AxiSEM Tutorial

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1 Overview

- 10min intro(what is AXISEM, ObsPy; what we want to do in the tutorial)
- 10min big run (maybe drop this, depending on progress next week)(2seconds, seismograms and not wavefields, 2 settings [different structures, sharpness of boundaries])
- 60min virtual box: data and AxiSEM
- 20min big run post processing
- installation of AxiSEM, obspy locally

2 Tutorial Overview

2.1 ObsPy

Some of the tools employed in this tutorial use ObsPy but the tutorial does not have a formal introduction to ObsPy due to temporal constraints. The VirtualBox image contains an extensive amount of training material for Python, ObsPy and some third party libraries intended to get you started. Furthermore one of the core developers of ObsPy is present and able to answer any questions you might have. You can find all material related to ObsPy at `~/Desktop/ObsPy`.

2.2 AxiSEM - Hands On

The goal of this initial task is to familiarize users with the basic principles behind AxiSEM, its input/output structures and peculiarities such as post-processing. An end-to-end approach (meshing to wavefield movie and seismograms) will be conducted for long-period settings within the virtual box.

2.3 Data versus modeling: Obspy, AxiSEM, SPECFEM

The main goal of this part of the tutorial is to use AxiSEM for realistic scenarios, compare the results with real seismograms and explore the effects of source parameters and backgound model on the waveforms. In particular, we will learn how to:

- Load data with Obspy and plot seismogram cross sections;
- plot data vs. AxiSEM and SPECFEM synthetics (at 20s);
- compare data vs. AxiSEM synthetics for various frequencies and background models;
- analyze the influence on different source parameters on waveforms.

2.4 Virtual Box content

The box is organized into 3 folders: AXISEM, OBSPY, EVENTS. The entire data-vs-modeling section is within EVENTS, including all data and pre-computed synthetics. AXISEM contains the source code and the precomputed run for the long-period section.

3 AxiSEM - Hands On

3.1 MESHER - generate a Mesh

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

```
$ cd Desktop/axisem/MESHER
$ vi inparam_mesh
```

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

```
BACKGROUND_MODEL      'prem_ani_light'
DOMINANT_PERIOD       100.0
NCPU                  1
WRITE_VTK             true
COARSENING_LAYERS     2
```

   The file should be self-explainatory. NB: Models without crust ('light') allow for a larger time step and hence run a lot faster on the box. The virtual box only has a single processor, so parallelization does not speed up the simulation.

2. Run the mesher, and watch the progress:

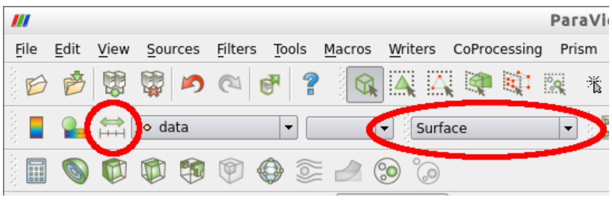
```
$ ./submit
$ tailf OUTPUT
```

   The meshing should be really quick 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'. You can open other vtk files to look at other properties of the model and the mesh. You might need to rescale the colorange 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_ani_light_100s
```

3.2 SOLVER - solve the elastic wave equation

1. Go to the ~/Desktop/axisem/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_ani_light_100s
ATTENUATION         true
SAVE_SNAPSHOTS      true
```

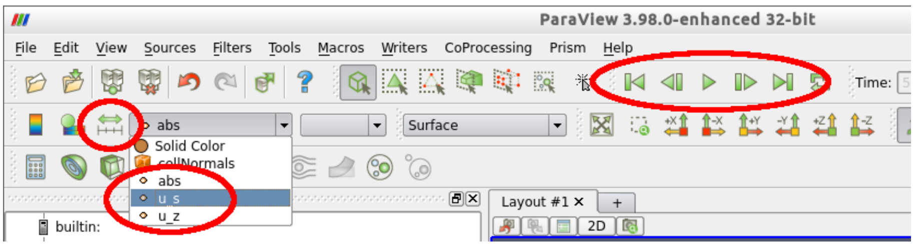
2. First, we are taking a look at a basic sourcetype: a vertical dipole. This is set by SIMULATION_TYPE single and defined in the sourceparams.dat file. Run the solver, giving the run a meaningful name:

```
$ ./submit.csh prem_ani_light_100s_mzz
```

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

```
$ cd prem_ani_light_100s_mzz
$ tailf OUTPUT_prem_ani_light_100s_mzz
```

   Once the run is finished, take a look at the wavefield with paraview: open the prem_ani_light_100s_mzz/Data/xdmf_x 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_ani_light_100s_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's run subdirectory

```
$ cd prem_ani_light_100s_event1
$ tailf MZZ/OUTPUT_MZZ
```

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

3.3 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 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_ani_light_100s_event1`) open the file `param_postprocessing`. It should contain these settings (auto generated by the solver):

   ```
   REC_COMP_SYS    enz
   CONV_PERIOD     100.0000
   CONV_STF        gauss_0
   ```

   The source mechanism (and only the 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...

4 Data versus modeling: AxiSEM, ObsPy and SPECFEM

The main goal of this part of the tutorial is to use AXISEM for realistic scenarios, compare the results with real seismograms and 3D sznthetics, and explore the effects of source parameters and backgound model on the waveforms. In case that you want more information, refer to Appendix-5 in which a complete example with all the commands and results is presented. For a brief walk-through, follow this:
Start from within the `~/Desktop/EVENTS/` directory:

1. Plot one of the events (listed in EVENTS directory, we choose EVENT-1 in this example):

   ```
   $ plot_station_event_distribution.py EVENT-1
   ```

   * For more information on the folder structure of your Virtual-box, refer to Appendix-2.

