An example *Geophysics* article, with a two-line title

Joe Dellinger and Sergey Fomel†*

ABSTRACT

This is an example of using geophysics.cls for writing *Geophysics* papers.

INTRODUCTION

Full Waveform Inversion (FWI) is considered one of the most efficient seismic imaging methods due to its ability to utilize all seismic phases present in the data (Pratt and Shipp, 1999; Schuster, 2017; Tarantola, 1986; Virieux and Operto, 2009). This involves comparing synthetic data with observed data (Gómez and Pestana*, 2017; Liu et al., 2017; Métivier et al., 2018), where the difference between them is known as the objective function. The rate of change of the objective function with respect to model parameters (Plessix, 2006) is used to iteratively update the model until the synthetic data from the updated model matches the observed data.

The nonlinear relationship between synthetic data and model parameters (Crase et al., 1990; Geng et al., 2018; Guo et al., 2021) leads to a multimodal nonlinear objective function, characterized by multiple local minima and maxima (ten Kroode et al., 2013), as shown in FIGURE. FWI utilizes calculus-based optimization methods, such as gradient descent, BFGS, and conjugate gradient, which typically direct the solution towards the nearest extrema. This can lead to FWI becoming trapped in local minima if the starting model is not within the basin of attraction (Fitchner, ETH). Consequently, if the starting model is in a localized basin of attraction, achieving convergence to the global minimum becomes impossible. Therefore, it is crucial to initialize the inversion with a model that is close to the global minimum.

Since its formulation, FWI has been the subject of extensive research aimed at addressing nonlinearity, with an emphasis on both modifying the objective function and developing effective methods for preparing initial models using global optimization. Modified objective function approaches include the use of multiscale strategies (Bunks et al., 1995; Ravaut et al., 2004; Schäfer et al., 2014; Sirgue and Pratt, 2004), which begin with low-frequency data for initial inversions and progressively incorporate higher frequencies. normalized cross-correlation objective function (Chi et al., 2015; Liu et al., 2017) focus on matching of phases to mitigate the effect of amplitudes, envelope-based objective function (Borisov et al., 2018; Chi et al., 2014) for updating long-wavelength models, and most recent optimal transport function (Brossier et al., 2016; Métivier et al., 2016, 2018) increases the convexity of the basin of attraction which increase the chance of falling the initial model in the basin of attraction of global minima. Global optimization methods (Arora et al., 1995; Locatelli and Schoen, 2021; Törn and Žilinskas, 1989) are also proposed to deal with non-linearity by preapring the initial model, these methods are inspired with the natural phenomena which are formulated to mathematical expresion as an optimization method. In geophysics, very fast simulated annealing (VFSA) inspired by annealing process in metallurgy (Ingber, 1989; Kirkpatrick et al., 1983; Sacks et al., 1989), genetic algorithm (GA) based on Darwin's theory of survival of fittest (Katoch et al., 2021; Michalewicz, 1996), and particle swarm optimization (PSO) based on the concept of swarm intelligence (Couceiro and Ghamisi, 2016; Kennedy and Eberhart, 1995; Shi and Eberhart, 1999; Wang et al., 2018) are most commonly used methods for seismic inversion. These methods have the ability to explore all the available search space to find a optimal solution this supermacy of global optimization motivated its utilization in prepasring the starting model for calculas based seismic inversion methods. the idea of preparing the initial model with the global optimization is because of the high exploration and slow exploitation (Dong et al., 2015; Ye and Pan, 2024) of these methods. once the initial model is prepared with the confidence that it lie in the basin of global minima then local optimization statred with this model because local minima methods have high exploitation rate. Datta and Sen (2016) used the VFSA for preapring the only initial model in this two step process, parameterization of model is accomplished by the zero offset section, Fu et al. (2021) proposed a paralled VFSA algorithm for 1.5D acoustic FWI where model parameters are simultaneously updated across multiple threads, Shiba and Irikura (2005) implemented the VFSA algorithm to estimate earthquake displacement and demonstrated that VFSA outperforms the GA in this task, Mendes et al. (2024) used a training image to guide the generation of realistic velocity model samples and enhance the convergence, Datta et al. (2019) impliment the VFSA where the sedimentary layers and salt bodies are represented by set of interfaces and ellipses respectively, Mazzotti et al. (2016) proposed GA FWI method involves parametrizing the subsurface with two grids: a coarse grid for inversion and a fine grid for modeling, Tran and Hiltunen (2012) demonstrates the potential of GA for improved characterization subsurface properties, Zeng et al. (2011) studied GA for Rayleigh wave inversion, Aleardi and Mazzotti (2017) proposed the seismic inversion with the GA with markov chain monte carlo (MCMC) method to deal with the uncertainties in the search space, Yang et al. (2017) developed a PSO based method for impedance inversion, Shaw and Srivastava (2007) demonstrates the effectiveness of PSO in inverting geophysical data for natural resource exploration, Ding et al. (2015) focusing on the application of PSO to solve geophysical inverse problems, specifically a 1D-DC resistivity case, Kaplanvural et al. (2020) The research contributes to the literature by demonstrating the ability of PSO to invert common-offset ground penetrating (GPR) traces and estimate dielectric properties, including conductivity and relative magnetic permeability, Fernández-Martínez et al. (2010) used PSO for reservoir characterization, and Fern and Garc (2010) PSO algorithm's application to the SP inverse problem.

