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Shotwavemod: An Open Package For Acoustic 2D/3D Seismic Wavefield and Shot Acquisition Modeling Using the Pseudo Spectral Element and Finite Difference Methods

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Abstract - Shotwavemod is an open package for 2D/3D acoustic seismic wave simulation, using the Pseudo Spectral Element and Finite Difference Method. It can also be used for forward modeling of seismic reflection acquisition. The shotwavemod offers straightforward execution of the simulation process, yet customizable parameters. The algorithm was optimized using vectorization and parallel computation to speed up the computational time. The simulation results of the Pseudo Spectral Element Method was compared to the Finite Difference Method. It is observed that the Finite Difference Method resulted in ringing artifacts as a numerical dispersion, particularly for higher frequencies. Nevertheless, with higher computational cost, the Pseudo Spectral Element Method effectively handles this numerical dispersion issue. The shotwavemod was tested for a complex velocity model of the Marmousi. The results are quite promising, where shot gathers of seismic reflections are successfully established corresponding to the complex structure of the Marmousi. The shotwavemod is accessible to the public, and is a suitable tool for educational and research purposes involving seismic wave simulation.

Keywords: seismic wave simulation, spectral element, finite difference, vectorization, parallel computing

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Introduction

The vast utilization of seismic waves in geosciences for various purposes is no longer a question. For instance, seismologists use seismic waves to locate the source of an earthquake, to estimate the risk of ground-shaking hazards, to predict the interior of the earth, and to image the subduction slab. Exploration geoscientists utilize refracted and reflected seismic waves to uncover the economic resources in the subsurface.

Observing the seismic wave phenomena provides substantial benefits. Nevertheless, a comprehensive understanding of how seismic waves propagate through complex mediums can not be obtained from observational data alone. Therefore, simulating seismic waves is required.

Several numerical methods are used to simulate the wave propagation. For instance, the Finite Difference Method (FDM) is used to solve the partial derivative equation of wave propagation in an anisotropic medium (Igel *et al.*, 1995). In 2007, a tutorial was provided to run a 3D acoustic wave simulation on limited CPU memory by using FDM (Etgen and O'Brien, 2007). A recently advanced scheme, Equivalent Staggered-Grid (ESG) is used to optimize FDM in 3D elastic wave stimulation (Zou *et al*., 2020).

Another approach to simulate the wave propagation is the Pseudo Spectral Element Method (SEM) which solves the partial derivative in the spectral domain. In 2000, the Pseudo Spectral Element Method was applied to simulate anisotropic wave propagation (Komatitsch *et al*., 2000). The widely known package for global wave field simulation, SPECFEM3D, uses the Pseudo Spectral Element Method (Komatitsch and Tromp, 2002a, 2002b).

Previous works have established strong foundations for modeling seismic wave propagation. Nevertheless, the availability of computer programmes to conduct seismic wave simulation with their own computing resource is rarely open to the public. Therefore, shotwavemod is presented as an alternative open package for 2D/3D acoustic-seismic wavefield and shot record modeling.

The explanation of numerical methodologies behind the shotwavemod could be found in the following section. Two numerical methods of the FEM and SEM were implemented. Pseudocodes of algorithms were provided for software reproducibility. In order to optimize the code, vectorization was implemented, reducing the usage of *for-loop* operation (repeating a set of instructions multiple times). The shotwavemod also takes advantage of CPUs availability by implementing a parallel computing scheme to speed up the simulation time.

The programme has been tested for the case of a simple 3D model of a layer cake medium and a complex 2D model of Marmousi. The reflected and transmitted wavefield phenomena are clearly observed at the velocity boundaries both for the FDM and SEM. Modeling artifacts as numerical dispersion occurred quite prominently in the FDM simulation, particularly in higher frequencies. Fortunately, the simulation of the SEM successfully eliminates the artifacts.

The shotwavemod package is a valuable tool for finding optimum shot acquisition parameters of reflection seismic survey; thus a representative of velocity model respect to the surveyed area is required. An example of shot acquisition template for 2D and 3D seismic survey is provided in the package. This template could be extended for a full scale seismic survey.

The shotwavemod package is also useful for teaching. This lightweight package can be run in a standard machine with flexible parameterization, allowing students to explore seismic wave behaviour in their designated scenarios. Students will have experience and better understanding of seismic wave behaviour using vivid or clear visualization from the package.

Theory and Method

Acoustic Wave Equation

Representation of acoustic wave equation as a partial differential equation (Greenberg, 1998) was written as:

$$u_{tt} = c^2 \nabla^2 u \qquad (1)$$

where:
c is compressional wave velocity,
∇^2 is second partial derivative, and
u is displacement.

For three dimensional cases, Equation 1 can be expressed as:

$$\frac{\partial^2 u}{\partial t^2} = c^2 \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) \qquad (2)$$

where x, y, z, are the 3D axes of wave propagation.

Exact solution of acoustic wave propagation as a function of time $u(t)$ can be obtained by solving Equation 2 using a second-order partial derivative of the wave equation. In a discrete world such as computer simulation, the solution of Equation 2 can be approximated using a numerical method such as the Finite Difference and Pseudo Spectral Element Methods.