2. To get an overview on both real data and AxiSEM seismograms: (e.g. PREM_ANISO for 5 seconds dominant period)

   ```
   $ plot_seismograms.py EVENT-1/AXISEM/PREM_ANISO_5sec
   ```

3. Window the waveforms for Pdiff and PKiKP seismic phases and plot the seismograms: (compared with real data)

   ```
   $ plot_seismograms.py EVENT-1/AXISEM/PREM_ANISO_5sec Pdiff
   $ plot_seismograms.py EVENT-1/AXISEM/PREM_ANISO_5sec PKiKP
   ```

4. Change the filter in `~/Desktop/EVENTS/SCRIPTS/plot_seismograms.py` script and compare the results with *SPECFEM3D*: (for changing the filter, open *plot_ seismograms.py* and change values at top of the file)

   Note: resolution in SPECFEM3D seismograms is 17 - 500 sec.

   ```
   $ plot_seismograms.py EVENT-1/AXISEM/PREM_ANISO_5sec Pdiff specfem3d
   $ plot_seismograms.py EVENT-1/AXISEM/PREM_ANISO_5sec PKiKP specfem3d
   ```

5. Compare the results for two different background models (*PREM_ ANISO_ 5sec* with *IASP91_ 5sec)* e.g. Pdiff phase:

   ```
   $ plot_seismograms.py EVENT-1/AXISEM/PREM_ANISO_5sec Pdiff EVENT-1/AXISEM/IASP91_5sec
   ```

6. Change the filter, as explained in step 4, and repeat step 5.

7. Compare the seismograms calculated for two different source mechanisms (PREM_ANISO_5sec and PREM_ANSIO_5sec_GCMT) for Pdiff phase: (For more information about the source parameters, refer to Appendix-1)

   ```
   $ plot_seismograms.py EVENT-1/AXISEM/PREM_ANISO_5sec Pdiff
   EVENT-1/AXISEM/PREM_ANISO_5sec_GCMT
   ```

8. Try different filter setting and compare the results. (Note: dominant period in synthetic seismograms is 5 sec.)

9. Find the time shift between the synthetics and real data, shift the synthetics accordingly and plot the results:

   ```
   $ plot_seismograms.py EVENT-1/AXISEM/PREM_ANISO_5sec Pdiff shift_synthetics
   ```

10. Map the calculated time shifts in step 9 on the location of stations:

    ```
    $ plot_travel_time_map.py EVENT-1
    ```

A APPENDIX-1: Events

Three events are selected for this tutorial (Figure-A1) with the following source characteristics:

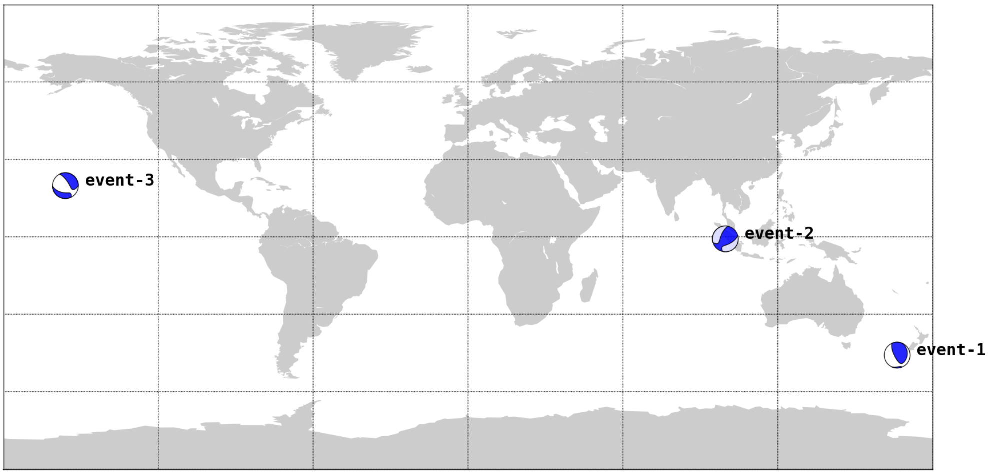


Figure A1: beach ball diagrams of event-1 to event-3 (based on GCMT catalog)

event-1

	GCMT	Inverted
Date-Time (UTC)	2009-07-15 09:22:49	-----
Location	OFF W. COAST OF S. ISLAND, N.Z.	-----
Latitude, Longitude	-45.850 °, 166.260 °	-----
Magnitude	7.8 MW	-----
Depth	23.5 km	24.0 km
Mrr, Mtt, Mpp	3.14e20, 0.759e20, -3.9e20	0.324e21, 0.303e20, -0.354e21
Mrt, Mrp, Mtp	2.59e20, -3.75e20, -0.028e20	0.161e21, -0.439e21, 0.455e20

event-2

	GCMT	Inverted
Date-Time (UTC)	2009-09-30 10:16:10	-----
Location	SOUTHERN SUMATRA, INDONESIA	-----
Latitude, Longitude	-0.790 °, 99.670 °	-----
Magnitude	7.6 MW	-----
Depth	77.8 km	82.0 km
Mrr, Mtt, Mpp	1.76e20, -0.765e20, -0.992e20	0.163e21, -0.148e20, -0.148e21
Mrt, Mrp, Mtp	0.658e20, -0.991e20, -1.94e20	0.349e20, -0.397e20, -0.157e21

event-3

	GCMT	Inverted
Date-Time (UTC)	2006-10-15 17:07:55	-----
Location	HAWAII	-----
Latitude, Longitude	19.830 °, -155.940 °	-----
Magnitude	6.7 MW	-----
Depth	48.0 km	28.0 km
Mrr, Mtt, Mpp	-0.816e19, 0.869e19, -0.053e19	-0.307e19, 0.356e19, -0.496e18
Mrt, Mrp, Mtp	0.063e19, -0.818e19, -0.853e19	-0.142e19,-0.355e19, -0.104e20

B APPENDIX-2: Folder structure

Figure A2 shows how the events (and their meta-data), waveforms and scripts are organized in the Virtual-box:

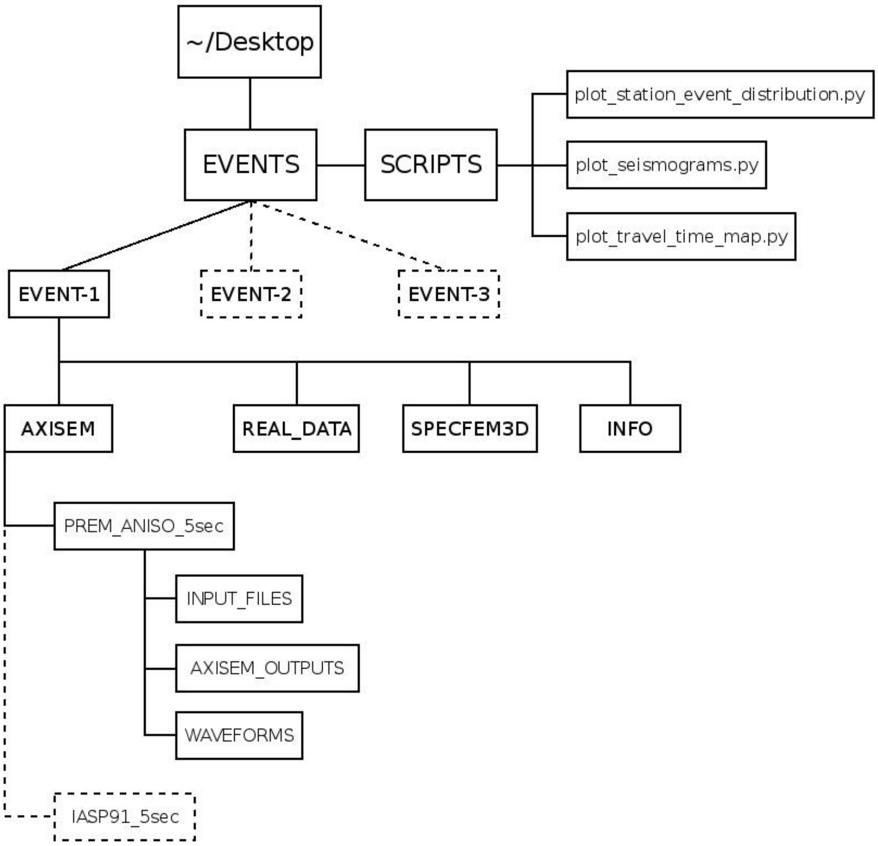


Figure A2: Folder structure

In *SCRIPTS* directory, there are three python scripts that we use here:

1. **plot_station_event_distribution.py**: maps event and stations of an event directory.
2. **plot_seismograms.py**: plotting/filtering seismograms for comparison purposes.
3. **plot_travel_time_map.py**: project the time shift measured by cross correlating the AXISEM waveforms and real data.

In *EVENTS* directory, there are three events, each with the following sub-directories:

1. **AXISEM**: contains seismograms simulated by AXISEM with the required PyAxi input files to re-produce them.
2. **REAL_DATA**: seismograms retrieved from *IRIS.* (refer to APPENDIX-4)
3. **SPECFEM3D**: waveforms simulated by SPECFEM3D for comparison purposes (downloaded from *IRIS*, refer to APPENDIX-4)
4. **INFO**: information about the event and stations: event_1.xml and STATIONS

C APPENDIX-3: A Quick Guide to PyAxi

PyAxi is a Python script developed as an interface for AXISEM. All the options available in AXISEM are included in only one input file (inpython.cfg). By running the script, all the necessary steps (MESHER, SOLVER and Post-Processing) will be done automatically.

All you should do to run PyAxi for an input file (inpython.cfg) and station list (STATIONS) is:

```
$ python PyAxi <inpython.cfg> <STATIONS>
```

and the rest should be done automatically. inpython.cfg is a conguration file that contains all the AXISEM options. To change the input file, open inpython.cfg with an editor. However, you could find some already prepared inpython.cfg files for the events in the Virtual-box. (refer to APPENDIX-2 for more information, Figure A2 *INPUT_FILES*) Therefore, to run AXISEM for the provided events (EVENT-1 and IASP91-5sec as an example), it is enough to replace:

```
<inpython.cfg>:
~/Desktop/EVENTS/EVENT-1/AXISEM/IASP91_5sec/INPUT_FILES/inpython.cfg

<STATIONS>:
~/Desktop/EVENTS/EVENT-1/AXISEM/IASP91_5sec/INPUT_FILES/STATIONS
```

D APPENDIX-4: Retrieving real data and SPECFEM3D seismograms automatically

obspyDMT (ObsPy Data Management Tool) is a command line tool for retrieving, processing and management of massive seismological data in a fully automatic way which could be run in serial or in parallel.

This tool is developed to mainly address the following tasks automatically:
1. Retrieval of waveforms (MSEED or SAC), response files and metadata from IRIS and ORFEUS (via ArcLink) archives. This could be done in *serial* or in *parallel* for single or large requests.
2. Supports event-based and continuous requests.
3. Extracting the information of all the events via user-defined options (time span, magnitude, depth and event location) from IRIS and EMSC (European Mediterranean Seismological Centre).
4. Updating the existing archives (waveforms, response files and metadata).
5. Processing the data in *serial* or in *parallel* (e.g. *Tapering, removing the trend of the time series, filtering and Instrument correction*).
6. Management of large seismic datasets.
7. Plotting tools (events and/or station locations, Ray coverage (event-station pair), epicentral-distance plots for all archived waveforms and seismicity maps).

