ShaVi-1.0 User Guide: Seismic Data Inversion

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ShaVi-1.0 offers advanced seismic data inversion capabilities, utilizing all information, including reflected, refracted, multiples, and diffracted phases available in the data. With a user-friendly design of the graphical user interface, this package is easily implementable and flexible, allowing users to perform inversions on a variety of machines. Additionally, users have the flexibility to modify the modules according to their specific requirements.

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1 Introduction

Full waveform inversion (FWI) is a technique used in studying underground structures through seismic data. It helps create a detailed image of what's beneath the Earth's surface. However, implementing FWI can be tough due to its complex math and high computational demands. To make it easier, we made ShaVi-1.0, a 2D acoustic FWI tool. It uses OpenMP API to handle computations and has a user-friendly interface for easy use on regular computers.

ShaVi-1.0's core code is in C language, designed so users can adjust parts as needed. The Graphical User Interface (GUI), made in Python, comes with handy features like real-time plotting and updates on the process status. It also has message and warning boxes for a smooth experience. The GUI includes a toolbox for generating acquisition geometry and plotting source-receiver locations. This GUI not only makes using the tool easier but also lets you analyze results in real-time.

1.1 Benefits

Seismic inversion software plays a crucial role in the field of geophysics, offering several benefits for understanding subsurface structures and optimizing exploration and reservoir characterization. Here are some key benefits of seismic inversion software:

- **Subsurface Imaging:** Seismic inversion software provides a detailed image of the subsurface by converting seismic data into meaningful geological information.

- **Reservoir Characterization:** It enables accurate characterization of reservoir properties such as porosity, permeability, and fluid saturation. This information is vital for optimizing oil and gas reservoir management, including well placement and production strategies.

- **Improved Geological Interpretation:** Seismic inversion enhances the interpretation of geological features by providing aids in identifying faults, stratigraphic layers, and other geological formations.

- **Quantitative Analysis:** Seismic inversion allows for quantitative analysis of subsurface properties.

- **Reduced Exploration Risks:** By providing a clearer understanding of subsurface conditions, seismic inversion software helps reduce exploration risks. It enables more informed decision-making in the selection of drilling locations and the assessment of reservoir potential.

- **Cost and Time Efficiency:** Seismic inversion software streamlines the interpretation process, reducing the time and effort required for manual analysis. This leads to increased efficiency in decision-making and a more cost-effective exploration process.

In summary, this is a valuable tool in the oil and gas industry, contributing to more accurate subsurface imaging, improved reservoir characterization, and informed decision-making throughout the exploration and production.

1.2 Key Features

A list of potential key features that associated with ShaVi-1.0

- Full Waveform Inversion (FWI) Capabilities
- Parallelization with OpenMP
- User-Friendly Graphical User Interface (GUI)
- Standalone Workstation Compatibility
- Modular Design in C Language
- Toolbox for Geometry Generation
- Real-Time Analysis and Visualization
- Adaptable Computational Time and Efficiency

2 Prerequisites

To use ShaVi-1.0 effectively, ensure that the system meets the following prerequisites listed below. In case of any challenges during installation or usage, consult the documentation or reach out to our support team for assistance.

- GNU Compiler Collection
- Python 3.0.0
- pip
- tkinter
- matplotlib
- numpy
- sys
- threading
- xlsxwriter
- pandas
- webbrowser
- shutil

3 Installation

1. GNU Compiler Collection is a powerful and widely used compiler that supports several programming languages, including C, C++.
   Installation: GNU Compiler Collection installation
2. Python is a powerful and flexible general-purpose language with many applications.
   Installation: Python installation process for Windows and for Ubntu
3. pip is standard tool for installing Python packages and their dependencies in a secure manner.
   Installation: pip
4. Tkinter stands as a Python library, serving as a tool to craft fundamental graphical user interface (GUI) applications.
   Installation: pip install tk
5. Matplotlib is a robust Python library designed for generating a wide spectrum of visualizations.
   Installation: pip install matplotlib
6. NumPy is a Python library used for working with arrays.
   Installation: pip install numpy
7. This module provides access to some variables used or maintained by the interpreter and to functions that interact strongly with the interpreter.
   Installation: pip install os-sys
8. The threading module allows multiple threads of execution to take place in a Python program.
   Installation: pip install threading
9. XlsxWriter is a Python module for writing files in the Excel 2007+ XLSX file format.
   Installation: pip install XlsxWriter
10. Pandas is a software library written for the Python programming language for data manipulation and analysis.
    Installation: pip install pandas
11. The webbrowser module provides a high-level interface to allow displaying web-based documents to users.
    Installation: pip install pycopy-webbrowser
12. The shutil module offers a number of high-level operations on files and collections of files. In particular, functions are provided which support file copying and removal.
    Installation: pip install shutil

One-Step Installation of Required Python Packages:
Execute the command below to install all necessary packages from the "dependencies.txt" file located in the "packages" folder in a single operation.
Installation: pip install -r dependencies.txt

4 Generation of Executable File

To ensure the successful execution of this package, follow these steps:

1. Navigate to the "src" folder.
2. Run the command: gcc main.c -lm -fopenmp -o ../bin/fwi.exe
3. This command will create an executable file named "fwi.exe" in the "bin" folder. Verify the presence of the generated executable file.

