JHVIT

Release 0.0.14

Maher Nasr

Nov 12, 2021

CONTENTS:

JHVIT is a python package for locating seismic event hypocenters on unstructured grids. The package is an extension of the joint hypocenter-velocity inversion method on tetrahedral meshes. It is mainly recommended for domains with steep topography, underground cavities and stratigraphic and abnormal geological contacts such as folds, faults and shear zones. The code is able to locate a wide range of seismic events going from major earthquakes and nuclear explosions to low and negative magnitude events. Target application areas include computational seismology, hydraulic fracture and microseismic monitoring of mining environments or in civil engineering projects.

The package is written in Python, uses an optimized c++ raytracing code wrapped in Cython and supports parallel computing.

CHAPTER

ONE

GETTING STARTED

1.1 Installing JHVIT

You can use pip to install the package by running:

```
pip install JHVIT
```

1.2 Requirements

JHVIT needs the following packages:

- cython (https://cython.org)
- numpy (https://numpy.org) with version >= 1.20.1
- scipy (https://www.scipy.org)
- ttcrpy (https://pypi.org/project/ttcrpy)
- vtk (https://www.vtk.org)

To run the package using many processes, it is highly recommended to have python-version 3.7.

CHAPTER

TWO

EXAMPLE

JHVIT can automatically read the inversion parameters and data from text files. We recommend to use this feature in order to store this information for future verifications or reuse. We present in this section the templates to prepare such files.

2.1 Parameter File

Users are invited to prepare parameter files and pass them as arguments to the proper JHVIT function. Contents of these files depends of the number of seismic phases to be used since more data and parameters are obviously required when inverting simultaneously P- and S-wave data. We give in the figures below two examples of these parameter files in the case of single-phase inversion (generally P-wave) and in the case of P- and S-wave data inversion. Users may use these templates to prepare their own parameter files by replacing text following the sharp symbol (#) by the proper values (remove the symbol # also).

base name	: #prefix to build output file names
mesh file	: #file containing the domain mesh
rcvfile	: #receiver data file
number of threads	: #thread number to perform parallel computing
arrival times	: #file containing data (arrival times)
Velocity P waves	: #file containing initial velocity model
known velocity points	: #file holding positions and velocity values of known points (optional)
Hypo0	: #file of first hypocenter guesses
Time calibration	: #file of calibration data
number of iterations	: #maximum number of iterations
num. iters. to get hypo.	: #maximum number of iterations for the hypocenter location step
inverse velocity	: # return a velocity model by inverting the data (bool)
reloc.hypo.in 2 steps	: #locate events in one or two steps (bool)
use static corrections	: #apply static corrections at stations (bool)
Verbose	: #return feedbacks on code progress (bool)
Save Velocity	: #save velocity at each iteration or for the last one
maximum stat. correction	: #ratio of static corrections and corresponding traveltimes (5-10%)
Vpmin	: #minimum velocity value
Vpmax	: #maximum velocity value
PAp	: #slope of penalty function
dVp max	: #maximum allowed perturbations for the velocity model
dx max	: #maximum allowed perturbations for the hypocenter coordinates
dt max	: #maximum allowed perturbations for origin times
alpha	: #Lagrangian multiplier relative to the velocity data point misfit
lambda	: #Lagrangian multiplier relative to the smoothness constraint
Gamma	: #Lagrangian multiplier relative to the penalty function
vertical smoothing	: #vertical to horizontal smoothness ratio
convergence Criterion	: #convergence criterion for the location step
uncertainty estm.	: #calculate the hypocenter parameter uncertainties (bool)
confidence level	: #confidence level for the hypocenter ellipsoid and the origin time.

Parameter file template for P-wave data inversion.

