Instruction

- Analysis of SPAC Method -

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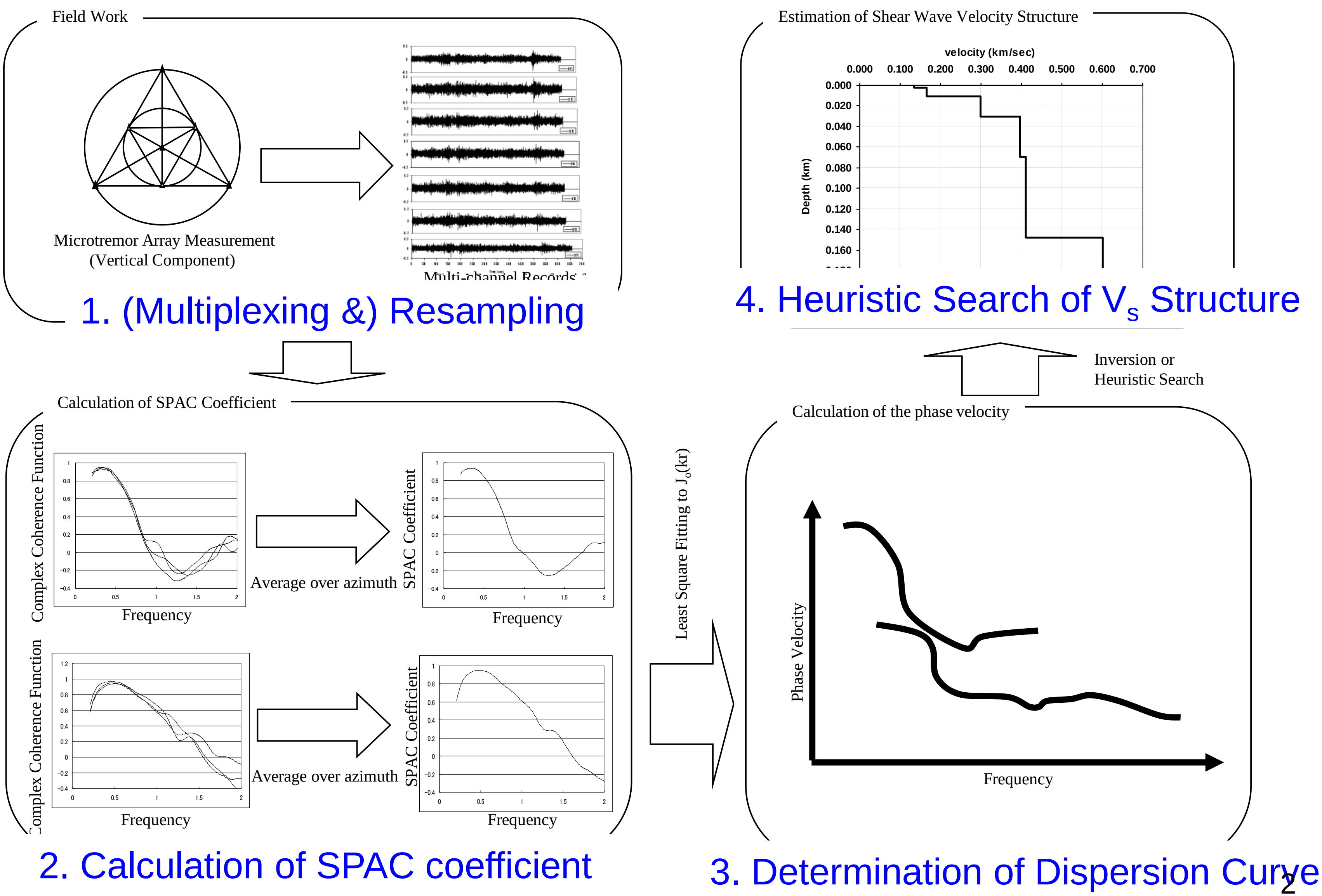
Procedures of analysis



Note: This version was developed on Linux: Ubuntu 16.04 LTS on VMWare Workstation Player 12.1.1 (build-3770994) on Windows10 Home 64bit (Build 14393) for 64bit PC, using gfortran compiler.

Operation on other OS may require additional revision or modification by users themselves.

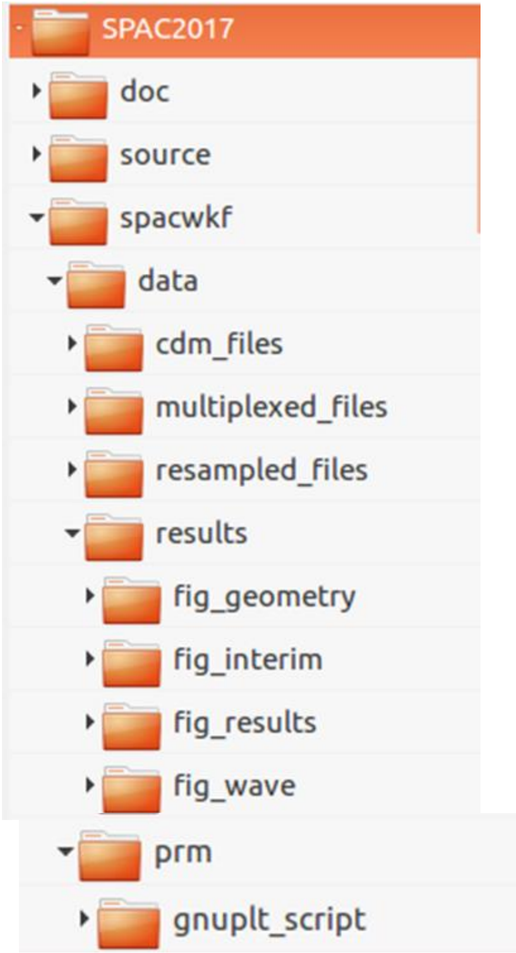
Execution of commands is conducted as

./*executable_file_name*.exe
or
sh *shell_script_file_name*.sh

If it is necessary to leave log file of execution

./*executable_file_name*.exe 2>&1 | tee ./spacwkf/log/*log_file_name*.log
or
sh *shell_script_file_name*.sh 2>&1 | tee ./spacwkf/data/log/*log_file_name*.log

Folder Structure



Every necessary programs and files are stored under the folder "SPAC2017". The command operation must be conducted in the same folder.

