Notes on global shear wave splitting analysis

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1 Introduction

These notes are designed to be an introduction to the process of making observations of shear wave splitting in global seismological settings. It highlights a few important papers to read and gives a brief explanation of what shear wave splitting is, and what it means.

Code or command line examples are given with a `$` prefix for `bash`, `%` for the C-shell (`csh`), and `SAC>` for commands in SAC.

2 Shear wave splitting

For some introductions to what it is, and how it's measured, have a look at Silver & Chan (1991),Savage (1999) and Long & Silver (2009), and some of the following:

1. Kendall & Silver (1998)
2. Nowacki et al. (2010), especially the supplementary information for details of the corrections that must be applied
3. Nowacki et al. (2011)

You should also pursue the references contained within these starting works on the phenomena of global anisotropy.

3 SAC

The Seismic Analysis Code ('SAC') is a command-line program for processing seismic data, with one channel per file. Files are binary, with a header part and a data part.

The code is long-established, but documentation is still poor. A fair introduction can be found at `http://ds.iris.edu/files/sac-manual/`, but better is the 'SAC Book' (Helffrich et al., 2013). (I have a copy of this at home which I can bring in if you ask me.) Below are the basics to get you started on using SAC for your project.

3.1 Installation and starting

SAC is installed using the module system on the Environment Linux machine. Load it using the

```
$ module load macsac
```

command. You can then run SAC with

```
$ sac
```

3.2 Help

SAC's online help is useful. Type `help command` to get help on `command`, and you can search with `help apropos topic` to search for `topic`.

3.3 Very basics

Some of the most common commands are:

`bandpass` or `bp`	Perform a band-pass filter on the traces in memory
`begindevice` or `bd`	Start up a graphical display for plotting
`plot1` or `p1`	Plot all current traces
`plot2` or `p2`	Plot all current traces, overlain on top of each other
`read` or `r`	Read a file or files into memory
`rtrend`	Remove any linear trend in the files in memory
`taper`	Apply a taper to the files in memory
`write` or `w`	Write a file or files to disk

See the SAC Book and the online help for details of each command and other common commands.

3.4 Graphics

By default SAC uses X. To start an X window in order to perform plotting, type

```
SAC> bd x
```

(short for `begindevice x`). Remember that if `ssh`ing into the faculty Linux machines, you will need to use the `-X` option to forward the X graphics to your own computer.

You will also want to turn 'quick-and-dirty plotting' off:

```
SAC> qdp off
```

To show a plot, you normally use the `p1` (short for `plot1` command to plot all current traces in memory on one plot. You can overlay all the traces by using `p2`.

3.5 Macros

SAC macros are collections of commands in a file, like a shell script. They can contain all the usual SAC commands, plus some other control flow constructs. See the SAC Book or the website for examples.

They are invoked at the SAC prompt by using the `macro` or just `m` commands, plus the name of the file, plus any arguments to the macro, e.g.:

```
SAC> m filter-files c 0.1 10
```

where our imaginary `filter-files` macro accepts two arguments to the `c` switch.

If the full path to the macro is not given, SAC will look in your macro directory, which is where you should keep often-used macros. You can tell SAC where this is with the `setmacro` command.

3.6 Setting things at startup

When run with an argument, the `sac` program will run the commands in the macro file it is supplied with. Usually, one writes an initialisation macro which is run each time you run `sac`. For example, my `sacinit.scm` macro looks like this:

```
* SAC init macro
* Path to where local macros are installed--change this
setmacro /nfs/see-fs-01_users/earanow/Applications/sacmacros
* Additional paths to other macros
setmacro more /home/ugrad-library/sheba/macro
* Change the shape of the plot window
window 1 x 0.3 1 y 0.1 1
* Begin plotting device
bd x
```

Note that `*`s at the start of a line indicate comments.

One can then alias the `sac` command so that it runs the init macro:

```
$ alias sac="sac $HOME/Applications/sacmacros/sacinit.scm"
```

This could also be put into your shell startup script.

4 Global seismic data acquisition and processing

4.1 Getting data

4.1.1 IRIS

The data we will be using will be mostly from IRIS (`http://www.iris.edu/`), which hosts most of the world's public broadband seismic data. There are many ways to access this (look at the website), but I suggest starting out with the JWEED program. This has been installed on the faculty Linux machines and can be run by launching `/home/ugrad-library/JWEEDv4.1r2/JWEEDv4.1r2`.