An extensively work is also done for finding a better global optimization method. A comparison of the performance of GAs to Monte Carlo is studied which find that GAs can achieve better fits with fewer model parameters and are computationally efficient (Sambridge and Drijkoningen, 1992). A comparison between the GA, and PSO is also performed, conclude that PSO outperform the GA (Ding et al., 2015; Mojica et al., 2019). Sajeva et al. (2017) presents a comparative analysis of four stochastic optimization methods—adaptive simulated annealing (ASA), GA, neighborhood algorithm (NA), and PSO for 1D elastic full-waveform inversion and residual static computation, this study finds that the choice of method should be guided by the nature of the objective function and the dimensional of the model space.

In this article, we present the application of PSO for generating an initial model for FWI,due to its ability to effectively balance exploration and exploitation within the solution space. The implementation of global optimization methods in seismic inversion faces the challenge of the curse of dimensionality due to the large number of model parameters involved (Dhabaria and Singh, 2024). This necessitates defining the model with a reduced number of parameters. To address this, we have defined the model in terms of depth and velocity at the interfaces, as well as the rate of change of velocity between these interfaces. The number of interfaces to be inverted is determined solely by the selected number of breaks. The depth and number of interfaces are constrained by the arrival times of major breaks observed in near-offset seismic trace, respectively. Meanwhile, the velocity at each interface and the rate of change of velocity are limited by realistic subsurface velocity values. For near-offset receivers, these major breaks are most likely caused by reflections. This inversion begins with a uniform 1D velocity-depth model and sources positioned at various horizontal locations. Using this method, the interfaces are inverted progressively from the surface to depth. The data inverted for a particular interface serves as the initial model for the inversion of the subsequent interface. This process is repeated for all shots, with 1D velocity-depth profiles interpolated to prepare a 2D initial model for FWI. We also conducted experiments to find the optimal combination of parameters. A multi-threaded computation is also implemented to simultaneously invert data for multiple shots.

PAPER BRIEF

method

METHODOLOGY

This approach involves two steps. First, a coarse velocity model is prepared using PSO by optimizing the depth, interface velocity, and the rate of change of velocity between interfaces. This model serves as an initial model for conventional gradient-based FWI in the second step.

Particle Swarm Optimization

Particle Swarm Optimization (PSO) is a stochastic method developed by James Kennedy and Russell Eberhart in 1995. Inspired by the social behavior of birds flocking to find food, they formulated a mathematical model to simulate this behavior. This model is widely applied to solve various optimization problems. They identified that the fundamental principle guiding birds' food-finding behavior is their ability to communicate with each other. Each bird in the process knows its current position ($\mathbf{x}_i(t)$) and best position ($\mathbf{p}_i(t)$), determined by evaluating the fitness using a cost function. Additionally, each bird shares its best position with others, contributing to the collective knowledge of the flock's best position ($\mathbf{g}(t)$). Each bird's next movement is adjusted by its own best, the flock's best, and its current position. This iterative process continues at each step, ultimately converging towards a globally optimal position through the collaborative effort of all birds.This natural phenomenon is mathematically described by the velocity update equation 1 and the position update equation 2.

