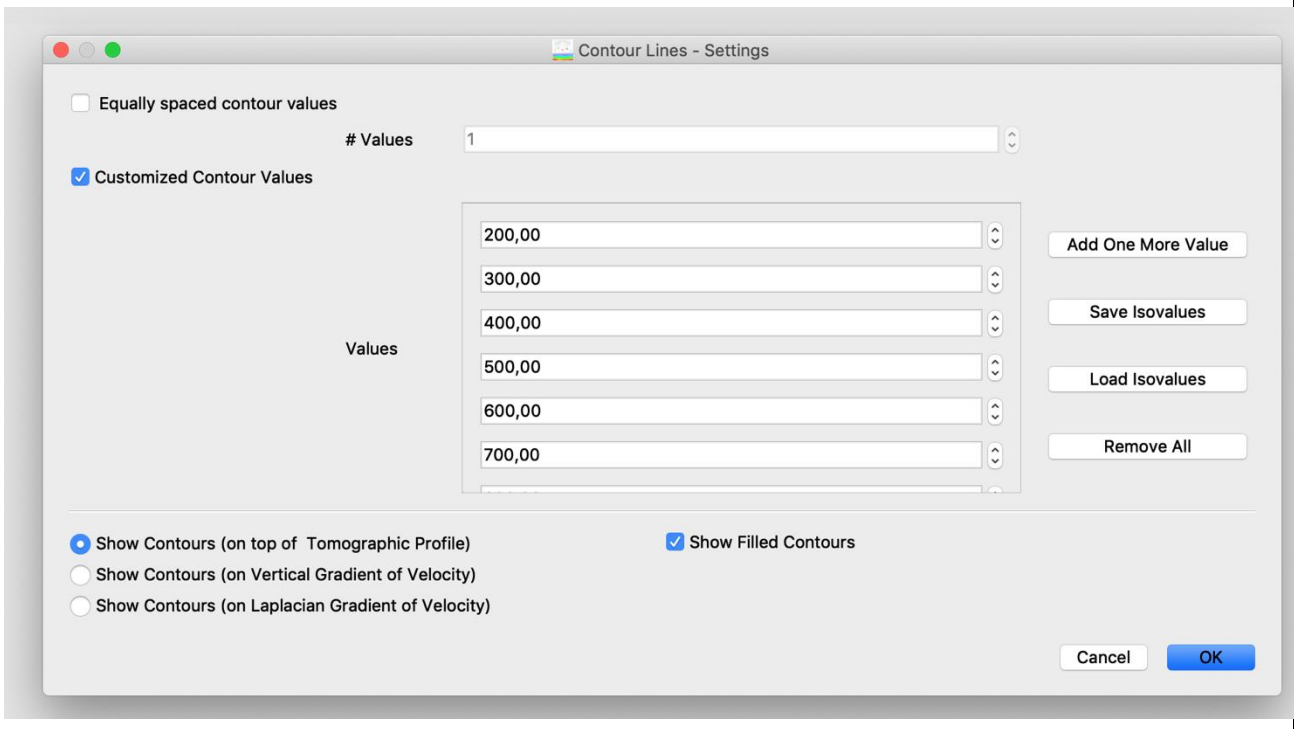
Dialog for setting the initial velocity model. Each layer is defined by a top depth and a bottom depth, each with a velocity. The velocity is interpolated linearly between the top and bottom values and between layers. Layers do not need to be continuous.