base name	: #prefix to build output file names
mesh file	: #file containing the domain mesh
rcvfile	: #receiver data file
number of threads	: #thread number to perform parallel computing
arrival times	: #file containing data (arrival times for P and S waves)
Velocity P waves	: #file containing initial P-wave velocity model
Velocity S waves	: #file containing initial S-wave velocity model
known velocity points	: #file holding positions and velocity values of known points (optional)
Hypo0	: #file of first hypocenter guesses
Time calibration	: #file of calibration data (for P and S waves)
number of iterations	: #maximum number of iterations
num. iters. to get hypo.	: #maximum number of iterations for the hypocenter location step
inverse velocity	: # return P and S wave velocity models by inverting data(bool)
inverse Vs/Vp	: # parametrize the inversion using the Vs/Vp and Vp models(bool)
reloc.hypo.in 2 steps	: #locate events in one or two steps (bool)
use static corrections	: #apply static corrections at stations (bool)
Verbose	: #return feedbacks on code progress (bool)
Save Velocity	: #save velocity at each iteration or for the last one
maximum stat. correction	: #ratio of static corrections and corresponding traveltimes (5-10%)
Vpmin	: #minimum P-wave velocity value
Vpmax	: #maximum P-wave velocity value
Vsmin	: #minimum S-wave velocity value
Vsmax	: #maximum S-wave velocity value
VpVs_min	: #minimum Vp/Vs ratio value
VpVs_max	: # maximum Vp/Vs ratio value
PAp	: #slope of P-wave penalty function
PAs	: #slope of S-wave penalty function
Pvpvs	: #slope of Vp/Vs penalty function
dVp max	: #maximum allowed perturbations for the P-wave velocity model
dVs max	: #maximum allowed perturbations for the S-wave velocity model
dx max	: #maximum allowed perturbations for the hypocenter coordinates
dt max	: #maximum allowed perturbations for origin times
alpha	: #Lagrangian multiplier relative to the velocity data point misfit
lambda	: #Lagrangian multiplier relative to the smoothness constraint
Gamma	: #Lagrangian multiplier relative to the penalty functions of Vp and Vs models
Gamma_vpvs	: #Lagrangian multiplier relative to the penalty function of Vp/Vs model
vertical smoothing	: #vertical to horizontal smoothness ratio
convergence Criterion	: #convergence criterion for the location step
uncertainty estm.	: #calculate the hypocenter parameter uncertainties (bool)
confidence level	: #confidence level for the hypocenter ellipsoid and the origin time

Parameter file template for P- and S-wave data inversion.

2.2 Domain discretization

JHVIT can automatically read domain meshes from separate files. At the moment, only mesh files generated using Gmsh can be recognized. To prepare such files, one must start by creating a geo file (describing the domain geometry) and pass it to Gmsh. For a simple 3D domain showing only topographic irregularities, users may utilize this python script: https://github.com/groupeLIAMG/JHVIT/blob/main/src/Mesh_Prep.py.

Note that MSH files created by Gmsh may vary depending on the considered version. Version 2. is the reference one compatible with JHVIT. The corresponding MSH file format must be similar to this example: https://github.com/groupeLIAMG/JHVIT/blob/main/examples/Model.msh

2.3 Data files

Input data should be organized in text files as shown in the figures below. For single phase inversion, these files should contain 3 columns abbreviated as following: Ev_idn (event indices), arrival times (arrival times) and rcv_index (corresponding receiver indices). In the case of P and S wave data inversion, a fourth column is added to specify the seismic phase (called Phase). Users are invited to use the same column labels to store their data in order to avoid bugs. The first lines are dedicated to insert optional comments and notes.

```
# Synthetic data
Ev_idn   arrival times    rcv_index
1         7.87272554        1
1         7.88024416        2
1         7.86444157        3
.             .             .
.             .             .
.             .             .
1         7.89047888        7
1         7.88758687        8
1         7.88875361        9
.             .             .
.             .             .
.             .             .
1         7.87859728       15
1         7.87795578       16
2         9.24157796        1
2         9.25020304        2
.             .             .
.             .             .
.             .             .
2         9.24837422        8
2         9.25377850        9
.             .             .
.             .             .
.             .             .
2         9.24524137       14
2         9.25741592       15
2         9.25411745       16
3        11.38396339        1
3        11.39169263        2
.             .             .
.             .             .
.             .             .
3        11.38903567        8
3        11.38733365        9
3        11.38572313       10
.             .             .
.             .             .
.             .             .
3        11.37459936       14
3        11.39568086       15
3        11.39519456       16
```

Data file template for P-wave inversion.

```
# Synthetic data ( P and S waves)
Ev_idn   arrival times    rcv_index        phase
1          7.87324649         1            P
1          7.87805834         2            P
.              .              .            .
.              .              .            .
.              .              .            .
1          7.88889117         7            P
1          7.88888229         8            P
1          7.89273529         9            P
.              .              .            .
.              .              .            .
.              .              .            .
1          7.87974900        15            P
1          7.87837546        16            P
1          7.88557918         1            S
1          7.89693308         2            S
1          7.87109548         3            S
.              .              .            .
.              .              .            .
.              .              .            .
1          7.91667262        10            S
.              .              .            .
.              .              .            .
.              .              .            .
1          7.87758587        14            S
1          7.90010873        15            S
1          7.89114704        16            S
2          9.24202777         1            P
2          9.24974567         2            P
.              .              .            .
.              .              .            .
.              .              .            .
2          9.25691069        15            P
2          9.25547888        16            P
2          9.24774546         1            S
2          9.25988804         2            S
.              .              .            .
.              .              .            .
.              .              .            .
2          9.26846245        15            S
2          9.27055185        16            S
3         11.38377157         1            P
.              .              .            .
.              .              .            .
.              .              .            .
3         11.39557133        16            P
3         11.39999844         1            S
.              .              .            .
.              .              .            .
.              .              .            .
3         11.42111537        16            S
```

Data file template for P- and S-wave inversion. We suppose herein a dataset with 3 seismic events recorded in 16 receivers each one.