Ensure the proper execution of these steps for the successful generation of the "fwi.exe" executable file.

5 Detail Explanation of Package

After installing all the required packages, to launch the FWI GUI, navigate to the "bin" folder. Execute the ShaVi-1.0.py file to run the package. Once executed, the user will be presented with an interface, as illustrated in Figure 1. The package consists of four primary windows and buttons to interact with the package, as marked in Figure 1, each offering distinct utilities to enhance the user's implementation experience. These windows are outlined below:

5.1 Data Input: Window 1

The initiation of the inversion process involves providing essential data by browsing through dedicated buttons located just below the data path window. This data includes observed seismic data, the initial model, source signature, and details regarding source and receiver locations, all presented in ".txt" format. The observed data can be inputted either in row-major or column-major format, determined by the key set in the parameter file. An initial model is a prerequisite for commencing the Full Waveform Inversion (FWI) process, which undergoes iterative refinement. The number of rows in the array representing the model signifies the depth, while the columns denote the length of the model. Additionally, the source signature plays a crucial role in generating synthetic data aligned with the defined acquisition geometry.

The acquisition geometry defines the grid points where the sources and receivers are located. These files, detailing the acquisition geometry, can be effortlessly generated and visualized using the "Acquisition Geometry" tab within the toolbox in the menu bar.

The generation of the parameter file is facilitated through the toolbox available in the menu bar. This file encompasses crucial parameters essential for defining aspects such as forward modeling, parallel computations, and absorbing boundaries. Detailed information about each parameter is provided in subsequent sections.

5.2 Visualization of Initial and Inverted Models: Window 2

This interface offers real-time visualization of both the initial and inverted models, allowing users to monitor the progress of the inversion process, as shown in Figure 1. Within this window, two buttons are available to plot the figures of the initial and