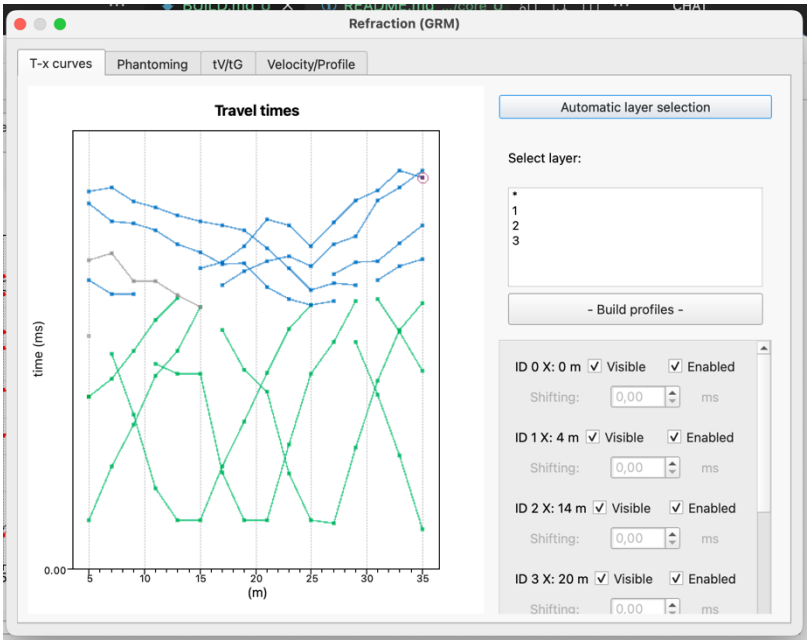
Dialog for starting the tomographic inversion. Five parameters are required. The number of external cycles (External iterations) is the number of times the solver recomputes the ray paths on the updated velocity model. The number of solver cycles (solver iterations) is the number of times the new velocity model is optimized while the ray paths are kept unchanged. The smoothing parameter is the number of cells around the central point that are used to average and distribute the updated velocity model. Since version 2024, the value in meters corresponding to the smoothing parameter is also shown. The default smoothing is asymmetric. Its purpose is to give more continuity to sub-horizontal structures. The maximum and minimum velocity (maximum and minimum velocity) are the velocity limits of the tomographic section. Values outside these limits are set to the nearest limit. The tomography normally runs on all available threads, unless the option Run in single thread mode is checked.



Dialog for selecting the color palette of the tomographic section. You can choose among predefined palettes or edit an existing one. When editing a palette, you can move the points to which a value is assigned, and add or remove them. The same editing tool is available in the main window below the tomographic section. It shows the changes to the palette in real time.