- $\mathbf{x}_i(t)$ be the position of particle i at iteration t.
- $\mathbf{v}_i(t)$ be the velocity of particle i at iteration t.
- $\mathbf{p}_i(t)$ be the personal best position of particle i until iteration t.
- $\mathbf{g}(t)$ be the global best position among all particles until iteration t.
- w be the inertia weight.
- c_1 and c_2 be the cognitive and social acceleration coefficients, respectively.
- r_1 and r_2 be random numbers uniformly distributed in the range $[0, 1]$.

The velocity and position update rules for each particle are given by:

$$\mathbf{v}_i(t+1) = w\mathbf{v}_i(t) + c_1 r_1(\mathbf{p}_i(t) - \mathbf{x}_i(t)) + c_2 r_2(\mathbf{g}(t) - \mathbf{x}_i(t)) \tag{1}$$

$$\mathbf{x}_i(t+1) = \mathbf{x}_i(t) + \mathbf{v}_i(t+1) \tag{2}$$

Where:

- w controls the influence of the previous velocity (inertia).
- c_1 and c_2 represent the trust of the particle in itself and in the swarm, respectively.
- r_1 and r_2 introduce stochasticity to the particle's movement.

Optimization Parameters

The updates in the Particle Swarm Optimization (PSO) algorithm are influenced by several controlling parameters, including the inertia weight (w), acceleration coefficients (c_1 and c_2), population size of the swarm, and the number of iterations. Among these, the inertia weight is the most critical tuning parameter as it balances the exploration and exploitation capabilities of PSO by adjusting the contribution of the particle's previous velocity. An inertia weight value between 0.4 and 0.9 is generally found to provide good convergence. The cognitive and social coefficients (c_1 and c_2) represent the confidence in a particle's own best position and the swarm's best position, respectively, and they influence the updated velocity of the particles. The number of particles in the swarm also affects convergence; as the number of particles increases, the search space expands, potentially leading to better convergence. Experimental studies have shown that a swarm size of around 30 particles is generally effective for finding solutions within optimal iterations. The number of iterations, as with all iterative optimization algorithms, significantly impacts the performance of PSO.

This contribution of different parameters for succes of PSO make it is necessary to decide the combination of these parameters precisely. we have performed experiments to find the optimal combination of this values, for these experiment we have choose four nonlinear functions Ackley, Griewank, Rastrigin, and Styblinski-Tang function shown in figure **??**, **??**, **??**, and **??** respectively. These experiments are performed to determine the optimal value of the optimization coefficient and examine the relationship between the number of iterations and swarm size. Since both swarm size and iteration count impact computational time, it is essential to balance these factors to achieve effective optimization while minimizing computational costs. To fairly compare the effects of swarm size and the number of iterations, the rate of increase for both parameters is kept consistent. Following this, PSO is applied to the Schwefel function using the parameters chosen from the previous experiment to achieve the parameters that lead to the best convergence. To analyze performance, accuracy is evaluated based on the maximum deviation using equation 3. Further details of these experiments are outlined below.

$$Accuracy(\%) = 100 - \left| \frac{optimal\ value - evaluated\ value}{optimal\ value - maximum\ deviation} \right| \times 100 \tag{3}$$

Where:

- *Optimal value*, best possible value of the objective function.
- *Evaluated value*, value of the objective function at a given point in the feasible domain.
- *Maximum deviation*, largest difference between the optimized value and the actual values.

1. Accuracy with Parameters: In this experiment, optimization is conducted for all specified test functions using varying values of c_1, c_2, and inertia weights, as illustrated in figures **??**, **??**, **??**, and **??**. To address the inherent randomness of this stochastic method, we perform 50 runs with 1000 iterations and calculate the average of these results as the final optimized values.

   This experiment concludes that a combination of inertia weights between 0.5 and 0.8, c_1 values ranging from 0.6 to 2.0, and c_2 values between 0.6 and 1.8 results in improved accuracy.

