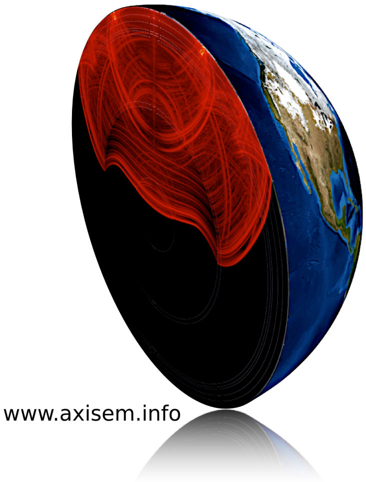

AxiSEMv1.0 Manual

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AxiSEM is a **parallel spectral-element method** to solve 3D wave propagation in a sphere with axisymmetric or spherically symmetric visco-elastic, acoustic, anisotropic structures. Such media allow the computational domain to be collapsed to a 2D disk, where the third, azimuthal dimension is solved analytically on-the-fly posteriori. This leads to extreme speedup by many orders of magnitude with respect to methods that discretize the 3D domain, and enables a full coverage of the seismic body- and surface wave frequency spectrum between 0.001-1Hz. The time-domain code delivers full spatio-temporal wavefields that can be stored on disk and transformed to frequency domain. Due to the dimensional reduction, global wave propagation at typical seismic of **periods down to 5 seconds can be tackled on laptops**, and at 1Hz on moderate clusters.
The Fortran 90 code is divided into a **Mesher**, a **Solver** utilizing the message-passing interface (MPI) for communication between separate domains, and comprehensive **post processing** for ease of visualization. The essential raison-d'être of this method is the efficient calculation of seismograms, wavefield movies, and those wavefields that underly sensitivity kernels to allow for tomographic inversions of any portion of a seismogram at any relevant frequency.

Portal for this code: www.axisem.info
Contact: info@axisem.info

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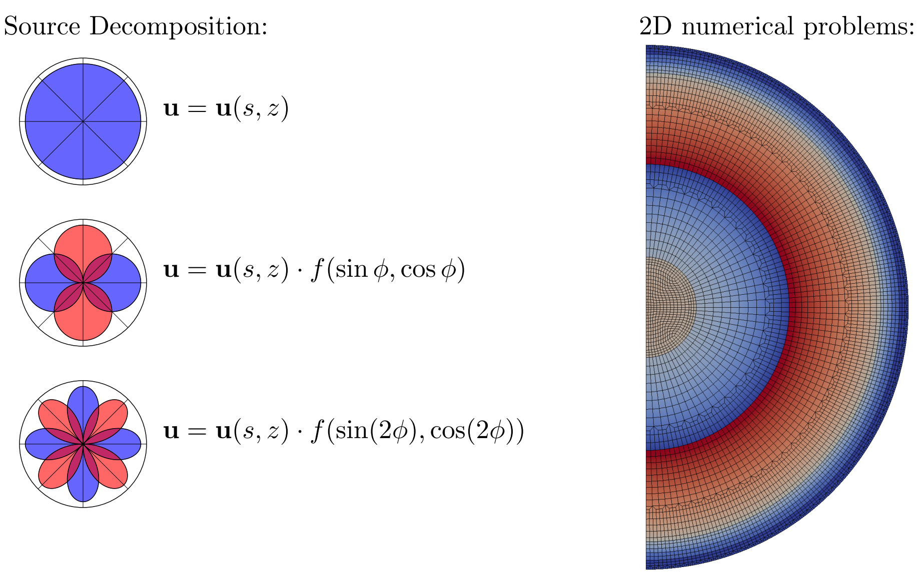
Contents

1 Preliminaries

1.1 The AxiSEM Concept

The basic idea behind AxiSEM is to take advantage of axial symmetry with respect to an axis going through the center of the earth and the source. In such axisymmetric models, the response to a moment tensor or single force point source can be expanded in a series of multipoles (mono-, di- and quadrupole). The dependence of the wavefield on azimuth ϕ can be solved analytically and the remaining 2D problems (four of them for a full moment tensor source) are solved numerically using a spectral element approach.