Finite Difference of Acoustic Wave Equation

The finite difference is one of the numerical methods for solving Equation 2, following the definition of derivative (Thomas *et al*., 2014):

$$f'(x)\frac{df(x)}{dx}=\lim_{h\to 0}\frac{f(x+h)-f(x)}{(x+h)-x}=\lim_{h\to 0}\frac{f(x+h)-f(x)}{h} \quad \text{......} \ (3)$$

Approximation for the solution of Equation 3 will provide a "near-exact" result if variable *h* is close to zero. For a computational purpose, the centered first derivative is written as an approximation:

$$f'(x)\approx\frac{f(x+h)-f(x-h)}{2h} \quad \text{..............................} \ (4)$$

Thus, the centered second derivative is represented by:

$$f'(x)\approx\frac{f(x+h)-f(x-h)}{h^2} \quad \text{............................} \ (5)$$

Performing mathematical substitution of the centered second derivative of Equation 5 for the acoustic wave equation, the following equation is obtained:

$$\frac{u(t+\Delta t)-2u(t)+u(t+\Delta t)}{\Delta t^2}=c^2\left(D_x^2u+D_x^2u+D_x^2u\right) \quad \text{......} \ (6)$$

$$D_x^2u=\frac{u_{i+1,j,k}-2u_{i,j,k}+u_{i-1,j,k}}{\Delta x^2}$$

$$D_y^2u=\frac{u_{i,1+j,k}-2u_{i,j,k}+u_{i,j-1,k}}{\Delta y^2}$$

$$D_z^2u=\frac{u_{i,j,k+1}-2u_{i,j,k}+u_{i,j,k-1}}{\Delta z^2} \quad \text{.................} \ (7)$$

where:
Δt is time sampling,
Δx, Δy, Δz, are grid sizes for *x*, *y*, *z*, axis respectively,
i, *j*, *k*, are indexes of *x*, *y*, *z*, grid (Igel, 2016).

Substituting Equation 7 to Equation 6, the wavefield representation for the extrapolated time is shown by:

$$u^{n+1}=2u^n-u^{n-1}+\Delta t^2c^2\left(D_x^2u+D_y^2u+D_z^2u\right) \quad \text{......} \ (8)$$

where *n* is n^{th} time iteration.

Fourier Transform of Partial Derivative

The derivative of a specific function can be calculated using the Fast Fourier Transform (Brigham, 1988):

$$FFT\{f'(x)\} = FFT\{(ik_x)\, f(x)\} \quad \text{.......................} \ (9)$$

Therefore,

$$f'(x) = FFT^{1}\{(ik_x)\, FFT\{f(x)\}\} \quad \text{.....................} \ (10)$$

where:
FFT is Fast Fourier Transform,
FFT^{1} is Inverse Fast Fourier Transform, and
k_x is wavenumber.

For the second derivative,

$$f''(x) = FFT^{1}\{(ik_x)^2\, FFT\{f(x)\}\} \quad \text{....................} \ (11)$$

Implementing properties of Fourier Transform to the wave equation Equation 2, there is:

$$\frac{\partial^2u}{\partial t^2}c^2\left(D_{x_1}^2p+D_{x_2}^2p+D_{x_3}^2p\right) \quad \text{..............................} \ (12)$$

$$D_{x_1}^2u=\frac{\partial^2u}{\partial x_{x_1}^2}=FFT^{-1}\left\{(ik_{xi})^2\,FFT\{u,axis=i\}\right\} \quad \text{.........} \ (13)$$

$\frac{\partial^2u}{\partial t^2}$ is solved using the Finite Difference Method, thus

$$\frac{u^{n+1}-2u^n+u^{n-1}}{\Delta t^2}=c^2\sum_{i=1}^{3}D_{x_i}^2u \quad \text{.................} \ (14)$$

$$u^{n+1}=2u^n-u^{n-1}+\Delta t^2c^2\sum_{i=1}^{3}D_{x_i}^2u \quad \text{...............} \ (15)$$

Equation 15 is known as the Pseudo Spectral Element Method for acoustic wave equation solution (Igel, 2016).

Pseudocode and Vectorization

Equation 8 was implemented for the Finite Difference Method and Equation 15 for the Pseudo Spectral Element Method for simulating 2D and 3D acoustic wave propagation. The pseudocode of 3D wave simulation is shown in Figure 1. Since there are three different axes of wave propagations, three times *for-loop* iterations had to be performed. The *for-loop* iteration causes the computation time to be more expensive. This condition is not practical when dealing with a significant amount of numerical grids such as 3D seismic survey simulation. Therefore, vectorization was implemented to reduce *for-loop* operations, as shown in Figure 2.

Result and Discussion

Wavefield Simulation

Shotwavemod package was developed to perform wavefield simulation on 2D and 3D synthetic P-wave velocity fields. The velocity fields are set to be a layer cake model for the convenience of wavefield behaviour analysis generated from both the Pseudo Spectral Element and Finite Difference Methods. Key parameters for 2D and 3D wavefield simulations are described in Tables 1 and 2.

With respect to the parameterization shown in Tables 1 and 2, the result of simulation using the Pseudo Spectral Element and Finite Difference Methods are shown in Figure 3. The results demonstrate ringing artifact following primary events, known as numerical dispersion, is prominent for the Finite Difference Method. The peak frequency effect was evaluated to the numerical dispersion by keeping the other parameters to be the same. By scrolling frequency values from low to high, the numerical dispersion starts to exist at around 120Hz, which is quite dominant in far offsets of first arrivals. Analyzing beyond 120 Hz was continued, and the numerical dispersion seems to get worst as frequency increases.