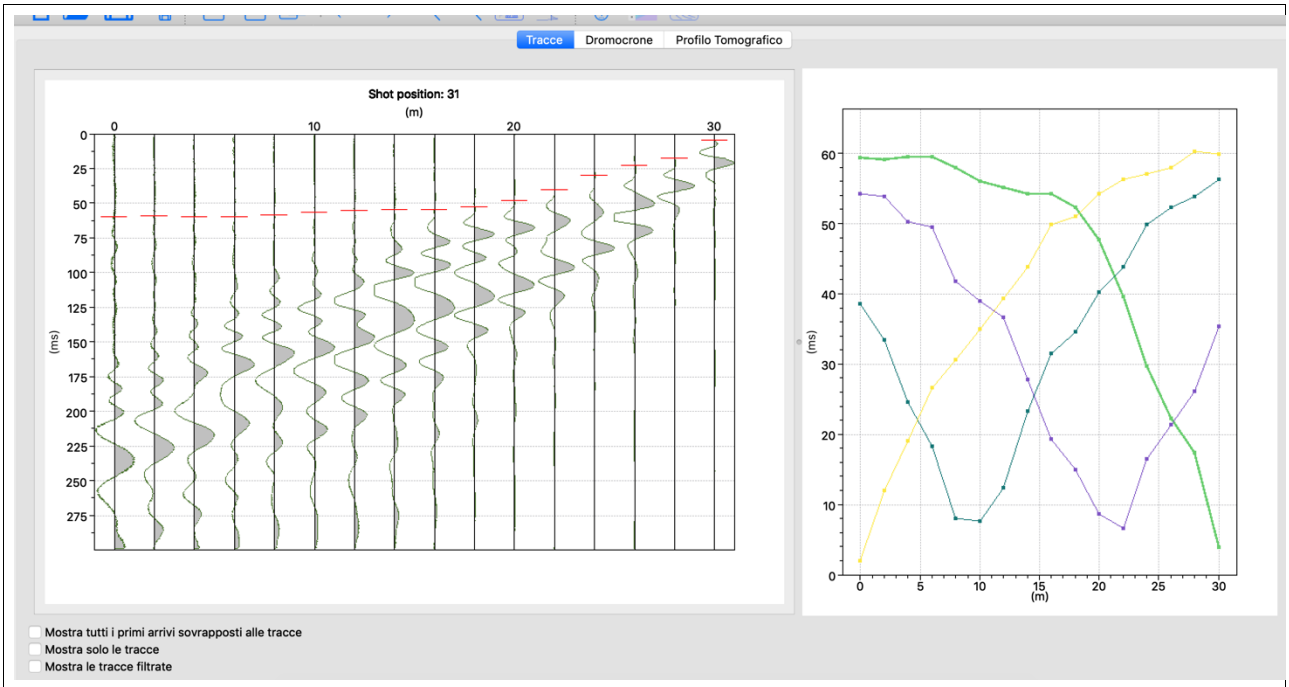


Dialog for customizing the section by drawing isovelocity lines. You can choose to define the number of isolines at equal spacing or at defined values. You can also choose to display the isolines filled with a uniform color or overlaid on the vertical velocity gradient.