2.4 Data calibration files

The available calibration data can be stored in specific files following predefined structure. In the case of single-phase inversion, data must be organized in 5 columns: the 1st column corresponds to shot indices (Ev_idn), the 2nd column for traveltime values (labeled arrival times), the 3rd column gives corresponding receiver (rcv_index). The last three columns (X, Y and Z) must contain positions of calibration shots. A sixth column would be added if both P and S waves are inverted in order to specify seismic phase of each calibration shot.

```
# Synthetic data (Calib. data)
Ev_idn   arrival times    rcv_index       X            Y              Z
1          0.06298            1        305.300      5723.720        0.7379
1          0.07147            2        305.300      5723.720        0.7379
.             .               .           .             .              .
.             .               .           .             .              .
.             .               .           .             .              .
1          0.07979            7        305.300      5723.720        0.7379
1          0.06588            8        305.300      5723.720        0.7379
1          0.05380            9        305.300      5723.720        0.7379
.             .               .           .             .              .
.             .               .           .             .              .
.             .               .           .             .              .
1          0.07540           15        305.300      5723.720        0.7379
1          0.07437           16        305.300      5723.720        0.7379
2          0.04669            1        305.300      5723.820        0.7459
2          0.05555            2        305.300      5723.820        0.7459
.             .               .           .             .              .
.             .               .           .             .              .
.             .               .           .             .              .
2          0.04520            8        305.300      5723.820        0.7459
2          0.03373            9        305.300      5723.820        0.7459
.             .               .           .             .              .
.             .               .           .             .              .
.             .               .           .             .              .
2          0.03877           14        305.300      5723.820        0.7459
2          0.05728           15        305.300      5723.820        0.7459
2          0.05858           16        305.300      5723.820        0.7459
3          0.04011            1        305.250      5723.920        0.7420
3          0.04644            2        305.250      5723.920        0.7420
.             .               .           .             .              .
.             .               .           .             .              .
.             .               .           .             .              .
3          0.03164            8        305.250      5723.920        0.7420
3          0.01753            9        305.250      5723.920        0.7420
3          0.01278           10        305.250      5723.920        0.7420
.             .               .           .             .              .
.             .               .           .             .              .
.             .               .           .             .              .
3          0.03645           14        305.250      5723.920        0.7420
3          0.05147           15        305.250      5723.920        0.7420
3          0.05277           16        305.250      5723.920        0.7420
```

Template of calibration data file for P-wave inversion.

```
# Synthetic data (Calib. data for P and S waves)
Ev_idn   arrival times    rcv_index       X            Y              Z            Phase
1         0.06459           1          305.300      5723.720        0.7379           P
1         0.06134           2          305.300      5723.720        0.7379           P
.            .              .             .             .              .             .
.            .              .             .             .              .             .
.            .              .             .             .              .             .
1         0.08065           7          305.300      5723.720        0.7379           P
1         0.06218           8          305.300      5723.720        0.7379           P
1         0.04856           9          305.300      5723.720        0.7379           P
.            .              .             .             .              .             .
.            .              .             .             .              .             .
.            .              .             .             .              .             .
1         0.06500          15          305.300      5723.720        0.7379           P
1         0.07852          16          305.300      5723.720        0.7379           P
1         0.11380           1          305.300      5723.720        0.7379           S
1         0.12705           2          305.300      5723.720        0.7379           S
1         0.10403           3          305.300      5723.720        0.7379           S
.            .              .             .             .              .             .
.            .              .             .             .              .             .
.            .              .             .             .              .             .
1         0.07845          10          305.300      5723.720        0.7379           S
.            .              .             .             .              .             .
.            .              .             .             .              .             .
.            .              .             .             .              .             .
1         0.09674          14          305.300      5723.720        0.7379           S
1         0.13822          15          305.300      5723.720        0.7379           S
1         0.14120          16          305.300      5723.720        0.7379           S
2         0.04583           1          305.300      5723.820        0.7459           P
2         0.05600           2          305.300      5723.820        0.7459           P
.            .              .             .             .              .             .
.            .              .             .             .              .             .
.            .              .             .             .              .             .
2         0.05636          15          305.300      5723.820        0.7459           P
2         0.05417          16          305.300      5723.820        0.7459           P
2         0.08901           1          305.300      5723.820        0.7459           S
2         0.09252           2          305.300      5723.820        0.7459           S
.            .              .             .             .              .             .
.            .              .             .             .              .             .
.            .              .             .             .              .             .
2         0.11298          15          305.300      5723.820        0.7459           S
2         0.10834          16          305.300      5723.820        0.7459           S
3         0.03906           1          305.250      5723.920        0.7420           P
.            .              .             .             .              .             .
.            .              .             .             .              .             .
.            .              .             .             .              .             .
3         0.05274          16          305.250      5723.920        0.7420           P
3         0.07691           1          305.250      5723.920        0.7420           S
.            .              .             .             .              .             .
.            .              .             .             .              .             .
.            .              .             .             .              .             .
3         0.10081          16          305.250      5723.920        0.7420           S
```

Template of calibration data file for P- and S-wave inversion.