Shot Record Modeling

Shot modeling is a process of generating seismic records by harvesting amplitude in a specific time sample at designated surface locations. For computational efficiency, shot modeling was performed *on the fly* within iterations, and the amplitude of the wavefield in certain samples was

```
Function finite_difference with input u, Δx, Δy, Δz, nx, ny, nz:
  Define each Dxu, Dyu, Dzu as matrix[nx, ny, nz]
  Assign 0 to all elements in Dxu, Dyu, Dzu.
  for i from 2 to nx-1 with increment 1 do
    for j from 2 to ny-1 with increment 1 do
      for k from 2 to nz-1 with increment 1 do
        Dxu[i,j,k] =  (u[i+1,j,k] - 2*u[i,j,k] + u[i-1,j,k])/Δx²
        Dyu[i,j,k] =  (u[i,j+1,k] - 2*u[i,j,k] + u[i,j-1,k])/Δy²
        Dzu[i,j,k] =  (u[i,j,k+1] - 2*u[i,j,k] + u[i,j,k-1])/Δz²
      end for
    end for
  end for
  output Dxu, Dyu, Dzu
end function

Input P-wave velocity as c
Input grid size of x, y, z as Δx, Δy, Δz respectively
Input number of grid of x, y, z as nx, ny, nz respectively
Input sampling time and maximum time as Δt and max_time
respectively

Define each u_old and u as matrix[nx, ny, nz]
Assign 0 to all elements in u_old and u.

Set source position as S_x, S_y, S_z
Define source amplitude as A as a function of t

for t from 1 to max_time do:
  Dxu, Dyu, Dzu = finite_difference(u, Δx, Δy, Δz, nx, ny, nz)
  u_new = 2*u - u_old + c²*Δt²*(Dxu, Dyu, Dzu)
  u_new[S_x, S_y, S_z] = u_new[S_x, S_y, S_z] + A[t]
  replace u_old with u
  replace u with u_new
  plot u_new
end for
```

Figure 1. Pseudocode of wave propagation using *for-loop* iteration.

```
  z = 2 to nz-1 with increment 1
  Dxu[x,y,z] =  (u[x+1,y,z] - 2*u[x,y,z] + u[x-1,y,z])/Δx²
  Dyu[x,y,z] =  (u[x,y+1,z] - 2*u[x,y,z] + u[x,y-1,z])/Δy²
  Dzu[x,y,k] =  (u[x,y,z+1] - 2*u[x,y,z] + u[x,y,z-1])/Δz²
  output Dxu, Dyu, Dzu
end function

Input P-wave velocity as c
Input grid size of x, y, z as Δx, Δy, Δz respectively
Input number of grid of x, y, z as nx, ny, nz respectively
Input sampling time and maximum time as Δt and max_time
respectively

Define each u_old and u as matrix[nx, ny, nz]
Assign 0 to all elements in u_old and u.

Set source position as S_x, S_y, S_z
Define source amplitude as A as a function of t

Define each Dxu, Dyu, Dzu as matrix[nx, ny, nz]
Assign 0 to all elements in Dxu, Dyu, Dzu.
for t from 1 to max_time do:
  Dxu, Dyu, Dzu = finite_difference(u, Δx, Δy, Δz, nx, ny, nz,
Dxu, Dyu, Dzu)
  u_new = 2*u - u_old + c²*Δt²*(Dxu, Dyu, Dzu)
  u_new[S_x, S_y, S_z] = u_new[S_x, S_y, S_z] + A[t]
```

Figure 2. Pseudocode of wave propagation using vectorization.

Table 1. Key Parameters for 2D Seismic Modeling

Parameter Name	Value
x - model width (m)	2100.0
z - model width (m)	1000.0
dx-grid interval (m)	5.0
dz-grid interval (m)	5.0
x-source location (m)	1050.0
z-source location (m)	0.0
recording time (s)	0.75
source time shift (s)	0.1
sampling rate (msec)	2
frequency (Hz)	200
receiver interval (m)	25
buffer zone (m)	300
surface multiple	0
buffer coefficient	0.0053

Table 2. Key Parameters for 3D Seismic Modeling

Parameter Name	Value
x - model width (m)	2100.0
y - model width (m)	4400.0
z - model width (m)	1000.0
dx-grid interval (m)	5.0
dy-grid interval (m)	5.0
dz-grid interval (m)	5.0
x-source location (m)	1050
y-source location (m)	2200.0
z-source location (m)	20.0
recording time (s)	1.2
source time shift (s)	0.1
buffer zone (m)	300
recint(m)	25
receiver line int (m)	300