Here, we use obspyDMT to retrieve both real data and SPECFEM3D seismograms. For more information about this tool please refer to the following webpage:
https://github.com/kasra-hosseini/obspyDMT

obspyDMT is installed on your virtual machine. By running the following commands, the real data used in this tutorial can be retrieved automatically:

Event-1:

```
./obspyDMT.py --datapath EVENT-1_real --min_date 2009-07-15 --max_date 2009-07-16
--min_mag 7.0 --min_depth 20 --list_stas ~/Desktop/EVENT-1/INFO/STATIONS
--offset 3600 --req_parallel --arc N
```

Event-2:

```
./obspyDMT.py --datapath EVENT-2_real --min_date 2009-09-30 --max_date 2009-10-01
--min_mag 7.0 --min_depth 70 --list_stas ~/Desktop/EVENT-1/INFO/STATIONS
--offset 3600 --req_parallel --arc N
```

Event-3:

```
./obspyDMT.py --datapath EVENT-3_real --min_date 2006-10-15 --max_date 2006-10-16
--min_mag 6.0 --min_depth 20 --list_stas ~/Desktop/EVENT-1/INFO/STATIONS
--offset 3600 --req_parallel --arc N
```

Moreover, the SPECFEM3D seismograms can be also retrieved in the same manner:

Event-1:

```
./obspyDMT.py --datapath EVENT-1 --min_date 2009-07-15 --max_date 2009-07-16
--min_mag 7.0 --min_depth 20 --list_stas ~/Desktop/EVENT-1/INFO/STATIONS
--specfem3D --offset 3600 --req_parallel --arc N
```

Event-2:

```
./obspyDMT.py --datapath EVENT-2 --min_date 2009-09-30 --max_date 2009-10-01
--min_mag 7.0 --min_depth 70 --list_stas ~/Desktop/EVENT-1/INFO/STATIONS
--specfem3D --offset 3600 --req_parallel --arc N
```

Event-3:

```
./obspyDMT.py --datapath EVENT-3 --min_date 2006-10-15 --max_date 2006-10-16
--min_mag 6.0 --min_depth 20 --list_stas ~/Desktop/EVENT-1/INFO/STATIONS
--specfem3D --offset 3600 --req_parallel --arc N
```

E APPENDIX-5: Data versus modeling (EVENT-1)

In this appendix, we follow the steps in the main tutorial and show the commands and outcomes for each step. For this reason, we focus on one of the events, EVENT-1.

Start from within the ~/Desktop/EVENTS directory:
1. Plot one of the events (listed in EVENTS directory, we choose EVENT-1 in this example):

```
$ plot_station_event_distribution.py EVENT-1
```

* For more information on the folder structure of your Virtual-Box, refer to Appendix-2.

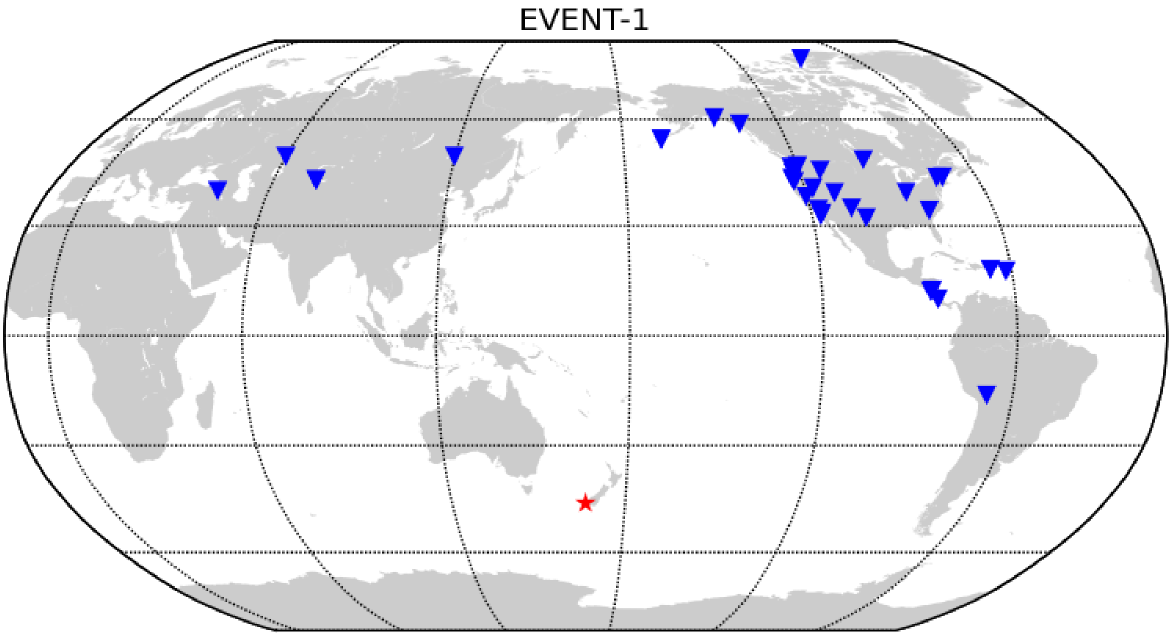


Figure A2: Event-station configuration for EVENT-1

2. To get an overview on both real data and pre-simulated seismograms: (e.g. PREM_ANISO for 5 seconds dominant period) [Figure A3]

```
$ plot_seismograms.py EVENT-1/AXISEM/PREM_ANISO_5sec
```

3.Cut the waveforms for Pdiff and PKiKP seismic phases and plot the seismograms: (compared with real data)

```
$ plot_seismograms.py EVENT-1/AXISEM/PREM_ANISO_5sec Pdiff
$ plot_seismograms.py EVENT-1/AXISEM/PREM_ANISO_5sec PKiKP
```

4. Change the filter in *plot_ seismograms.py* script and compare the results with *SPECFEM3D*: (for changing the filter, open *plot_ seismograms.py* and change values at top of the file)
For this example, ????? we change hfreq (high frequency) in line 34 to 0.05Hz (20sec) and *lfreq* to 0.01Hz: (Figure A5)

```
$ plot_seismograms.py EVENT-1/AXISEM/PREM_ANISO_5sec Pdiff specfem3d
$ plot_seismograms.py EVENT-1/AXISEM/PREM_ANISO_5sec PKiKP specfem3d
```

5. Compare the results of two different background models (*PREM_ ANISO_ 5sec* with *IASP91_ 5sec)* for Pdiff phase: (Figure A6).

```
$ plot_seismograms.py EVENT-1/AXISEM/PREM_ANISO_5sec Pdiff
EVENT-1/AXISEM/IASP91_5sec
```