1.2 Software and hardware requirements

1.2.1 Essential requirements

Operating system The software should run on any UNIX-like operating system and has been tested on Linux (Debian, Ubuntu, Cray et al), MacOS X. Running on windows is probably not possible, but has never been tested so far.

Compilers: Fortran 90 compiler (tested on ifort, gfortran-4.6, portland, Cray)

Libraries: MPI, NetCDF (optional), fftw (optional)

Systems: Unix-based OS (tested on Linux, MacOS, Cray XT4, XE6 and XK7)

Tools: tcshell, perl

Useful tools

ObsPy: Needed for the automated tests. Follow the instructions for your system on `http://www.obspy.org`.

Paraview: Can be used to check meshes and watch wavefield movies.

Google Earth: Can be used for a quick overview on seismograms at the locations of the receivers.

gnuplot: Used to make quick overview

1.2.2 NetCDF

AxiSEM allows to output larger datasets, especially wavefields in the NetCDF format. The current version also has full support for binary dumps, but the development will move towards NetCDF containers.
Unfortunately, the installation of the NetCDF libraries is not foolproof yet.

HPC systems: The libraries should be provided by the system. Use the recommended settings.

Ubuntu 12.10 and newer : The code is working with the NetCDF libraries delivered with Ubuntu from version 12.10 (for gfortran). They can be installed by
`sudo apt-get install libnetcdff5`

Ubuntu 12.04 and older; MacOS : The libraries delivered with Ubuntu 12.04 and earlier do not seem to work reliably. We therefore generally recommend to compile the NetCDF libraries from source. This can be done with the script *make_netcdf.sh* in the `SOLVER/UTILS` directory. It downloads current versions of the zlib, hdf5 and netcdf4 libraries from `http://www.unidata.ucar.edu`, compiles them and runs the included tests. By default, the new libraries are installed in `$(HOME)/local`. In the first lines of the script, specify your compiler (has to be the same as the one you are using for Axisem). The script should be run from a scratch directory like `/tmp`:

```
cd /tmp
$AXISEM_DIRECTORY/SOLVER/UTILS/make_netcdf.sh
```

Especially the HDF5 compilation will produce tons of warnings. They can be ignored, as long as the tests pass. If one of the tests should fail, the reason is most likely a wrong compiler configuration. We can offer only very limited support for the compilation of the libraries.

Windows : While we never tested it, installation of NetCDF on Windows should be possible: `http://www.unidata.ucar.edu/software/netcdf/docs/faq.html#windows_netcdf4_2`

1.3 Preparation of a Debian/Ubuntu Linux system

To prepare a fresh Debian-based Linux system, the absolutely necessary packages can be installed with:

```
sudo apt-get install gfortran build-essential tcsh openmpi-bin libopenmpi-dev
```

The processing and visualization tools can be installed with:

```
sudo apt-get install paraview gnuplot
```

2 Running the code

2.1 Quick start

This is the step-by-step, blackbox procedure, i.e. running a workflow from raw source code to analyzing seismograms and wavefield movies upon pre-set parameters. It assumes your system fulfils all requirements mentioned above.

The default simulation parameters are:

PREM velocity model (isotropic, anelastic, continental crust)

50 s dominant period of the mesh

2 CPUs used for the SOLVER

1800s seismogram length

Explosion source

100 km source depth

Start from within the `AXISEM` directory:

1. `./copy_templates` ⇒ creates various input files from templates
2. Check file `make_axisem.macros`, whether the compiler settings fit your system.
3. `cd MESHER`
4. Check file `inparam_mesh`, for background model, period of simulation and number of CPUs
   Default is *PREM*, *20 s* and *2 CPUs* and runs within a few minutes on a modern PC.
5. `./submit.csh` ⇒ Check file `OUTPUT`.
6. Wait for "`....DONE WITH MESHER`" to appear in `OUTPUT`.
7. `./movemesh.csh PREM_50s` ⇒ moves mesh files to `../SOLVER/MESHES/PREM_50s`.
8. `cd ../SOLVER`
9. In `inparam_basic` set the value for `MESHNAME` to the meshname from above (e.g. `PREM_50s`)
10. `./submit.csh PREM_exp50s_gauss_1800s` ⇒ compiles and runs the code
11. `cd PREM_exp50s_gauss_1800s` ⇒ Check `OUTPUT_PREM_exp50s_gauss_1800s`.
12. Wait for "`PROGRAM axisem FINISHED`" to appear in `OUTPUT_PREM_exp50s_gauss_1800s`
    (use `tail -f OUTPUT_PREM_exp50s_gauss_1800s`).
13. `./post_processing.csh`
14. `cd Data_Postprocessing`
15. `googleearth`, open `googleearth_src_rec_processed.kml`, click earthquake (info), receivers (seismograms).
16. `matlab`, run `plot_record_section.m`, plotting all components of displacement seismograms.

If the Solver is re-run with different parameters but the same mesh, you may start at step 9. To change model, frequency or number of CPUs, repeat steps 3. to 7. and select the new mesh in `SOLVER/inparam_basic`.
The solver input can be changed in `inparam_basic` between 8. and 9., changing post-processing input between 11. and 12. Using a new mesh requires recompilation of the solver (done automatically in step 9.). If post processing parameters are changed, also change the post processing directory or delete the old one.

2.2 MESHER - generate a Mesh

1. Open a terminal, go to the ~MESHER folder and open the `inparam_mesh` file with your favourite editor:

   ```
   $ cd MESHER
   $ vi inparam_mesh
   ```

   The parameters should be readily set, but you might want to double check and verify:

   ```
   BACKGROUND_MODEL     'prem_iso'
   DOMINANT_PERIOD      50.0
   NCPU                 2
   WRITE_VTK            true
   COARSENING_LAYERS    3
   ```

   The file should be self-explanatory. NB: Models without crust ('light') allow for a larger time step and hence run a lot faster. WARNING: Only write vtk files if the dominant period is rather large, i.e. above 10 or 20s, as these files become exceedingly large.

2. Run the mesher, and watch the progress:

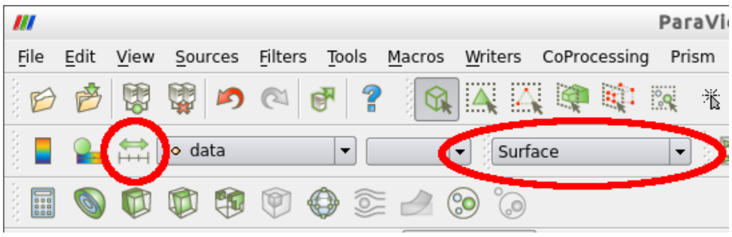
   ```
   $ ./submit.csh
   $ tail -f OUTPUT
   ```

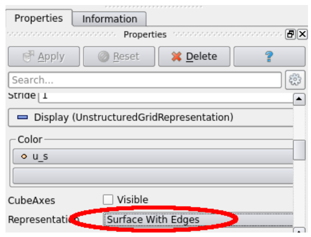
   The meshing should be really fast for the chosen parameters. Wait for `....DONE WITH MESHER !` to appear.

3. Take a look at the mesh with paraview

   ```
   $ paraview
   ```

   Open one of the vtk files in the subfolder `Diags`, e.g. `mesh_vp.vtk` and click apply in the properties panel on the left (you might get an OpenGL Error on the virtual box, which you can ignore). To see the mesh, change the representation from 'surface' to 'surface with edges' (On some host systems, the dropdown menu seems to be messed up, in that case go to the 'Display' context in the 'Properties' panel on the left. If the plot appears all yellow, click on play). You can open other vtk files to look at other properties of the model and the mesh. You might need to rescale the color range by clicking on the left-right arrow symbol in the top left.