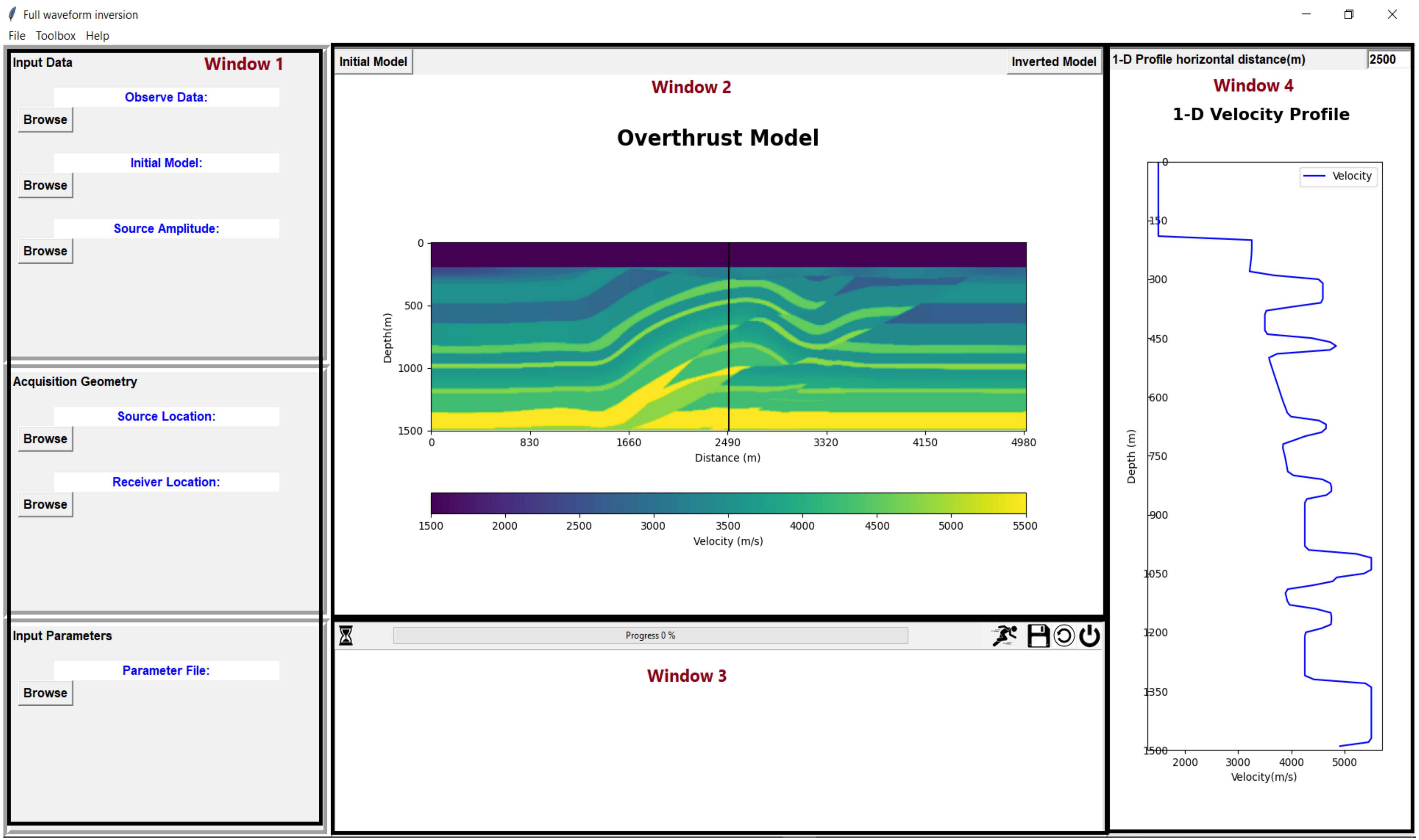

Figure 1: Interface of ShaVi-1.0.

inverted models. For demonstration purposes, an overthrust model is plotted in this window. A color bar is incorporated to facilitate the analysis of model velocities. Notably, the black line on the model plot corresponds to the 1D velocity-depth profile plotted in window 4.

5.3 Live Progress Updates and Misfit Calculation: Window 3

Tracking the real-time progress of the inversion process is crucial to estimating the time required for its completion, a feature presented in the window 3. It includes a progress bar indicating the ongoing process's completion percentage. Furthermore, the window displays valuable information about receivers and sources, along with details on the objective function. This information provides valuable insights into the convergence rate of the inversion process.

5.4 1D Velocity-Depth Profile Visualization: Window 4

Window 4 in this package serves as a utility for plotting the 1D velocity-depth profile of both the initial and inverted models. This profile allows for a comparative analysis of the results with the initial model. To choose the location of the 1D profile, input the horizontal distance on the model's axis in window 4. Refresh the "inverted model" button in window 2 to update and visualize the selected profile.

5.5 Menu Bar

This package includes a user-friendly menu bar, augmenting its functionality. Users can seamlessly generate the parameter file using the dedicated "Parameters" and "Acquisition Geometry" tools, demonstrated in Figures 2 and 3, respectively. The menu bar further offers a valuable visualization of the acquisition geometry, aiding users in understanding the spatial layout of their data. These tools are explained in more detail in the following sections:

5.5.1 Parameters

A successful FWI process necessitates accurate numerical values for parameters, ensuring a seamless inversion experience. These parameters are intricately linked to forward modeling for synthetic data generation, parallel computation resources, and absorbing conditions. A comprehensive explanation of all these parameters is provided in Table 1. The parameters are input through the tool available in the menu bar, illustrated in Figure 2. Hovering the cursor over the text provides information about each parameter. The save button allows users to save the parameter file, while the load button enables the loading of a previously prepared parameter file for edits.

5.5.2 Acquisition Geometry

The acquisition geometry file contains information about source and receiver locations in grid numbers. The acquisition geometry file can be generated using the "Acquisition Geometry" tool in the toolbox, as depicted in Figure 3. Information about the number of receivers and sources is input through this window, with lower and upper bounds associated with the range of grid numbers to be covered by placing

Table 1: Parameters

Parameter	**Explanation**
Number of samples	Discrete data points obtained from continuous seismic recordings.
Sampling interval,	The time interval between consecutive digital samples.
Depth of model	Size of the model along the vertical ($z - axis$) represented by number of grids points.
Width of model	The horizontal extent of the model along ($x - axis$) represented by number of grids points.
Grid size	Spacing between grid points.
Depth of source	Vertical position of the seismic source within the discretized model.
Depth of receiver	Vertical position of the receivers within the discretized model.
Number of shots	The total count of individual seismic energy sources.
Number of receiver	The number of geophones used to record seismic data for a shot.
Processors	Available computation units.
Iterations	Maximum number of iterations for which the process is repeated.
Boundary key (0 or 1)	Key to activate or deactivate absorbing boundary conditions (ABCs).
Absorbing layer,	The number of grids reserved for the absorbing boundary conditions (ABCs).
Type of objective function (0 or 1)	Key to choose Norm or normalized cross-correlation objective function.
Mute upper layer	The grids at near-surface where the model is not updated
Mute boundary layer	Non-updating boundaries
Data layout	Key to select the data layout.

the receivers and sources. After entering this information, a spreadsheet opens, as shown in Figure 4 (this spreadsheet is generated for 10 sources and 20 receivers for demonstration purposes). Receiver locations corresponding to each receiver are entered in this sheet, and source and receiver files are subsequently generated. To plot the acquisition geometry, source and receiver files are fed before clicking on the "Geometry Plot" button.

