

***mcmc_eq* - Bayesian Markov chain Monte Carlo simultaneous inversion for local earthquake hypocentres and 1-D velocity structure**

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This is a short description of the Markov chain Monte Carlo inversion code suitable for inversion of P&S wave travel time data of local earthquakes to simultaneously locate earthquakes, and derive 1D velocity models (V_p , V_p/V_s) and station corrections. The code is an implementation of a transdimensional, hierarchical Markov chain Monte Carlo inversion. Hierarchical means, that the data noise (everything which cannot be explained by the models) is treated as unknown and as a variable in the inversion. The noise model (for 4 P and 4 S classes) is assumed to have a Gaussian distribution. Transdimensional means, that the number of layers (Voronoi cells) to describe the model is treated as unknown and variable. This number represents a proxy to the model complexity. The variables to describe/estimate the data noise and the number cells will be determined during model space exploration (Markov chains). Technical details can be found in Bodin (PhD thesis), Bodin et al. (2012) and Ryberg & Haberland (2019).

The code basically represents a stochastic (Monte Carlo) equivalent of the inversion code *velest* (Kissling et al., 1994). In particular it is quite similar when following the approach to calculate the so-called “Minimum 1D model” which means to run *velest* with a variety of different initial models and parameters (e.g. starting models with different number of layers, range of velocities etc.). See Husen et al (1999) or Kissling et al. (1994) for examples of the Minimum-1D model approach. Of course, some limitations, assumptions and approximations of *velest* are treated differently in our code. Furthermore, our approach resembles somehow aspects of the statistical concept of NonLinLoc (Lomax et al., 2000), however, only regarding the hypocentre localization part.

The inversion run consists of two separate parts: the model space exploration by constructing Markov chains and, in a second step, the analysis of the models of those chains (averaging, statistical analysis, construction of reference model). In- and output files for all codes are ASCII files. A forward code, i.e. calculation of synthetic data files for a given model is provided as well.

To use the code it is assumed to have a gcc compiler installed on a Linux PC, the provided scripts need the GMT package installed. We have run the code on a computer with Ubuntu 20.04.01 and gcc 9.4.0, Red Hat Enterprise Linux 8 and gcc 12 and GMT 4.5.5 (quite old). In version 3, we also provide updated scripts that are written in bash and GMT6. Access to a (Linux) cluster with plenty of CPUs is HIGHLY recommended to run multiple Markov chains simultaneously. Our experience is that running multiple chains instead of a single one significantly accelerates the inversion process, i.e. actual time to wait for the inversion result.

The actual MCMC code is provided together with some GMT scripts for displaying purpose, no GUI whatsoever.

Compilation

Firstly you have to compile the code by typing *make clean*

This step prepares the compilation, then type *make* to compile. This should produce the following codes

mcmc_eq - the inversion code

fw - forward code to generate synthetic data

analyse_eq - used to derive the reference solution by analysing the output of multiple runs of *mcmc_eq*.

Testing

Before running the inversion with your own data we recommend to generate a synthetic data set for a known model (velocity, earthquakes, station corrections) and run an inversion. The example provided here (from Ryberg & Haberland, 2019) has an ideal station and quake distribution (small azimuthal gaps). After the inversion the output can be compared with the true model. If this inversion run had been successful, we recommend to “replace” the travel times by the own data set, adjust the configuration file and run the actual inversion. In version 3, we also provide a second synthetic example based on an idealized volcano seismic network (e.g., Pesicek & Ryberg, 2024).

Example

You can generate the synthetic model and calculate the travel time data set by running *make_synthetics*.

This will generate the velocity model, calculate synthetic travel times, add some Gaussian distributed noise (time jitter, pick class dependent) to them – file *picks*.

Then you should run the inversion code multiple times (say 100) by either manual typing

```
./mcmc_eq config_eqx.dat rjx-000.out picks
./mcmc_eq config_eqx.dat rjx-001.out picks
./mcmc_eq config_eqx.dat rjx-002.out picks
...
./mcmc_eq config_eqx.dat rjx-099.out picks
```

Ignore the output on the command line (this is a “progress” report). Every run for the example will take around 1-3 hours (depending on your CPU speed).