The source codes of the programs are stored in the subfolder "source", whereas the subfolder "doc" includes document files including this instruction manual.

The subfolder of work space "spacwkf" contains the subfolder "prm" for parameter files that includes script files of GNUPLOT and the subfolder "data" for data files including graphic ones.

Note: GNUPLOT scripts files

The folder “SPAC2017” includes files of GNUPLOT scripts.

Interim.plt
results.plt
etc.

and others under the subfolder ./spacwkf/prm/gnuplt_scripts

These can be loaded on GNUPLOT as load ‘????’
Some programs create the scripts of GNUPLOT in that the command

‘set terminal x11’ ,

Is included. This works on the GNUPLOT on Ubuntu and may be that on Windows.

If any problem on Windows, it is worth to try to replace it with

‘set terminal wxt’ .

Note: Executable files

The folder “SPAC2017” includes several executable files. Their source code files are stored in the subfolder ./source. Then, the following command is required to re-compile them if necessary. In the folder SPAC2017, type in the following command.

```
gfortran ./source/???.for  –o ???.exe
```

In case of problems caused by the incompatibility between Fortran77 and Fortran95,

```
gfortran  -ff2c ./source/???.for  –o ???.exe
```

Executable files must be stored in the folder SPAC2017. This means that it is not necessary to move the executable files.

Note: Shell script files

The folder “SPAC2017” includes several shell script files.
They are composed of few executing commands to reduce the typing tasks in data processing.
The following command can execute the shell script files.

sh *shell_script_file_name*.sh

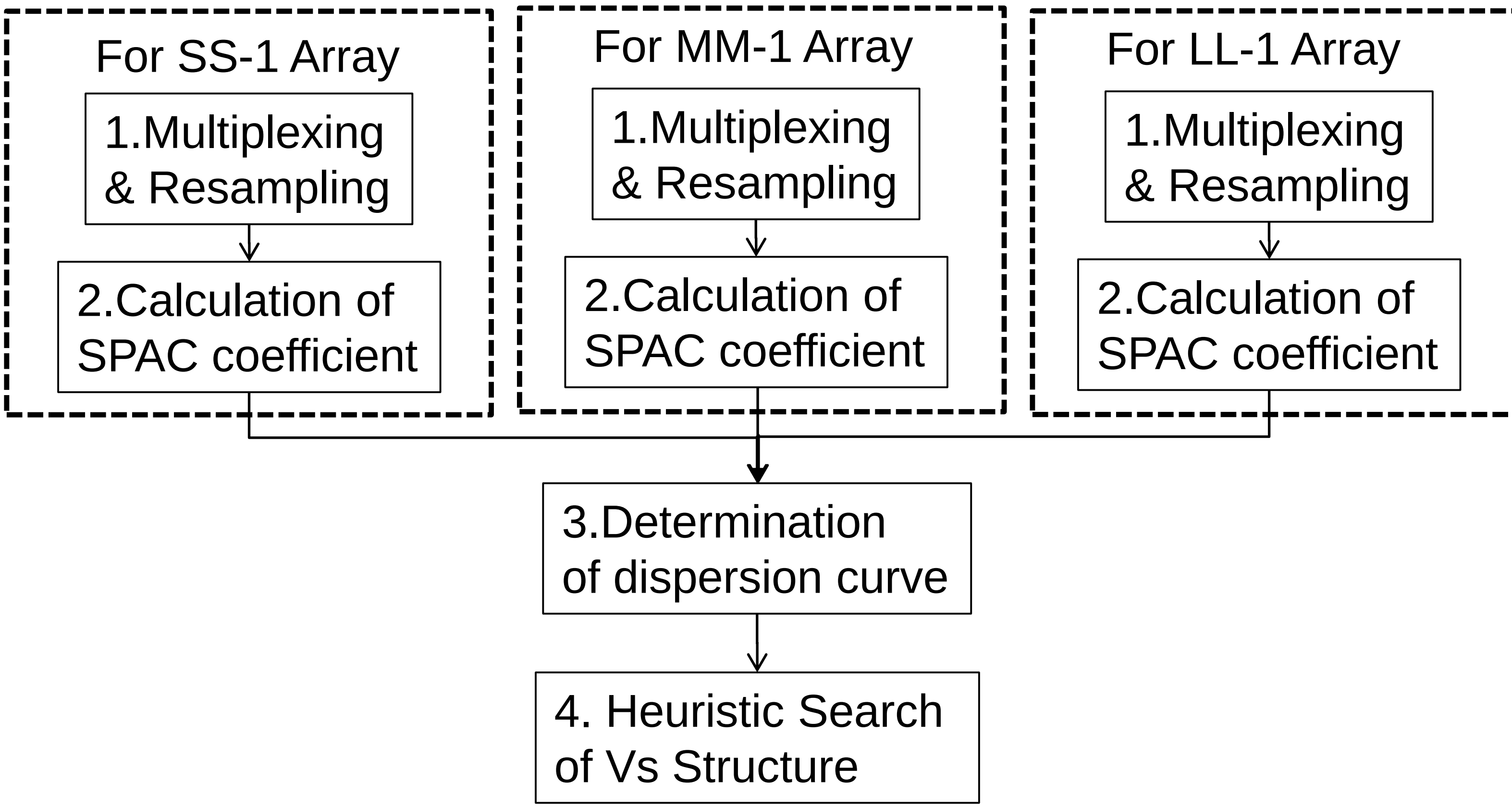
As the contents of the shell script files contained in this program package are simple, they can work as batch files. However, it is necessary to activate batch files using the following.

