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PestoSeis: A Python package for educational seismology

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Summary

PestoSeis is a Python package aimed at educational seismology. It contains tools to solve two-dimensional seismic problems in terms of traveltimes, rays, acoustic and elastic wave propagation, and related plotting functions. Moreover, a set of functions performing basic seismic processing for exploration geophysics is provided. The entire package is written in the Python language to allow users to explore the code to gain a better understand of the numerical algorithms used while simultaneously minimizing third-party dependencies and, thus, simplifying the installation process. A set of illustrative examples covering all included algorithms are provided.

Statement of Need

PestoSeis is a numerical laboratory written in the Python language and contains a suite of functionalities which can be used as learning tools for concepts in seismology. One of the primary design goals of PestoSeis is simplicity and ease of use. It contains a set of functions related to different aspects of seismology, ranging from simple straight ray computations to a full-waveform elastic solver for two-dimensional (2D) problems. It thus collects several routines within a single package allowing the user to explore different topics in seismology using a hands-on approach. Moreover, a complete set of examples demonstrating the functionalities of the code are provided, with the combined aim of illustrating some common seismological applications in addition to demonstrating how to utilize the software.

The entire package is written in Python to avoid the need of linking to external libraries written in a compiled language and to allow the user to directly explore the code in order to understand how the algorithms work. Furthermore, dependencies on other third-party packages are kept to a minimum to simplify the installation process while also enhancing the interpretability of the source code for the user. PestoSeis can thus be used, for instance, in a course on seismology where a set of exercises can be designed to help illustrate how certain principles can be applied in practice.

PestoSeis addresses the following set of 2D seismic problems:

- computation of traveltimes for given source and receiver positions provided a layered or grid-based velocity model and assuming straight rays;
- computation of traveltimes for given source and receiver positions provided a grid-based velocity model using a finite-difference method (fast marching);
- backtracing rays from the result of traveltime calculations in heterogeneous models;
- performing simple linearized ray tomography using a least squares approach;
- computing acoustic or elastic seismic wave propagation using a finite-difference method;
- performing some basic seismic processing for exploration seismology;

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- plotting various input and output data related to the aforementioned applications.

Package Content

`PestoSeis` contains three main submodules:

1. traveltimes and rays (`ttimerays`);
2. seismic wave propagation (`seismicwaves2D`);
3. seismic processing (`reflectionseismo`).

Each one of these categories considers a specific use case and provides a variety of functions tailored at solving problems within the considered application. In the following, an overview of the core functionalities of the submodules are provided.

Traveltimes and rays

`PestoSeis` provides functions to perform the following computations in heterogeneous media:

1. traveltimes given a velocity model by solving the eikonal equation (Rawlinson & Sambridge, 2004; Sethian, 1996);
2. trace "bent" rays;
3. straight rays;
4. in special case of a horizontally layered medium, use Snell's law to compute ray paths, traveltimes, and the distance covered by the ray.

The functions provided in `pestoseis.ttimerays` allow the user to compute rays and traveltimes for a 2D velocity model which is discretized on a rectilinear grid constructed from inputs provided by the user. The available functions allow the user to set up and solve simple 2D tomographic inverse problems and thus aims to serve as a guide for how travel time tomography can be performed in practice. These kind of calculations are useful not only in the field of Earth sciences but also, for instance, in medical imaging, where traveltimes (time-of-flight in the medical literature) are used to infer the internal structure of parts of the human body (Ulrich et al., 2022).

Figure 1 shows an example from the field of medical imaging with computed traveltimes, bent ray paths, and straight ray paths through a speed-of-sound model mimicking human breast tissue (e.g. Ulrich et al. (2022)). The computed traveltimes can then be used to set up a tomographic inverse problem which may, for instance, be solved with a simple linear inversion under Gaussian assumptions (least squares approach) (Tarantola, 2005).