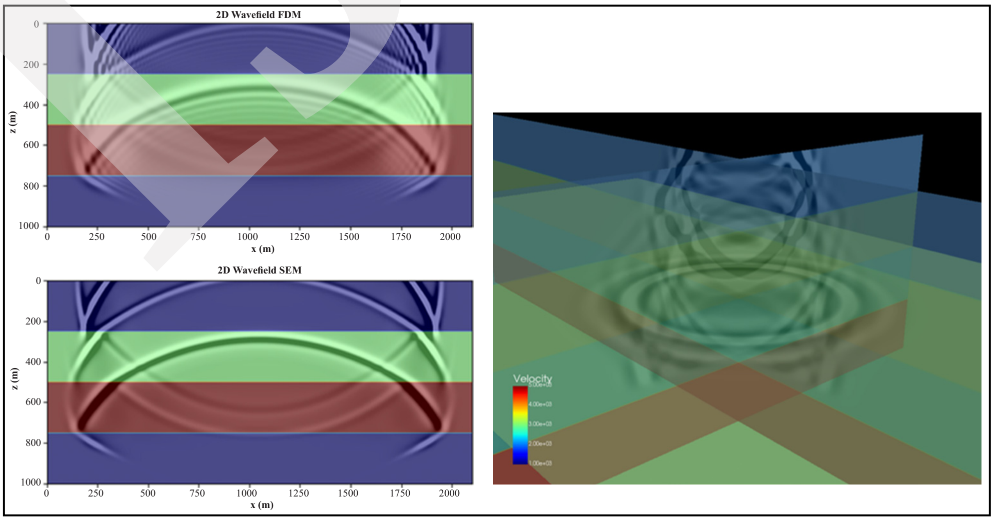

Figure 3. 2D seismic wavefield modeling using the Finite Difference Method (top-left), Pseudo Spectral Element Method (bottom-left), and 3D seismic wavefield modeling using the Pseudo Spectral Element Method (right panel).

collected in memory until the whole iteration was accomplished. The full collection of amplitudes represents a shot record, which was saved in a specific directory for further analysis.

The pseudocode in Figure 4 illustrates how 2D shot gathers were generated. Shot gather consists of *i* samples and *k* traces, *k* respect to the index of wavefield that matches receiver coordinates in a survey design. Two steps of *for-loop* need to be supplied to the programme. The first step is iteration for wavefield at *i* time sample, and the second step is iteration for *k* trace location. The number of traces was stored in predefined *ridx* indexes, which depended on receiver locations in the geometry design.

To avoid reflected waves at model boundaries, absorption parameters, buffer thickness and buffer coefficient (Cerjan *et al*., 1985) were implemented on all sides by default. However, at the surface, the user has control over setting surface-related multiple to be *on* or *off*. In order to have better amplitude integrity is far offset, defining a buffer zone outside the range of seismic acquisition lines and outside the receiver location was recommended. In this way, the effect of absorption can be reduced while maintaining free reflected boundaries. An option for setting source depth was provided to mimic common land seismic acquisition in which dynamite sources are planted at a certain depth for better coupling. The source delay time option was designed to avoid any numerical problem at the earlier burst. Therefore, zero amplitude samples at earlier recordings have to be compensated.

Figure 5 shows the comparison of 2D seismic records generated from the Pseudo Spectral Element and Finite Difference Methods. Shooting parameters are shown in Table 1 with split spread geometry. The first arrival and three primary reflections depict the velocity contrast of the model. As shown in the wavefield simulation, numerical dispersion is clearly diminished in the shot record of the Pseudo Spectral Element Method. Unfortunately, this superiority must be paid by computation cost at somewhat seven times slower than the Finite Difference Method. However, by utilizing multiprocessing parallelism and recent computer hardware advancements, the method is worth considering for solving big-

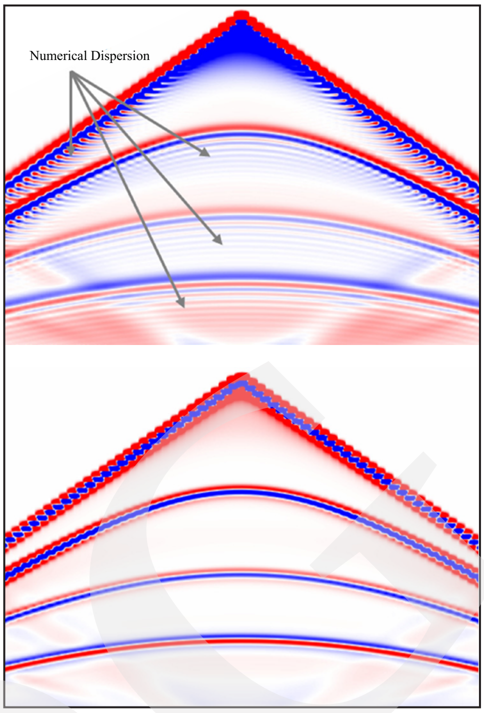

Figure 5. 2D shot gather representations by using parameterization in Table 1. The Finite Difference (top) and Pseudo Spectral Element Methods (bottom). Both shot gathers were generated with the same parameterizations.

```
Input the name of receiver as ridx
Input number of sampling time as nt
Get  wavefield  from  the  result  of  function  finite_difference  or
spectral_element form shotwave package
set k = 0
for i from 1 to nt do:
  k += 1
  for k is index of each value in ridx and x is the value in ridx do:
    shot[i, k] = wavefield[0, x]
  end for
end for
```

Figure 4. Pseudocode for generating 2D shot gather.

scale seismic modeling projects, especially when high-frequency seismic sources are used.

Parameterization in Table 2 was designed for a 3D seismic shot modeling with six receiver lines. For each receiver, lines contain a certain number of receivers. The number of receiver lines and receiver positions in each line can be adjusted depending on user preference by the following algorithm (Figure 6).

```
recpos = from buff to 1 + (ymax - buff) with
increment recint
reclinepos = from buff to 1 + (xmax - buff) with
increment recline_int
```

Figure 6. Pseudocode for defining number of receiver lines and receiver positions in each line. *Buff* is a buffer zone, *ymax* is y model width, *xmax* is x model width, *recint* is receiver interval, and *reclinepos* is receiver line interval position. Hence, there are the schematic diagram for acquisition geometry (Figure 7).