chmod u+x *shell_script_file_name*.sh

For execution as a batch file,
./*shell_script_file_name*.sh

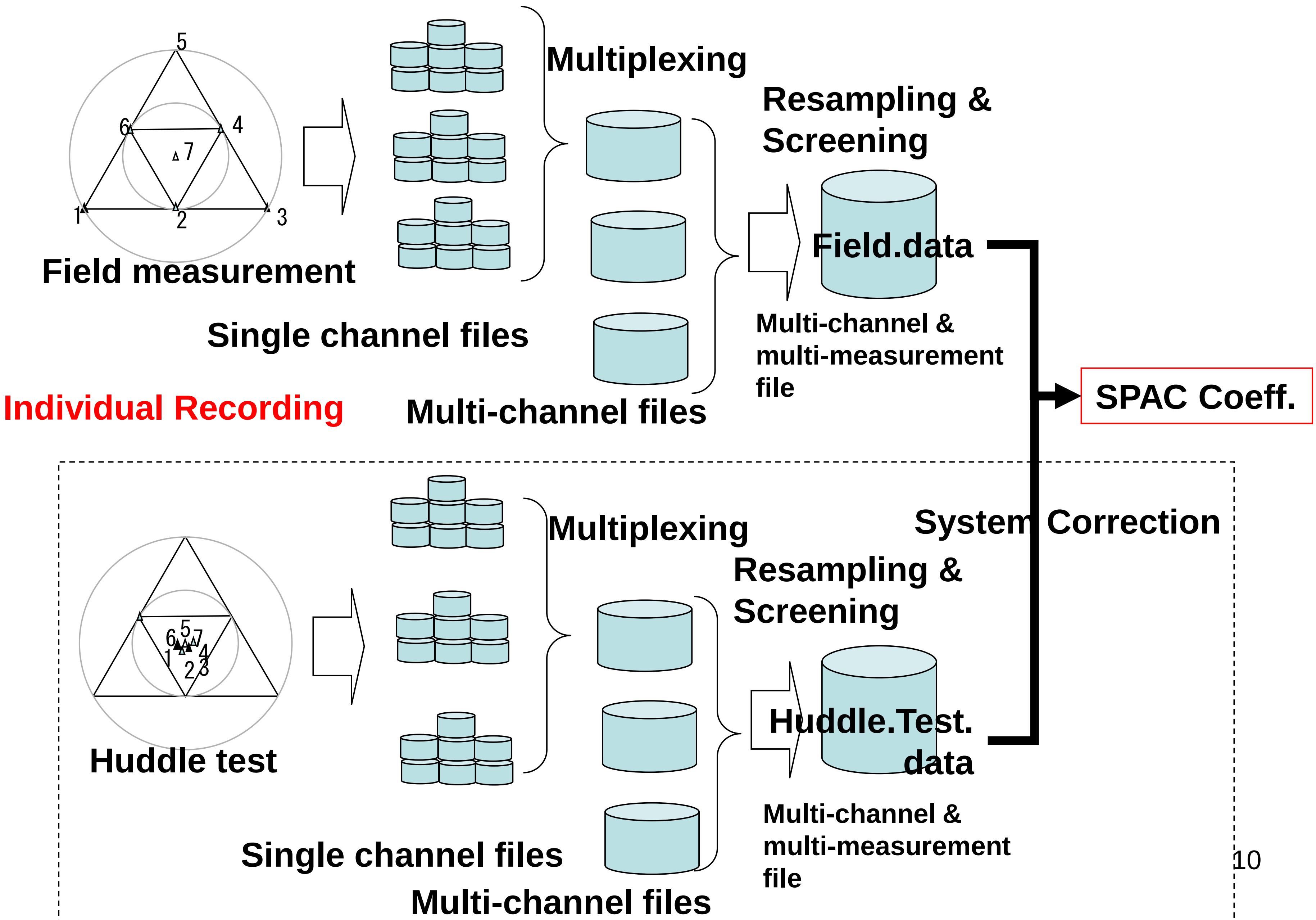
Note: Example

An example that consists of two arrays of different sizes is shown below.
+ SS-1 Array: 7 points equilateral triangle array with the center
+ MM-1 Array: 4 points equilateral triangle array with the center
+ LL-1 Array: 4 points equilateral triangle array with the center



1. (Multiplexing &) Resampling

Flow of the data processing for the conventional SPAC



1. Multiplexing & Resampling

1.1. Multiplexing (Optional)

Single channel files are combined into a multi-channel file
(This step is not necessary for the multi-channel recording cases)

multipx6.exe + ./spacwkf/prm/multipx6.prm

First step is to edit the parameter file multipx6.prm.

However, it is recommendable for users to make own conversion program from her/his original format files directly to multiplexed files of the format explained below.

Terminology

Multiplexing:

To sort the data individually stored in single channel files into a multi-channel file of the time-sequential format.

Huddle test:

Common input motion recording to determine the difference of the system characteristics among the recording system and/or channels.
The seismometers used in field measurement are put close each other like a huddle and simultaneous recording is conducted.