2. Accuracy with iterations: Here, accuracy is assessed while maintaining a constant swarm size of 30 and an initial iteration count of 1000, which is then increased by factors of 1.67, 2.0, 2.67, 3.00, 5, and 10, to examine how the number of iterations impacts accuracy across all test functions. The results indicate that as the number of iterations increases, accuracy improves, reaching a maximum close to 100 % when iterations are increased to 10 times, as illustrated in figure **??**.

3. Acuuracy with swarm size: In this study, accuracy is evaluated across all tests by varying the swarm size, starting with 30 particles and increasing it by factors of 1.67, 2.0, 2.67, 3.00, 5, and 10, while keeping the number of iterations constant at 1000. The findings indicate that as the swarm size increases, accuracy improves to approximately 70 %.

From these experiments for finding the optimization parameters, it is concluded that an optimal combination of inertia weights between 0.5 and 0.8, c_1 values ranging from 0.6 to 2.0, and c_2 values between 0.6 and 1.8 leads to enhanced accuracy. Additionally, increasing the number of iterations relative to the number of particles is beneficial, as it provide improved accuracy while maintaining similar computational costs.
The parameters that performed well in the previous experiments with test functions are used to evaluate the rate of convergence for the Schwefel function, as shown in figure **??**. This additional test function focuses solely on the objective function with respect to the number of iterations, as illustrated in figure **??**. The aim of this study is to identify a combination of optimization parameters that achieve a better rate of convergence, enabling optimized results to be obtained within fewer iterations. Figure **??** illustrates that higher values of inertia do not show convergence, while lower values of inertia exhibit a high rate of convergence but fail to reach the optimized value. An inertia value of 0.6 demonstrates good convergence with different c_1 and c_2 values. This analysis reveals that c_1 at 1.8 and c_2 at both 1.8 and 2.4 converge to zero, albeit slowly. In contrast, c_1 at 2.4 and c_2 ranging from 1.2 to 1.8 exhibit a good rate of convergence, reaching near zero within 100 iterations. Based on this analysis, the optimal parameters for further seismic inversion are set as inertia at 0.6, c_1 at 2.4, and c_2 between 1.2 and 1.8.

Model Parameterization

The seismic model includes physical parameters defined at densely packed grid points, often in the thousands, leading to an exponentially expanding search space that complicates the implementation of PSO. Therefore, it is essential to create a method for defining these velocity models with fewer parameters before implementing PSO, ensuring that the resulting output model can effectively serve as an initial model for FWI.

We propose a technique to define model with 1D depth-velocity profiles at sparse horizontal positions, as illustrated in Figure **??** with white vertical lines. This model is representing a layered marine environment, where the velocity gradually increases with depth, ranging from 1500 to 4700 m/s. Additionally, it features a low-velocity layer situated between two high-velocity layers. The depth of interface in terms of grid point (d_i^k), where i represents the i^{th} interface for the k^{th} depth-velocity profile, (g_i^k) denotes the rate of change of velocity between the $(i-1)^{th}$ and i^{th} interfaces, and (v_i^k) indicates the velocity of the model at the i^{th} interface. These multiple, sparsely located depth-velocity profiles are interpolated using cubic splines to create an initial model. It is also assumed that no two interfaces intersect, as this is geologically implausible. Furthermore, the search space is restricted to feasible physical parameters. With these constraints, PSO is employed to optimize the three parameters for each layer in the development of the initial model.

PSO for Preparing Initial Model

The workflow of this implementation is illustrated in Figure **??**. It shows that initial model preparation begins with a uniform 1D depth-velocity profile as the initial model, where the velocity is same as upper layer and three parameters—depth, velocity at the interface, and the rate of change of velocity—are used as input parameters initially which are set to zero. A synthetic trace for this model is generated using an 8^{th}-order spatial scheme and a 2^{nd}-order temporal scheme. The synthetic trace is then compared to the observed data using the L2 norm, as described by equation 4. The observed data consists only near-offset data, where the major peaks are likely caused by reflectors directly beneath the shot location. The major peaks are selected from the observed data to guide the inversion process, with a focus on progressively inverting the reflectors defined by grid points. This approach falls into the category of over-parameterization as explained by (Sen Stoffa 1991), where the model is described by microlayers with thickness equal to the grid spacing. The inverted model justifying a particular peak used as an initial model for the next one. This process is repeated until the inversion successfully accounts for all the selected peaks for a shot. We allow flexibility in the timing of the selected peaks since it is not always precise to pinpoint the exact peak. The peaks resulting from multiples will not significantly impact the model because the interfaces causing these multiples have already been accounted. We sparsely select the shot locations and repeat this process for all chosen shots. Using the inverted reflectors from these shots, we create an initial model through interpolation and smoothing. This serves as the initial model for FWI.