5.6 Functionality of Buttons

Initial Model: This button is designed to plot the initial model, providing users with a visual representation of the starting point for the inversion process.
Inverted Model: Once the inversion process is initiated, clicking this button plots the inverted model, allowing users to observe the evolving subsurface structure as the inversion progresses.
Progress (Hourglass): This button serves to update the progress of the inversion process. It provides users with real-time information on the ongoing status.
Run: Clicking the "Run" button initiates the inversion process. It is the command to start the computational procedures that result in the inverted model.
Save: Users can utilize this button to manually save the inverted velocity model. However, it's worth noting that the model is automatically saved to the output file, providing convenience and ensuring data preservation.
Restart: In case a user wishes to restart the process, the "Restart" button is available. Clicking this button resets the inversion, allowing users to make adjustments or start anew.
Quit: To exit the package, users can click the "Quit" button. This action closes the package interface, concluding the session.
For additional support, a dedicated help section is incorporated into the menu bar, providing users with easy access to a tutorial video. This tutorial serves as a valuable resource, offering step-by-step guidance for smooth navigation and effective utilization of the package. These supplementary features contribute to an enriched user experience, promoting ease of use and a comprehensive understanding of the software's capabilities.
Upon completion of the process, users can locate the inverted data in a file named "output"

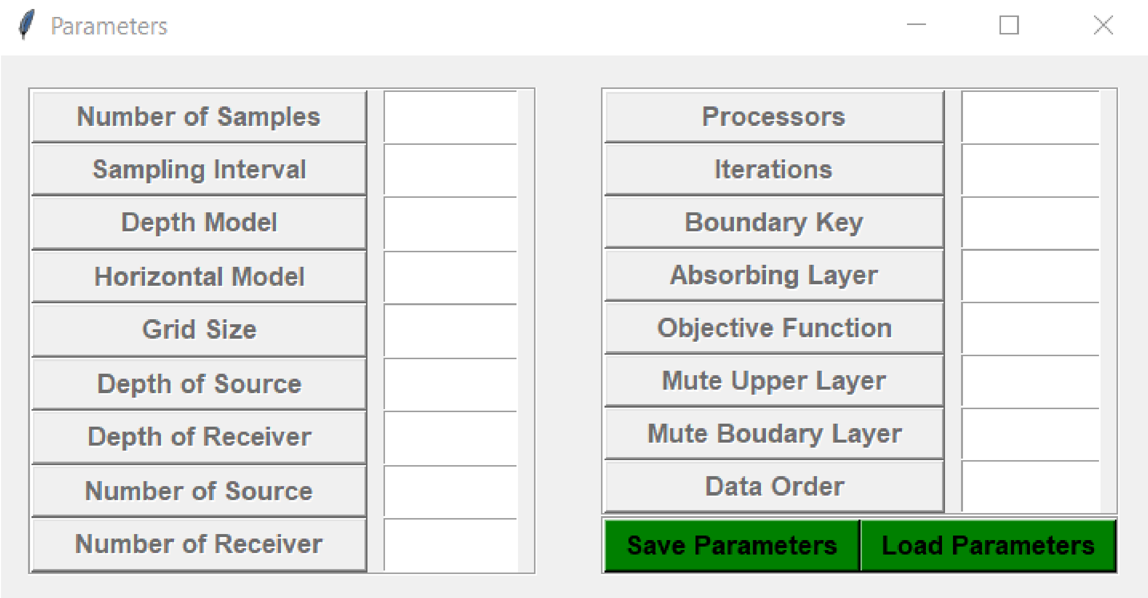

Figure 2: Parameters file generation tool.

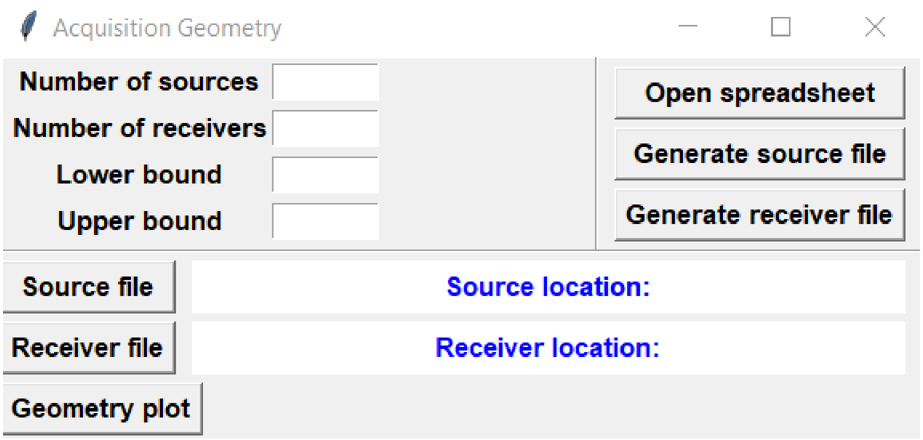

Figure 3: Acquisition geometry file generation tool.

