Seismic Tomography

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- Minimum 1D model
Minimum 1D model

We solve the non-linear coupled hypocenter velocity problem by linearization of $T_i$ with first order Taylor Series:

$$T_i = f(h^{est}_n, m^{est}_k) + \frac{\partial f(h,m)}{\partial h_1} \Delta h_1 + \ldots$$

$$+ \frac{\partial f(h,m)}{\partial m_1} \Delta m_1 + \ldots$$

How to find $h^{est}_n$ and $m^{est}_k$?

Minimum 1D model
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The best initial reference model and hypocenter locations are those that represent a 1D least square solution to the coupled velocity-hypocenter problem (Kissling et al., 1994).

Advantages:

- Non-linearity is less severe in 1D.
- Solution to the 1D problem is computationally less intensive, thus the full set of linear diagnostics can be computed.

Shareware VELEST
Minimum 1D model

Shareware VELEST:

Solving the coupled hypocenter velocity problem by simultaneous inversion of hypocenter locations, 1D velocities, and station corrections.

Probing the solution space:

Trail and error process with varying 1D velocity models. Each inversion consists of several iterations to solve the coupled hypocenter velocity problem.

We should start our 3D inversion in the vicinity of the global minimum!
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Characteristics of a good minimum 1D model:

- Hypocentral parameters are estimated with equal precision for all earthquakes.

- Velocity within each layer reflects average velocity at this depth range (weighted by the ray distribution).

- Station delays reflect near-surface geology and large-scale deviations from 1D structure (f.e. subducting slabs).

Very suitable model for earthquake location!

Velocities may not be geologically meaningful!

How to compute minimum 1D model?
Minimum 1D model

Recipe to calculate minimum 1D model:

1. Select ~500 of the best events (i.e. small GAP, high number of observations).

2. Establish geometry and intervals of potential 1D models using all available a priori data (i.e. refraction, reflection data).

3. Invert a series of varying initial velocity models using the same earthquake data and inversion parameters.

4. Select the most appropriate (data misfit, geological meaningful) 1D model and test stability of the minimum.
Minimum 1D model

1. Data selection

Resolution matrix for well constrained event (GAP<180°):

<table>
<thead>
<tr>
<th></th>
<th>ot</th>
<th>x</th>
<th>y</th>
<th>z</th>
</tr>
</thead>
<tbody>
<tr>
<td>o</td>
<td>0.9994</td>
<td>-0.0025</td>
<td>0.0022</td>
<td>0.0040</td>
</tr>
<tr>
<td>x</td>
<td>-0.0025</td>
<td>0.9595</td>
<td>0.0192</td>
<td>0.0165</td>
</tr>
<tr>
<td>y</td>
<td>0.0022</td>
<td>0.0192</td>
<td>0.9536</td>
<td>-0.0437</td>
</tr>
<tr>
<td>z</td>
<td>0.0040</td>
<td>0.0165</td>
<td>-0.0437</td>
<td>0.8670</td>
</tr>
</tbody>
</table>

All diagonal elements are close to 1.0, except for focal depth -> focal depth less well constrained!
Minimum 1D model

1. Data selection

Resolution matrix for poorly constrained event (GAP $>180^0$):

\[
\begin{pmatrix}
0.9975 & -0.0184 & -0.0013 & 0.0027 \\
-0.0184 & 0.8247 & -0.0087 & 0.0020 \\
-0.0013 & -0.0087 & 0.9093 & -0.0981 \\
0.0027 & 0.0020 & -0.0981 & 0.7879 \\
\end{pmatrix}
\]

Strong decrease in diagonal element for x and z -> coupling between x and z coordinate!

Only earthquakes with GAP $< 180^0$ should be selected!
Minimum 1D model

1. Data selection (example from Switzerland)

544 events
GAP < 180°
nobs > 8

Selected events need to be representative for data used in tomographic study!
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2. Establishing geometry

There is a trade-off between number of earthquakes and number of velocity layers!

more phases; better approximation of velocity gradients
-> more realistic

V<sub>K</sub> VELOCITY OF LAYER (K)
Δz CHANGE IN DEPTH OF HYPOCENTER

Fig. 12. One-dimensional model and hypocenter location. A change in the calculated depth of a hypocenter will cause a larger change in the calculated travel time for a 1D model with fewer layers (model B). Considering the likelihood of velocity gradients, a 1D model with several layers (model A) allows the tracing of a more realistic ray path. Using model B for hypocenter location calculations, the observed arrivals at the stations may be interpreted as belonging to many fewer phases as compared to the use of model A, which accounts better for lateral variations of the apparent velocity by introducing more phases. The dependence of the hypocenter depth on the velocity model is smaller for model A. Thus for routine earthquake location in an area of known lateral velocity variations, model A (assuming the same average velocity over the full depth range and assuming enough a priori information to establish such a multilayered model) is preferable.