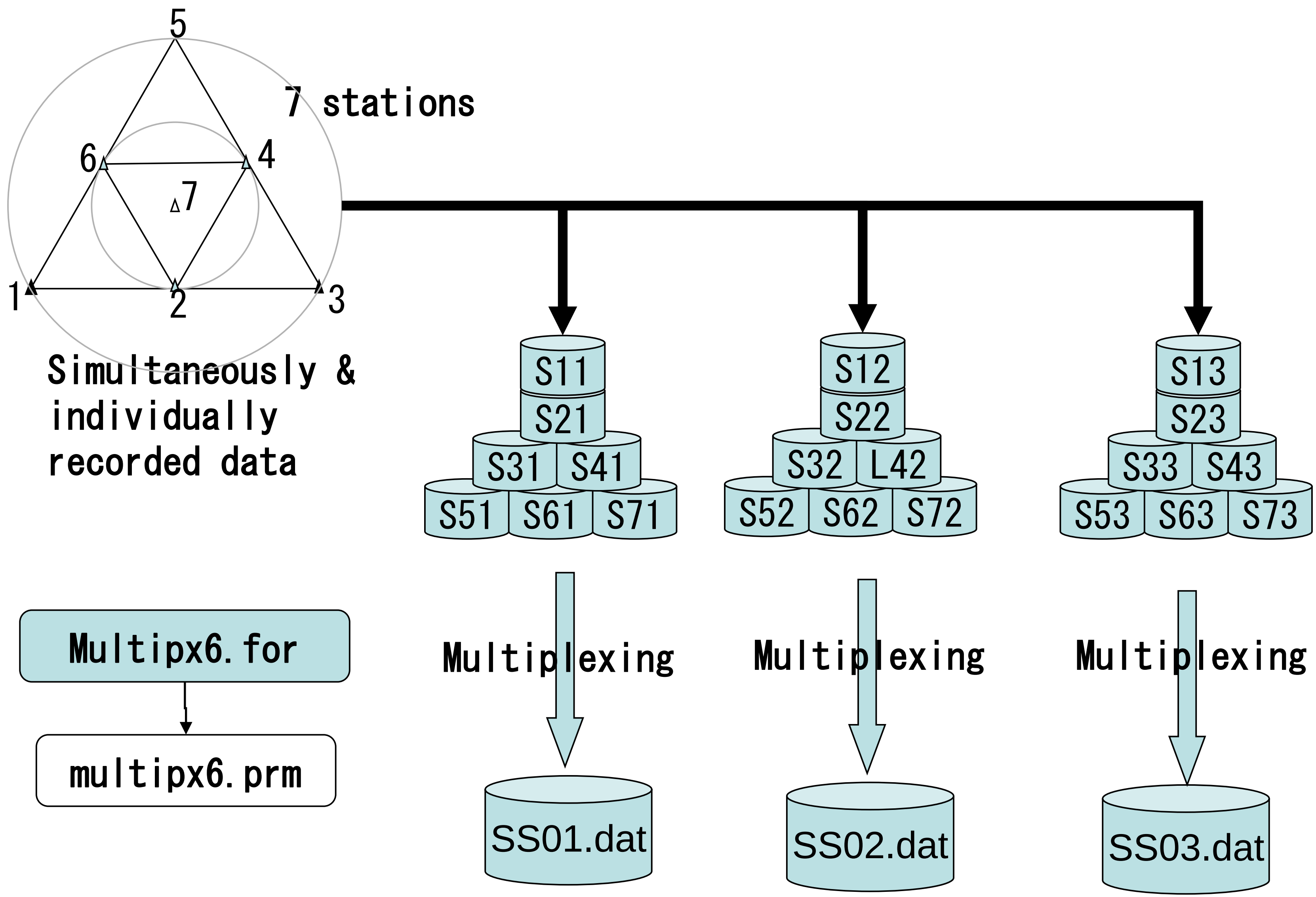
Re-sampling:

It can be done to thin the data out in order to reduce the size of data files and the load to PC for processing. This can cause the aliazing effect. Then, it Is necessary to apply the digital anti-alias filter that has high cut characteristics before thinning out.

System correction:

The difference of the characteristics among the recording system can be corrected using the data obtained by huddle tests.

Multiplexing the single channel files



Multi-channel files

Warning:

The program multipx6.exe does not have the functionality to adjust the time difference among the single channel files. The input files must have the same timing.

Confirm the following:
+ All input files have the same sampling interval.
+ All input files have their first datum that are sampled at the same time.

multipx6.prm

1st case

```
 3                            :Number of cases
                              :This blank is necessary
 4 0.01                       :Number of Channels,dt
0.0   163.83                  :tst,tdur
1.e11  mkine                  :scale(input data is divided by this scale),unit(a5)
0 3 0.005 1.0 1.5             :nfilter(=1:apply), ncharacter(=2:lowpass,=3:bandpass),fl,fh,fs
 4   .cdm                     :nattach, cattach
2 MM                          :n_out(A12),cout    ("**.dat" is attached)
MM-1, Iwaki City Hall, Dec.22, 2012                 :comment(A50)
21 8                          :number of measurement in the same array configuration,n_character
sxm21001 sxm21002 sxm21003 sxm21004
...
sxm23601 sxm23602 sxm23603 sxm23604
```

2nd case

```
                              :This blank is necessary
 7 0.002                      :Number of Channels,dt
0.0    32.766                 :tst,tdur
3.16e2  mkine                   :scale(input data is divided by this scale)
0 3 0.005 1.0 1.5             :nfilter(=1:apply), ncharacter(=2:lowpass,=3:bandpass),fl,fh,fs
 4   .cdm                     :nattach, cattach
2 SS                          :n_out(A12),cout    ("**.dat" is attached)
SS-1, Iwaki City Hall, Dec.22, 2012                 :comment(A50)
30 8                          :number of measurement in the same array configuration,n_character
sxs10101 sxs10102 sxs10103 sxs10104 sxs10105 sxs10106 sxs10107
…
sxs13001 sxs13002 sxs13003 sxs13004 sxs13005 sxs13006 sxs13007
```

3rd case

```
                              :This blank is necessary
 4 0.01                       :Number of Channels,dt
0.0   163.83                  :tst,tdur
3.16e10  mkine                  :scale(input data is divided by this scale)
0 3 0.005 1.0 1.5             :nfilter(=1:apply), ncharacter(=2:lowpass,=3:bandpass),fl,fh,fs
 4   .cdm                     :nattach, cattach
2 LL                          :n_out(A12),cout    ("**.dat" is attached)
LL-1, Iwaki City Hall, Dec.22, 2012                 :comment(A50)
28 8                          :number of measurement in the same array configuration,n_character
sxl21001 sxl21003 sxl21005 sxl21007
…
sxl24601 sxl24603 sxl24605 sxl24607
```

multipx6.prm

```
 3                   :Number of cases
                     :This blank is necessary
 4 0.01              :Number of Channels,dt
0.0   163.83         :tst,tdur
1.e11  mkine         :scale(input data is divided by this scale),unit(a5)
0 3 0.1 1.0 1.5 :nfilter(=1:apply),ncharacter(=2:lowpass,=3:bandpass),fl,fh,fs
 4   .cdm            :nattach, cattach ➔ Input single channel file name
2 MM                 :n_out(A12),cout ("**.dat" is attached)
MM-1, Iwaki City Hall, Dec.22, 2012              :comment(A50)
21 8       :number of measurement in the same array configuration,n_character
sxm21001 sxm21002 sxm21003 sxm21004 ←— 1st
...
sxm23601 sxm23602 sxm23603 sxm23604 ←— 21th measurement
```

1ch 2ch 3ch 4ch

Input file names : sxm2??0?.cdm

consist of the character string ‘sxm2??0?’ of 8 characters plus another character string ‘.cdm’ of 4 characters. These character strings and their number of characters are indicated in the 7th line for the latter and the 11th line and below for the former. Program ‘multipx6.exe’ automatically combines them and read the data from the files.

Output file name: SS01.dat for the 1st measurement. ’01’ shows the numbering of measurement.

