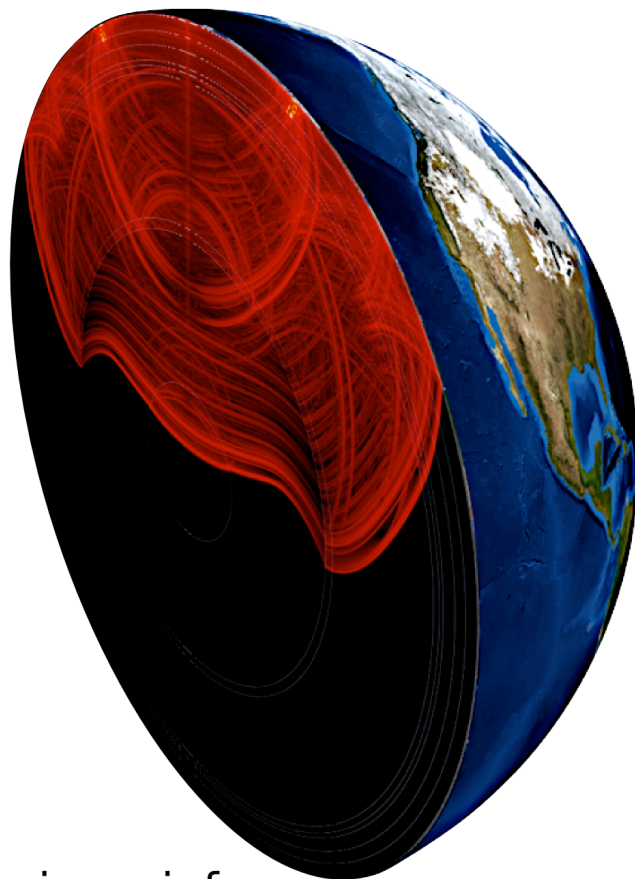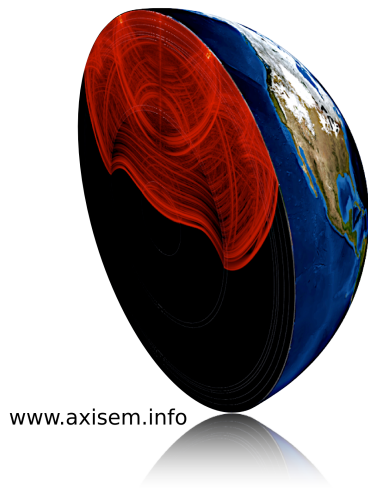COMPUTATIONAL INFRASTRUCTURE FOR GEODYNAMICS (CIG)

AxiSEM

User Manual
Version 1.2

www.axisem.info

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AXISEMV1.2 MANUAL

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www.axisem.info

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
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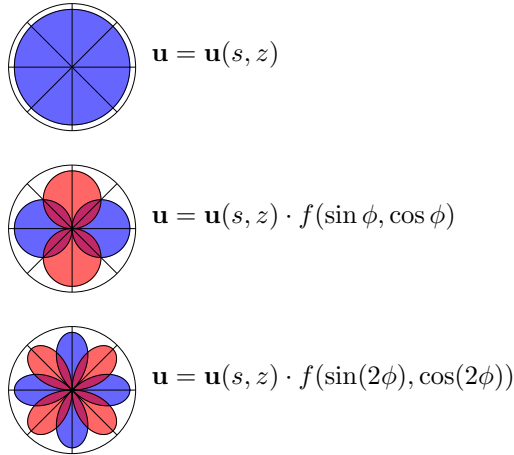
# Contents

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 3D 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.