4. Move the mesh to the solver directory and give it a meaningful name:

   ```
   $ ./movemesh.csh PREM_50s
   ```

2.3 SOLVER - solve the elastic wave equation

1. Go to the ~SOLVER folder and open the inparam_basic file with your favourite editor:

```
$ cd ../SOLVER
$ vi inparam_basic
```

   The parameters should be readily set, but you might want to double check and verify:

```
SIMULATION_TYPE      single
SEISMOGRAM_LENGTH    1800.
RECFILE_TYPE         stations
MESHNAME             PREM_50s
ATTENUATION          true
SAVE_SNAPSHOTS       true
```

   WARNING: Only save snapshots if the mesh is rather low resolution, e.g. above 20s as these files become exceedingly large. You may alternatively opt to only plot a fraction of the 2D domain which can be set in inparam_advanced.

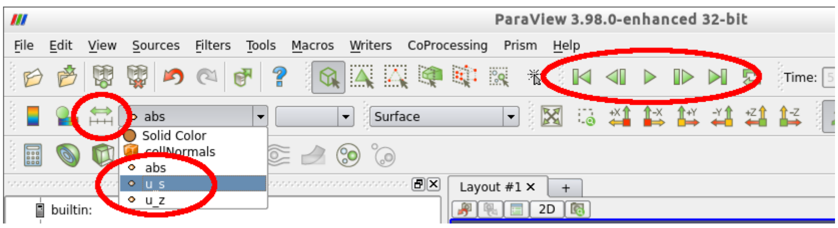
2. First, we are taking a look at a basic sourcetype: a vertical dipole, which has a monopole radiation pattern. This is set by SIMULATION_TYPE single and defined in the inparam_source file. Run the solver, giving the run a meaningful name:

```
$ ./submit.csh PREM_exp50s_gauss_1800s
```

   This command compiles the code if needed and starts the simulation. You can observe the progress in the outputfile:

```
$ cd PREM_exp50s_gauss_1800s
$ tail -f OUTPUT_PREM_exp50s_gauss_1800s
```

   Once the run is finished, take a look at the wavefield with paraview: open the PREM_exp50s_gauss_1800s/Data/xdmf_xml_0000.xdmf file and click apply. Go to the last snapshot and rescale the color range, then click on play to see the wave propagate. You can also choose different components of the wavefield or the absolute value. For paraview experienced users: choose absolute value and a logarithmic colorscale to see all wave types at once (e.g. 'black body radiation' looks nice).



3. Now simulate seismograms for a full moment tensor source: the source is defined in the CMTSOLUTION file and the one referred to as 'event-1' in the later tasks. Stations are defined in the STATIONS file. Go back to the SOLVER directory and change the inparam_basic file such that:

```
SIMULATION_TYPE      moment
SAVE_SNAPSHOTS       false
```

   Run the solver, giving the run a meaningful name:

```
$ ./submit.csh prem_50s_event1
```

This command compiles the code if needed and starts four simulations at once, each simulating a basic source type (two monopoles, a dipole and a quadrupole, for details see *Nissen-Meyer et al., 2007*). You can observe the progress in the outputfiles in each job's subdirectory

```
$ cd prem_50s_event1
$ tail -f MZZ/OUTPUT_MZZ
```

Once all the jobs are done (check with `htop`), you can proceed with postprocessing.

2.4 POSTPROCESSING - rotate and sum seismograms and wavefields

Postprocessing is a key feature of AxiSEM: the source mechanism and source time function can be modified without redoing the more expensive simulation.