2.5 Receiver files

Users can prepare their receiver files as following: In the first line they must specify the number of receivers to be used followed by the coordinates X, Y and Z of each one written at the rate of on receiver per line.

```
16
305.4200  5724.0010  0.6853

305.4300  5724.0410  0.6687

305.4300  5723.9660  0.6346

305.4520  5723.9660  0.6566

305.3800  5724.0010  0.6996

305.3800  5724.0460  0.6923
   ..        ..        ..
   ..        ..        ..
   ..        ..        ..

305.4300  5724.0420  0.6200

305.4520  5724.0420  0.6420
```

Example of a receiver file. Receiver coordinates are given in the MTM system.

2.6 Initial velocity values and hypocenter positions

Initial estimates for velocity models and hypocenter coordinates may be stored in text files that can be indicated in the parameter files. A a simple homogeneous model is usually sufficient. The initial velocity file contains in this case a single value corresponding to the chosen velocity. Users are referred to Nasr et al. (2021) to properly select a velocity value that facilitates code convergence. If a complex model has to be set, the velocity values must to be sorted according to the node indices. The first hypocenter estimates can be stored in a five-column text file. These columns are labeled: Ev_idn (hypocenter indices), t0 (origin times), X, Y and Z (spatial coordinates). Note that the initial positions of hypocenters should be all different to avoid a singular Jacobian matrix.

```
# Synthetic data
Ev_idn       t0       X            Y             Z
1          7.87   305.300     5723.900       0.600

2          9.24   305.250     5723.900       0.615

3         11.38   305.300     5723.800       0.620

4         11.68   305.200     5723.900       0.600

5         13.85   305.250     5723.900       0.640

6         15.47   305.200     5723.800       0.620

7         16.59   305.300     5723.700       0.600

8         17.46   305.300     5723.950       0.620

9         18.16   305.350     5723.900       0.600

10        26.53   305.300     5723.850       0.610
```

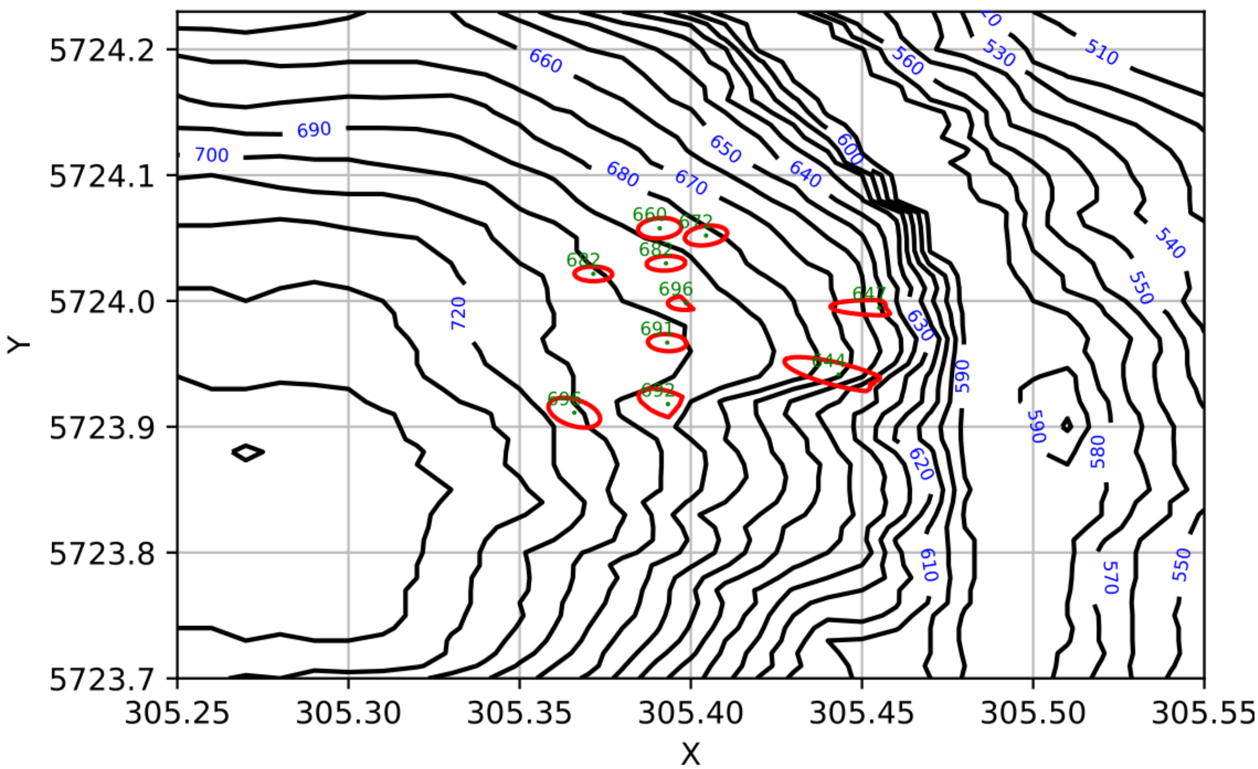
Example of initial hypocenter file.