Source Decomposition: 2D numerical problems:

$\mathbf{u} = \mathbf{u}(s, z)$

$\mathbf{u} = \mathbf{u}(s, z) \cdot f(\sin\phi, \cos\phi)$

$\mathbf{u} = \mathbf{u}(s, z) \cdot f(\sin(2\phi), \cos(2\phi))$
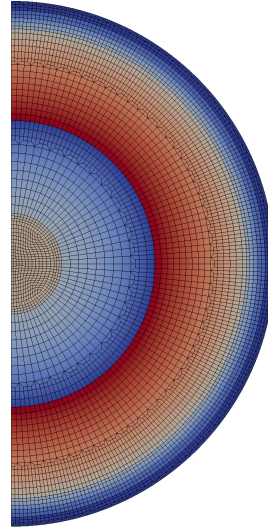
1.2 Software and hardware requirements

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, SuSe, RedHat, Mageia, Cray et al) and MacOS X.

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

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

Systems: Unix-based OS on desktop scale (tested on Linux and MacOS)
and HPC scale (tested on Cray XT4, XE6 and XK7, HECToR (UK National Supercomputing Service), SuperMUC (Leibniz-Rechenzentrum, Garching), Pacman (Arctic Region Supercomputing Center).

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 plots

matlab: Used for plotting record section (script included)

1.2.2 NetCDF

AxiSEM allows to output larger datasets, especially wavefields in the NetCDF format.
Unfortunately, the installation of the NetCDF libraries may still be cumbersome; below we list some limited support for installing NetCDF.

HPC systems: The libraries should be provided by the system. Use the recommended settings. AxiSEM has worked reliably with NetCDF versions starting from 4.2. If you want to use the new Parallel NetCDF output, choose a package named netcdf-mpi or similar.

Ubuntu 12.10 and newer, Debian Wheezy and newer : The code is working with the NetCDF libraries delivered with the system (for gfortran). They can be installed by
`sudo apt-get install libnetcdff5` Note that this only installs libraries for serial output. However, serial output is fine for any number of processors usually encountered on self-administered Ubuntu machines (read: <200 CPUs).

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 can half an hour and 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 wave-field 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

Vertical dipole source

100 km source depth

Start from within the `AXISEM` directory:

1. `./copytemplates.csh` ⇒ 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*, *50 s* and *2 CPUs* to be running 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. move mesh files to `../SOLVER/MESHES/` directory and give it a name `./movemesh.csh PREM_50s`

8. `cd ../SOLVER`

9. In `inparam_basic` set the value for `MESHNAME` to the meshname from above (here: `PREM_50s`)

10. `./submit.csh PREM_mrr_50s_gauss_1800s` ⇒ compiles and runs the code

11. `cd PREM_mrr_50s_gauss_1800s` ⇒ go to the run directory.

12. Wait for "`PROGRAM axisem FINISHED`" to appear in `OUTPUT_PREM_mrr_50s_gauss_1800s`
    (use `tail -f OUTPUT_PREM_mrr_50s_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
NTHETA_SLICES       2
NRADIAL_SLICES      1
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 (i.e. on the order of seconds) 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.
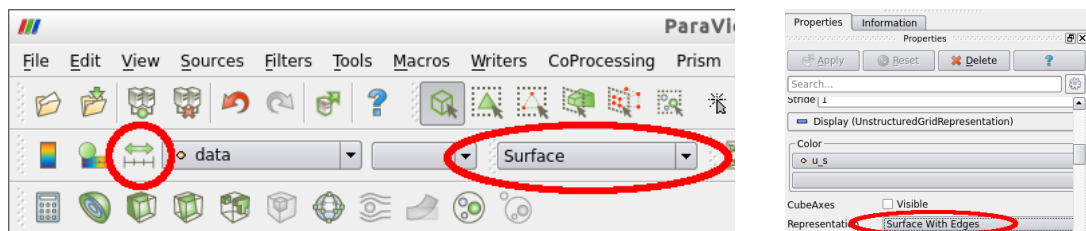
4. Move the mesh to the solver directory and give it a meaningful name:

```
$ ./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
   ```

   Set these parameters:

   ```
   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_mrr_50s_gauss_1800s
   ```