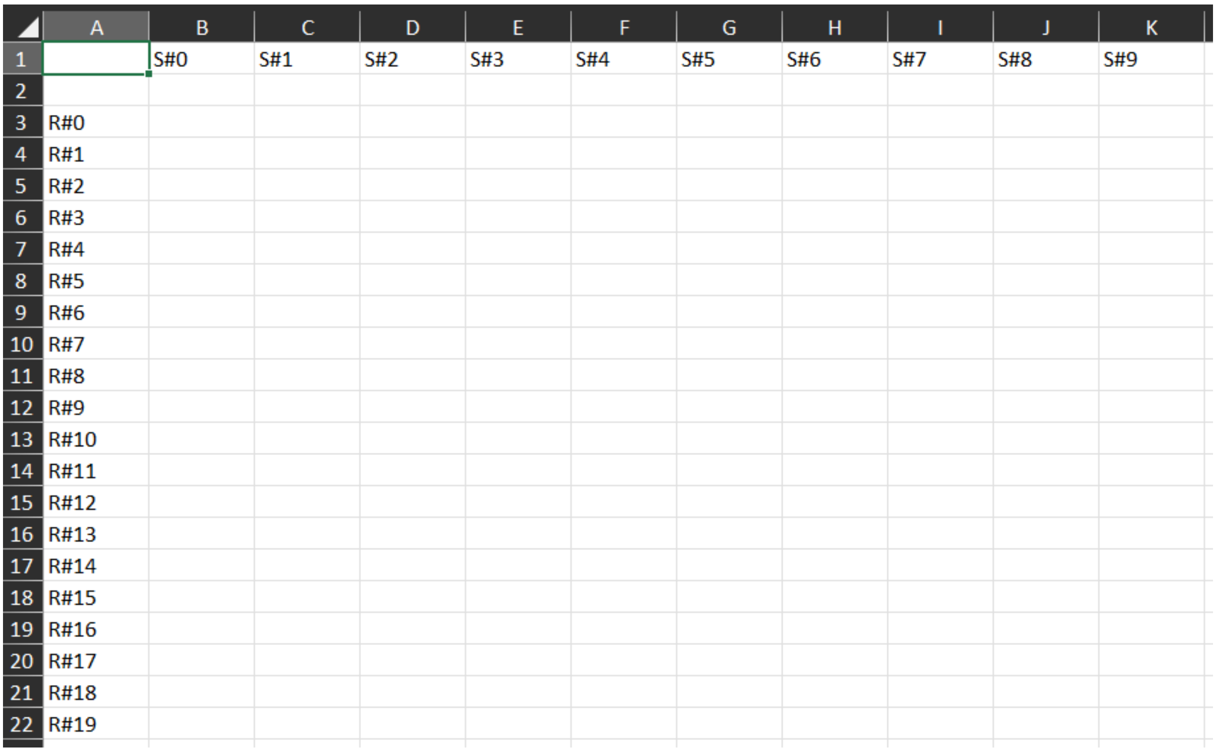

Figure 4: Spreadsheet with 10 source and 20 receivers.

6 Test Cases

Three test cases involve synthetic geological models —Three blocks, Marmosui, and Overthrust— with varying dimensions, each with specified source and receiver configurations is used to assess the expected functionality of the package. Each test case includes inputs, expected results, and a set of procedures to systematically execute the tests. The main aim is to confirm that the software meets its intended requirements and ensure its reliability before using it in real-world situations.

6.1 Case 1: Three Block Model

The Three-Block model serves as a straightforward test case for evaluating this package. The model's dimensions are 500 x 1000 meters, as illustrated in Figure 5, partitioned into small square grids with dimensions of 10 meters each. This model features three low-velocity blocks, each with a velocity of 1800 m/s, situated at different depths, having a uniform background velocity of 2000 m/s. The recovery process for this true model, shown in Figure 5 (a), commences with an initial model, depicted in Figure 5 (b). The peak frequency of the observed data and source signature is 10 Hz. The necessary data for the inversion process is located in the folder labeled "test/case_1_block_model".

Observe Data ———— observe.txt
Initial Model ———— initial_model_block.txt
Source Signature ————- source_amp.txt
Source Locations ————- source.txt
Receiver Locations ———— receiver.txt
Parameters ———— parameter.txt