1. For the previous simulation, the contribution of the elemental sources needs to be summed up to get seismograms for a full moment tensor source. In the main rundirectory (`prem_50s_event1`) open the file `param_postprocessing`. It should contain these settings (auto generated by the solver):

   ```
   REC_COMP_SYS     enz
   CONV_PERIOD      50.0000
   CONV_STF         gauss_0
   ```

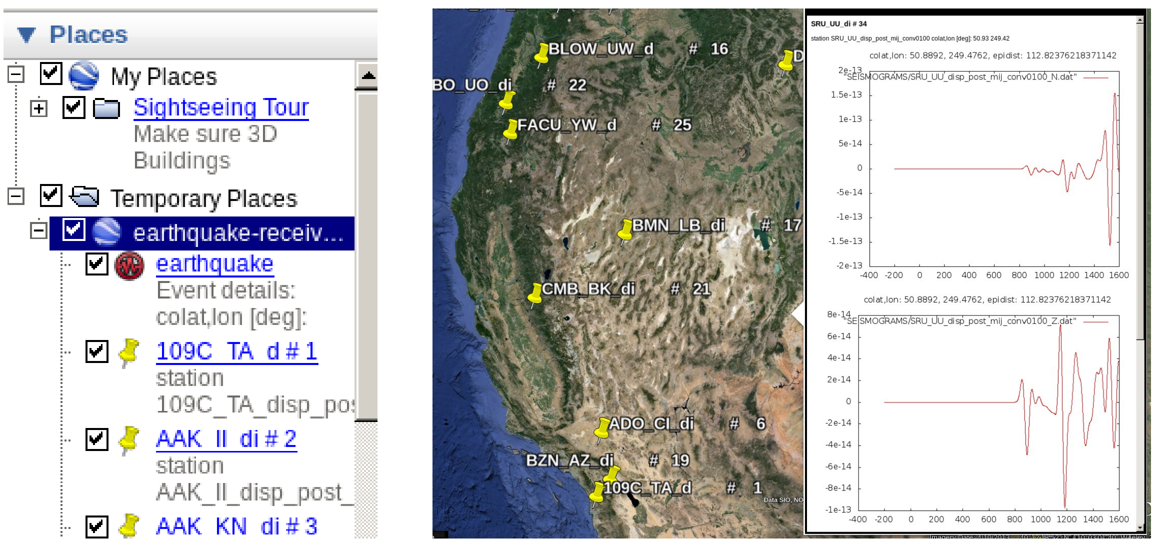
   The source mechanism (depth and location cannot be changed in postprocessing) is read from the `CMTSOLUTION` file in the same directory. Start the postprocessing:

   ```
   $ ./postprocessing.csh
   ```

   The resulting seismograms and plots can be found in the directory `Data_Postprocessing`. Seismograms can be viewed with

   ```
   $ cd Data_Postprocessing/GRAPHICS
   $ gpicview <filename.gif>
   ```

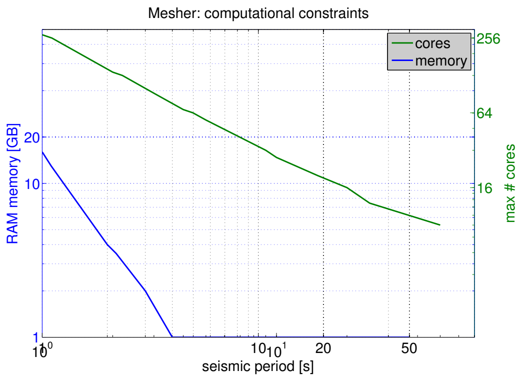
   For a nice overview, you can use `google-earth` (might not run on all computers and depends on internet connection). Open the `googleearth_src_rec_seis.kml` file in the `Data_Postprocessing/` directory (double check the exact path, google-earth might have something older from history which is quite confusing). You should now see the earthquake and the receivers in the places menu on the left.

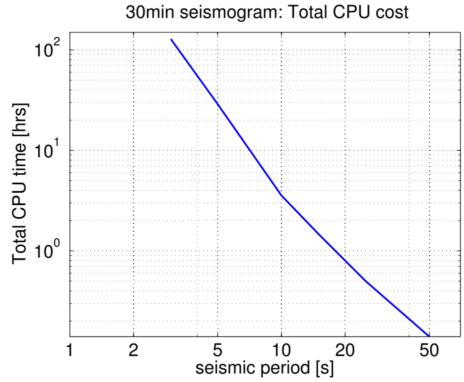
   

   Click on the stations or source to see more...