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

   ```
   $ cd PREM_mrr_50s_gauss_1800s
   $ tail -f OUTPUT_PREM_mrr_50s_gauss_1800s
   ```

   Once the run is finished, take a look at the wavefield with `paraview`: open the `PREM_mrr_50s_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).
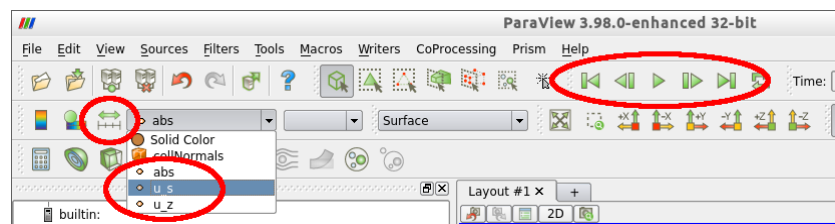
3. Now simulate seismograms for a full moment tensor source: the source is defined in the `CMTSOLUTION` file and the one referred to as 'event-1' in the later tasks. Stations are defined in the `STATIONS` file. Go back to the `SOLVER` directory and change the `inparam_basic` file such that:

   ```
   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     0.
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 your favorite image viewer, e.g. `eog`:

```
$ cd Data_Postprocessing/GRAPHICS
$ eog <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.
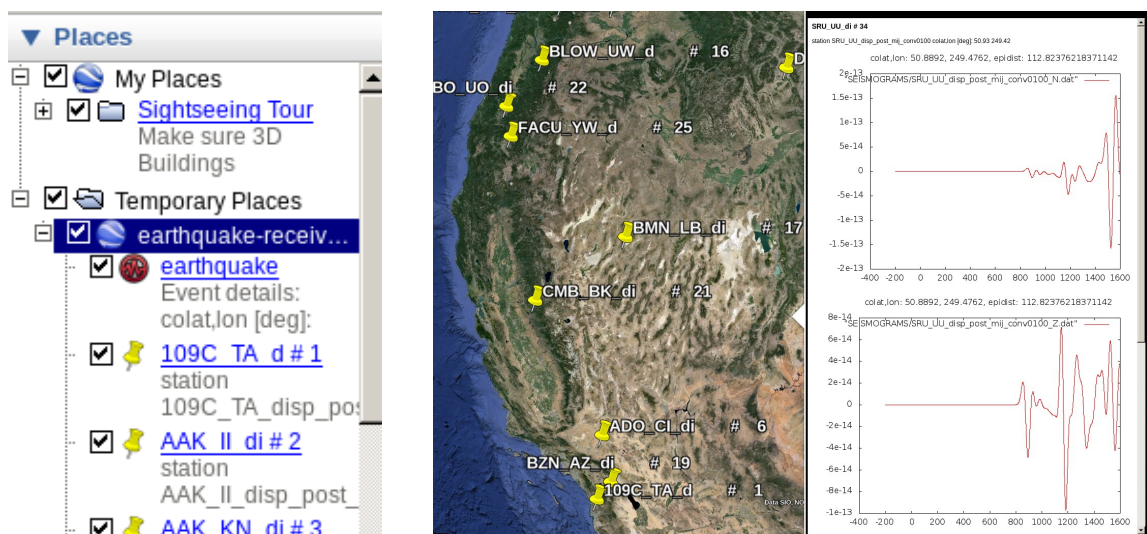

Click on the stations or source to see more...