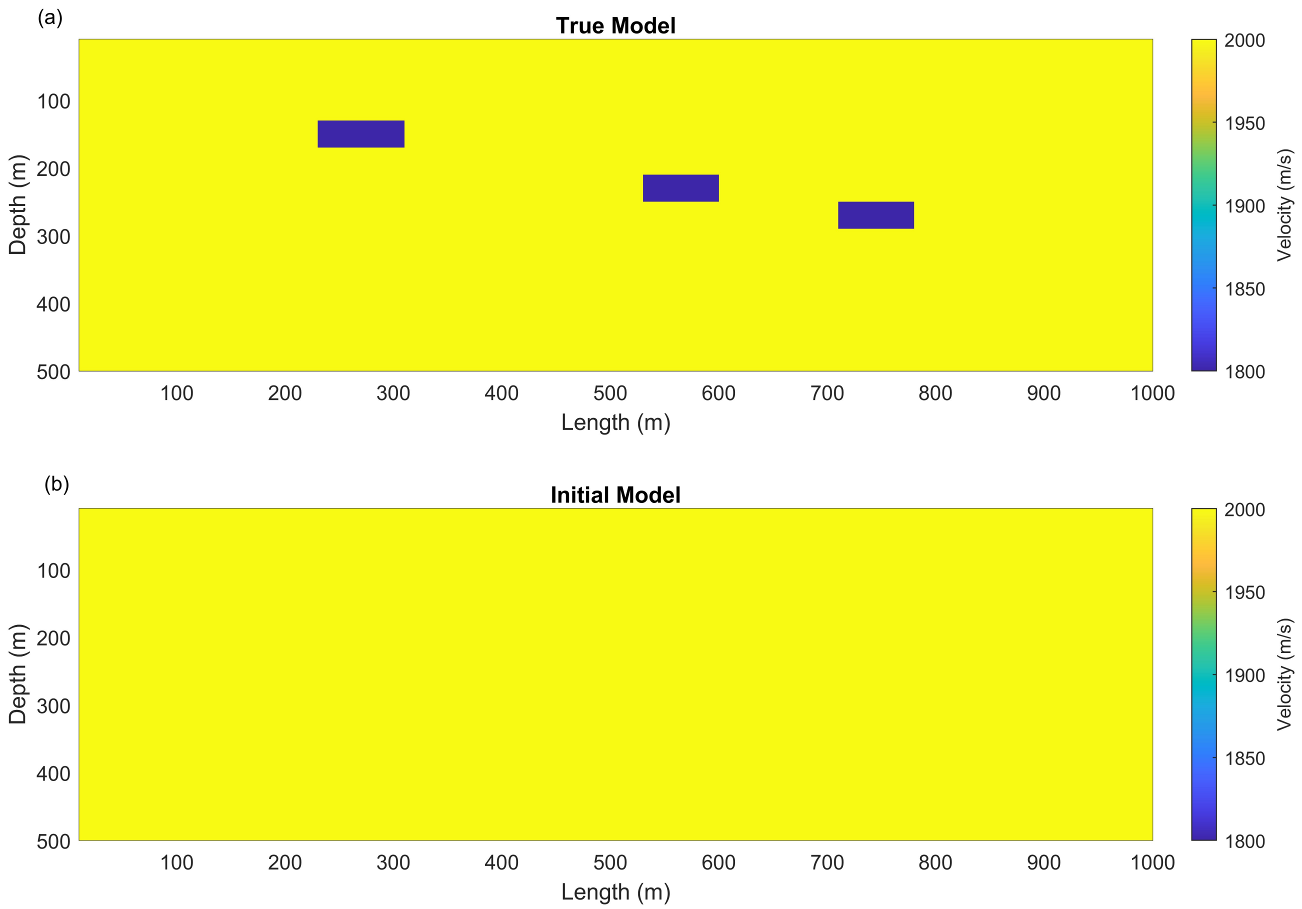

Figure 5: Block model, (a) True model, and (b) Initial model.