Read the explanatory notes in the program for guidance.

4.1.2 CNSN

Some of the data will be from the Canadian National Seismic Network, CNSN (`http://earthquakescanada.nrcan.gc.ca/stnsdata/cnsn/`). Data from there must be accessed via `http://earthquakescanada.nrcan.gc.ca/stndon/AutoDRM/autodrm_req-eng.php`, but one must manually request a stream of data starting at some time. Therefore, you need to know the start time of the earthquake already, and filtering by distance or azimuth is not possible.

The Canadian National Data Centre (CNDC) will provide data in SEED format, which can be converted to SAC format using the `rdseed` program:

```
$ /home/ugrad-library/rdseed/rdseed.rh6.linux_64 -df CNDC_20151109.090500
<< IRIS SEED Reader, Release 5.3.1 >>
        d = read data from tape
        Taking input from CNDC_20151109.090500
Writing [...]
```

You will need to change the endianness of the SAC files that are produced:

```
$ sactosac -m *SAC
```

These data will not have their headers correctly filled, so you will need to update the following SAC headers with the correct values for the earthquake:

- evlo (longitude in degrees east),
- evla (latitude in degrees north),
- evdp (depth in km),

which can be done using the `changeheader` or `ch` command like so:

```
SAC> r *KAPO*
2007.202.13.27.00.0000.CN.KAPO..BHN.D.SAC 2007.202.13.27.00.0000.CN.KAPO..BHE.D.SAC
SAC> ch evlo -71.272 evla -8.133 evdp 644.9
```

You will have to set the origin time of the earthquake using the special `ch o gmt` option, which fills in several headers at once, using the GMT (UTC) time of the earthquake. The O header variable is the time relative to which all other headers are measured, so for `ttsac` for work, this should be set like so:

```
SAC> ch o gmt 2007 202 13 27 04 410
```

Since you will also need to change any other header variables to be relative to this time, you can use the `ch allt` command to shift these to the right times:

```
SAC> * The &1,o is a reference to a header variable, in this case 'o'
SAC> ch allt (0 - &1,o&)
SAC> * Save these changes
SAC> w over
```

Do `help ch` for more information.

4.2 Processing

Typically, you will download data around the predicted arrival time of the S wave from the earthquake of interest. However, not every seismic station will have a good signal from this event, and some might be noisy, have data missing, or not be the correct type of instrument. You will have to remove the stations which are no use.

You will then want to apply the following steps to get the data ready for analysis:

- Remove the data trend
- Taper the signal
- Filter

Typically, teleseismic S arrivals have a dominant frequency of about 0.1 Hz, so it is usually best to set the upper limit of a band-pass filter to about 0.3 Hz. The lower limit should not be higher than about 0.05 Hz, but the lower the better. This is because a band-limited signal will look much like a sine wave, and introduce errors into the shear wave splitting analysis.

When filtering, it is vital to apply a zero-phase filter, because phase shifts in the arrivals can change the shear wave splitting measured from them. To achieve this, always use the `p 2` options to the SAC filtering commands. This applies two passes—both a forward and backward pass—and will avoid phase shifts. Note that the effective number of poles (i.e., how sharply the filter rolls off from pass to stop) is doubled when doing two passes.

4.3 Identifying phases

Typically, one is interested in a specific seismic arrival (or 'phase'). In this case, we will be looking at the S wave. But how to identify this in the seismograms? Typically, one uses the catalogue earthquake location and time to predict the arrival times of the S wave, based on a 1D model of the Earth, such as PREM or ak135. There are standard tools available to do this, such as ttimes or the TauP toolkit, TauP. These are both installed on the faculty Linux machines. ttimes must be set up by adding the following directory to your `PATH` environment variable:

- `/home/ugrad-library/iasp-grh/bin`

TauP can be accessed by loading the taup module with module add taup.

When looking at seismograms in SAC, provided that the headers have the requisite information about the earthquake and seismograms (i.e., the earthquake time and location, and the seismometer location), you can use the ttsac macro to show when the arrivals are predicted:

```
SAC> m ttsac
```

(Follow instructions in section 5.1 to set things up properly.) Note you can use the xlim t1 t2 option to the ttsac macro to show only a portion of the trace in memory, where t1 is the start time, and t2 the end time.