2.5 Computational aspects

Running in a 2D computational domain, the code is (obviously) significantly faster than comparable 3D methods.
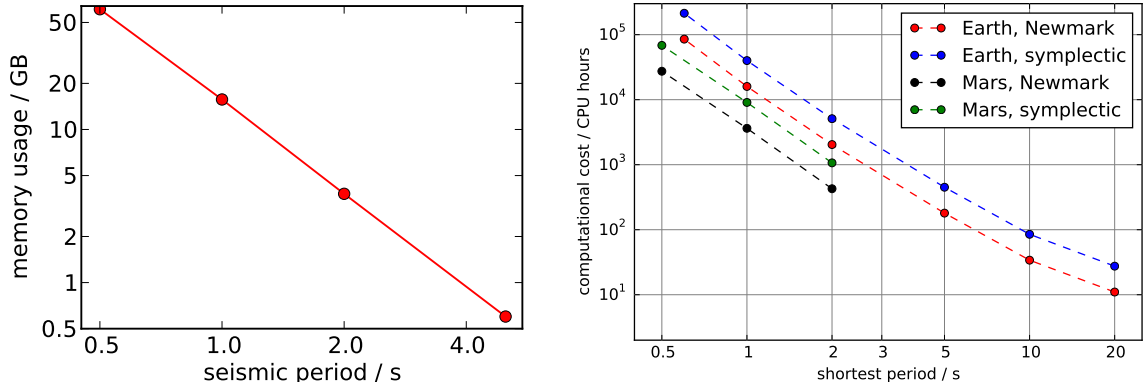
On the left, you may deduct the mesher's RAM occupation as a function of frequency. Going towards very high resolution (around and above 1Hz), you will need a rather fat node (> 16GB RAM) for the (shared memory) meshing. On the right, we depict the computational cost associated with the solver to compute seismograms of one hour length for Earth and Mars and for the second order Newmark as well as the fourth order symplectic time scheme. 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. Scaling of CPU hours is approximately to the third power of the maximum frequency. As a rule of thumb, using the symplectic scheme is advisable when propagating waves for more than 100 wavelengths.
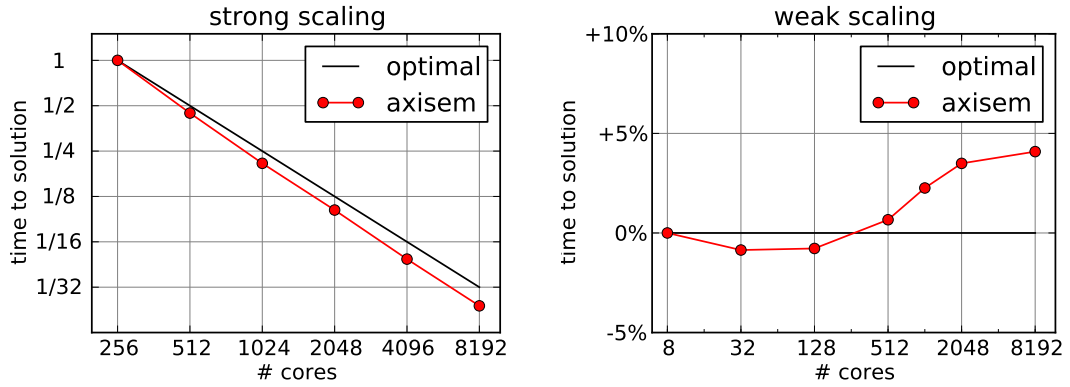
Scalability plots from test runs on a Cray machine at CSCS, Switzerland. The left shows strong scaling (fixed global problem size), the right plot weak scaling (fixed problem size per CPU).

3 Typical use cases

3.1 Change source type

`SOLVER/inparam_source`, `SOLVER/CMTSOLUTION` and `SOLVER/inparam_basic`. AxiSEM has three 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. `SIMULATION_TYPE force`:
   The submit.csh script starts two separate simulations for the basic types P_r and P_θ. This mode is used to compute the databases for instaseis. Note, that the postprocessing does not handle these runs yet appropriately.