CHAPTER THREE

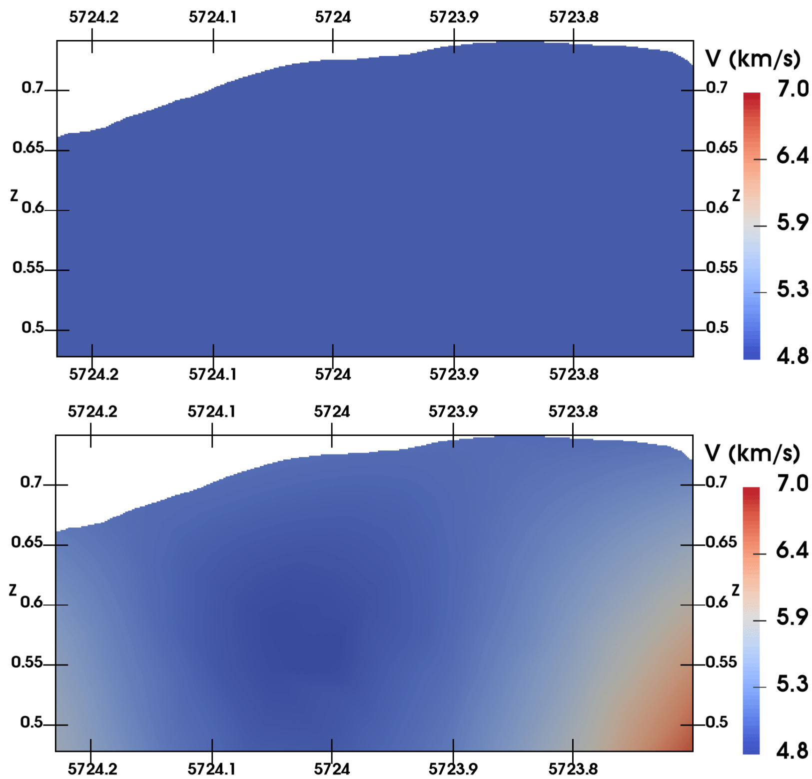
RESULTS

If no bugs occur, `JHVIT` will return a python dictionary containing an estimation of: - Hypocenter coordinates and their origin times. - Static correction values at the stations. - Velocity models for P-wave and eventually S-wave or the Vp/Vs ratio model. - Convergence states of each hypocenter. - Parameter uncertainty: this includes the origin time uncertainty and the confidence ellipsoid of each seismic event. - Data misfit norms.

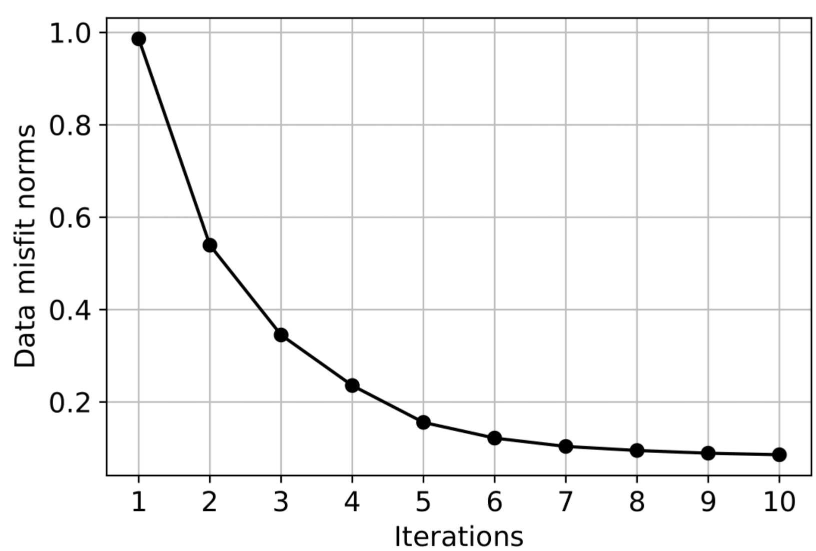
Examples of expected results are presented below. These results can be reproduced by running the test code: https://github.com/groupeLIAMG/JHVIT/blob/main/examples/Example.py