$$O(syn^k, obs^k) = \sqrt{\sum_{i=1}^{N} (syn^k - obs^k)^2} \tag{4}$$

Where obs^k and syn^k indicate the observed data and synthetic data generated from the model, respectively; k refers to the shot number, and N represents the total samples.

Full Waveform Inversion

The model prepared using PSO serves as an initial model for FWI. Synthetic data is generated with this model and compared with the observed data, a process known as misfit calculation. Common methods for this calculation include the L2 norm, normalized cross-correlation function, Huber norm, and optimal transport function. The gradient of the objective function with respect to the model parameters is then calculated, which aids in updating the model. This iterative process ultimately leads to the recovery of velocity model.

ACKNOWLEDGMENTS

I wish to thank Ivan Pšenčík and Frédéric Billette for having names with non-English letters in them. I wish to thank Červený (2000) for providing an example of how to make a bib file that includes an author whose name begins with a non-English character and Forgues (1996) for providing both an example of referencing a Ph.D. thesis and yet more non-English characters.

APPENDIX A

APPENDIX EXAMPLE

```
%\documentclass[paper]{geophysics}
\documentclass[paper,revised]{geophysics}
\usepackage{cleveref} %for cref


% An example of defining macros
\newcommand{\rs}[1]{\mathstrut\mbox{\scriptsize\rm #1}}
\newcommand{\rr}[1]{\mbox{\rm #1}}
\usepackage{natbib}
\bibliographystyle{plainnat}
```

```
\begin{document}

\title{An example \emph{Geophysics} article, \\ with a two-line title}

\renewcommand{\thefootnote}{\fnsymbol{footnote}}

\ms{GEO-Example} % paper number

\address{
\footnotemark[1]BP UTG, \\
200 Westlake Park Blvd, \\
Houston, TX, 77079 \\
\footnotemark[2]Bureau of Economic Geology, \\
John A. and Katherine G. Jackson School of Geosciences \\
The University of Texas at Austin \\
University Station, Box X \\
Austin, TX 78713-8924}
\author{Joe Dellinger\footnotemark[1] and Sergey Fomel\footnotemark[2]}

\footer{Example}
\lefthead{Dellinger \& Fomel}
\righthead{\emph{Geophysics} example}

\maketitle

\begin{abstract}
  This is an example of using \textsf{geophysics.cls} for writing
  \emph{Geophysics} papers.
\end{abstract}

\section{Introduction}

Full Waveform Inversion (FWI) is considered one of the most efficient seismic imaging
\par
The nonlinear relationship between synthetic data and model parameters \citep{Crase19
\par
Since its formulation, FWI has been the subject of extensive research aimed at addres
\par
An extensively work is also done for finding a better global optimization method. A c
\par
In this article, we present the application of PSO for generating an initial model fo
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\par
PAPER BRIEF


method \ref{method}
\section{Methodology}
This approach involves two steps. First, a coarse velocity model is prepared using PS
\subsection{Particle Swarm Optimization}
Particle Swarm Optimization (PSO) is a stochastic method developed by James Kennedy a
\begin{itemize}
\item \( \mathbf{x}_i(t) \) be the position of particle \( i \) at iteration \( t \).
\item \( \mathbf{v}_i(t) \) be the velocity of particle \( i \) at iteration \( t \).
\item \( \mathbf{p}_i(t) \) be the personal best position of particle \( i \) until i
\item \( \mathbf{g}(t) \) be the global best position among all particles until itera
\item \( w \) be the inertia weight.
\item \( c_1 \) and \( c_2 \) be the cognitive and social acceleration coefficients,
\item \( r_1 \) and \( r_2 \) be random numbers uniformly distributed in the range \(
\end{itemize}

The velocity and position update rules for each particle are given by:
\begin{equation}
\mathbf{v}_i(t+1) = w \mathbf{v}_i(t) + c_1 r_1 (\mathbf{p}_i(t) - \mathbf{x}_i(t)) +

\label{eqn:pso_1}
\end{equation}

\begin{equation}