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 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:

```
ANELASTIC       T
ANISOTROPIC     T
UNITS           m
COLUMNS    radius     rho     vpv     vsv     qka     qmu     vph     vsh     eta
           6371000.  2600.   5800.   3200.   57827.  600.    5800.   3200.   1.00000
           6356000.  2600.   5800.   3200.   57827.  600.    5800.   3200.   1.00000
#          Discontinuity   1, depth:      15.00 km
           6356000.  2900.   6800.   3900.   57827.  600.    6800.   3900.   1.00000
           6346600.  2900.   6800.   3900.   57827.  600.    6800.   3900.   1.00000
#          Discontinuity   2, depth:      24.40 km
           6346600.  3380.   8190.   4396.   57827.  600.    8190.   4611.   0.90039
           6341600.  3380.   8186.   4397.   57827.  600.    8186.   4607.   0.90233
           6336600.  3379.   8183.   4398.   57827.  600.    8183.   4602.   0.90428
           6331600.  3379.   8179.   4399.   57827.  600.    8179.   4598.   0.90622
```

In the header, four keywords are mandatory to describe the following model:

- ANELASTIC: Is the model anelastic (viscoelastic) or not?

- ANISOTROPIC: Is the model anisotropic or not?

- UNITS: Are the units in this file given in *SI*-units? Allowed values:

  - m *SI*-units: (m, m/s, kg/m^3)
  - km km, km/s, g/cm^3. These units are often used because the values are between 1 and 10.

- COLUMNS: Describe the column order in the file. Necessary values:

  - For an elastic, isotropic model:
    * radius/depth (radius or depth of the layer. Allows to define the position of the layers in radius (beginning from the center) or depth (beginning from the surface)
    * rho (ρ, density)
    * vpv (α, vertical P-velocity)
    * vsv (β, vertical S-velocity)
  - For an anelastic model additionally:
    * qka (Q_κ)
    * qmu (Q_μ)
  - For an anisotropic model additionally:
    * vph (horizontal P-velocity)
    * vsh (horizontal S-velocity)
    * eta (anisotropic parameter η)

This header is followed by an arbritrary number of lines with velocity layers, where # marks comment lines. The header variables UNITS and COLUMNS allow to customize the structure of these lines, which should facilitate the import of external models from other programs.

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 file, select one of the internal models in MESHER/inparam_mesh, enable the option WRITE_1DMODEL and run the MESHER. It will write a valid input file of the selected model into MESHER/Diags/1dmodel_axisem.bm. 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 (Read: Planets, moons and tennis balls can be simulated, single electrons probably not).

3.5 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 on the order of 8, larger numbers work for very high frequencies. It can be left at 1 for

`NTHETA_SLICES`<64 CPUs, but should be increased then to reduce MPI communication. To ensure scaling, each processor should have at least about 500 elements.

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.

3.6 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.

3.7 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.

3.8 Change source time function

`SOLVER/inparam_advanced`, change parameter `SOURCE_FUNCTION`l:
AxiSEM generally calculates displacement seismograms. The source time function selected here is equivalent to the moment function $m(t)$. Note that to calculate seismograms similar to those of an earthquake (i.e. with a persistent displacement at the source), the setting `errorf` has to be used. Note that that is different to the literature that usually defines the source time function as the moment rate function $\dot{m}(t)$. However, it is consistent with SpecFEM.

To create seismograms with a flat, zero-phased source spectrum, use the setting `dirac_0`. Seismograms calculated with this setting can be convolved with other source functions in AxiSEM postprocessing or manually with a program of your choice. However, note that seismograms or wavefields calculated with a `dirac_0` STF will contain numerical noise. Therefore, visualization and wavefield plotting should be done using `errorf` or one of the Gaussian STFs.

3.9 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 (Nissen-Meyer et al, 2014).
`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.

3.10 Time Schemes

For high frequencies and propagation lengths over 100 wavelengths, the symplectic time scheme is recommended instead of the default Newmark scheme to keep the dispersion errors small (compare benchmarks in van Driel & Nissen-Meyer 2014a,b):
In `SOLVER/inparam_advanced` set `TIME_SCHEME` to `symplec4`.

3.11 *Instaseis*-ready wavefield output in netcdf format

- Compile with netcdf (see section **??** for hints on the installation): in `make_axisem.macros` set `USE_NETCDF` to `true` and if netcdf is not in your `PATH`, also set `NETCDF_PATH` to the location of your netcdf installation. If you have netcdf compiled with MPI and run on a supercomputer, using `USE_PARALLEL_NETCDF true` might be beneficial for short period runs.