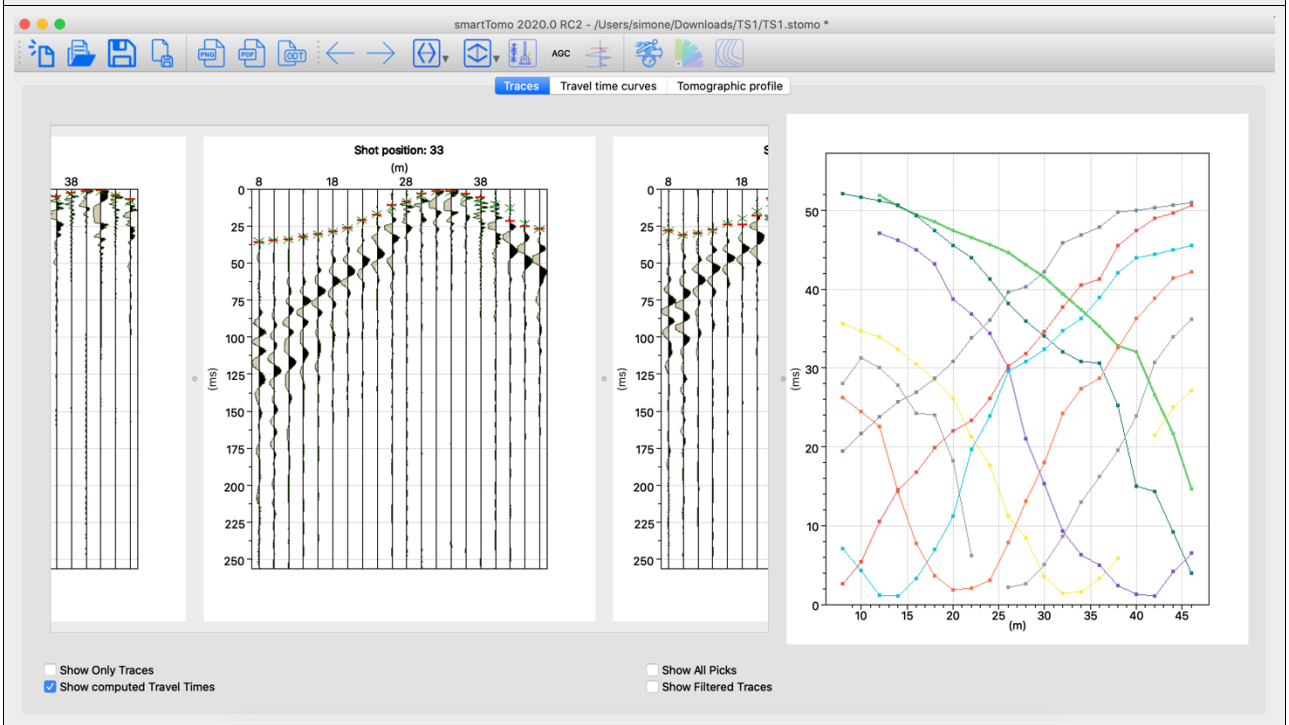


Dialog for refraction processing. The list at the top lets you select the layer assigned to the group of traveltime curves that you select on the graph on the left.
You can assign the traveltime curves to the layers automatically by pressing the button Automatic layer selection