You can also add arrival times directly to SAC files' headers using the taup_setsac command in the shell, remembering to use the -evdpkm flag to tell TauP that the units of depth of the earthquake in the files' headers are km, not m:

```
$ taup_setsac -ph S-0 -evdpkm *.BH?
```

In this case, we've asked taup_setsac to put the time of the S wave into header T0, with the name ('S') in KT0. These will be displayed when you plot the trace.

5 SHEBA

5.1 Installation

This has been installed on the faculty Linux machine as well. To set it up, source the environment setup file /home/ugrad-library/sheba/shebaenv.sh or /home/ugrad-library/sheba/shebaenv.csh, depending on your choice of shell. You will also need to add /home/ugrad-library/sheba/macro to your SAC macro path using the setmacro command (as in the example in section 3.6).

5.2 Using

Assume the following:

- You have three SAC-format seismogram files, corresponding to three components of the instrument, called:
  - STA.BHE, the east component
  - STA.BHN, the north component
  - STA.BHZ, the vertical.
- You have already cut, filtered and otherwise processed the files ready for analysis
- They all have the same start and end time
- They are all sampled at the same rate

5.3 The SHEBA macro

In general, you will use a command similar to the following for analysing shear wave splitting with SHEBA:

```
SAC> m sheba file STA
```

Here, '`STA`' is the common part of the files' names *before* any component name. This can be as long or as short as you like, but all three files must have the same first part of their name, before the 'suffix'. There must also be a dot between the first part and the suffix.

The macro also allows several other options, including applying a correction for the source and receiver. Look at the macro itself for details of these options.

If the component suffixes are not `BHE`, `BHN`, and `BHZ`, then use the `comps` argument to the `sheba` macro:

```
SAC> m sheba file STA comps 00.HHE 00.HHN 00.HHZ
```

for example, when you have files called `STA.00.HHE`, etc.

5.4 Picking shear wave splitting analysis windows

SHEBA has the option (default) to use multiple shear wave splitting windows successively, and use the similarity or otherwise of the splitting inferred in each window to make inferences about the quality of the measurement, and which is the optimum splitting analysis window. We will always make use of this facility. To use this, do