Shot gather is in 3D matrix form consisting of *i* amplitude samples, *m* receiver line, and *n* traces for each receiver line. Zero value in *wavefield* variable represents the collection of amplitude samples at a surface location. The surface buffer zone has been taken into account by skipping the second axis of the wavefield matrix with an integer value of *buff/dz*.

3D shot was generated from the collection of amplitude information at the designated position of receivers during the wavefield at any time sample (Figure 8).

Figure 9 shows a 3D shot record using the Pseudo Spectral Element Method with param-

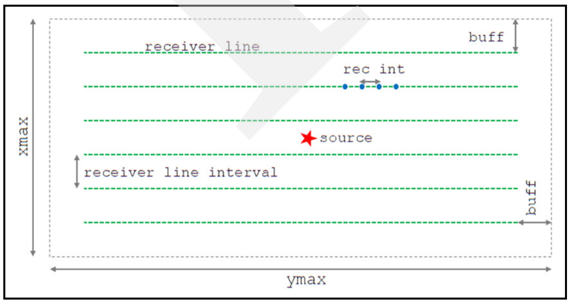

Figure 7. Schematic diagram for 3D shot modeling generated from Table 2 parameterization. 3D shot was generated from the collection of amplitude information at the designated position of receivers during the wavefield at any time sample (Figure 8).

```
Input the name of source as sidx
Input the name of receiver as ridx
Get wavefield from the result of function finite_difference or
spectral_element
for m is index of each value in sidx and j is the value in sidx do:
  for n is index of each value in ridx and x is the value in ridx do:
    shot[m, i, n] = wavefield[j, x, 0]
  end for
end for
```

Figure 8. Pseudocode for generating shot gathers.

eterization and shot geometry described in Table 2 and Figure 7, respectively. The 2D/3D shot seismic modeling cases can be used as a seismic acquisition template. Full-scale seismic survey modeling can be conducted by managing indexes of a given velocity field for each shot record. Demonstration for a full-scale 2D shot modeling using the Marmousi model (Versteeg, 1994) is presented in the next section.

Pseudo Spectral Element Method on the Marmousi Model

P-wave velocity of the Marmousi model is used to test the shotwavemod package viability for the 2D Pseudo Spectral Element Method. The Finite Difference method was not applied to the Marmousi model because, as demonstrated in Figure 5, this method produced poor results with significant numerical dispersion. Extending it to the more complex Marmousi model would likely yield even less reliable results. For given grid points, the total number of generated seismic shot records is 730 shots. Processed-based parallelism of multiprocessing was leveraged to speed up the modeling. To let the machine perform other housekeeping tasks (routine tasks that help keep a programme running smoothly), a few cores free was left. An illustration of multiprocessing parallelism architecture is shown in Figure 10.

Tasks were split into a number of shot records being generated. Each CPU core is responsible for computing a complete wavefield modeling. Results were then stored in a temporary space upon concatenation (Figure 11).

Multicore processing distributes linear tasks for each core to perform shot generation independently. Index of shot location was used to flag output files that will be concatenated to generate shooting sequences.

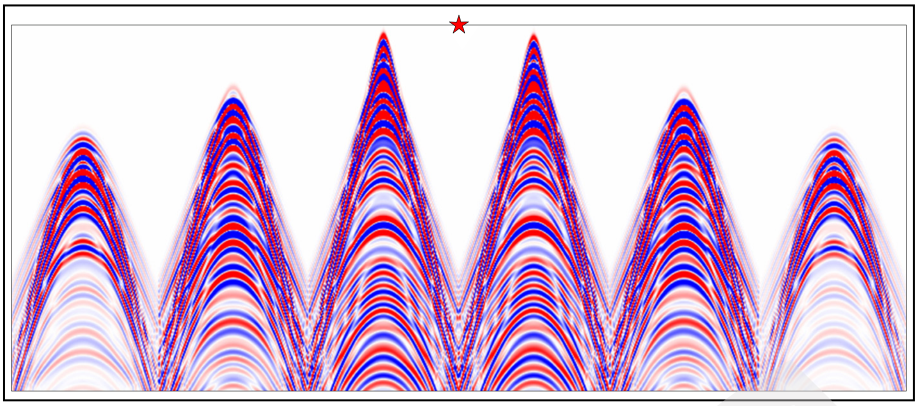

Figure 9. 3D shot record using a layer cake velocity model with the Pseudo Spectral Element Method using parameters shown in Table 2. The red star represents the relative source location.