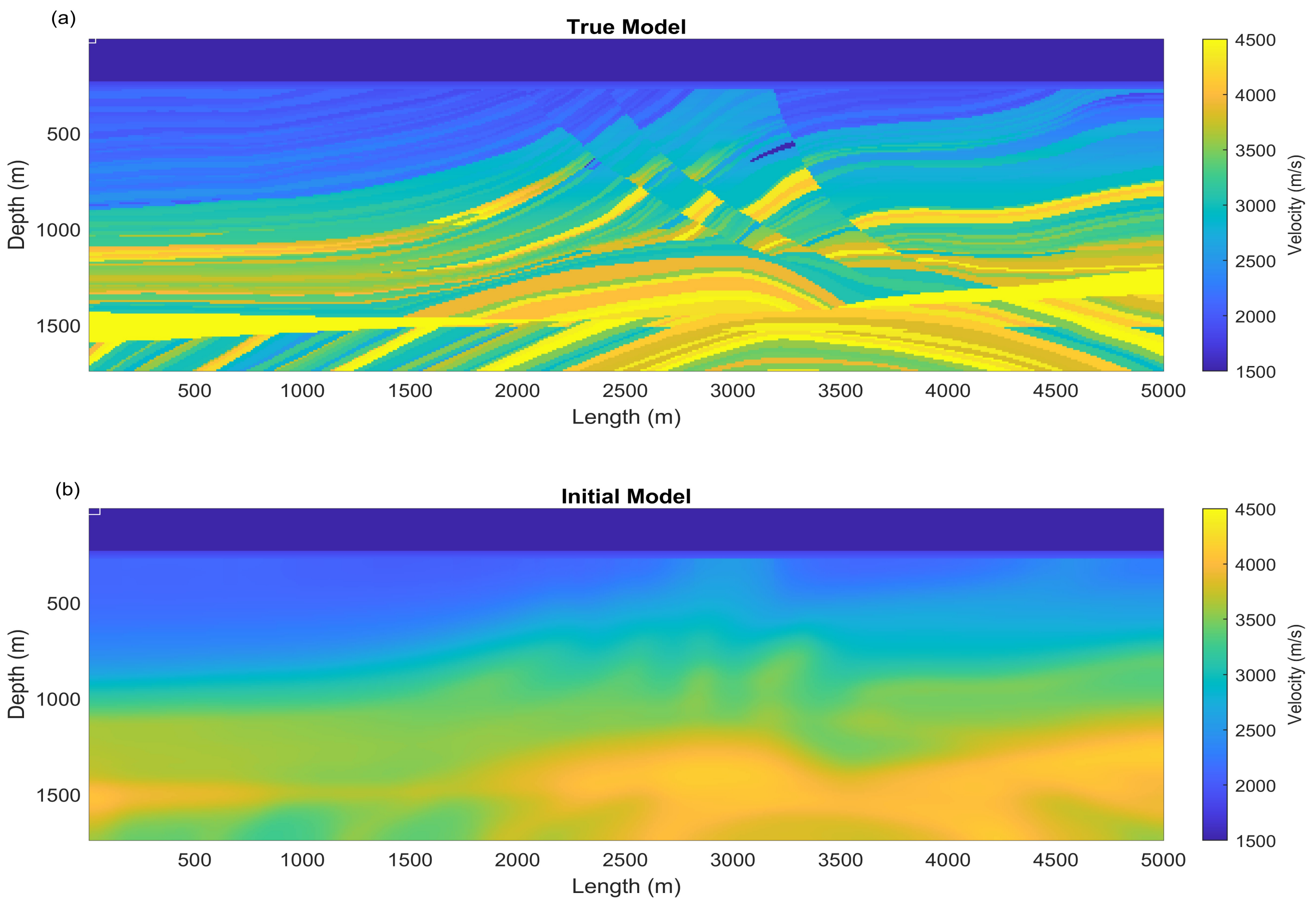

Figure 6: Marmousi model, (a) True model, and (b) Initial model.

6.2 Case 2: Marmosui Model

Data for the Marmousi model is provided for testing, with dimensions of 1740 x 5000 meters, as depicted in Figure 6, and a grid spacing of 10 meters. The Marmousi model serves as an invaluable test case for assessing the performance and accuracy of seismic inversion algorithms. This geological model presents intricate features including faults, salt bodies, and various subsurface structures, creating a challenging yet representative scenario for seismic data inversion techniques. The inversion process utilizes observed data corresponding to the true Marmousi model (Figure 6 (a)), starting with the initial model illustrated in Figure 6 (b).

The necessary data for the inversion process for Marmousi model is located in the folder labeled "test/case_2_marmousi_model". This folder contains data for various frequencies, enabling users to leverage a multiscale strategy for inversion. It is important for users to exercise caution when selecting the initial model, as the initial model for each higher frequency inversion is derived from the inverted model at a lower frequency.

Observe Data ———— observe_<frequency>.txt
Initial Model ———— initial_model_marmousi.txt
Source Signature ————- source_amp_<frequency>.txt
Source Locations ————- source.txt
Receiver Locations ———— receiver.txt
Parameters ———— parameter.txt

6.3 Case 3: Overthrust Model

Comprehensive testing data for the Overthrust model is made available, offering detailed insights for evaluation. The dataset encompasses dimensions of 1500 x 5000 meters, as visually represented in Figure 7. The grid spacing employed for this model is set at 10 meters, providing a finely detailed representation of the subsurface structures. This dataset serves as a valuable resource for assessing and validating the performance of this package in the context of the Overthrust model's geological complexity. The inversion process for the Overthrust model utilizes observed data corresponding to the true Overthrust model, as depicted in Figure 7 (a). The process begins with the initial model illustrated in Figure 7 (b).

The requisite data for the inversion process specific to the Overthrust model is conveniently located in the designated folder labeled "test/case_3_overthrust_model." Within this folder, users can access data for various frequencies, presenting an opportunity to employ a multiscale strategy for inversion. However, users should exercise caution in the selection of the initial model, as each higher frequency inversion's initial model is derived from the inverted model at a lower frequency.

Observe Data ———— observe_<frequency>.txt
Initial Model ———— initial_model_marmousi.txt
Source Signature ————- source_amp_<frequency>.txt
Source Locations ————- source.txt
Receiver Locations ———— receiver.txt
Parameters ———— parameter.txt