Location of a set of 10 seismic events plotted on topographic map. Green dots are the estimated geographic position of the hypocenters. The red outlines give the projections of the confidence ellipsoids on the horizontal plane. The Z-component of each hypocenter is specified nearby.



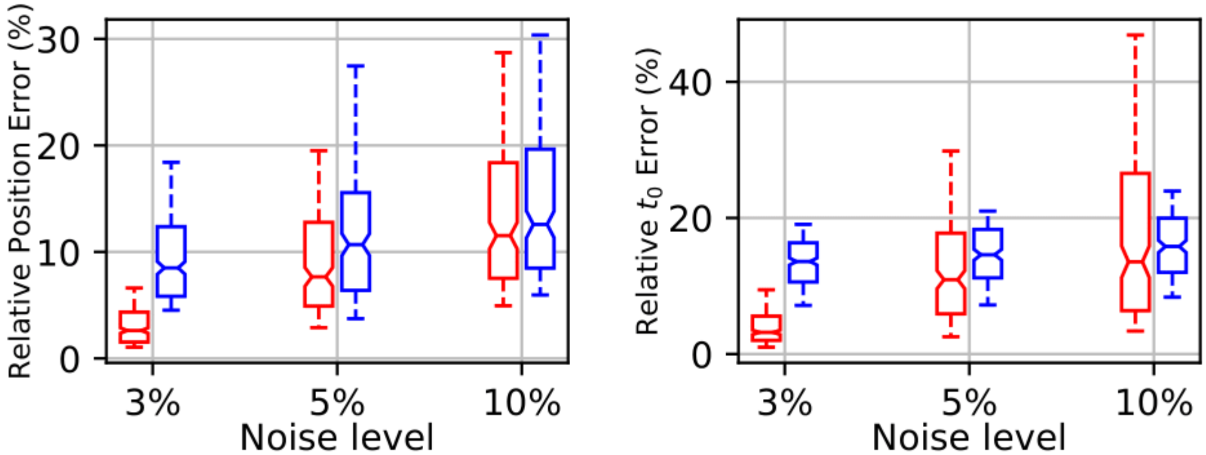
Comparison between the true velocity model and the model obtained by inversion for a synthetic seismic dataset with 5% of gaussian noise. Leftmost figure: true model. Rightmost: inverted model.



Evolution of the data misfit norms as a function of iterations.

3.1 Noise effects

A test involving 3 datasets with 3 noise levels (3%, 5% and 10%) and two different models (homogeneous and layered) was performed to assess the JHVIT robustness. For the hypocenter coordinates, obtained relative errors vary between 2.5% to 12% of the average distance sources-receivers while the origin time errors between 3% and 16%. In general, we noted lower errors for the homogenous model. Note also that velocity models are less sensitive to noise than the hypocenter parameters. This may be explained by the implemented Tikhonov constraint that acts as a filter by cutting off the contribution of the small eigenvalues of the Jacobian matrix.



Relative errors of hypocenter positions and origin times versus noise percentage. Red and blue boxplots refer respectively to the errors calculated for the homogeneous and layered model.

CHAPTER

FOUR

CODE DOCUMENTATION

Here is the Documentation of the main functions callable in `JHVIT`.

4.1 Module JHVIT.JHVI_Tetra

`JHVI_Tetra.`**`jntHypoVel_T`**(*data*, *caldata*, *Vinit*, *cells*, *nodes*, *rcv*, *Hypo0*, *par*, *threads=1*, *vPoints=array([], dtype=float64)*, *basename='Vel'*)

Joint hypocenter-velicoty inversion from P wave arrival time data parametrized using the velocity model.