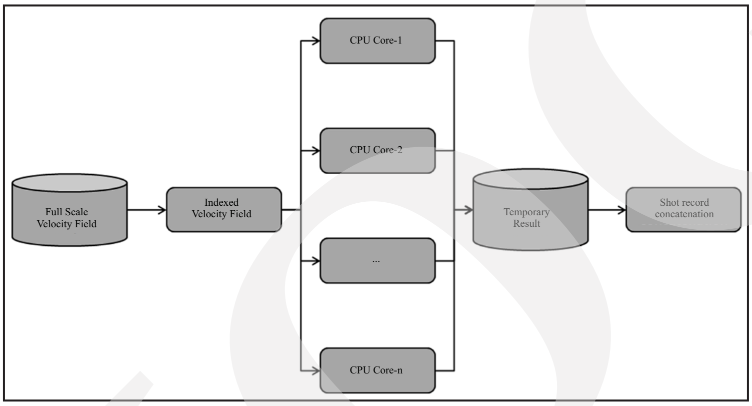

Figure 10. Schematic diagram for full scale shot modeling using multiprocessing parallelism architecture.

```
Input marmuousi as model
Input all parameters for function spectral_element or finite_difference
(shotwave package)
Function multiprocessing  with input shotnumbers, model, spectral_element
parameter:
    model1 = model[:, shotnumbers: shotnumbers + nx]
    Function of spectral_element(model1, all parameters)
end function

shotnumbers = [0, mx ,1]; mx is model second dimension
ncpu = number of cpu - 2  # 2 cores is set to be free of task
for m from 1 to number of shots do:
   for i to 1 to ncpu do:
      k = i + (m * ncpu)
      p do multiprocessing
   end for

   for process from 1 to number of processes do:
      concatenate process
   end for

end for
```

Figure 11. Pseudocode for multiprocessing.

Figure 12 shows P-wave speed of the Marmousi Model resembles a complex geological setting consisting of numerous normal faults, lithology interbeds, structural and stratigraphic traps, as well as hydrocarbon deposits. The geometry of the Marmousi was generated using

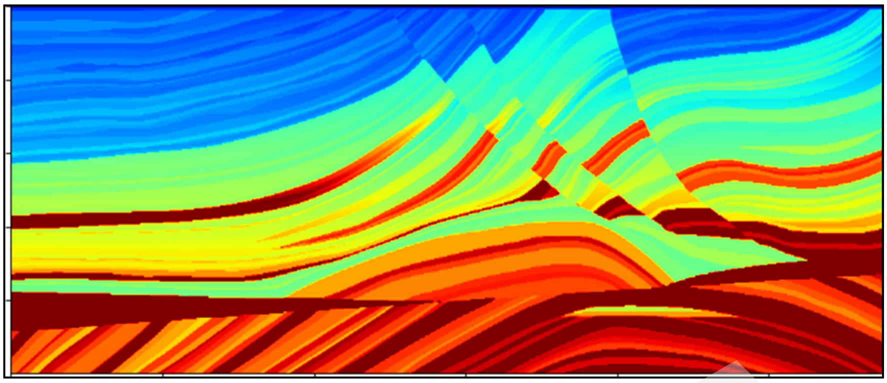

Figure 12. P – wave speed of Marmousi model.

the analog of the North Quenguela through the Cuanza Basin (Versteeg, 1993).

Shot records at several locations using the Pseudo Spectral Element Method on the Marmousi model (Figure 13). Evaluation at several locations is suggested to obtain suitable acquisition parameters, such as peak frequency, receiver interval, source interval, offset, recording length, sampling rate, and buffer parameters. For instance, user could custom-shot interval and acquisition sampling rate to reduce computation time. A suitable shot interval and acquisition sampling rate depends on how complex the model geological settings are. Moreover, these parameters must consider the spatial and vertical resolution of the recordings.

The 2D seismic section shown in Figure 14 results from shot modeling on Marmousi model using the Pseudo Spectral Element Method. The section contains unmigrated 731 traces obtained from near traces of each shot record. The main geological features exhibited in the Marmousi model are well-imaged, even though some numerical noises and diffraction exist. Further seismic processing, such as denoising and migration, is required to obtain the final seismic section.

Pseudo Spectral Element Method on Real Data

This section demonstrates the application of the Pseudo Spectral Element Method to real seismic data. Figure 15 presents a 2D seismic section, and the corresponding subsurface model is shown in Figure 16. Wavefield modeling was conducted on this model (Figure 17) using specified seismic survey parameters. The resulting wavefield model was then processed into a brute-stack section (Figure 18). The brute-stack section reveals clear subsurface geological structures, indicating that the chosen seismic survey parameters are effective for subsurface imaging

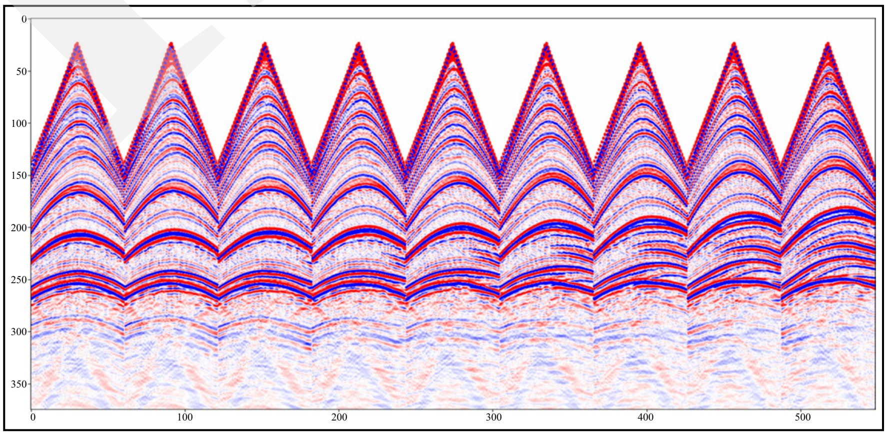

Figure 13. Sample of shot records at several locations for Marmousi model.