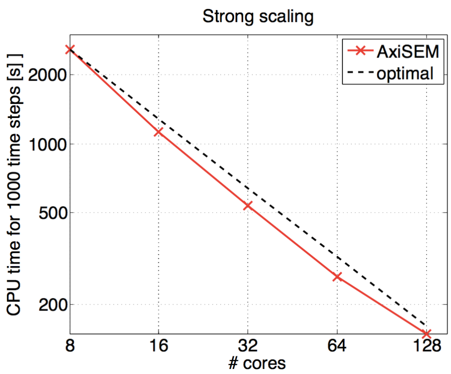
2.5 Computational aspects

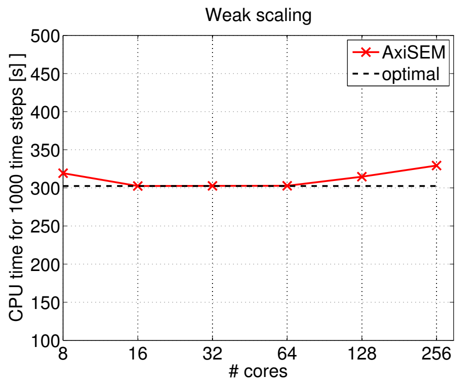
Running in a 2D computational domain, the code is (obviously) significantly faster than comparable 3D methods.





On the left, you may deduct the mesher's RAM occupation as a function of frequency. Going towards very high resolution (around and above 1Hz), you will need a rather fat node (> 32GB RAM) for the (serial) meshing. On the right, we depict the computational cost associated with the solver to compute seismograms of 30 min length. The relation between seismic period and CPU-hours is an approximate proxy to estimate how many cores and wall-clock time is optimal for your infrastructure.





Scalability plots from test runs on a Cray machine at CSCS, Switzerland. The left shows strong scaling (fixed global problem size), the right plot weak scaling (fixed problem size per CPU). A forthcoming publication (see below, (1)) will show scaling up to 8000 CPUs.

3 Typical use cases

3.1 Change source type

`SOLVER/inparam_source`, `SOLVER/CMTSOLUTION` and `SOLVER/inparam_basic`. Axisem has two principal modes, which are selected by the value `SIMULATION_TYPE` in `SOLVER/inparam_basic`.

1. `SIMULATION_TYPE single`:
   The Solver simulates one basic source, which can be one of the following:

monopoles:	M_{rr}	explosion	$M_{\theta\theta} + M_{\phi\phi}$	P_r
dipoles:	$M_{\theta r}$	$M_{\phi r}$	P_θ	P_ϕ
quadrupoles:	$M_{\theta\phi}$	$M_{\theta\theta} - M_{\phi\phi}$		

   where M_{ii} are moment tensor sources with the mentioned components of M set to one and the others to zero, P_i is the same for single forces.
   Choose the source type and set the source depth and amplitude in `SOLVER/inparam_source`.

2. `SIMULATION_TYPE moment`:
   The submit.csh script starts four separate simulations for the basic types M_{rr}, $M_{\theta\theta} + M_{\phi\phi}$, $M_{\theta r}$, $M_{\theta\phi}$. You have to run the postprocessing script after the simulation to sum them up correctly.
   Before the simulation, set the source depth and the moment tensor in `SOLVER/CMTSOLUTION`.