\mathbf{x}_i(t+1) = \mathbf{x}_i(t) + \mathbf{v}_i(t+1)
\label{eqn:pso_2}
\end{equation}

Where:
\begin{itemize}
\item \( w \) controls the influence of the previous velocity (inertia).
\item \( c_1 \) and \( c_2 \) represent the trust of the particle in itself and in th
\item \( r_1 \) and \( r_2 \) introduce stochasticity to the particle's movement.
\end{itemize}
\subsection{Optimization Parameters}
The updates in the Particle Swarm Optimization (PSO) algorithm are influenced by seve
\\
This contribution of different parameters for succes of PSO make it is necessary to d
\begin{equation}
Accuracy (\%) = 100 - \left| \frac{optimal \ value - evaluated \ value}{optimal \ val
\label{eqn:accuracy}
\end{equation}
```

```
Where:
\begin{itemize}
\item \(Optimal \  value\), best possible value of the objective function.
\item \(Evaluated \ value\), value of the objective function at a given point in the
\item \(Maximum \ deviation\), largest difference between the optimized value and the
\end{itemize}
\begin{enumerate}
\item Accuracy with Parameters: In this experiment, optimization is conducted for all
%\begin{figure}
% \includegraphics[width=\paperwidth]{Fig/ackley.png}
% \caption{Ackley function.}
% \label{fig:ackley}
%\end{figure}
%\begin{figure}
% \includegraphics[width=\paperwidth]{Fig/griewank.png}
% \caption{Griewank function.}
% \label{fig:griewank}
%\end{figure}
%\begin{figure}
% \includegraphics[width=\paperwidth]{Fig/rastrigin.png}
% \caption{Rastrigin function.}
% \label{fig:rastrigin}
%\end{figure}
%\begin{figure}
% \includegraphics[width=\paperwidth]{Fig/styblinski.png}
% \caption{Styblinski-Tang function.}
% \label{fig:styblinski}
%\end{figure}

This experiment concludes that a combination of inertia weights between 0.5 and 0.8,
% \begin{sidewaysfigure}
% \includegraphics[width=\paperwidth]{Fig/ackley_para_vs_accuracy.jpeg}
% \caption{Optimization of the Ackley function with varying inertia weights, \(c_1\),
% \label{fig:acc_ackley}
% \end{sidewaysfigure}
% \begin{sidewaysfigure}
% \includegraphics[width=\paperwidth]{Fig/griewank_para_vs_accuracy.jpeg}
% \caption{Optimization of the Griewank function with varying inertia weights, \(c_1\
% \label{fig:acc_griewank}
% \end{sidewaysfigure}
% \begin{sidewaysfigure}
% \includegraphics[width=\paperwidth]{Fig/rastrigin_para_vs_accuracy.jpeg}
% \caption{Optimization of the Rastrigin function with varying inertia weights, \(c_1
% \label{fig:acc_rastrigin}
% \end{sidewaysfigure}
```

```
% \begin{sidewaysfigure}
% \includegraphics[width=\paperwidth]{Fig/styblinski_para_vs_accuracy.jpeg}
% \caption{Optimization of the Styblinski-Tang function with varying inertia weights,
% \label{fig:acc_styblinski}
% \end{sidewaysfigure}

\item Accuracy with iterations: Here, accuracy is assessed while maintaining a consta
% \begin{figure}
% \includegraphics[width=0.8\paperwidth]{Fig/iteration_vs_accuracy.jpeg}
% \caption{Accuracy variation with iterations keeping the swarm size at 30 for all te
% \label{fig:acc_itr}
% \end{figure}

\item Acuuracy with swarm size: In this study, accuracy is evaluated across all tests
\end{enumerate}
From these experiments for finding the optimization parameters, it is concluded that
\\
The parameters that performed well in the previous experiments with test functions ar
%\begin{figure}
% \includegraphics[width=0.8\paperwidth]{Fig/schwefel.png}
% \caption{Schwefel function.}
% \label{fig:schwefel}
%\end{figure}

%\begin{figure}
% \includegraphics[width=0.8\paperwidth]{Fig/con_vs_itr.jpg}
% \caption{Objective function versus iteration for Schwefel function.}
% \label{fig:con_schwefel}
%\end{figure}

\subsection{Model Parameterization}
The seismic model includes physical parameters defined at densely packed grid points,
\\
We propose a technique to define model with 1D depth-velocity profiles at sparse hori

%\begin{figure}
% \includegraphics[width=0.8\paperwidth]{Fig/parameterization.jpg}