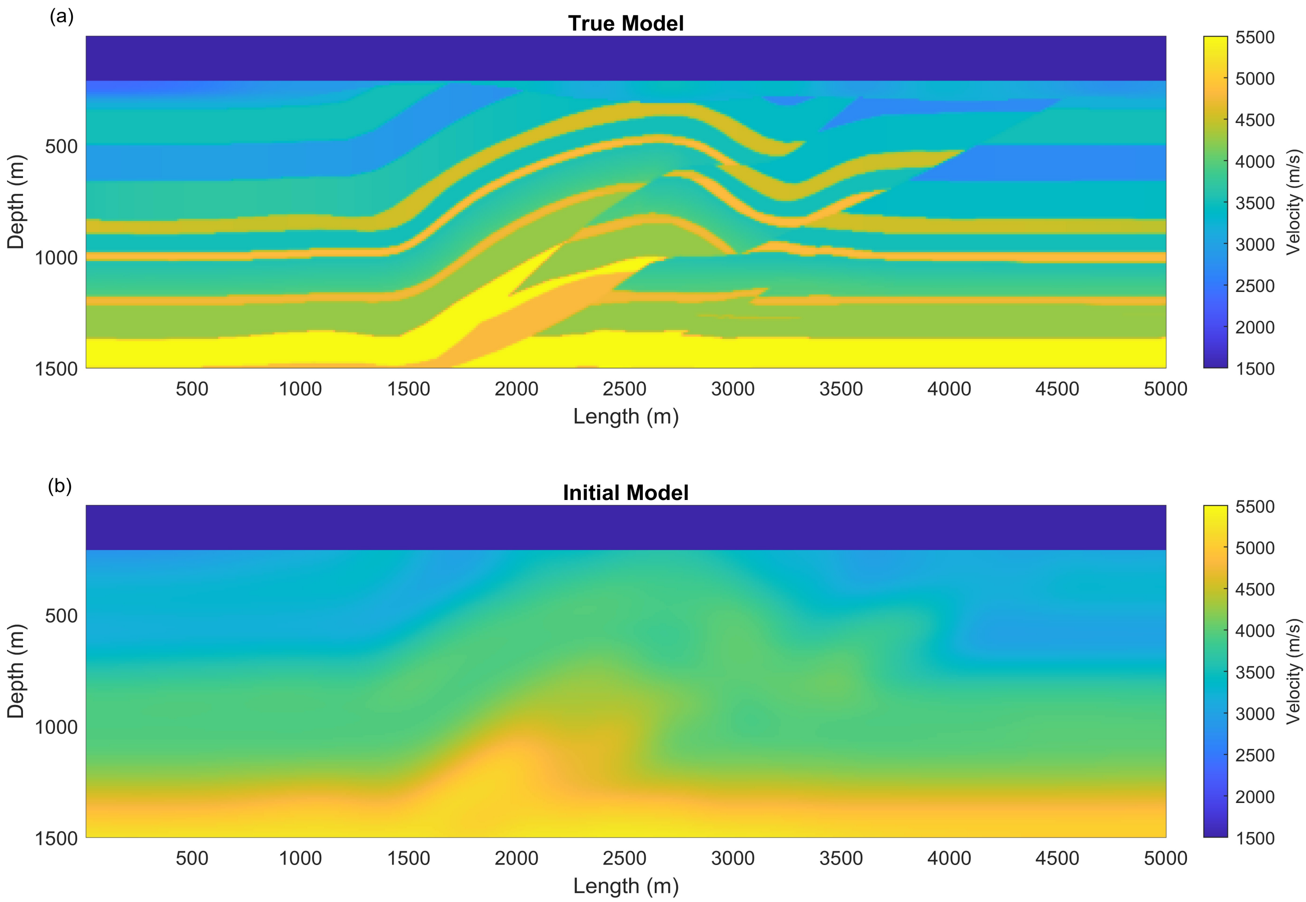

Figure 7: Overthrust model, (a) True model, and (b) Initial model.

7 Executing the Package Without GUI

Users have the option to execute the package without utilizing the user interface through the following command. However, it's important to note that this approach restricts real-time visualization and interaction with the results and inversion process.

Command: executable <path_to_parameter> <path_to_source_signature> <path_to_initial_model> <path_to_observe_data> <path_to_source_position> <path_to_receiver_position>

8 Auxiliary

Users are equipped with an auxiliary package enabling the generation of data for other synthetic models. Within the folder labeled "synt_data_generator," two essential codes, namely "source.c" for generating the source signature and "real_data.c" for observed data generation, can be found.

8.1 Process to Generate Source Signature:

To generate the source signature, users are required to specify the desired frequency of the signal in line number 7 of the "source.c" code and execute the following commands:
Command 1: gcc source.c -lm
Command 2: executable <path_to_parameter>
This process will generate a source signature file in the "input" folder named "source_amp.txt", which can subsequently be utilized for observed and synthetic data generation. The parameter file necessary for this process can be prepared using the toolbox provided within the main package.

8.2 Process to Generate Observed Data for Synthetic Model:

To generate the observed data for synthetic model, users are required to execute the following commands:
Command 1: gcc real_data.c -lm -fopenmp
Command 2: excecutable <path_to_parameter> <path_to_source_signautre> <path_to_real_model> <path_to_source_position> <path_to_receiver_position>
This process will generate an observed data file in the "input" folder named "observe.txt". The parameter and acquisition geometry files are necessary for this process can be prepared using the toolbox provided within the main package.

9 Support

For assistance regarding the package, our team is available to address your inquiries and technical needs.
You can contact us at vvats@iitk.ac.in or vikasvats17293@gmail.com.