Alternatively, you might use a job queuing system on a Linux cluster system like for instance *slurm*. We provide three scripts to run chains for a *slurm* based systems:

run_sequence, *run.job*, and *srun_mcmc_eq.sh*. For instance type *run_sequence 100* to start 100 chains (each calling *run.job*). Have a look at those scripts and adjust them to your *slurm* system.

When all calculations are done, 100 files containing a sequence of models is generated and stored in the *rjx-*.out* files.

In a next step you might look at the evolution of the misfit and number of layers by typing *dispe*

It generates a PostScript file (*evo.ps*) where you can see the evolution of the misfit (bottom) and model dimension (number of layers) of the models of the Markov chain for all chains in a heat-map style. Since all chains start with random models the misfit is high at the beginning and then gradually decreases (burn-in phase), finally reaching a stable level where the model space exploration starts. Black are the misfits (cell numbers) for all models of the chains, blue are the values for all model beyond the burn-in phase and red are values for the 90% (see *dispe*) best fitting, post burn-in models. Expressed differently, red are the 90% best fitting from the “blue” models. Sometimes several chains might have difficulties to converge (for instance get trapped in local misfit minima), by taking only 90% of the best fitting models we can “automatically” exclude the models from problematic chains from further analysis. Try other than 90% values in case you have more (less) problematic chains!

Once you determined a suitable value (90%) you could proceed with the next step: deriving a reference model by averaging post burn-in models.

Executing the script *disp_m_average_sl* generates the reference model from the inversion runs and stores it in *resmcnx.dat* (shown in *xselect.ps*).

Several other scripts are provided for reference:

Executing the script *disp_error* generates produces a comparison between the true and inverted model (*error.ps*).

disp_eq generates a map with all quake locations (*eq.ps*).

disp_eq_z shows the location distribution of an individual quake (# provide in *disp_eq_z*) in a heat-map (*eq_200.ps* for quake # 200).

disp_msft_dist show the input travel time picks and the predicted ones, sorted according to epicentral distance (*msftp.ps*).

Given the almost “perfect” distribution of sources and receivers, the recovery of the model (i.e. quake locations, station corrections, velocity model, data noise) is quite good. Some smoothing at the edges of the velocity jumps is expected due to the fact that we added noise to the data (see *make_synthetics*). Less noise will lead to better recovered models, and vice-versa.

Input, output and configuration file description

All input and output files are in ASCII format.

Travel time picks (file *picks*):

The file containing the travel time picks (*picks*) is in the following format:

```
# 0 47 36 1104637590.560000
N408 073 P 12.300 24.420 -1.629 7.79909 3
N520 102 P -2.780 21.492 -0.022 5.84615 2
...
B407 019 P -2.187 -33.630 -0.240 12.3349 3
N408 073 S 12.300 24.420 -1.629 13.0245 0
N520 102 S -2.780 21.492 -0.022 11.7472 2
...
# 1 11 5 1104737417.580000
N521 103 P -37.895 48.354 -1.318 4.79113 0
...
```

The lines starting with “#” indicate information about an event (earthquake).

Event number (starting with 0, increasing monotonous, no gaps!)

number of P travel time picks, make sure it matches the actual number of picks

number of S travel time picks, make sure it matches the actual number of picks

reference time

In case you want to keep a position of an earthquake (i.e. depth at 10 km) fixed, please add -9999 - 9999 10.0 to the line. “-9999” acts as a placeholder for a value to be inverted.

The next lines contain the actual arrival time picks:

Station name (actually not used later on)

station number (starting with 0, increasing monotonous, no gaps! Should match the station names)

wave type: P or S

x y z station coordinates (in km) with negative z values “above” sea level
relative pick time (with) respect to the reference time in the line starting with “#”
pick class (from 0 to 3 for P & S).

next event data subset.