% \caption{layered model.}
% \label{fig:parameterization}
%\end{figure}

\subsection{PSO for Preparing Initial Model}
The workflow of this implementation is illustrated in Figure \ref{fig:work_flow}. It
We sparsely select the shot locations and repeat this process for all chosen shots. U
```

```
%\begin{figure}
% \includegraphics[width=0.5\paperwidth]{Fig/flow_chart.png}
% \caption{Work-flow.}
% \label{fig:work_flow}
%\end{figure}

\begin{equation}
O(syn^k, obs^k) = \sqrt{\sum_{i=1}^{N} \left( syn^k - obs^k \right)^2}
\label{eqn:l2norm}
\end{equation}

Where \(obs^k\) and \(syn^k\) indicate the observed data and synthetic data generated

\subsection{Full Waveform Inversion}
The model prepared using PSO serves as an initial model for FWI. Synthetic data is ge
\label{method}


\begin{acknowledgments}
I wish to thank Ivan P\v{s}en\v{c}\'{\i}k and Fr\'ed\'eric Billette
for having names with non-English letters in them.  I wish to thank
\cite{Cerveny} for providing an example of how to make a bib file that
includes an author whose name begins with a non-English character and
\cite{forgues96} for providing both an example of referencing a Ph.D.
thesis and yet more non-English characters.
\end{acknowledgments}

\append{Appendix example}


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\append{The source of the bibliography}

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APPENDIX B

THE SOURCE OF THE BIBLIOGRAPHY

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  year =   1994
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  year   = {1996}
}


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abstract = {Full-waveform inversion (FWI) has become a popular method to estimate ela
author = {Datta, Debanjan and Sen, Mrinal K.},
doi = {10.1190/GEO2015-0339.1},
file = {:C\:/Users/VIKAS/AppData/Local/Mendeley Ltd./Mendeley Desktop/Downloaded/Datt
issn = {19422156},
journal = {Geophysics},
mendeley-groups = {global_optimization},
number = {4},
pages = {R211--R223},
title = {{Estimating a starting model for full-waveform inversion using a global opti
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volume = {81},
year = {2016}
}


@article{Fu2021,
author = {Fu, Xin and Innanen, Kristopher A and Project, Crewes},
file = {:C\:/Users/VIKAS/AppData/Local/Mendeley Ltd./Mendeley Desktop/Downloaded/Fu,
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pages = {1--3},
title = {{A new parallel simulated annealing algorithm for 1 . 5D acoustic full-wavef
year = {2021}
}


@article{Shiba2005,
abstract = {A source inversion method using very fast simulated annealing is proposed
author = {Shiba, Yoshiaki and Irikura, Kojiro},
doi = {10.1186/BF03351837},
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abstract = {Full waveform inversion (FWI) has been a successful tool to build high re
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abstract = {The history, empirical evidence and classical explanations of the signifi
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@INPROCEEDINGS{kennedy,
author={Kennedy, J. and Eberhart, R.},
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abstract = {Particle swarm optimization (PSO) is a population-based stochastic optimi
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@Inbook{Couceiro2016,
author="Couceiro, Micael
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@article{Ye2024,
abstract = {An adaptive ensemble of surrogates assisted optimization algorithm combin
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author = {Dong, Huachao and Song, Baowei and Wang, Peng and Huang, Shuai},
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@article{nirmit2024,
author = {Dhabaria, Nirmit and Singh, Satish C},
title = "{Hamiltonian Monte Carlo based elastic full-waveform inversion of wide-angle
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