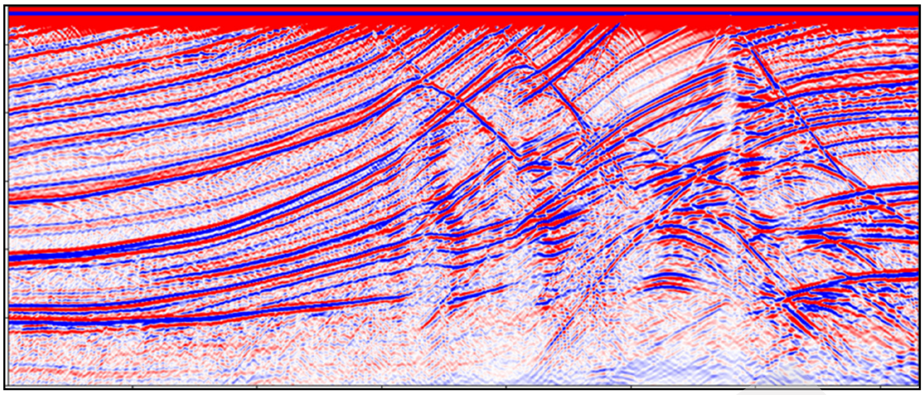

Figure 14. 2D seismic section consists of unmigrated near trace of each shot record.

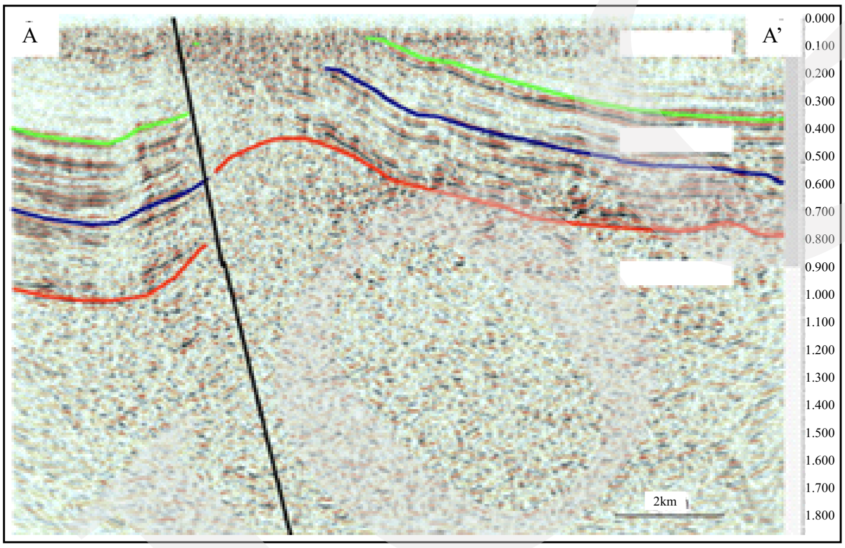

Figure 15. Real 2D seismic section.

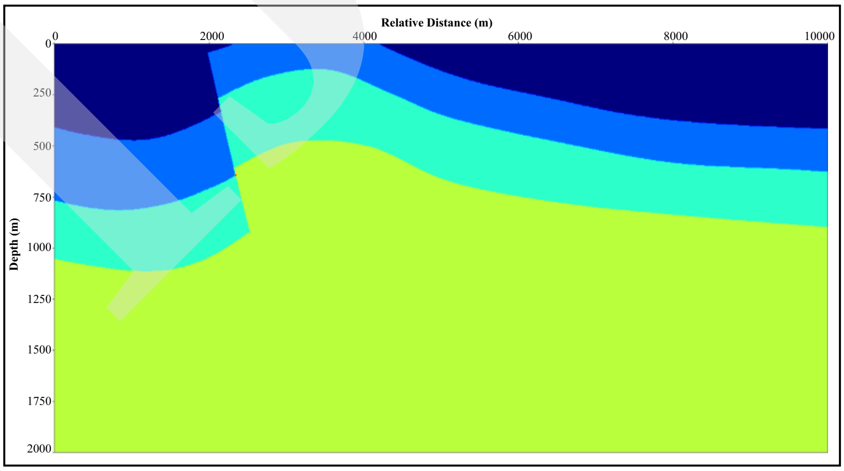

Figure 15. Real 2D seismic section.

in this surveyed area. This result suggests that these parameters are suitable for generating clear subsurface images under the conditions present in this region. Then, the seismic survey

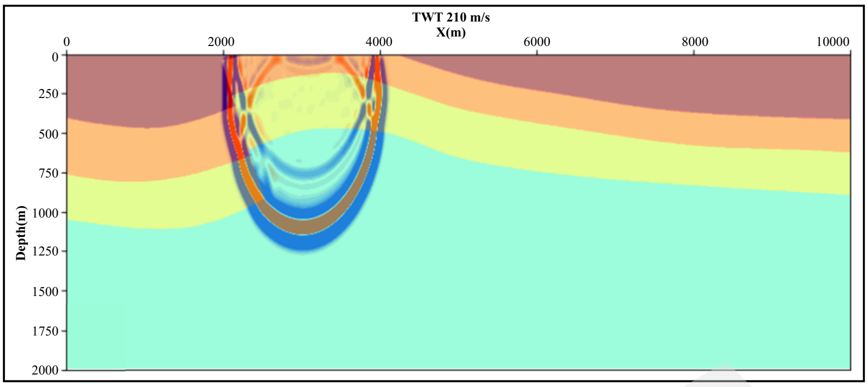

Figure 17. 2D seismic wavefield modeling using the shotwavemod.