Configuration file (*config_eqx.dat*) with line numbers added:

```
# value(s) # comment(s)
1 2.0      # forward dx
2 200      # forward NX
3 200      # forward NY
4 62       # forward NZ
5 -200.0   # model starts at X0
6 -200.0   # model starts at Y0
7 -4.0     # model starts at Z0
8 200      # max # of cells/layers
9 2.0      # minimum vel
10 12.0     # maximum vel
11 1.0      # minimum vpv
12 3.0      # maximum vpv
13 0.001    # minimum noise
14 10.0     # maximum noise
15 -5.0     # min residual
16 5.0      # max residual
17 10.0     # sdev for x dummy
18 10.0     # sdev for y dummy
19 5.0      # sdev for z
20 0.05     # sdev for vel
21 0.02     # sdev for vp/vs
22 0.01     # sdev for noise
23 1.0 2    # sdev x EQ, factor for epicenter search acceleration
24 1.0      # sdev y EQ
25 1.0      # sdev z EQ
26 0.02     # sdev residual
27 0.05     # minimum layer thickness in fractions of dz, i <0 no LVZ !!! should be !=0
28 1 0 0.0 0.0 # reference station + flag, =0: zero mean, =1: p fixed, =2: P&S fixed, =-1:
invert for P only, =-2 for S only
29 0        # Voronoi cells if = 0, triangulation if = 1
30 50000 250000 # number of models in chain
31 2000     # output every nth model
32 -77 1    # if <0 true random search, otherwise from seed n, 0=str 1=eik
33 QN QVRPBDMN # model modification tests
34 0 VRN    # 0-mcmc, 1-prior only, 2-output regular grid, 3-input from model file: V
and/or Q R N, i.e 3 QV
35 1 dummy 1 # dummy
36 5.0 0.5 0.03 # vp to start with
37 1.9 0.2     # vp/vs to start with
38 15 5        # cell number to start with
39 1.0         # start_noise
40 0.0 0.0     # delay & sdev to start with
41 0.5 0.5     # start EQ location from center (horizontal) or surface (vertical) 1 for full
space
```

1. grid increment of the grid (forward calculation of travel times). Warning: halving the increment causes 4 time larger run times. For setting up the configuration file and testing: use a coarse grid

2. NX – number of grid points in X direction

3. NY – number of grid points in Y direction

4. NZ – number of grid points in Z direction

5. X0 – starting X position (i.e. left corner)

6. Y0 – starting Y position (i.e. left corner)

7. Z0 – top of model (negative if above “above” sea level)

Make sure that NX, NY, NZ, X0, Y0, Z0 includes all stations and potentially all quakes. Z0 & NZ should be deep enough for all quakes.

8. maximum number of layers, should be large enough, otherwise not essential

Sampling ranges for model properties:

9. minimum Vp velocity

10. maximum Vp velocity, both should span a wide range (including non-physical values) to ensure sufficient sampling of the posterior distributions

11. minimum Vp/Vs

12. maximum Vp/Vs, again wide range...

13. minimum noise level for all pick classes

14. maximum noise level, again wide range...

15. minimum station corrections

16. maximum station correction, ...

Model proposal “steps”:

17. not used

18. not used

19. random movement steps of layers along depth in km, this is the standard deviation of a gaussian random number

20. random step for Vp velocity in km/s, this is the standard deviation of a gaussian random number for changing the velocity in a layer

21. same for Vp/Vs ratio

22. same for data noise

23. same for quake “movements” in X direction, second value is factor applied to the first one to accelerate the search in the first phase

24. same for Y direction

25. same for Z direction

26. random movement steps for station correction

Small proposal steps will result in a “steepest gradient search”, you might get trapped in a local misfit minimum. Huge steps will result in a classical Monte Carlo search where most of the proposed models will be discarded because of bad misfits. Make a test run with one chain and have a look at the end of the result file (rjx-000.out). There is a summary of the acceptance rate for every step. Try to adjust the step values so that acceptance rate between 30 and 50% is achieved.

27. only models are accepted if the minimum thickness of a layer is exceeded (fraction of grid increment). If this value is negative, only models without a Vp and/or Vs low velocity layer are accepted. Make it small positive if you allow low velocity zones or small negative if not.

28. reference station:

xx 0 xx xx : zero mean of P & S station corrections (recommended)

12 1 value_p value_s : if you want to have station #12 correction for P fixed at value_p
 12 2 value_p value_s : if you want to have station #12 correction for P&S fixed at
 value_p/value_s
 12 -1 xx xx : if you want to invert for P station corrections only
 12 -2 xx xx : if you want to invert for S station corrections only

Recommended is xx 0 xx xx → zero mean station corrections.