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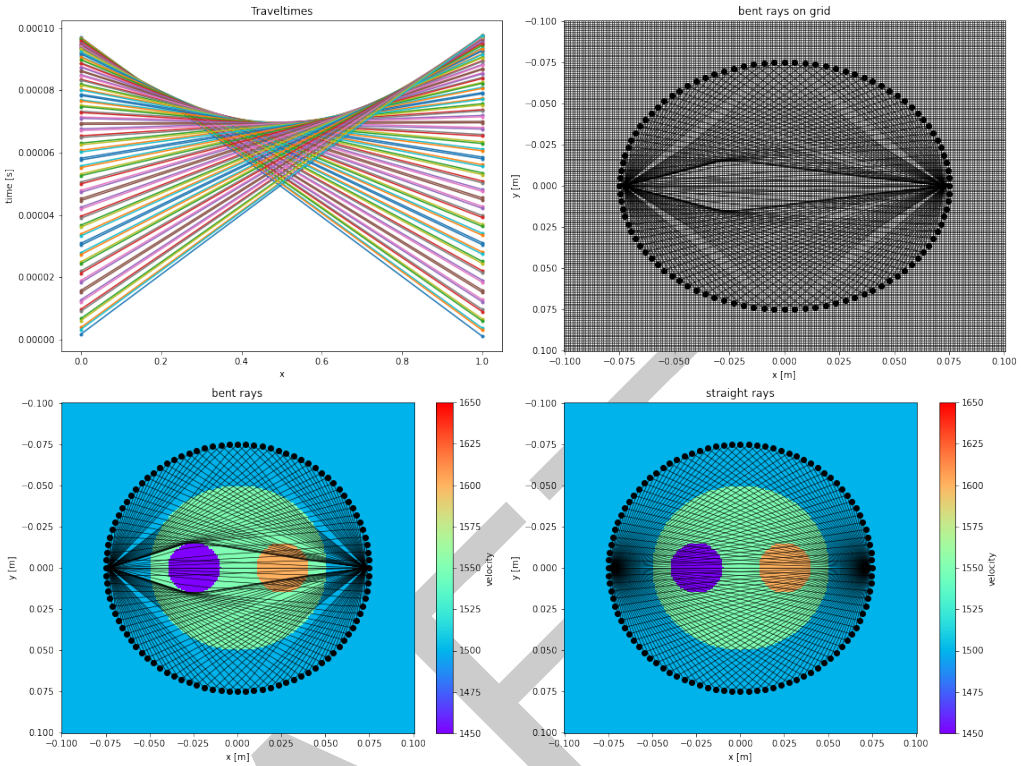

Figure 1: Visualization of computed travel times and rays (bent rays and straight rays) using the functions in `pestoseis.ttimerays`. In this example, a numerical breast phantom is considered as used in medical ultrasound to study the ray paths through the medium and subsequently compute the according travel times from an array of sources and receivers surrounding the breast phantom.

Seismic wave propagation

`PestoSeis` provides means to compute wave propagation in 2D for:

1. acoustic media solving the acoustic wave equation;
2. elastic media solving the elastic wave equation.

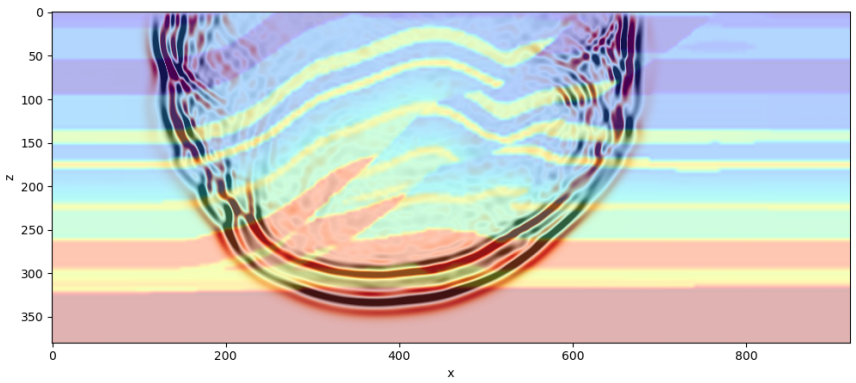

Figure 2: A snapshot of an acoustic seismic wavefield where the wavefield is overlayed on the velocity model. The depicted overthrust model is adapted from Aminzadeh & Brac (1997).