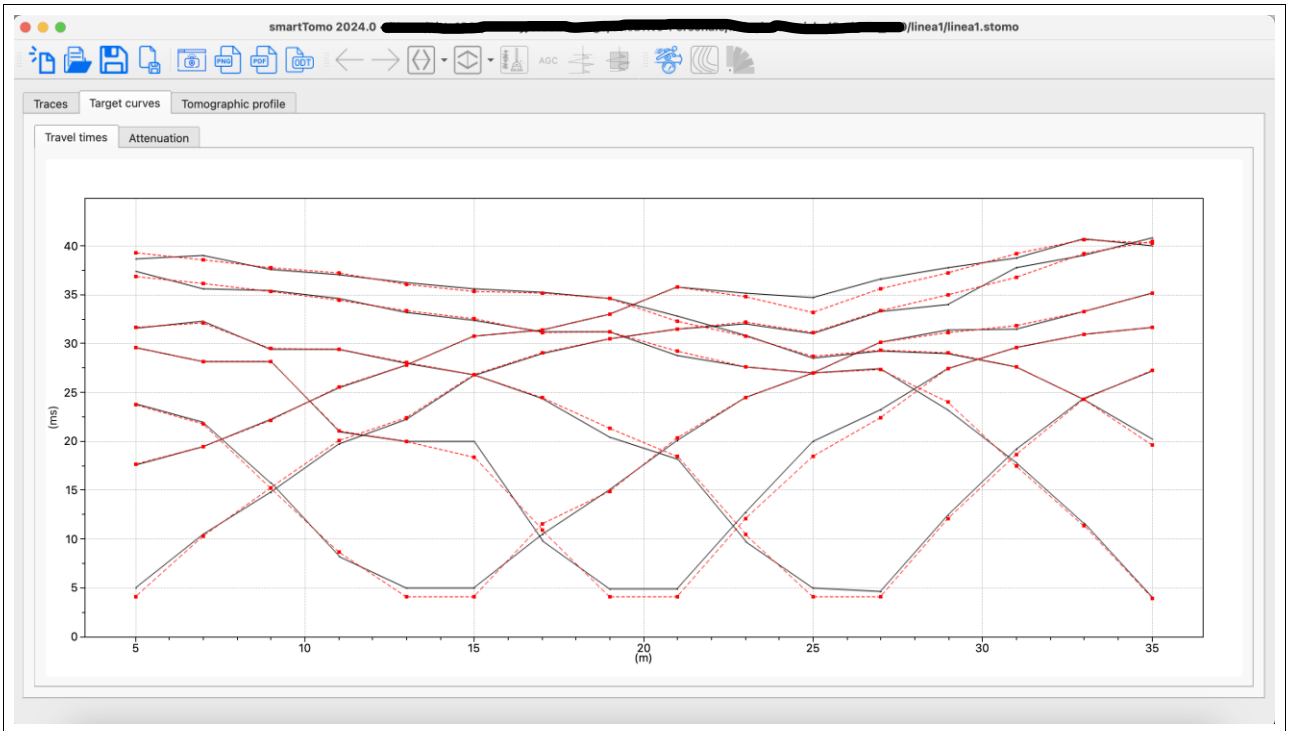
Main window



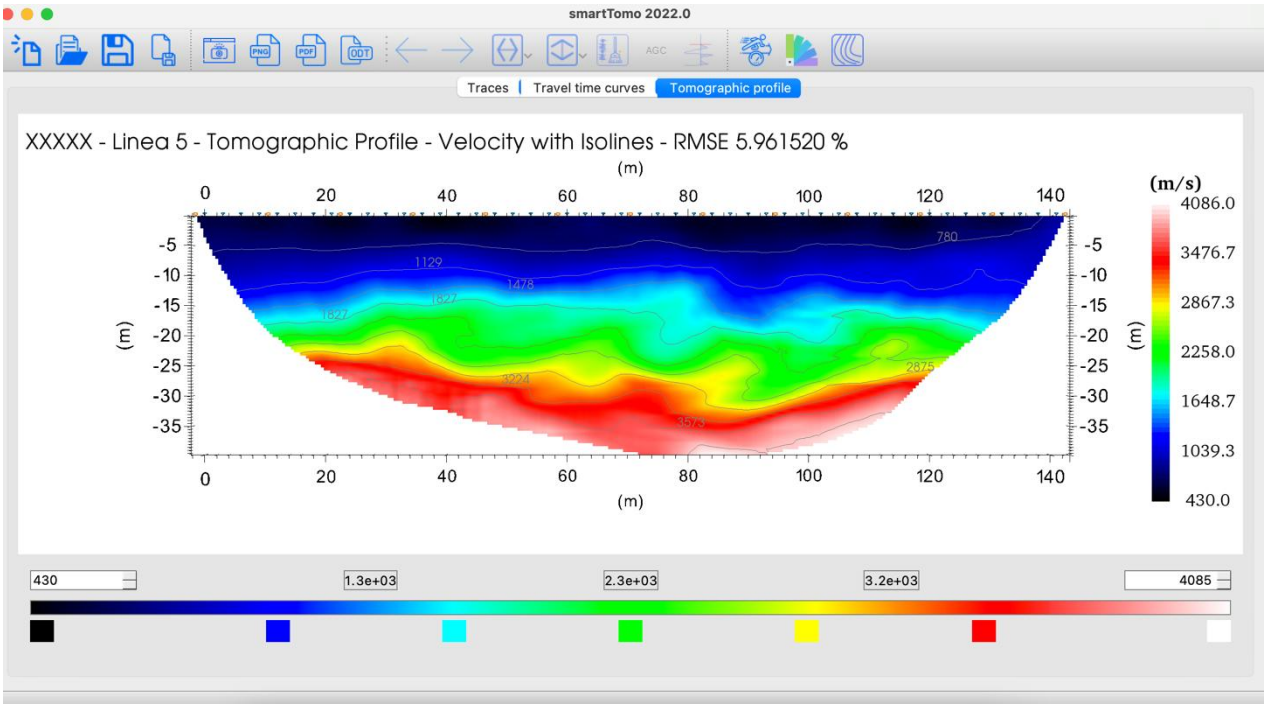
Display of the traces and preview of the traveltime curves.



Display of the traces and preview of the traveltime curves in side-by-side trace display mode.



Display of the objective curves. This window shows the fit between the measured curves (solid line) and the curves computed during processing (dashed line). The more the two lines overlap, the closer the computed model is to the measured one. This view is the best place to check fitting problems caused by wrongly set minimum or maximum velocities.