29. if 0 then constant velocity layers (Voronoi equivalent), if 1 then linear interpolation.
 Recommended is 0!

30. two values: number of Markov chain models in phase 1 and phase 2. To accelerate the search we split the generation of the individual Markov chains into two phases: during the first phase the velocity model is kept unchanged, i.e. at the starting model (see line 33). This allows the quakes to roughly “move” to the epicenters. In the following phase a complete search is performed.

31. only every 2000th model is put into the output file (decimation).

32. if the first number is negative, the seed value for the random number generation is random. Positive numbers are used as a seed number and allow to reproduce Markov chains. Use negative numbers for a complete random search. The second number controls the calculation of travel times, use 1 for the eikonal solver.

33. controls the modification of the model (velocity, quake locations, etc.). First string is for the first search phase, second string for the second phase.

Q - means quake locations are perturbed

N - stands for data noise level perturbations (hierarchical search)

V - stands for Vp/Vs perturbations

P - stands for P velocity model perturbations

M - stands for moving a velocity layer

R - stands for station correction perturbations

B & D allows for adding/removing layers (transdimensional search)

For instance, QN QVRPBDMN would do an hypocenter and data noise search in the first phase, mainly to get rough epicenter locations, and a full search (velocity, station corrections, quake locations) in the second phase. QN QVRPMN would do the same, but it would not be transdimensional, i.e. no adding/removing of layers instead keeping the number of layers fixed. A string without R would give an inversion without station corrections. No V in the string would keep the Vp/Vs ratio fixed (to the starting values, line 37).

34.

0 - full Markov chain searched

1 - takes all models, independent on misfit: this allows to get the prior distribution of parameters

2 - not used

3 - start search not from random points in model space but uses complete (or parts of) model from file model.dat, the following string controls what part of the model is used as a starting model:

V - reads the velocity model (Vp, Vp/Vs)

R - reads the station corrections

N - reads the data noise levels

Q - reads the quake locations

This feature can be used, for instance if you have a fixed velocity model, noise levels and station corrections and you want to locate quakes only. In this case use 1 VRN and put “Q Q” in line 33

35. not used

Starting model description:

36. “5.0 0.5 0.03 “ means random starting velocities (V_p) having a gaussian distribution with mean of 5.0 km/s and standard deviation of 0.5 km/s. The mean value is additionally changed according to the actual depth of that layer by adding a value according to the depth gradient of “0.03”. This allows for models which have an average gradient of “0.03”, i.e. the tendency of increasing velocity with depth. The standard deviation value adds a random component to the starting model.

37. same as line 36, but for starting V_p/V_s ratios. No gradient value is used.

38. Number of layers in starting model, same as line 37. If you want to have a fixed number of layers in the starting model, keep the second value 0. If you want to have a nearly equal distribution of layers, make the second value very large.

39. starting noise level in seconds.

40. starting values for station corrections. Same interpretation as line 38.

41. starting locations of quakes, first value controls the horizontal, second the vertical distribution. With “1.0 1.0” all starting positions will be equally distributed in the search space. “0.0 0.0” puts all starting positions in the center at $z=Z_0$ of search space. “1.0 0.0” puts all quakes at the surface, but with equally distributed horizontal positions. “0.5 0.5” puts the starting positions in a cuboid (half the horizontal and vertical size of the entire search space) centered in the search space.

Description of output files

Every run of a chain produces an output file which is used by *analyse_eq* to derive the reference solution (by calculating means and standard deviations of velocity model, quake locations and station corrections. The output file is written in ASCII and can further be used for other purposes (check the convergence, analyze the evolution of a quake location, check for “gaussianess” of quake depth, etc.). It contains every Markov chain model (decimated by line 31 in the configuration file) has the following format:

```
...
mod Q. 499 4 1.312747 0.980134 1.029198 0.970430 0.943791 1.067327 0.931820
1.042970 1.021411 6.772923 6.021207 1.760000 6.936615 6.439525
1.760000 2.097335 5.509153 1.760000 15.273323 8.603680 1.760000
```

mod – marker

Q. - recent model modification (line 33 in configuration file) or ST when starting model

499 - model number in chain

4 - number of velocity layers in present model

1. 312747 - RMS misfit of present model

0.980134 - estimate of data noise for P pick class 0

1.029198 - estimate of data noise for P pick class 1

0.970430 - estimate of data noise for P pick class 2

0.943791 - estimate of data noise for P pick class 3

1.067327 - estimate of data noise for S pick class 0

...