(Kissling, 1988)
Minimum 1D model

3. Inversion with varying initial models

All models converge to more or less the same velocity model with similar data fit, except for shallow layers (< 10 km) which contain no earthquakes.
Minimum 1D model

3. Inversion with high/low initial models

High and low input models converge to the preliminary minimum 1D model for depths < 50 km.
Minimum 1D model

4. Stability tests

- Randomly shifted hypocenter locations
- Systematically shifted hypocenter locations

- Accuracy of Hypocentre Locations

Table 1:

<table>
<thead>
<tr>
<th>Event</th>
<th>Depth shift [m]</th>
<th>Sigma [m]</th>
<th>Mean [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-1200</td>
<td>1450</td>
<td>794</td>
</tr>
<tr>
<td>2</td>
<td>4000</td>
<td>483</td>
<td>-390</td>
</tr>
<tr>
<td>3</td>
<td>8000</td>
<td>714</td>
<td>-1035</td>
</tr>
</tbody>
</table>

- Improvement on hypocentre locations using OBH data

Figure 7: Hypocentre determination in the seismogenic zone of the Nazca Plate

Figure 8: a) Apart from the applied velocity model, hypocentre(locations systematically shifted hypocenter locations

Figure 9: The diameter of the circle represents the uncertainty of the blasts within the mine. The first

Figure 10: shows the azimuthal coverage and Table 2 lists the hypocentre locations obtained with and

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4. Stability tests

Relocating blasts with known location to assess accuracy of minimum 1D model.

![Graph showing mislocation in longitude and focal depth for relocated events with and without adjusted near-surface velocities.](image)
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5. Station corrections in minimum 1D model

- Station corrections are an integral part of a minimum 1D model.

- They compensate near-surface velocity heterogeneity beneath a station and for large-scale velocity deviations (e.g. subducting slab, dipping Moho).

- Station corrections are computed relative to a reference station (set to zero) and to the velocity of the top layer.

- Negative station corrections: true velocities are faster than model
Positive station corrections: true velocities are slower than model.
Minimum 1D model

5. Geological meaningful interpretation of station corrections

negative station corrections: real velocities are faster than model
negative station corrections: real velocities are slower than model

Shallow Moho
Bündner Schiefer
Ivrea body

Station corrections:
- 0.5 s
- 0.5 s
- 0 s

Minimum 1D model

Ivrea body
Minimum 1D model

5. Interpretation of min. 1D model

Different data sets based on Moho topography

- northern Switzerland
- southwest Switzerland
- southeast Switzerland
Minimum 1D model

5. Interpretation of min. 1D model

Seismic velocities in a minimum 1D model are average velocities weighted by the ray distribution!

- Normal upper crust
- Clear Moho
- No clear Moho due to mixing of lower crust and upper mantle velocities
Minimum 1D model

Detecting systematic errors

The computation of a minimum 1D model allows to check each parameter (hypocenter, station delay, velocity) individually since, unlike a 3D model, a 1D model may not absorb most systematic errors with false (3D) structures.

1. Wrong station coordinates

![Polar diagram distance/azimuth showing the travel time residuals in seconds at station PAL: a) using wrong station coordinates, and b) using correct station coordinates.](image)

- **a)** Original coordinates
- **b)** Corrected coordinates

unrealistic residual distribution

original coordinates  corrected coordinates
Minimum 1D model

Detecting systematic errors

2. Timing problems

Station crt06 shows a very large positive station delay (compared to crt05), which can be indicative for a possible clock error.

Stations BUS and CDM show very different stations delays although they are located only 800 m apart.
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Testing performance of min. 1D model as initial reference model.

Synthetic velocity structure

Data set

Figure 2. Seismicity in the Loma Prieta magnitude 7.1 earthquake (October 17, 1989) region. Earthquakes (crosses) that were recorded on the U.S. Geological Survey’s permanent seismic station network (triangles) and that provide the basis for the synthetic data set used in the test (see text) are shown. Nodes of the velocity model grid are marked by dots. SF, San Andreas fault; CF, Calaveras fault; SL, shoreline (stippled); X,Y, Cartesian coordinate system; Y10, location of cross sections (Figure 3).

(Kissling et. al, 1994)
Minimum 1D model

Testing performance of min. 1D model as initial reference model.

Starting models

Schematic representation

Slower velocities at shallower layers for a priori model but faster velocities at greater depth.

(Kissling et. al, 1994)
Minimum 1D model

Testing performance of min. 1D model as initial reference model.

Comparison of tomographic results A and B with synthetic velocity structure allows to assess the performance of each initial reference model.
Minimum 1D model

Testing performance of min. 1D model as initial reference model.

3-D inversion results

Tomographic results depend on the choice of the initial reference model. The use of a minimum 1D model yields results that are closer to the true model!

(Kissling et. al, 1994)
Minimum 1D model

Homework assignment

- Test stability of preliminary min. 1D model for southwest Switzerland.

- Run Velest on three different models.

- Compare final models and discuss station corrections.

- Files and instructions can be found on datconv.ethz.ch. Each group will have its own subdirectory, named group1, 2, 3.