Display of the tomographic section with the isolines of equal velocity. This view can be customized with different options

List of figures

Figure 1 (a) Example of a cell with 4 nodes; (b) display of the possible seismic rays that join the nodes of the cell. Increasing the number of nodes increases the detail and accuracy of the ray paths. It also increases memory use. 5
Figure 2 Geometric scheme of the Generalized Reciprocal Method (GRM). A and B are shot points, G, X, Y are geophones. D is the projection of geophone G onto the refractor. V1<V2 8
Figure 3 Data transformation along the network, for MjolNET M1 (top) and MjolNET M3 (bottom): from the raw input data to the internal features extracted by the network, up to the final result. 9
Figure 4 Splash screen with the language selection dialog 13
Figure 5 Dialog for setting the preferences; 14
Figure 6 Seismic file selection window 16
Figure 7 Editing window for the seismic line geometry 16
Figure 8 Geometry setting window with the options for loading from file 17
Figure 9 Geometry setting. A single line of geophones is listed on the right 21
Figure 10 The geophone box contains 2 groups of geophones. The first (ID 0) has coordinates from 30 to 60 and the second (ID 1) from 0 to 30. 21
Figure 11 Dialog in which you can set the shot geometry and the geophone line to which the acquisition refers. 22
Figure 12 Grid parameters 22
Figure 13 borehole import window with column mapping and data preview 25
Figure 14 borehole management window with the stratigraphy and logs of the borehole . 26
Figure 16 tomographic section with overlaid borehole and stratigraphic legend 27
Figure 17 Dialog to set the coordinates of the ends of the spread 27
Figure 18 Filter window. If both the high-pass and the low-pass filter are selected, a band-pass filter is applied. 28
Figure 19 Picking tab of the Settings with the AI-assisted autopicking options (MjolNET M1) 29
Figure 20 Magnifier active during manual picking of a trace 30
Figure 21 Dialog window to view and edit arrival times 31
Figure 22 Dialog window to set the size of the sampling window for the signal intensity .. 32
Figure 23 On the left: sampling windows (highlighted in green) of the signal used to calculate the intensity. On the right: intensity plot against geophone position. 33
Figure 24 Settings of the tomography run parameters 34
Figure 25 Example of manual assignment of the seismic layers to the first arrivals in a refraction processing 38
Figure 26 *The yellow spot highlights where wrong shot position is; the computed travel times (red dotted line) has a flat low value zone that does not match measured one.* 41
Figure 27 Tomographic profile calculated with a minimum velocity that is too high: a large part of the section is flattened at the minimum value set in the parameters. 42
Figure 28 Traveltime curves for the profile in Figure 20. A minimum velocity that is too high produces wrongly calculated traveltime curves, especially near the shot points, with times that arrive too early. 43

Figure 29 Seismic profile calculated with a maximum velocity that is too low. 44
Figure 30 Traveltime curves for Figure 22 calculated with a maximum velocity that is too low. The yellow areas highlight the strong delay of the calculated curves (red) with respect to the measured ones (black)..... 44
Figure 31 Setting the geophone geometry 46
Figure 32 Editing the shot geometry settings.....47
Figure 33 AI Filter Comparison window with AI filtered model and AI difference map 52
Figure 34 Normalized vertical velocity gradient profile. Higher gradient values identify the zones with a larger velocity increase.....54
Figure 35 Example of a profile showing the information density 55
Figure 36 Dialog to choose the palette 56
Figure 37 Palette customization. Note the two buttons to load and save a custom palette..57
Figure 38 Dialog for contour line display. It highlights the option to choose how many contour lines have a printed value, and the font size of the label applied to the lines.....59
Figure 39 Dialog to set the refractor display style 60
Figure 40 Image export dialog. You can choose what to export. You can also choose whether to place the color palette labels at regular intervals or at the positions of the palette handles. The font scale parameter scales the font size in the saved images..... 62
Figure 41 Properties panel with a tomographic profile selected and its parameters.....67
Figure 42 sheet export window with the format and resolution options..... 68
Figure 43 print layout editor with a multi-page sheet being composed..... 68
Figure 45 Settings window with the unit choice and palette previews..... 69