…

SS30.dat for the 30th measurement. ’30’ shows the numbering of measurement.

These output file names consist of the character string ‘MM’ of 2 characters as indicated in the 8th line. The following two integers show the numbering of measurement. ‘.dat’ is attached to all automatically.

The data from tst to tst+tdur are processed in every files.

Values read from the input files are divided by the scale factor given in the 5th line. This value must be selected to make the unit of data in the output file is ‘mkine’, i.e., 1.0E-5 M/sec for ground velocity. For ground acceleration ‘gal’, i.e., 1.0E-2 M/sec^2 should be used. Otherwise the amplitudes of the data will be erroneously shown in the output figures.

sxm21001.cdm:

Example: format of input file (dt=0.01 sec) of single channel data
in ./spacwkf/data/cdm_files

```
File=01001.cdm       ch. 1
                  unit
                   V
     0 00:00:00.000  -0.1396391E+11
     1 00:00:00.010  -0.1513392E+11
     2 00:00:00.020  -0.1472600E+11
     3 00:00:00.030  -0.1314799E+11
     4 00:00:00.040  -0.7706377E+10
     5 00:00:00.050  -0.3947473E+10


 16383 00:02:43.830  -0.7844215E+10
```

3 lines for header

Data lines:

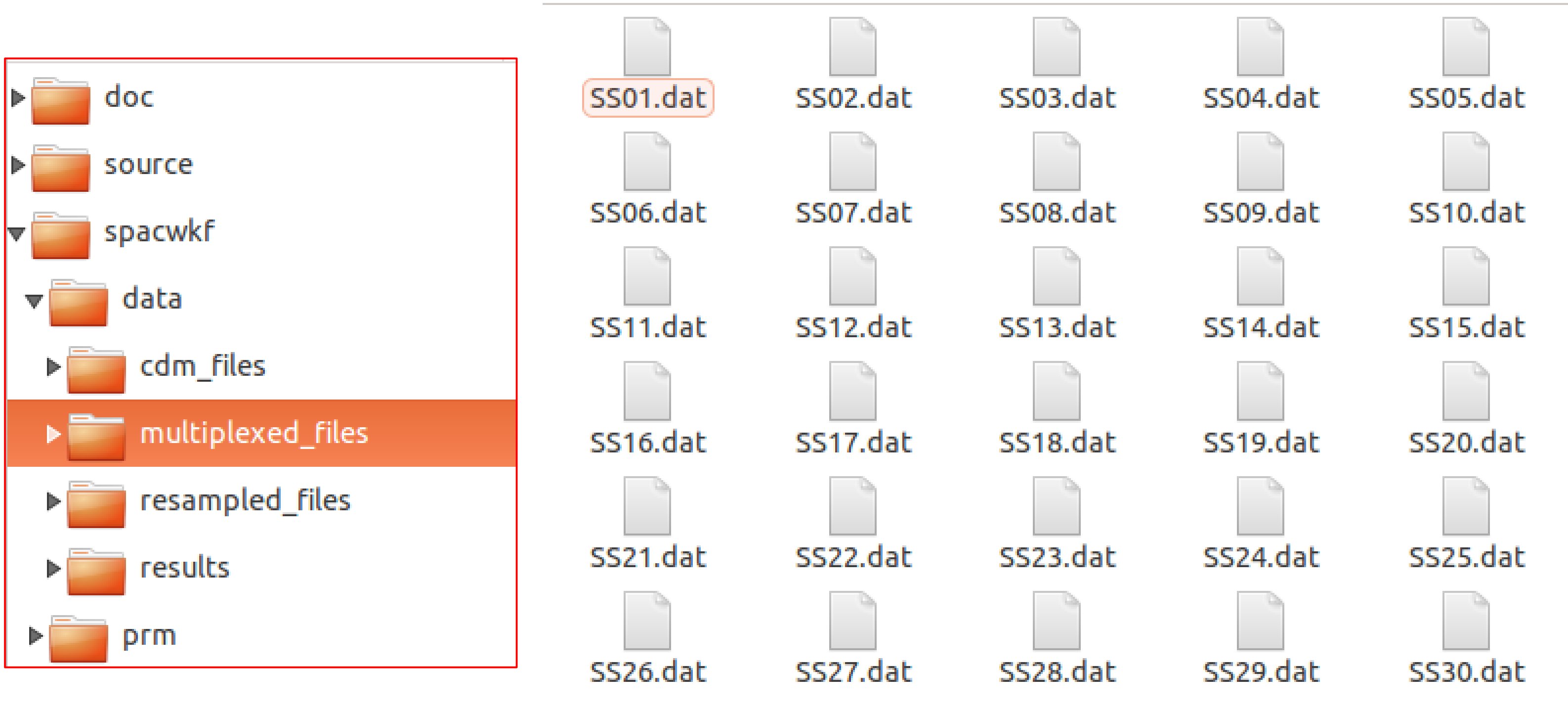
Numbering, (A8) time, (A13) data (e16.7)

Example of execution (from the folder SPAC2017):

```
~$./multipx6.exe
```

```
 Working Folder=./spacwkf/prm/
  Nch=           4  dt=   9.99999978E-03
  Scale Factor=   9.99999980E+10
  Does this scale convert the unit of data mkine ?
  Please change the value if not.
           0           3   4.99999989E-03   1.00000000       1.50000000
 MM-1, Iwaki City Hall, Dec.22, 2012               :
           1 -th measurement:           4
sxm21001 sxm21002 sxm21003 sxm21004
       16383



 ./spacwkf/data/multiplexed_files/MM01.dat
           2 -th measurement:           4
…
 Normal End
```

Example of output file (stored in the subfolder ./spacwkf/data/multiplexed_files




```
  7  0.0020      0.3160E+03   16382  mkine
SS-1, Iwaki City Hall, Dec.22, 2012                :
    0.000000 -0.0000000E+00 -0.0000000E+00 -0.0000000E+00  0.0000000E+00 -0.0000000E+00  0.0000000E+00 -0.0000000E+00
    0.002000 -0.8961562E-04  0.5361709E-05 -0.2044998E-04  0.1081865E-03 -0.1978091E-05  0.2530022E-04 -0.4171700E-04
    0.004000 -0.1640327E-03  0.8138977E-04 -0.1974745E-04  0.1997052E-03  0.2068763E-04  0.4874512E-04 -0.9626019E-04
…
```

1st line: channel number, dt, scale factor, number of samples, unit
2nd line & below: time, 1ch,2ch,3ch,…, 7ch.