The acoustic and elastic wave equations in 2D are solved using finite differences on a staggered

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grid in both space and time in the `pestoseis.seismicwaves2D` submodule (Bunks et al., 1995; Komatitsch & Martin, 2007; Pasalic & McGarry, 2010; Virieux, 1986). Staggered grids generally allow for better accuracy with a minimal increase in computational overhead.

In order to compute wave propagation in either an acoustic or an elastic medium, the user needs to specify the parameters of the grid used to construct the velocity models, the source-receiver geometry, and a source time function with a given dominant frequency. Furthermore, the user must select the desired boundary conditions as either reflecting, a Gauss taper (acoustic formulation only), or convolutionary perfectly matched layers (Komatitsch & Martin, 2007); free surface boundary conditions may also be optionally set at the top of the model.

The function returns a seismogram recorded at the specified receiver locations as well as a set of snapshots of the wavefield (see figure 2). Additionally, it is possible to save a collection of wavefield snapshots as a `.mp4` movie file that illustrates the propagation of the seismic waves through the medium. These functions aim to equip the user with the ability to quickly set up and visualize small scale 2D simulations.

Seismic processing

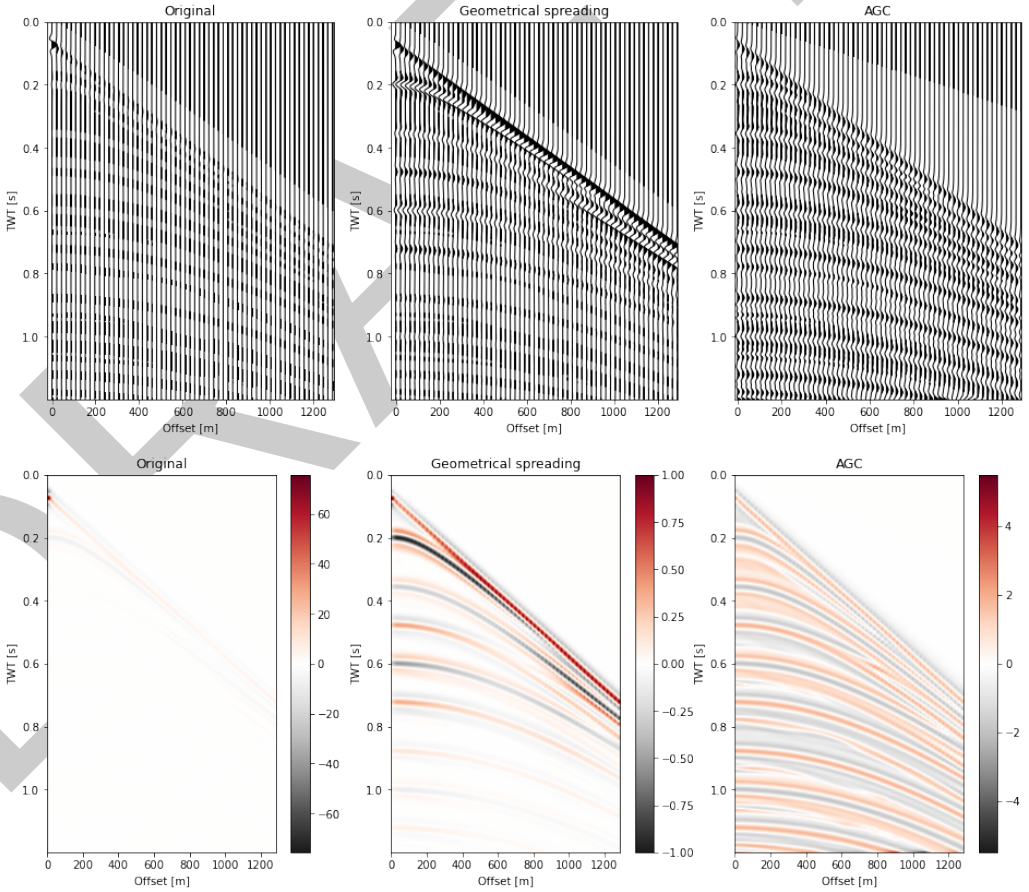

Figure 3: An example of seismic processing where the original data are corrected for geometrical spreading and amplitude gain.

The submodule `pestoseis.reflectionseismo` provides a series of routines for processing the resulting data using a number of methods which are commonly used in practice within seismology (Öz, 2001). Examples of processing routines implemented within `PestoSeis` include arranging the data in shot gathers, generating a wiggle plot of the shot gathers, normal

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moveout (NMO) correction, correcting for geometrical spreading, and applying automatic gain control (AGC) to a shot gather (see figure 3). Furthermore, some functionalities which can be used for filtering the data in the frequency-wavenumber domain are also provided. Similar to the forward modeling tools outlined previously, the main focus of these processing functions is to provide the user with rudimentary tools which are commonly used in seismology so that they can experiment with processing methods which are commonly used in both industry and academia.