6. Change the filter, as explained in step 4, and repeat step 5. Here, we increase the *hfreq* to 0.2Hz and *lfreq* to 0.05Hz (Figure A7).
7. Compare the seismograms calculated for two different source parameters (PREM_ANISO_5sec and PREM_ANSIO_5sec_GCMT) for Pdiff phase: (For more information about the source parameters, refer to Appendix-1) [Figure A8]

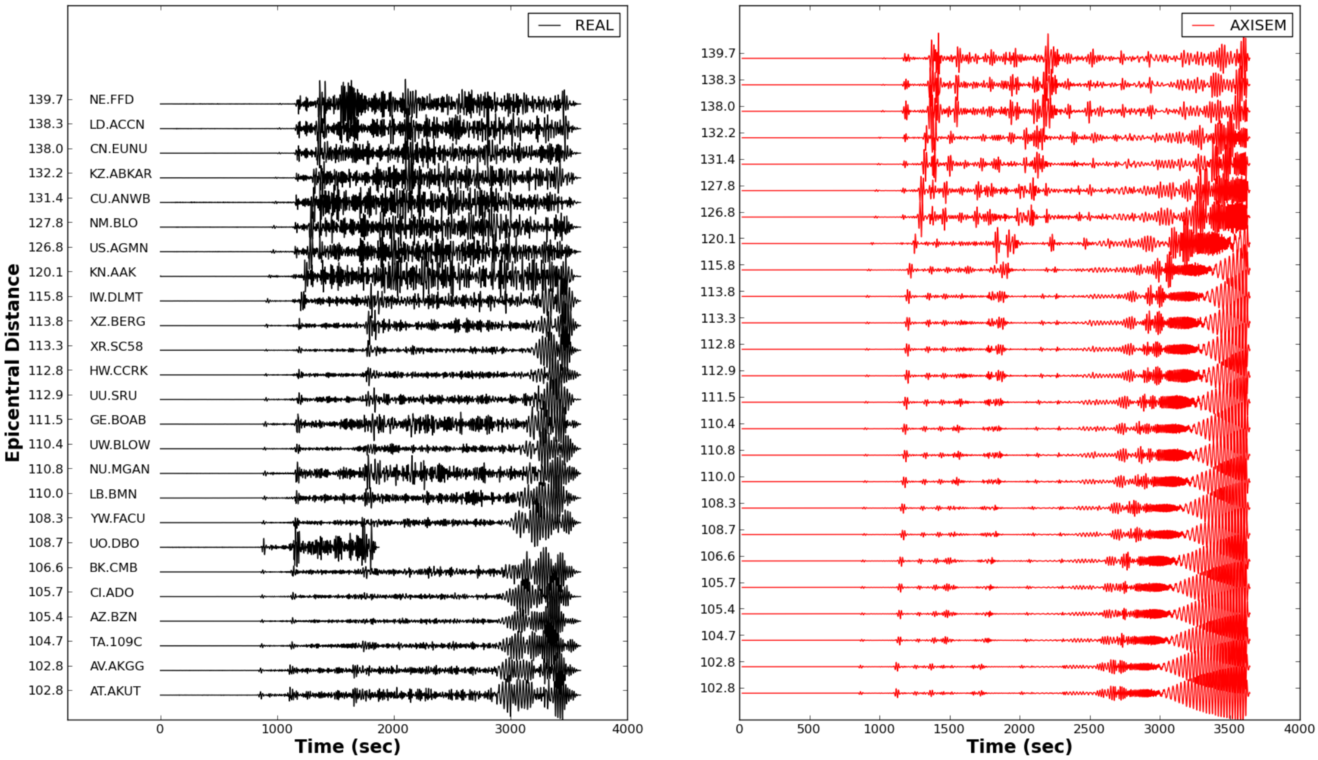


Figure A3:Real and AXISEM waveforms for EVENT-1

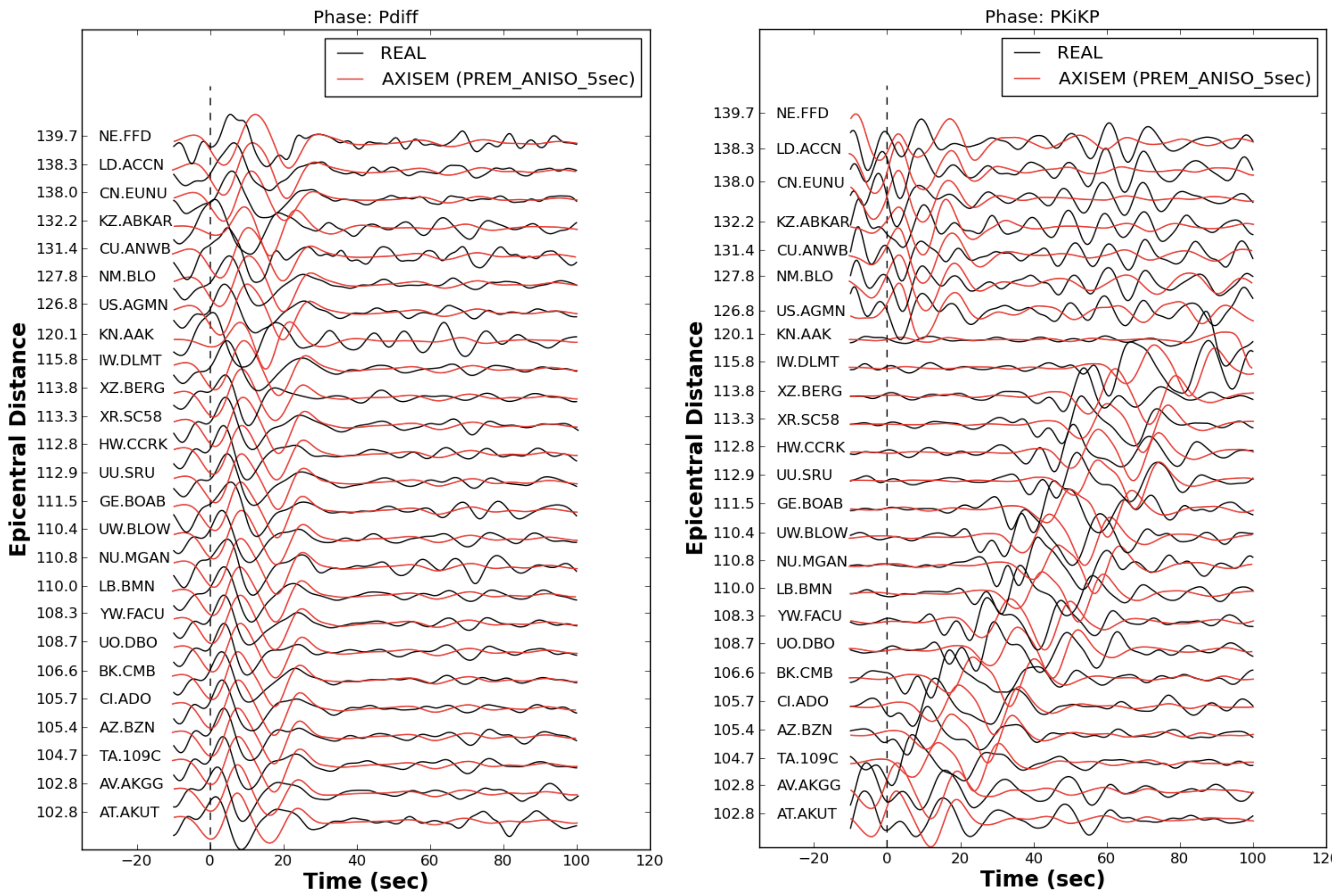


Figure A4: Comparison between real and synthetic waveforms for Pdiff and PKiKP phases. (without alignment)

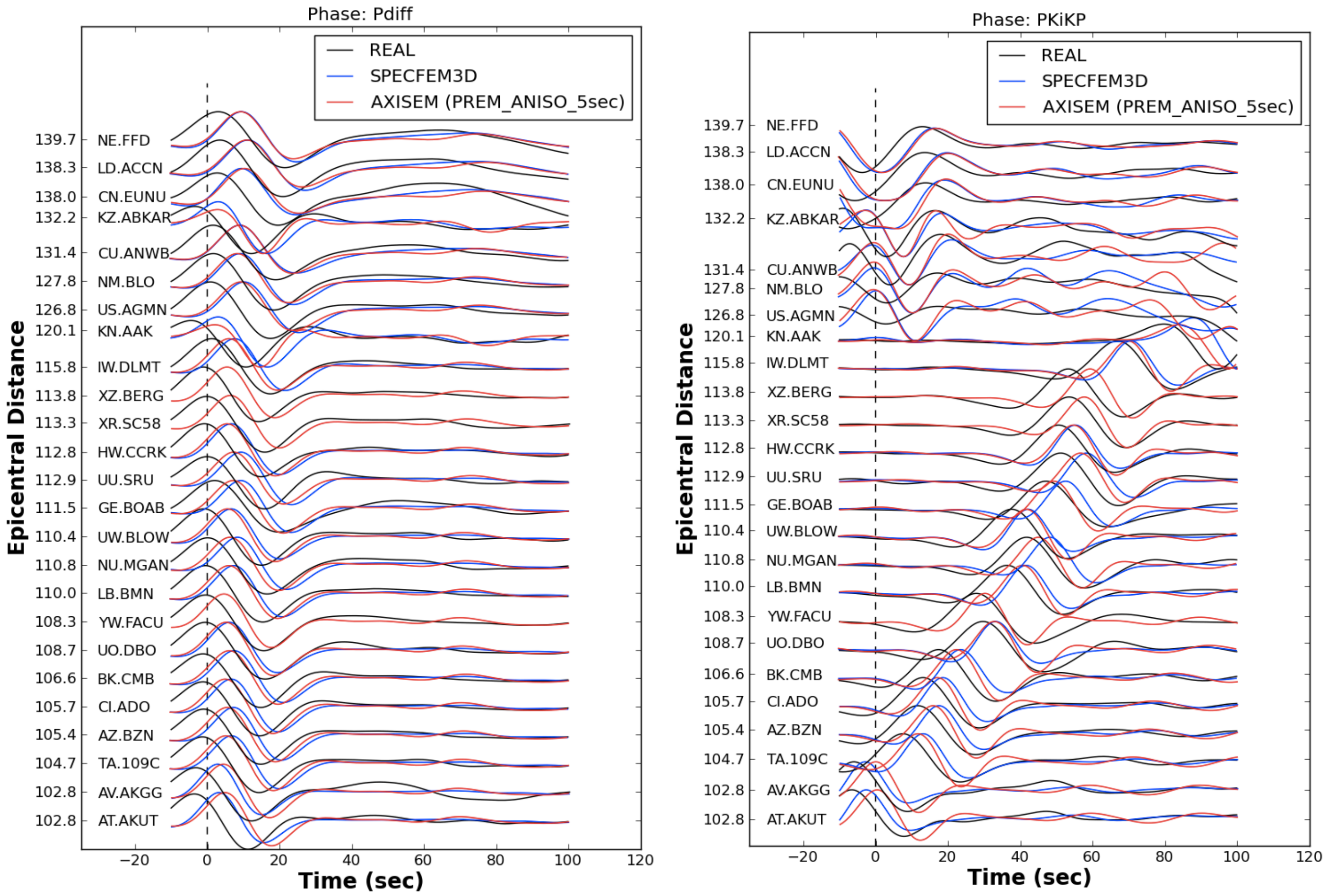


Figure A5: Comparison between real, AXISEM and SPECFEM3D waveforms for Pdiff and PKiKP phases.