Parameters

- **data** (*np.ndarray, shape(arrival time number, 3)*) – Arrival times and corresponding receivers for each event..
- **caldata** (*np.ndarray, shape(number of calibration shots, 3)*) – Calibration shot data.
- **Vinit** (*np.ndarray, shape(nnodes,1) or (1,1)*) – Initial velocity model.
- **cells** (*np.ndarray of int, shape (cell number, 4)*) – Indices of nodes forming the cells.
- **nodes** (*np.ndarray, shape (nnodes, 3)*) – Node coordinates.
- **rcv** (*np.ndarray, shape (receiver number,3)*) – Coordinates of receivers.
- **Hypo0** (*np.ndarray, shape(event number, 5)*) – First guesses of the hypocenter coordinates (must be all diffirent).
- **par** (*instance of the class Parameters*) – The inversion parameters.
- **threads** (*int, optional*) – Thread number. The default is 1.
- **vPoints** (*np.ndarray, shape(point number,4), optional*) – Known velocity points. The default is np.array([]).
- **basename** (*string, optional*) – The filename used to save the output file. The default is 'Vel'.
- **Returns** –
- **--------** –
- **output** (*python dictionary*) – It contains the estimated hypocenter coordinates and their origin times, static correction values, velocity model, convergence states, parameter uncertainty and residual norm in each iteration.

JHVI_Tetra.**jntHyposlow_T**(*data*, *caldata*, *Vinit*, *cells*, *nodes*, *rcv*, *Hypo0*, *par*, *threads=1*, *vPoints=array([], dtype=float64)*, *basename='Slowness'*)

Joint hypocenter-velicoty inversion from P wave arrival time data parametrized using the slowness model.

Parameters

- **data** (*np.ndarray, shape(arrival time number, 3)*) – Arrival times and corresponding receivers for each event.
- **caldata** (*np.ndarray, shape(number of calibration shots, 6)*) – Calibration shot data.
- **Vinit** (*np.ndarray, shape(nnodes,1) or (1,1)*) – Initial velocity model.
- **Cells** (*np.ndarray of int, shape (cell number, 4)*) – Indices of nodes forming the cells.
- **nodes** (*np.ndarray, shape (nnodes, 3)*) – Node coordinates.
- **rcv** (*np.ndarray, shape (receiver number,3)*) – Coordinates of receivers.
- **Hypo0** (*np.ndarray, shape(event number, 5)*) – First guesses of the hypocenter coordinates (must be all diffirent).
- **par** (*instance of the class Parameters*) – The inversion parameters.
- **threads** (*int, optional*) – Thread number. The default is 1.
- **vPoints** (*np.ndarray, shape(point number,4), optional*) – Known velocity points. The default is np.array([]).
- **basename** (*string, optional*) – The filename used to save the output files. The default is 'Slowness'.

Returns **output** – It contains the estimated hypocenter coordinates and their origin times, static correction values, velocity model, convergence states, parameter uncertainty and residual norm in each iteration.

Return type python dictionary

JHVI_Tetra.**jntHypoVelPS_T**(*obsData*, *calibdata*, *Vinit*, *cells*, *nodes*, *rcv*, *Hypo0*, *par*, *threads=1*, *vPnts=(array([], dtype=float64), array([], dtype=float64))*, *basename='Vel'*)

Joint hypocenter-velocity inversion from P- and S-wave arrival time data parametrized using the velocity models.

Parameters

- **obsData** (*tuple of two np.ndarrays (shape(observed data number, 3))*) – Observed arrival time data of P- and S-waves.
- **calibdata** (*tuple of two np.ndarrays (shape (number of calibration shots, 5))*) – Calibration data of P- and S-waves.
- **Vinit** (*tuple of np.ndarrays (shape (nnodes, 1) or (1,1))*) – Initial velocity models of P- and S-waves.
- **cells** (*np.ndarray of int, shape (cell number, 4)*) – Indices of nodes forming the cells.
- **nodes** (*np.ndarray, shape (nnodes, 3)*) – Node coordinates.
- **rcv** (*np.ndarray, shape (receiver number,3)*) – Coordinates of receivers.
- **Hypo0** (*np.ndarray, shape(event number, 5)*) – First guesses of the hypocenter coordinates (must be all diffirent).
- **par** (*instance of the class Parameters*) – The inversion parameters.

- **threads** (*int, optional*) – Thread number. The default is 1.
- **vPnts** (*tuple of two np.ndarrays, optional*) – Known velocity points of P- and S-waves. The default is (np.array([]), np.array([])).
- **basename** (*string, optional*) – The filename used to save the output files. The default is 'Vel'.

Raises **ValueError** – If the Vs/Vp ratio is inverted instead of Vs model and some known velocity points are given for the S wave and not for the P wave.

Returns **output** – It contains the estimated hypocenter coordinates and their origin times, static correction values, velocity models of P- and S-waves, hypocenter convergence states, parameter uncertainty and residual norm in each iteration.

Return type python dictionary

JHVI_Tetra.**jntHyposlowPS_T**(*obsData*, *calibdata*, *Vinit*, *cells*, *nodes*, *rcv*, *Hypo0*, *par*, *threads=1*, *vPnts=(array([], dtype=float64), array([], dtype=float64))*, *basename='Slowness'*)

Joint hypocenter-velocity inversion from P- and S-wave arrival time data parametrized using the slowness models.