Tutorials

Finally, a number of tutorials that provide examples on how to use the functions within `PestoSeis` are provided in the form of Jupyter notebooks. These tutorials showcase different numerical scenarios and can be used to get started with `PestoSeis`.

References

Aminzadeh, F., & Brac, J. (1997). *SEG/EAGE 3-D Overthrust Models*. Zenodo. https://doi.org/10.5281/zenodo.4252588

Bunks, C., Saleck, F. M., Zaleski, S., & Chavent, G. (1995). Multiscale seismic waveform inversion. *Geophysics*, *60*(5), 1457–1473. https://doi.org/10.1190/1.1443880

Komatitsch, D., & Martin, R. (2007). An unsplit convolutional perfectly matched layer improved at grazing incidence for the seismic wave equation. *GEOPHYSICS*, *72*(5), SM155–SM167. https://doi.org/10.1190/1.2757586

Öz, Y. (2001). Seismic Data Analysis. In *Seismic Data Analysis*. Society of Exploration Geophysicists. https://doi.org/10.1190/1.9781560801580.fm

Pasalic, D., & McGarry, R. (2010). Convolutional perfectly matched layer for isotropic and anisotropic acoustic wave equations. *SEG Technical Program Expanded Abstracts 2010*, 2925–2929. https://doi.org/10.1190/1.3513453

Rawlinson, N., & Sambridge, M. (2004). Wave front evolution in strongly heterogeneous layered media using the fast marching method. *Geophysical Journal International*, *156*(3), 631–647. https://doi.org/10.1111/j.1365-246X.2004.02153.x

Sethian, J. A. (1996). A fast marching level set method for monotonically advancing fronts. *Proceedings of the National Academy of Sciences*, *93*(4), 1591–1595. https://doi.org/10.1073/pnas.93.4.1591

Tarantola, A. (2005). *Inverse problem theory and methods for model parameter estimation*. SIAM.

Ulrich, I. E., Boehm, C., Zunino, A., Bösch, C., & Fichtner, A. (2022). Diffuse ultrasound computed tomography. *The Journal of the Acoustical Society of America*, *151*(6), 3654–3668. https://doi.org/10.1121/10.0011540

Virieux, J. (1986). P-SV wave propagation in heterogeneous media: Velocity-stress finite-difference method. *Geophysics*, *51*(4), 889–901. https://doi.org/10.1190/1.1442147

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