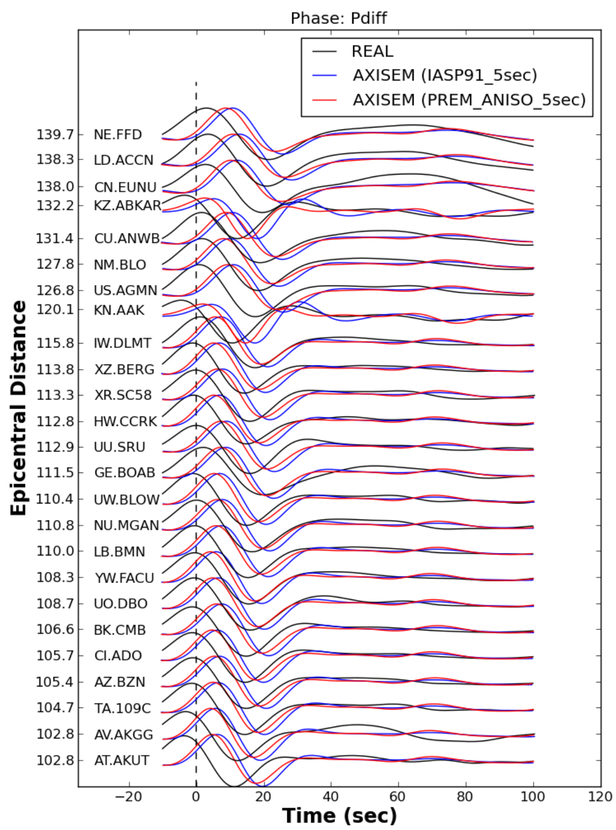


Figure A6: Comparison between real and AXISEM waveforms for two different background models (Pdiff).

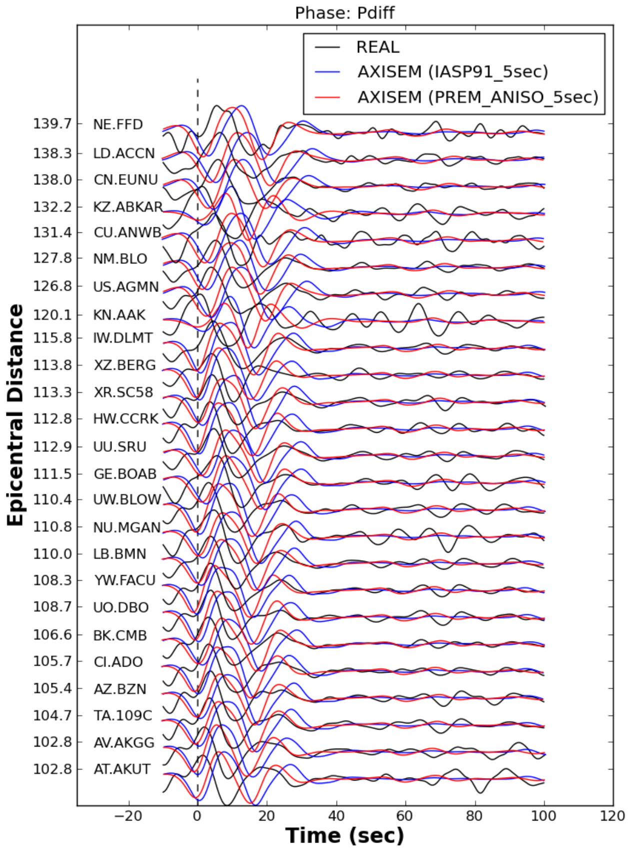


Figure A7: Comparison between real and AXISEM waveforms for two different background models (Pdiff).

```
$ plot_seismograms.py EVENT-1/AXISEM/PREM_ANISO_5sec Pdiff
EVENT-1/AXISEM/PREM_ANISO_5sec_GCMT
```

8. Change the filter, as explained in step 4, and repeat step 7. ????? Here, we decrease the *hfreq* to 0.05Hz and *lfreq* to 0.01Hz. (Figure A9)
9. Find the time shift between the synthetics and real data, shift the synthetics accordingly and plot the results: (Figure A10)

```
$ plot_seismograms.py EVENT-1/AXISEM/PREM_ANISO_5sec Pdiff shift_synthetics
```

10. Map the calculated time shifts in step 9 on the station locations: (note that it always plots the results of the latest comparison, i.e. Pdiff here)

```
$ plot_travel_time_map.py EVENT-1
```

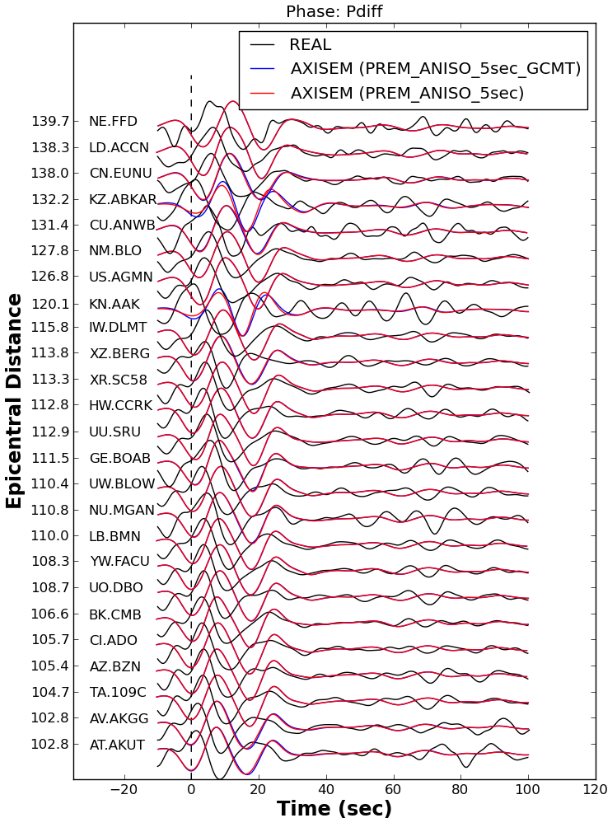


Figure A8: Comparison between real and AXISEM waveforms for two different source parameters (Pdiff).