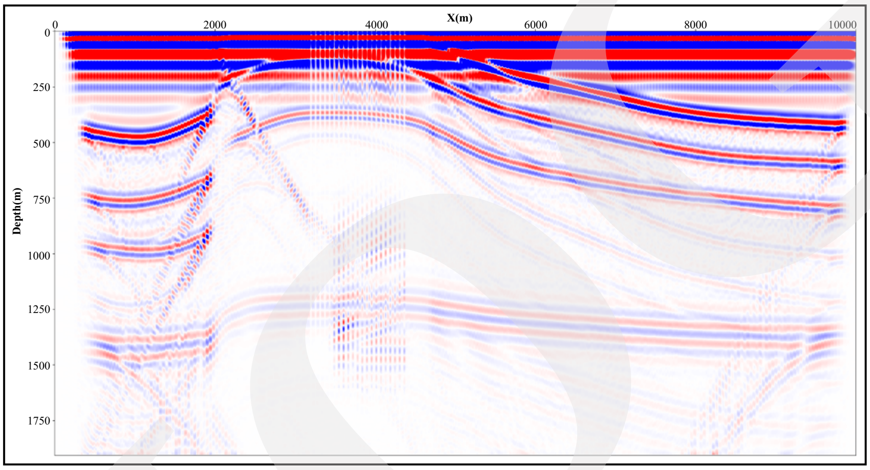

Figure 18**.** Seismic brute-stack of model.

parameter can be applied to the next acquisition. Moreover, since the modeling is designed to generate prestack traces in shot domain, it enables users to sort in any domain such as in common mid point gathers. Figure 19 shows dat in cmp domain at the crest of structure of Figure 15. The gather provides insight for users to define suitable acquisition parameters particularly minimum offset, maximum offset, and receiver interval respect to geological targets.

Package Repositories

The shotwavemod package is written in Python programming language and has been tested as a compiled package for Linux Operating System. The package can be downloaded from GAIA's GitHub repositories (https://github.com/gaia-up/shotwavemod). The compiled programmes can be seen in Table 3.

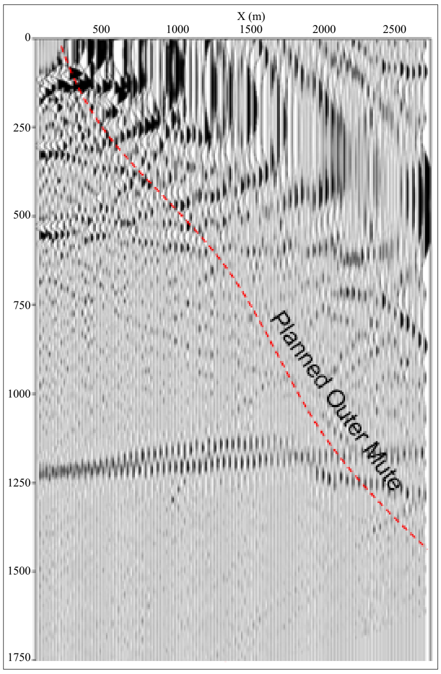

Figure 19. CMP gather at the crest of structure.

Table 3. List of Programmes in Shotwavemod Package

ProgramME	Purpose
SEISMIC2DFDM	2D Seismic Wave and Shot Simulation using the Finite Difference Method
SEISMIC3DFDM	3D Seismic Wave and Shot Simulation using the Finite Difference Method
SEISMIC2DSEM	2D Seismic Wave and Shot Simulation using the Pseudo Spectral Element Method
SEISMIC2DSEMMULTICORES	2D Seismic Wave and Shot Simulation using the Pseudo Spectral Element Method by using multicores
SEISMIC3DSEM	3D Seismic Wave and Shot Simulation using the Pseudo Spectral Element Method
GEOM2D	Geometry Assignment
SEGYOUT	SEGY output

Each programme has a complementary parameter file (par), and should be in the same directory as the main programme. The parameter file contains the value of variables that are required for simulating the process. Users are allowed to modify the parameterization value and velocity model as desired. The programme will recall the parameter file if being executed. The result will be stored at the defined directory in NumPy (Python Library) file format. Thus, Python and the required library are needed for the visualization of shot and wavefield modeling. Examples of Python script format files are also provided to run the programmes and to visualize the results.

Conclusion

The shotwavemod package contains programmes for simulating acoustic seismic wavefields in 2D and 3D mediums. It could be used for forward modeling of shot acquisition. The package is demonstrated that it is capable for 2D/3D seismic wavefield and shot record simulation. Numerical dispersion was observed to appear in higher frequencies of the Finite Difference Method. The Pseudo Spectral Element Method has successfully solved this issue with a higher computational cost as a trade-off.

Several techniques were introduced to optimize the computation time, including vectorization and parallel computation. Vectorization is used to substitute for-loop iteration by matrix operation. Meanwhile, parallel computation with multiple core utilization is worth simulating a model with a significant amount of numerical grids. The results from the simulations provide promising outcomes. The shotwavemod package is open to the public, and the recent package release could be downloaded from GAIA GitHub repository.

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