Warning!

- The declared array size for input data in multipx6.for is 1,200,000. This gives the constraint: tdur/dt < or =1,200,000
- Similarly   nch< or =15

For much longer data file:

“multipx6.for” can handle 1200,000 samples of 15 channels at once. If you have data of longer recording time, it is recommendable to separate them beforehand.
An alternative may be the following way of using “tst” and “tdur” in ”multipx5.prm” can let you utilize the data fully.

For the 1st operation:

```
   0.0    3600.0                  :tst(start time)),tdur(duration) in sec.
```

For the 2nd operation:

```
3600.01   3600.0                  :tst(start time)),tdur(duration) in sec.
```

For the 3rd operation:

```
7200.01   3600.0                  :tst(start time)),tdur(duration) in sec.
```

…

Namely, “multipx6.for”skips int(tst/dt) data and then starts reading the next data.

Example Data files: These are already multiplexed.

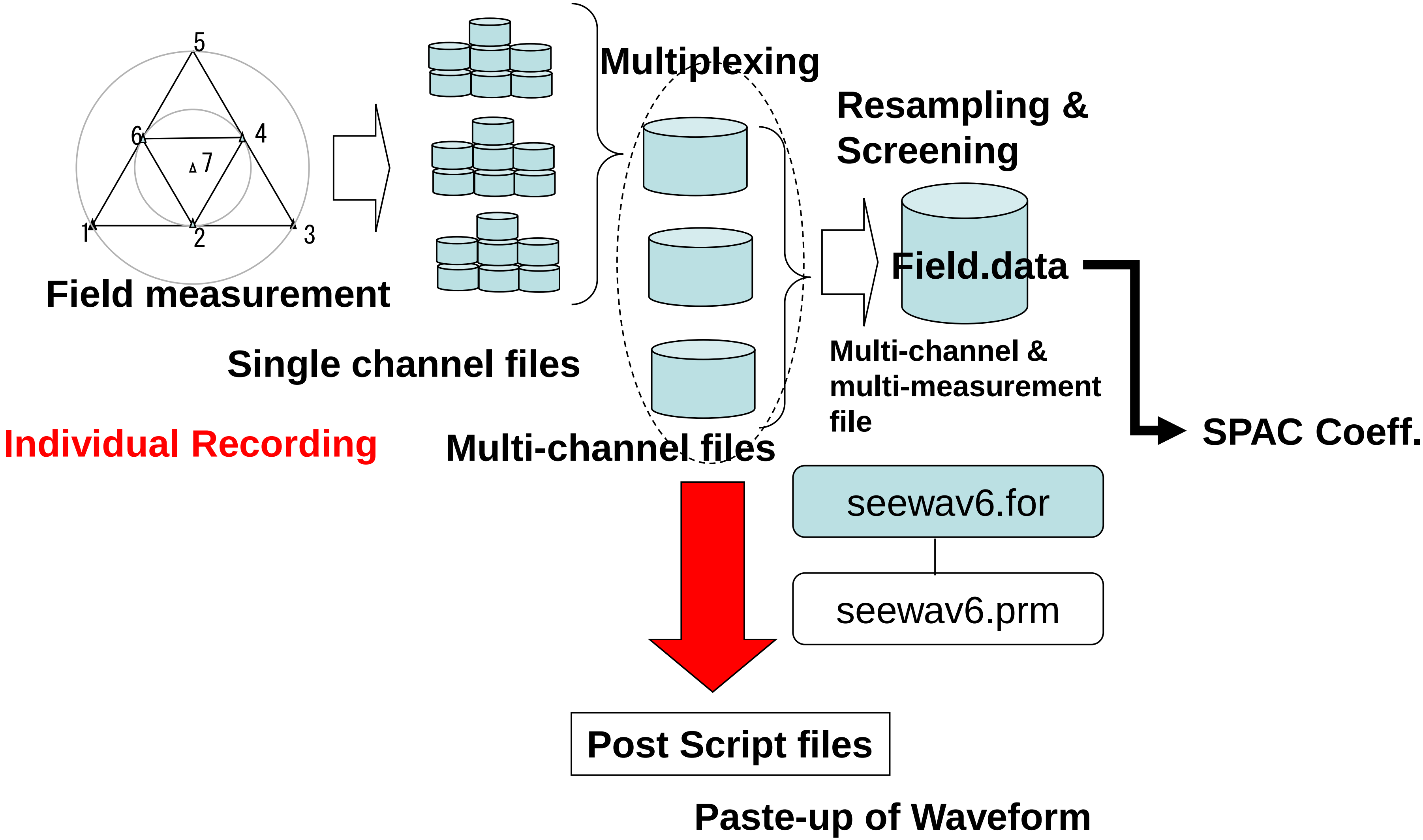
multi_SS.tar.gz
multi_MM.tar.gz
multi_LL.tar.gz

Copy these three compressed files into the subfolder "./spacwkf/data/multiplexed_files" for exercise with these example Data files.