Run `postprocessing.csh` in the simulation directory afterwards. You can run postprocessing for different moment tensors on the same simulation, but not for different depths (since the forward simulation depends on the depth). The `CMTSOLUTION` file is a standard format and can be downloaded from many sites in the web, including `http://www.globalcmt.org/CMTsearch.html`

3.2 Change station locations

`SOLVER/STATIONS` or `SOLVER/receivers.dat`, depending on `SOLVER/inparam_basic`, parameter `RECFILE_TYPE`
`SOLVER/STATIONS`: Similar to *SPECFEM3D Globe*, an ASCII file with six columns, which are: station name, network name, latitude, longitude, elevation, depth (n.b: AxiSEM puts all receivers to the surface, the last two rows are ignored).

```
 RAYN   GD  23.52   45.50  0.0  0.0
 PALK   GD   7.27   80.70  0.0  0.0
 MAJO   GD  36.54  138.21  0.0  0.0
 ERM    GD  42.02  143.16  0.0  0.0
```

The station names are used by post_processing to assign names to the seismogram files.
`SOLVER/receivers.dat`: Plain ASCII file with number of receivers in the first line and then nrec lines with colatitude and longitude.

```
 7
0.0 0.0
30.0 0.0
60.0 0.0
90.0 0.0
120.0 0.0
150.0 0.0
180.0 0.0
```

3.3 Change background model

`MESHER/inparam_mesh`, parameter `BACKGROUND_MODEL`:
afterwards the steps from 5 have to be rerun. Supported models are

```
# prem_iso:                 Isotropic continental PREM model
# prem_iso_solid:           like 'prem_iso', replace fluid outer core with vs=vp/sqrt(3)
# prem_iso_onecrust:        like 'prem_iso' but extend lower crust to surface
# prem_iso_light:           like 'prem_iso' but with mantle material extended to surface
# prem_iso_solid_light:     like 'prem_light', but in fluid outer core vs=vp/sqrt(3)
#
# prem_ani:                 Anisotropic continental PREM model (actual PREM)
# prem_ani_onecrust:        like 'prem_ani' but extend lower crust to surface
# prem_ani_light:           like 'prem_ani' but with mantle material extended to surface
#
# ak135                     AK135 (Isotropic, PREM attenuation)
# ak135f                    AK135 (Isotropic, own attenuation)
# iasp91:                   Isotropic IASP91 model with PREM density and attenuation
# external:                 Layered external model, give file name in EXT_MODEL, the
#                           inner core needs to be big enough, check VTK output.
```

3.4 Change number of CPUs

`MESHER/inparam_mesh`, parameter `NTHETA_SLICES` and `NRADIAL_SLICES`:
The number of CPUs used is the product of the two parameters.
`NTHETA_SLICES` needs to be 1, 2, 4 or a multiple of 4. To get a suggestion for optimal decomposition, run the Mesher with `ONLY_SUGGEST_NTHETA true` and check the OUTPUT file.
`NRADIAL_SLICES` should be less than 8. It can be left at 1 for `NTHETA_SLICES`<64 CPUs, but should be increased then to reduce MPI communication.
N.B: This value is for ONE simulation. To calculate the wavefield of a full moment tensor, 4 parallel simulations have to be run and the number of necessary CPUs is `NTHETA_SLICES`* `NRADIAL_SLICES`*4.

3.5 Change the maximum frequency of the simulation

`MESHER/inparam_mesh`, parameter `DOMINANT_PERIOD`:
As a rule of thumb: Simulations with `DOMINANT_PERIOD`>10s can be run with 2 or 4 CPUs on a modern workstation and cost around 1 CPUh.

3.6 Calculate the response to a full moment tensor solution

`SOLVER/inparam_basic`, change parameter `SIMULATION_TYPE` to `moment`:
The moment tensor, depth and location of the source must be set in the file `CMTSOLUTION`. The submit.csh script starts four separate runs in parallel, the postprocessing script sums the results to get correct seismograms.

3.7 Change seismogram length or sampling rate

`SOLVER/inparam_basic`, change parameter `SEISMOGRAM_LENGTH`:
Default value is 1800 s, although the exact length is rounded to the next multiple of the simulation time step. There is no maximum limit, AxiSEM has been run for 400000s (5 days) to compare amplitude spectra with a normal modes summation.
`SOLVER/inparam_advanced`, change parameter `SAMPLING_RATE`:
By default, the sampling rate is set to the time step length of the simulation. We strongly recommend to leave it as such to avoid aliasing. The resampling can better be done with *ObsPy* or another tool that supports filtering.