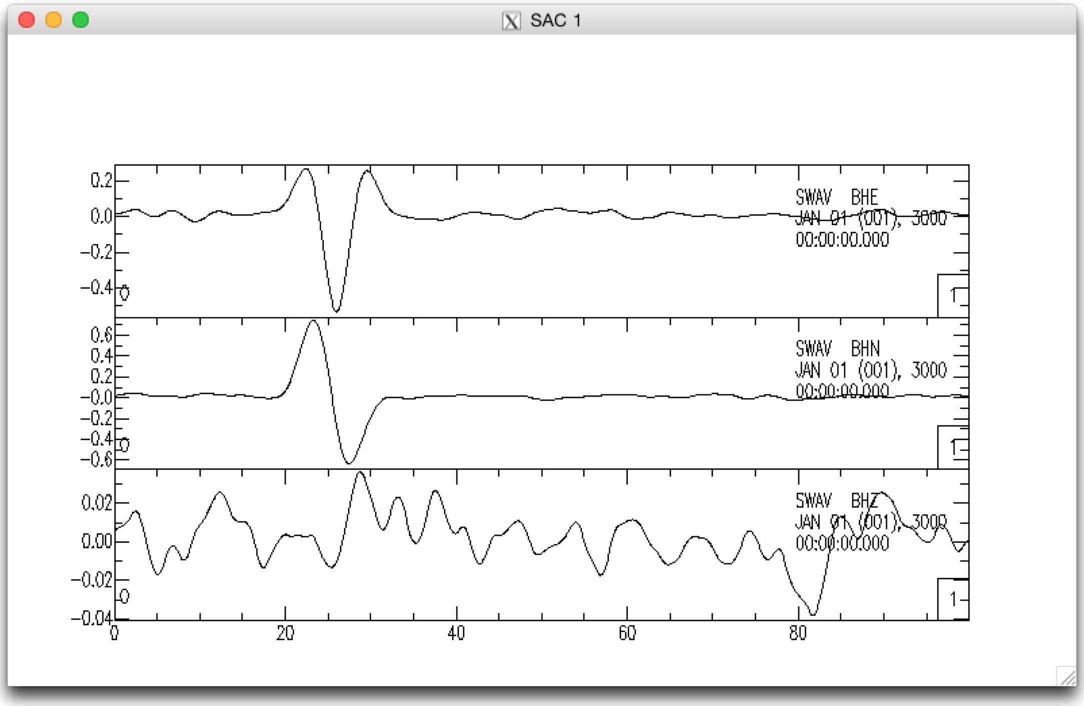
```
SAC> m sheba file STA nwind 5 5
```

This will use 25 splitting windows—all the possible combinations of five different starting window times, and five different ending times. You will be asked to pick these by choosing a range of window times at the start and end of the desired analysis period. You must *separately* pick the range of the start and stop windows.

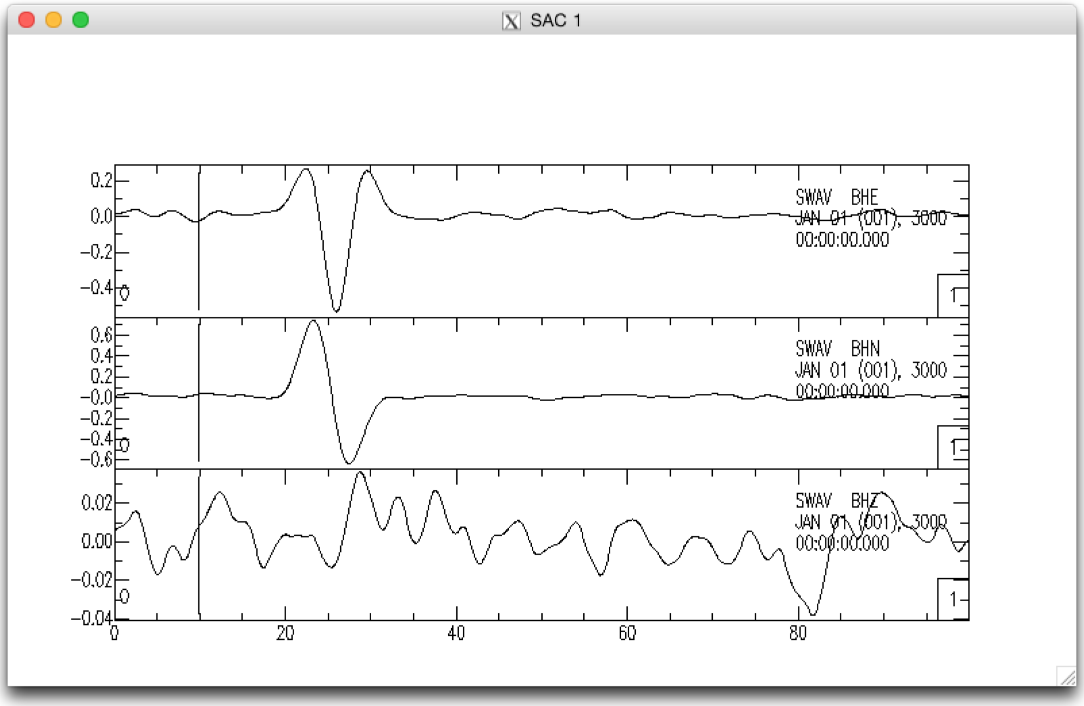
After running the macro, you will see the following:

```
---------------------------------------------
-          S H E B A - Version 0.997        -
---------------------------------------------
-             James Wookey, 2010            -
---------------------------------------------
filename base: wave
comp: BHE
comp: BHN
comp: BHZ
Input files:  wave.BHE wave.BHN wave.BHZ
Pick range of window STARTS - A begins window, F ends it.
NOTE: NOT WHOLE PHASE!
```