1.2. Plot Waveform

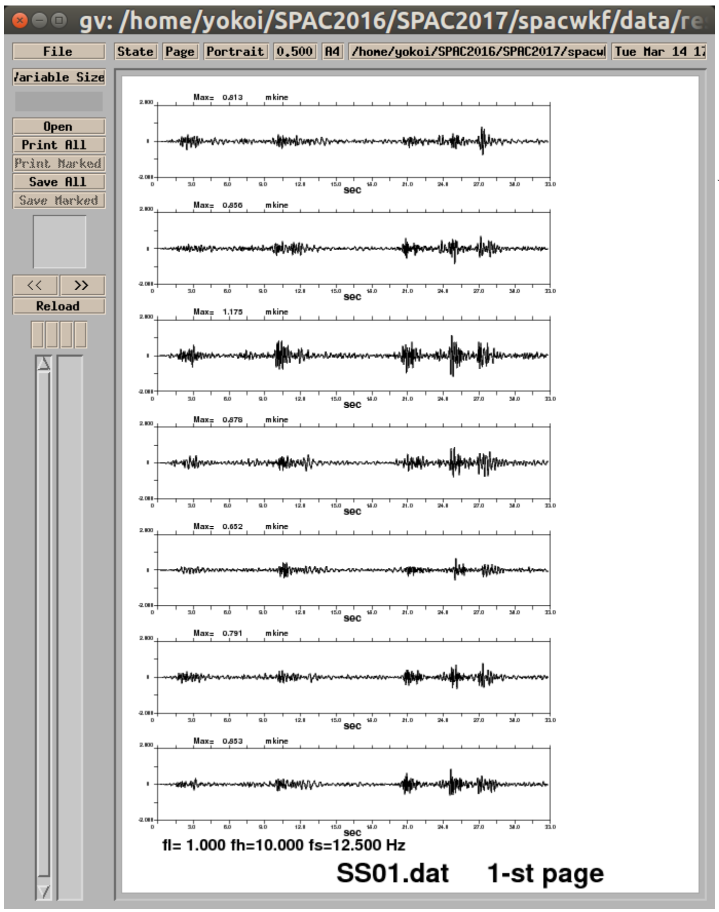
seewav6.exe+ ./spacwkf/prm/seewav6.prm

Flow of the data processing for the conventional SPAC



Multi-channel file: SS01.dat

```
 7   0.0020      0.3160E+03   16382  mkine
SS-1,  Iwaki City Hall,  Dec.22,  2012                 :
     0.000000 -0.0000000E+00 -0.0000000E+00 -0.0000000E+00  0.0000000E+00 -0.0000000E+00  0.0000000E+00 -0.0000000E+00
     0.002000 -0.8961562E-04  0.5361709E-05 -0.2044998E-04  0.1081865E-03 -0.1978091E-05  0.2530022E-04 -0.4171700E-04
     0.004000 -0.1640327E-03  0.8138977E-04 -0.1974745E-04  0.1997052E-03  0.2068763E-04  0.4874512E-04 -0.9626019E-04
...
```



seewav6.for

seewav6.prm

SS01.ps

Figures in Multi-page Post Script file. Post Script file can be opened, for example, by "gv &", where "gv and "&" stand for "ghost view" and background operation.

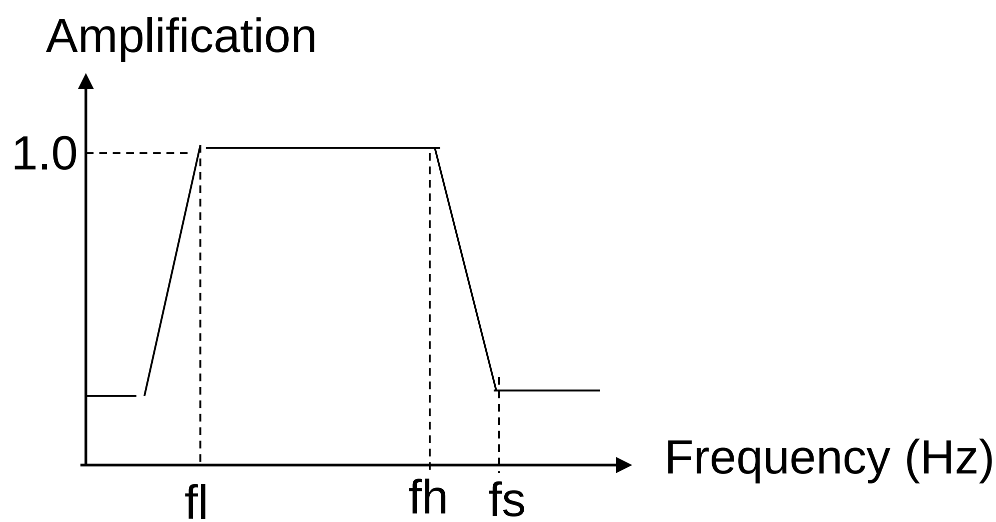
If "ghost view" is not installed yet:
sudo apt-get install gv

seewav6.prm

dtl denotes the time duration that corresponds to 1cm along the time axis.
In one page, 28*dtl/dt time step can be plotted. If the file has more, new pages are automatically added as much as necessary and multi-page PS file is created.

```
 7                            :nch
1  1.0 10.0 12.5 3            :nfilter,fl,fh,fs,nchara(=2:lowpass, =3:bandpass)
  1.5                         :dtl(sec/cm),25,50==>10,20 min/page
30 8                          :n_mea,n_character
SS01.dat
SS02.dat
…
SS30.dat
```

Band Pass Filter



nfilter=0: no effect
nfilter=1: bandpass filter is applied

This BPF does not affect to the data files.

If the records have significant DC-offset
(base line shift due to DC component)

seewav6.prm

```
  7                    :nch
 1  0.1 50.  60.0      :nfilter,,fl,fh,fs
  1.0                  :dtl(sec/cm)
 30 8                  :n_mea,n_character
 SS01.dat
 ...
 SS30.dat
```

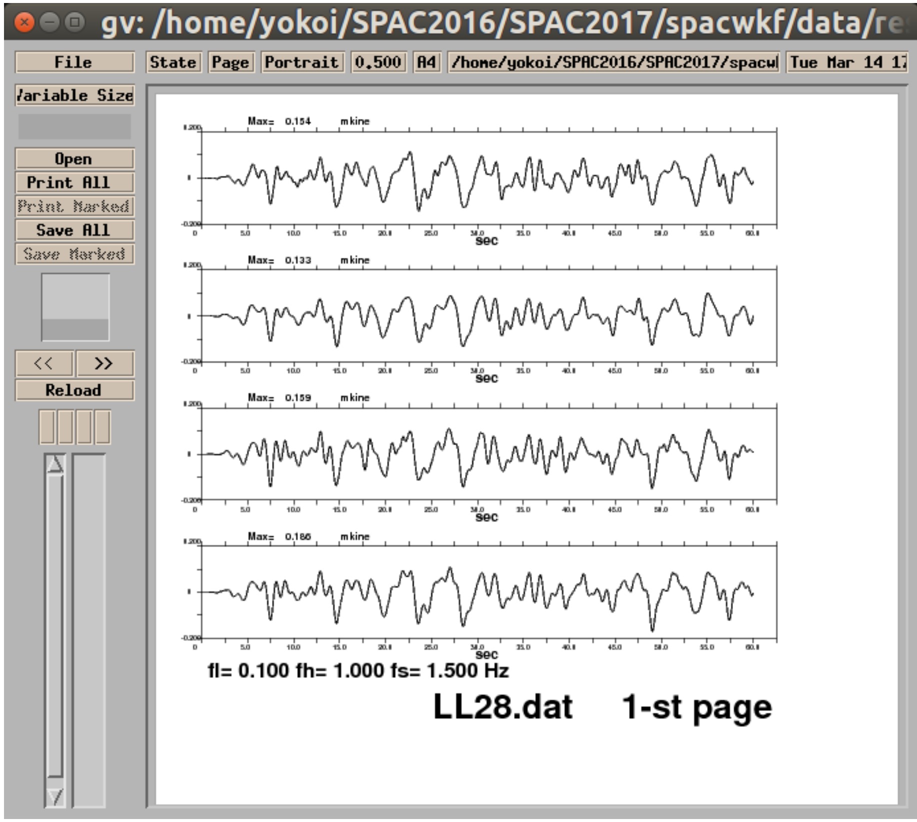
Set nbandpass = 1 and fs>Nyquist frequency