6.772923 6.021207 1.760000 - center of layer 1, P-velocity and V_p/V_s -value for that layer

6.936615 6.439525 1.760000 - center of layer 2, P-velocity and Vp/Vs-value for that layer
...

EQ Q. 499 0 1.312747 14.197362 -0.165403 3.026431 20131105231753.808594 -0.443368

EQ – marker indicating quake information

Q. - recent model modification (line 33 in configuration file) or ST when starting model

499 - model number in chain

0 – quake number (same as in travel time pick file)

1. 312747 - RMS misfit of present model

14.197362 -0.165403 3.026431 - present quake location (x,y,z)

20131105231753.808594 – reference time (same as in travel time pick file)

-0.443368 – relative (with respect to reference time) origin time

...

RES Q. 499 0 1.312747 0.000000 0.000000

RES - marker indicating station corrections

Q. - recent model modification (line 33 in configuration file) or ST when starting model

499 - model number in chain

0 – station number (same as in travel time pick file)

1. 312747 - RMS misfit of present model

0.000000 0.000000 – P and S station correction for those stations

...

At the end of the file one can find the following lines:

Lines with “BF” indicate the model (velocities, quake locations, etc.) with the smallest misfit.

Lines starting with “cnt” give some statistics:

cnt RMS tested 640267 - number of all models for which the misfit is tested

cnt noise a/r 4760 20882 – accepted/rejected models where data noise changes were tested

cnt P-vel a/r 11413 7152 – accepted/rejected models where velocity changes were tested

..

same for Vp/Vs, quake location, station corrections, layer movements, birth/death (adding/removing) of a velocity layer

These values (ratios) can be used to modify the proposal steps (lines 19-26 in configuration file) to optimize the model space exploration. Acceptance rates between 30 and 50 % would be optimal. If the actual acceptance rate is too small, decrease the appropriate proposal step and vice versa.

The output of all chains (beyond the burn-in phase) has to be analysed by *analyse_eq* to derive a “reference model”. Running this code produces “average models”, i.e. calculates means and standard deviations of the velocity model, quake locations, station corrections and estimates for data uncertainties (data errors).

A typical output (ASCII) contains lines starting with STAN, EQ, EZ, RES, BINP and NOISE.

STAN – velocity model

STAN depth mean(Vp) sdev(Vp) mean(Vp/Vs) sdev(Vp/Vs) emean(Vp) esdev(Vp)
emean(Vp/Vs) esdev(Vp/Vs) max_prob(Vp) max_prob(Vp/Vs) boundary

- depth [km]
- mean(Vp) [km/s], classical mean
- sdev(Vp) [km/s], classical uncertainty
- mean(Vp/Vs), classical mean
- sdev(Vp/Vs), classical uncertainty
- emean(Vp) [km/s], “excess” mean:

a modified mean value for Vp: this is the mean of the Vp distribution “exceeding” the equal distribution between minimum and maximum Vp from config.dat. This makes it possible to recover reasonable Vp (and Vp/Vs, ...) values in model regions with poor ray coverage!

- esdev(Vp), emean(Vp/Vs), esdev(Vp/Vs)...
- max_prob(Vp), Vp with maximum probability
- max_prob(Vp/Vs), Vp/Vs with maximum probability
- boundary: likelihood of a sharp Vp and/or Vp/Vs boundary at that depth (scaled to 1)

EQ – quake information

EQ # x y z dx dy dz Tref Tsrc dTsrc fit

quake number from pick file

x,y,z average source location [km]

dx, dy, dz their uncertainties [km]

Tref reference time from pick file

Tsrc relative (to Tref) source time

dTsrc its uncertainty

fit a value which indicates how well the depth distribution is gaussian with small values indicating gaussian distribution

EZ # x y z dx dy dz Tref Tsrc dTsrc fit

depth values are calculating under the assumption of a potentially clipped gaussian distribution. This gives more reliable depth values (and uncertainties) for shallow quakes.