Parameters

- **obsData** (*tuple of two np.ndarrays (shape(observed data number, 3))*) – Observed arrival time data of P- and S-waves.
- **calibdata** (*tuple of two np.ndarrays (shape (calibration shot number, 6))*) – Calibration data of P- and S-waves.
- **Vinit** (*tuple of np.ndarrays (shape (nnodes, 1) or (1,1))*) – Initial velocity models of P- and S-waves.
- **cells** (*np.ndarray of int, shape (cell number, 4)*) – Indices of nodes forming the cells.
- **nodes** (*np.ndarray, shape (nnodes, 3)*) – Node coordinates.
- **rcv** (*np.ndarray, shape (receiver number,3)*) – Coordinates of receivers.
- **Hypo0** (*np.ndarray, shape(event number, 5)*) – First guesses of the hypocenter coordinates (must be all diffirent).
- **par** (*instance of the class Parameters*) – The inversion parameters.
- **threads** (*int, optional*) – Thread number. The default is 1.
- **vPnts** (*tuple of two np.ndarrays, optional*) – Known velocity points of P- and S-waves. The default is (np.array([]),np.array([])).
- **basename** (*string, optional*) – The filename used to save the output files. The default is 'Slowness'.

Raises **ValueError** – If the Ss/Sp ratio is inverted instead of Vs model and some known velocity points are given for the S wave and not for the P wave.

Returns **output** – It contains the estimated hypocenter coordinates and their origin times, static correction values, velocity models of P- and S-waves, hypocenter convergence states, parameter uncertainty and residual norm in each iteration.

Return type python dictionary

JHVI_Tetra.**jointHypoVel_T**(*inputFileParam*, *model='slow'*)

Joint hypocenter-velocity inversion using P wave data.

Parameters

- `inputFileParam` (*string*) – Text file containing inversion parameters and data filenames.
- `model` (*string*) – Sought model : 'vel' for an inversion problem parametrized using the velocity model,'slow' for an inversion problem parametrized using the slowness model. The default is 'slow'.

Returns It contains the estimated hypocenter coordinates and their origin times, static correction values, velocity model, convergence states, parameter uncertainty and residual norm in each iteration.

Return type python dictionary

`JHVI_Tetra.`**`jointHypoVelPS_T`**(*inputFileParam*, *model='slow'*)

Joint hypocenter-velocity inversion using P- and S-wave arrival time data.

Parameters

- `inputFileParam` (*string*) – Text file containing inversion parameters and data filenames.
- `model` (*string*) – Sought models: 'vel' for an inversion problem parametrized using the velocity model, 'slow' for an inversion problem parametrized using the slowness model. The default is 'slow'.

Returns It contains the estimated hypocenter coordinates and their origin times, static correction values, velocity models of P and S waves, hypocenter convergence states, parameter uncertainty and residual norm in each iteration.

Return type python dictionary

`JHVI_Tetra.`**`readEventsFiles`**(*time_file*, *waveType=False*)

Read a list of seismic events and corresponding data from a text file.

Parameters

- `time_file` (*string*) – Event data filename.
- `waveType` (*bool*) – True if the seismic phase of each event is identified. The default is False.

Returns **data** – Event arrival time data

Return type np.ndarray or a list of two np.ndarrays

CHAPTER FIVE

REFERENCES

For more details and information, users are invited to look into these references:

- Block, L.V. (1991): Joint hypocenter-velocity inversion of local earthquake arrival time data in two geothermal regions. Doctoral thesis, Massachusetts Institute of Technology. https://onlinelibrary.wiley.com/doi/abs/10.1111/1365-2478.12930.
- Block, L.V., Cheng, C.H., Fehler, M.C., Phillips, W.S.(1994): Seismic imaging using microearthquakes induced by hydraulic fracturing. Geophysics 59(1), 102-112. https://doi.org/10.1190/geo1992-0156.
- Giroux, B. (2001): Auscultation des barrages en béton par écoute microsismique: détectabilité et localisation des événements. Doctoral thesis, Université de Montréal. https://publications.polymtl.ca/8641/.
- Nasr, M., Giroux, B., Dupuis, J.C.(2020): A hybrid approach to compute seismic travel times in three-dimensional tetrahedral meshes. Geophys. Prospect. 68(4), 1291-1313. https://doi.org/10.1111/1365-2478.12930.
- Nasr, M., Giroux, B., Dupuis, J. C. (2021): Python package for 3D joint hypocenter-velocity inversion on tetrahedral meshes: Parallel implementation and practical considerations. Comput. Geosci., (submitted).

CHAPTER

SIX

INDICES AND TABLES

- genindex
- modindex
- search

INDEX

J

R