3.8 Use external 1D velocity model

`MESHER/inparam_mesh`, change parameter `BACKGROUND_MODEL` to `external` and `EXT_MODEL` to the filename of your model. The model should be stored in a file of the following form:

```
  F T
         740
6371000.  2600.00  5800.00  3200.00  57827.0    600.0  5800.00  3200.00  1.00000
6356000.  2600.00  5800.00  3200.00  57827.0    600.0  5800.00  3200.00  1.00000
6356000.  2900.00  6800.00  3900.00  57827.0    600.0  6800.00  3900.00  1.00000
6346600.  2900.00  6800.00  3900.00  57827.0    600.0  6800.00  3900.00  1.00000
6346600.  3380.75  8110.62  4491.01  57827.0    600.0  8110.62  4491.01  1.00000
6341600.  3380.20  8107.53  4489.16  57827.0    600.0  8107.53  4489.16  1.00000
6336600.  3379.66  8104.44  4487.32  57827.0    600.0  8104.44  4487.32  1.00000
6331600.  3379.12  8101.35  4485.48  57827.0    600.0  8101.35  4485.48  1.00000
6326600.  3378.57  8098.25  4483.64  57827.0    600.0  8098.25  4483.64  1.00000
...
```

The first line contains two boolean entries: First, whether the model is anisotropic, second whether the model is anelastic. The second line contains the number of layers in the file. Afterwards the model parameters for each layer are set in the order:
radius (in meter), ρ, V_{PV}, V_{SV}, Q_κ, Q_μ, V_{PH}, V_{SH}, η.
The order of the layers is arbitrary, but the radius has to be monotonous. First order discontinuities are enforced by double layers with the same radius (see layers 2/3 and 4/5 in the example) and are honoured by the MESHER. For an example, enable the option `WRITE_1DMODEL` in `MESHER/inparam_mesh` and run the MESHER. It will put a valid input file of the selected model into the DIAG directory. Modify this file according to your needs.
The overall radius of the body is given by the radius of the outermost layer and can take any reasonable value.

3.9 Include lateral heterogeneities (2.5D simulation)

`SOLVER/inparam_basic`, change parameter `LAT_HETEROGENEITY` to true:
The actual heterogeneity model is set in `SOLVER/inparam_hetero`.

4 References

Directly dealing with this code:

When using this code, please cite one or more of these publications.

(1) Tarje Nissen-Meyer, Martin van Driel, Simon Stähler, Kasra Hosseini, Stefanie Hempel, Ludwig Auer, Alexandre Fournier, 2013. *AxiSEM: Broadband 3D seismic wavefields in axisymmetric media*, submitted to Solid Earth.

(2) Tarje Nissen-Meyer, F. A. Dahlen, A. Fournier (2007), *Spherical-earth Fréchet sensitivity kernels*, Geophysical Journal International 168(3),1051-1066. doi:10.1111/j.1365-246X.2006.03123.x

(3) Tarje Nissen-Meyer, A. Fournier, F. A. Dahlen (2007), *A two-dimensional spectral-element method for spherical-earth seismograms-I. Moment-tensor source*, Geophysical Journal International 168(3), 1067-1092. doi:10.1111/j.1365-246X.2006.03121.x

(4) Tarje Nissen-Meyer, A. Fournier, F. A. Dahlen (2008), *A two-dimensional spectral-element method for spherical-earth seismograms - II. Waves in solid-fluid media*, Geophysical Journal International, 174(3), 873-888. doi:10.1111/j.1365-246X.2008.03813.x

(5) Tarje Nissen-Meyer (2007), *Full-wave seismic sensitivity in a spherical Earth*, Ph.D. thesis, Princeton University (This includes refs (2)-(4) and more details.)

Other references:

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