- In `SOLVER/inparam_advanced` set `USE_NETCDF` to `true` to use netcdf output in the solver

- In `SOLVER/inparam_advanced` set `DATA_DIR` to some location where you have enough free space and in case you use parallel IO this should be on a parallel file system

- further settings in `SOLVER/inparam_advanced` to generate a full database, that is all epicentral distances and source down to 700km and using the fourth order spatial scheme:

```
SOURCE_FUNCTION      gauss_0

KERNEL_WAVEFIELDS    true

KERNEL_DUMPTYPE      displ_only
KERNEL_SPP           4
KERNEL_SOURCE        igno

KERNEL_COLAT_MIN     0.
KERNEL_COLAT_MAX     180.

KERNEL_RMIN          5671.
KERNEL_RMAX          7000.
```

- in `SOLVER/inparam_basic` set `SIMULATION_TYPE` to `force` to simulate both the vertical and the horizontal database. To generate just one of the two, set it to `single` and select either `thetaforce` or `vertforce` in `SOLVER/inparam_source`

- once the AxiSEM runs are finished, go to the rundirectory and run `./fieldtransform.sh` (in case of single runs just run `./fieldtransform` directly). This rechunks the wavefields in the netcdf file to optimize them for reading as time series instead of snapshots.

3.12 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`. This functionality is currently under development and not documented. See the example files `SOLVER/inparam_hetero.TEMPLATE` for an idea of what to do.

4 References

Official release paper:

When using this code, please cite this publication:

(1) Tarje Nissen-Meyer, M. van Driel, S. C. Stähler, K. Hosseini, S. Hempel, L. Auer, A. Colombi, and A. Fournier (2014), *AxiSEM: broadband 3-D seismic wavefields in axisymmetric media*, Solid Earth, 5, 425-445.
doi:10.5194/se-5-425-2014

Directly dealing with this code:

When especially using certain aspects of this code (like anisotropy or attenuation), please cite one or more of these publications.

(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.)

(6) Martin van Driel and Tarje Nissen-Meyer (2014), *Seismic Wave Propagation in Fully Anisotropic Axisymmetric Media*, Geophysical Journal International 199 (2), 880–893.
doi:10.1093/gji/ggu269.

(7) Martin van Driel and Tarje Nissen-Meyer (2014), *Optimized Viscoelastic Wave Propagation for Weakly Dissipative Media*, Geophysical Journal International 199 (2) 1078–1093.
doi:10.1093/gji/ggu314.

Other references:

(8) Martin van Driel, Lion Krischer, Simon Stähler, Kasra Hosseini, and Tarje Nissen-Meyer (2015), *Instaseis: Instant Global Broadband Seismograms Based on a Waveform Database*, To be submitted to Solid Earth

(9) Deville, M. O., Fischer, P. F., Mund, E. H. (2002), *High-Order Methods for Incompressible Fluid Flow*, Vol. 2, Cambridge monographs on Sppl. & Comp. Math., Cambridge University Press.

(10) Tufo, H. M., Fischer, P. F. (2001), *Fast Parallel Direct Solvers For Coarse Grid Problems*, 61, 151-177, J. Par. and Dist. Comput.

(11) Bernardi, C., Dauge, M., Maday, Y. (1999), *Spectral Methods for Axisymmetric Domains*, Vol. 3, Series in Appl. Math., Gauthier-Villars, Paris.

(12) Chaljub, E. (2000), *Modélisation numérique de la propagation d'ondes sismiques en géométrie sphérique: Application à la sismologie globale*, Ph.D. thesis, Université de Paris 7.

(13) Komatitsch D., Tromp, J. (2002), *Spectral-element simulations of global seismic wave propagation—I. Validation*, 149, 390-412, Geophys. J. Int.