RES – station corrections

RES # st_corr_p st_corr_s dstat_corr_p dstat_corr_s

station number from pick file

st_corr_p, st_corr_s station corrections for P and S travel times

dst_corr_p, dst_corr_s their uncertainties

BINP – 2D histogram of Vp

BINP Vp_value depth occurrence

Vp_value P velocity bin

depth [km]

occurrence hit count

same for BINV for Vp/Vs

NOISE – noise level (i.e. data uncertainties) for every pick classical

NOISE Pn0, Pn1, Pn2, Pn3, Pn4, Sn0, Sn1, Sn2, Sn3, Sn4, dPn0, dPn1, ...

Pn0 – data noise for P picks & pick class 0
Pn1 – data noise for P picks & pick class 1
...
Sn0 – data noise for S picks & pick class 0
...
dPn0 data noise uncertainty of data noise for P picks & pick class 0
...

Inversion of own data

After successful inversion of the provided synthetic data set, try to convert your picks to the same format as *picks*. Then run the inversion.

Note on choice of grid increment (line 1 in configuration file): as mentioned above, it has a strong influence on the computational time. Given the nature of the eikonal solver used to calculate travel times for a given velocity model, sparse grids potentially introduce errors in the predicted travel times. This is especially true for short source-receiver distances, expressed in grid increments. Distances shorter than ~3-5 grid increments will be affected most. But: our experience is that even very sparse grid increments will still lead to a sufficient reference model. So it is worth to start with a quite sparse grid, adjust all the parameters in *config.dat*, run a test inversions. If the final model looks reasonable, try to decrease the grid increment, run the inversion again and compare with the results of the sparser grids. Check if the final models converge, i.e. show similar major features (velocity model and quake locations).

Using the code, disclaimer

This *mcmc_eq* package is distributed in the hope that it will be useful, but WITHOUT ANY WARRANTY; without even the implied warranty of MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE.

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If you use this program for an academic project or a commercial project, citing this paper would be appreciated:

Ryberg & Haberland (2019): Bayesian simultaneous inversion for local earthquake hypocentres and 1-D velocity structure using minimum prior knowledge, *Geophys. J. Int.*(2019)218,840-854, doi: 10.1093/gji/ggz177

The latest version of the code can be found here:

https://github.com/tryberg/mcmc_eq

References

Bodin, T., PhD thesis: Transdimensional Approaches to Geophysical Inverse Problems, download <http://perso.ens-lyon.fr/thomas.bodin/publi.html>

Bodin, T., Sambridge, M., Rawlinson, N., and Arroucau, P. (2012): Transdimensional tomography with unknown data noise, *Geophys. J. Int.*, 189, 1536–1556, doi 10.1111/j.1365246X.2012.05414.x

S. Husen, E. Kissling, E. Flueh, G. Asch, Accurate hypocentre determination in the seismogenic zone of the subducting Nazca Plate in northern Chile using a combined on-/offshore network, *Geophysical Journal International*, Volume 138, Issue 3, September 1999, Pages 687–701, <https://doi.org/10.1046/j.1365-246x.1999.00893.x>

Kissling, E., W.L. Ellsworth, D. Eberhart-Phillips, and U. Kradolfer (1994) Initial reference models in local earthquake tomography, *J. Geophys. Res.*, 99, 19635-19646, 1994.

Lomax, A., J. Virieux, P. Volant and C. Berge (2000) Probabilistic earthquake location in 3D and layered models: Introduction of a Metropolis-Gibbs method and comparison with linear locations, in *Advances in Seismic Event Location* Thurber, C.H., and N. Rabinowitz (eds.), Kluwer, Amsterdam, 101-134.

Pesicek, J. D., & Ryberg, T. (2024). Reference 1D Seismic Velocity Models for Volcano Monitoring and Imaging: Methods, Models, and Applications. *Seismological Research Letters*, 95(5), 2722–2744. <https://doi.org/10.1785/0220240070>

Ryberg & Haberland (2019): Bayesian simultaneous inversion for local earthquake hypocentres and 1-D velocity structure using minimum prior knowledge, *Geophys. J. Int.*(2019)218,840-854, doi: 10.1093/gji/ggz177