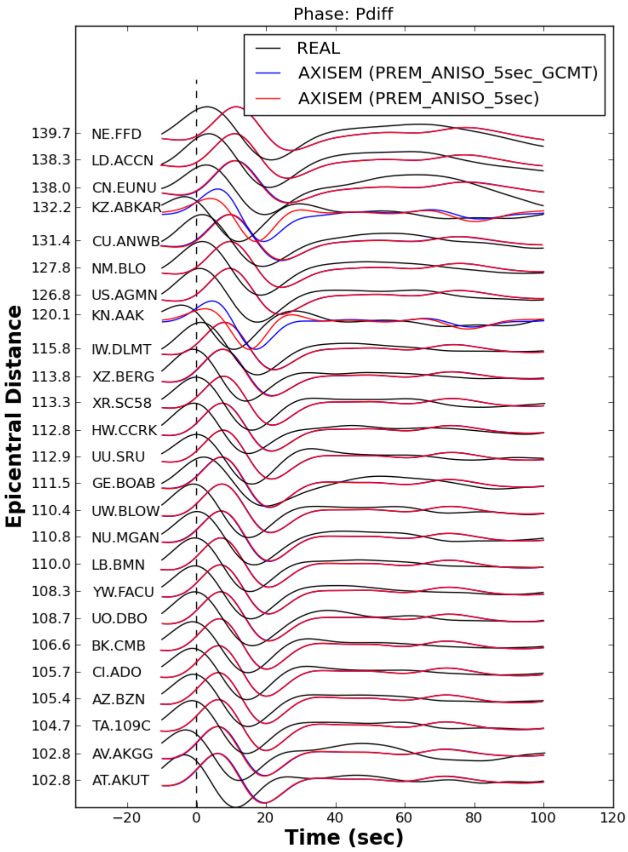


Figure A9: Comparison between real and AXISEM waveforms for two different source parameters (Pdiff).

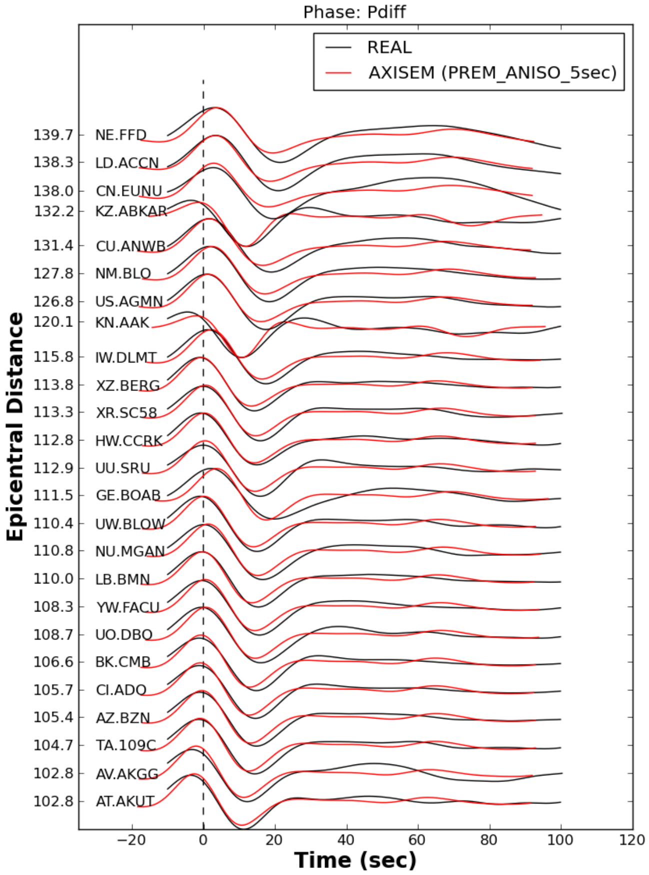


Figure A10: Comparison between real and AXISEM waveforms for Pdiff. AXISEM waveforms are shifted in order to gain the maximum cross correlation coefficient.

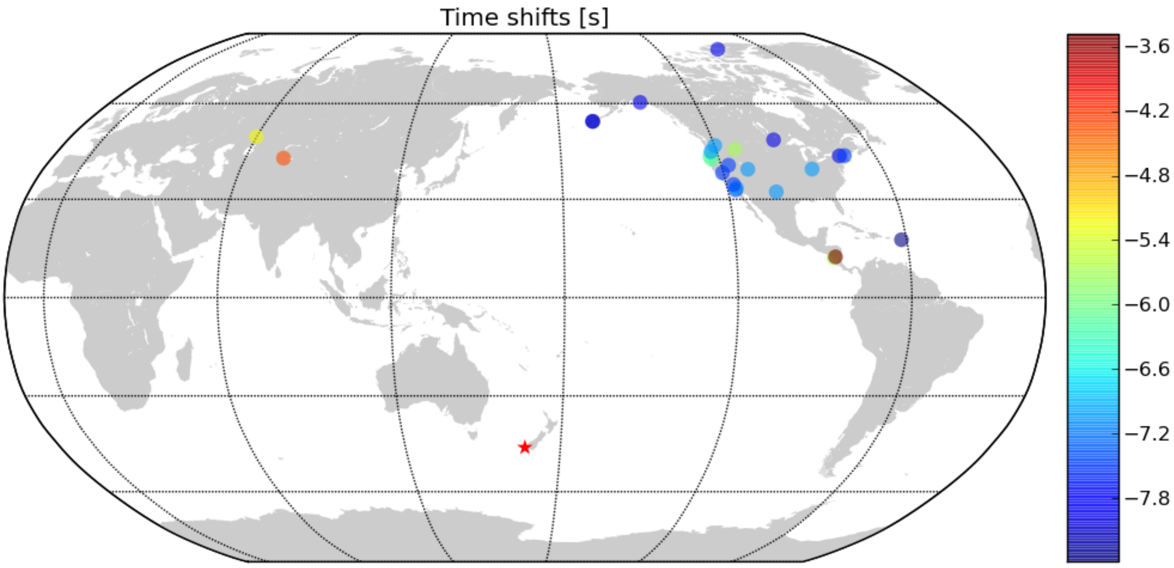


Figure A11: Time shift calculated by cross correlation between real and AXISEM wavefons. Blue color indicates that Pdiff in real data arrived sooner than that in the synthetic one.