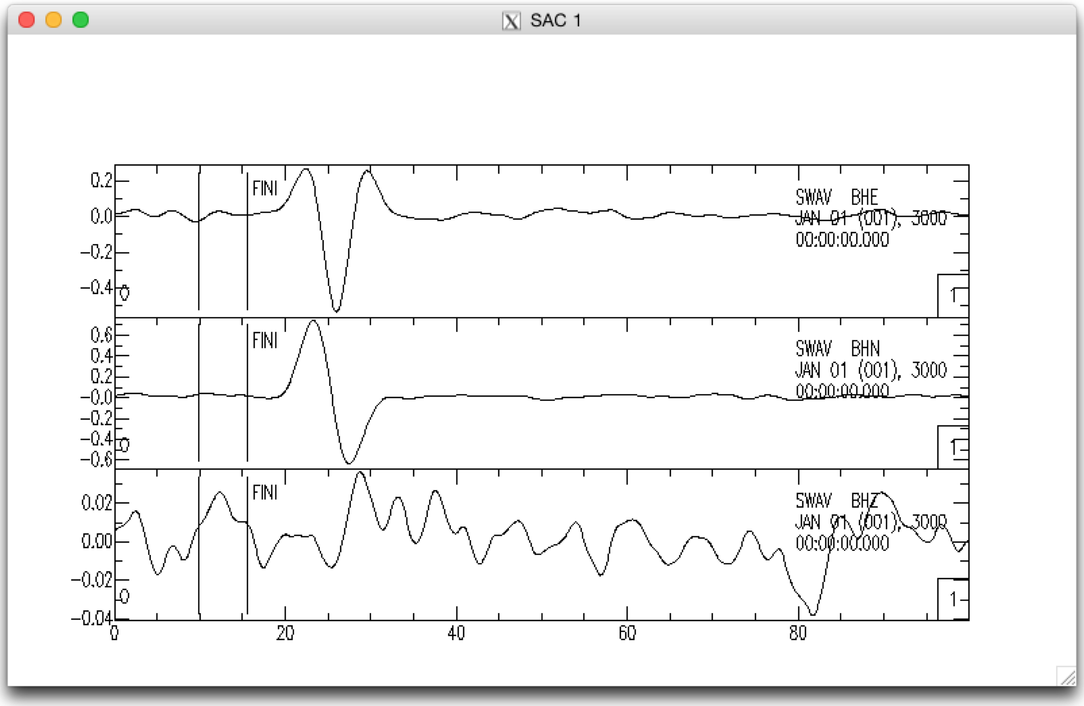
Your graphics terminal will show a plot of the traces using SAC's `ppk` command:



Our analysis window obviously should include the large amplitude arrival (synthetic in these images), but we must first choose a range of windows before the arrival. Do as the macro instructs, and pick the start of the window range with the `A` key:

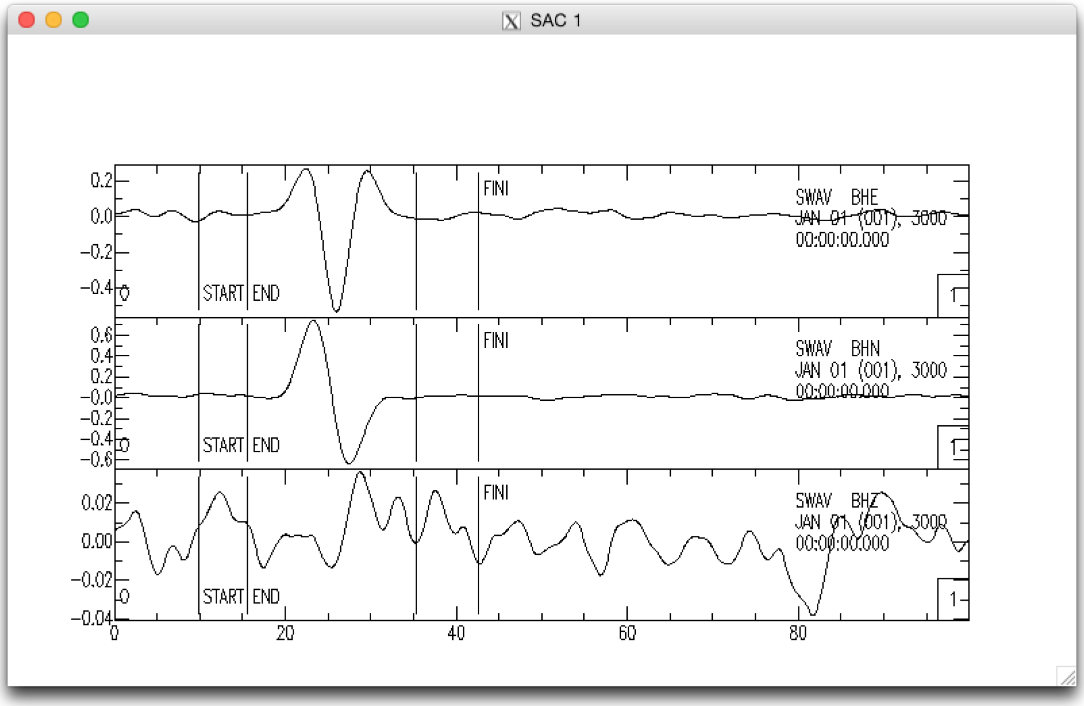


then the end with the F key:



You can repick the start and end with the A and F keys as often as you want until you are happy with the selection, then press Q to confirm.

You now must pick the range of end analysis windows, so will repeat the procedure but after the signal of interest, like so:



When completing the range of end analysis windows, SHEBA will carry on and perform the splitting analysis for all windows and present you with the results. The output will be similar to:

```
 Second eignval. minimisation.

================================================================================
-                 S H E B A  -  Shear-wave Birefringence Analysis              -
--------------------------------------------------------------------------------
-                         Version 1.01 - James Wookey 2014                     -
================================================================================

 > Checking trace header
 > Checking trace header
 > Checking trace header
 > Running multiple window shear-wave splitting
 no. windows to cycle =          100
  1      9.800 -   35.250s  tlag = 1.97500 +/- 0.08125  fast =   31.000 +/-   2.500
  2     10.433 -   35.250s  tlag = 1.97500 +/- 0.07500  fast =   31.000 +/-   2.250
[ ... ]
 99     14.859 -   42.521s  tlag = 2.00000 +/- 0.16250  fast =   30.000 +/-   4.750
```

```
100    15.491 -  42.521s  tlag = 2.00000 +/- 0.16250  fast =  30.000 +/-   4.750
 Done all windows, running cluster analysis
 cluster no.=           1  error =    1.11871632E-04  n=          23
 cluster no.=           2  error =    4.27975392E-05  n=          77
 cluster            1  passes n>          5
 cluster            2  passes n>          5
 error_int   13.8021851
 error_int   80.6896133
================================================================================
  RESULT for:wave
================================================================================
 s-wave window =   11.0648632      -    35.2495003      seconds
 lag      =   2.00000000     +/-   8.12500045E-02  seconds
 fast     =   30.0000000     +/-   2.50000000      degrees
 spol     =   179.954254     +/-   8.46120194E-02  degrees
--------------------------------------------------------------------------------
 Q =  0.938  L2/L1(%) =   27.83 (pre-corr.)   0.15 (post-corr.)  SNR =  30.67
================================================================================
 Reading pars
 Header values recovered
 Generating plot...
  -> Input traces in input orientation
 Generating plot...
  -> Original and linearised traces in source radial-transverse
 Generating plot...
  -> Particle motion
 -> Error surface and cluster analysis, q in window to exit ...
SAC>
```

5.5 Applying a receiver correction

We will normally need to remove the splitting due to anisotropy near the seismic station when performing our analyses. These will be based on SKS splitting parameters at the station which I will have suggested. If the value of the fast orientation at the station is ϕ_{SKS} (`phi_SKS`), and the delay time is δt_{SKS} (`dt_SKS`), you can apply the correction using the `corr` argument to the `sheba` macro in SAC:

```
SAC> m sheba file STA nwind 5 5 corr phi_SKS dt_SKS
```

You would then pick the shear wave splitting analysis window ranges the usual way.

References

Helffrich, G., Wookey, J., & Bastow, I., 2013. *The Seismic Analysis Code: A primer and user's guide*, Cambridge University Press.

Kendall, J.-M. & Silver, P. G., 1998. Investigating causes of D$''$ anistropy, in *The Core-Mantle Boundary Region*.

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Nowacki, A., Wookey, J., & Kendall, J.-M., 2010. Deformation of the lowermost mantle from seismic anisotropy, *Nature*, **467**(7319), 1091–1095, doi:10.1038/nature09507.

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