⇩

Waveform plots with DC-offset correction, but without applying bandpass filter, are given.

Example of execution:

```
$ ./seewav6.exe
 ./spacwkf/prm/seewav6.prm
           1  0.100000001       1.00000000       1.50000000              3
          28           8
 ./spacwkf/data/multiplexed_files/LL01.dat
  DC-offset removed & tapered;
  0.154889539      0.200000003
./spacwkf/data/results/fig_wave/LL01.ps
LL01.dat     1-st page
…
 ./spacwkf/data/multiplexed_files/LL28.dat
  DC-offset removed & tapered;
  0.186059728      0.200000003
./spacwkf/data/results/fig_wave/LL28.ps
LL28.dat     1-st page
~/SPAC2017 $
```



Output files:

PostScript files are stored in the folder:

./spacwkf/data/results/fig_wave

with extension “ps”. Use “gv &” to draw it.

1.3. Re-sampling & Screening

Re-sampling & Screening

resample5.exe + ./spacwkf/prm/resample5.prm

or

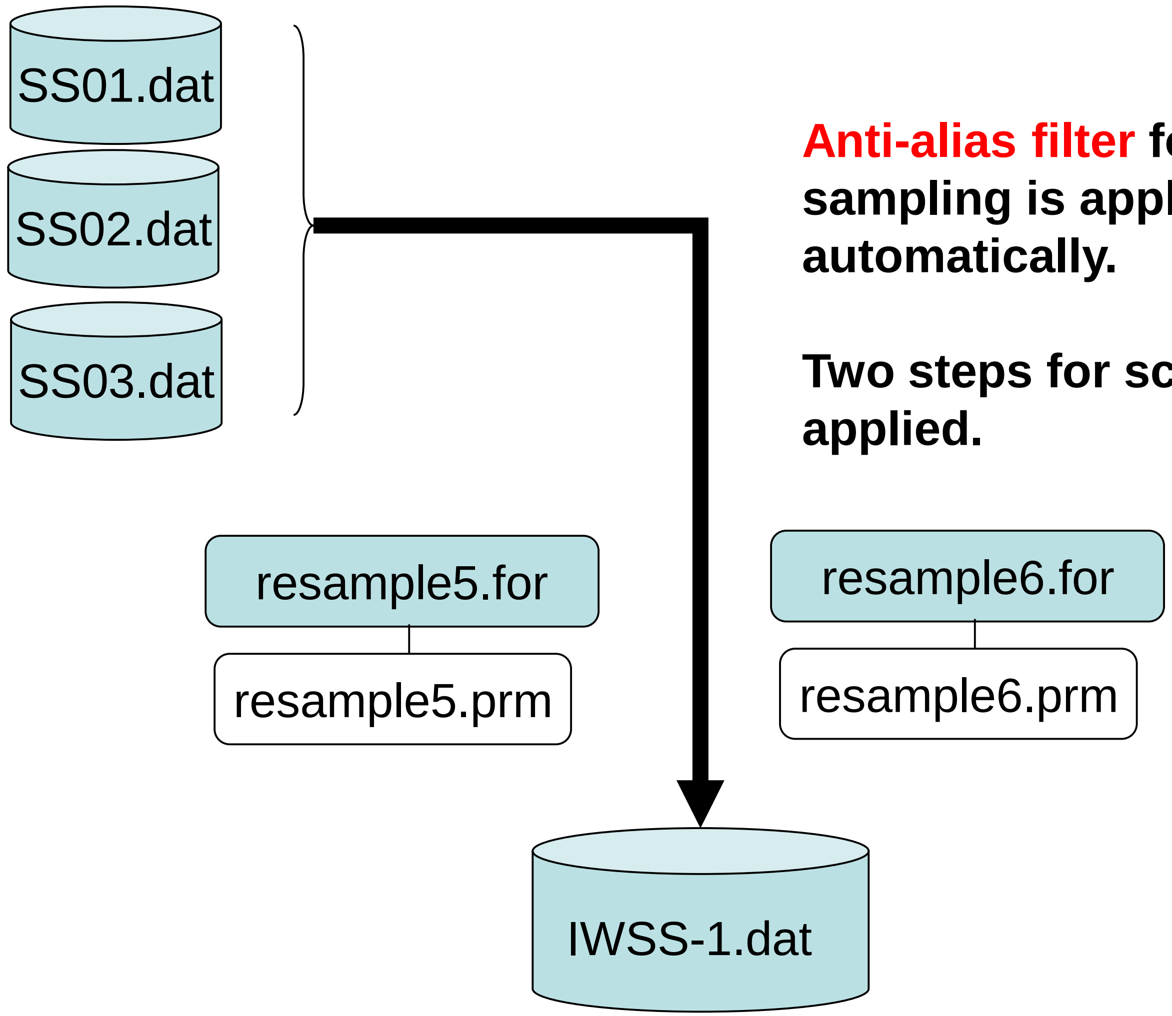
resample6.exe + ./spacwkf/prm/resample6.prm

Then, check the selected time blocks using

seeblk1.exe + seeblk1.prm

Re-sampling & Screening

Multi-channel data files from the same array configuration



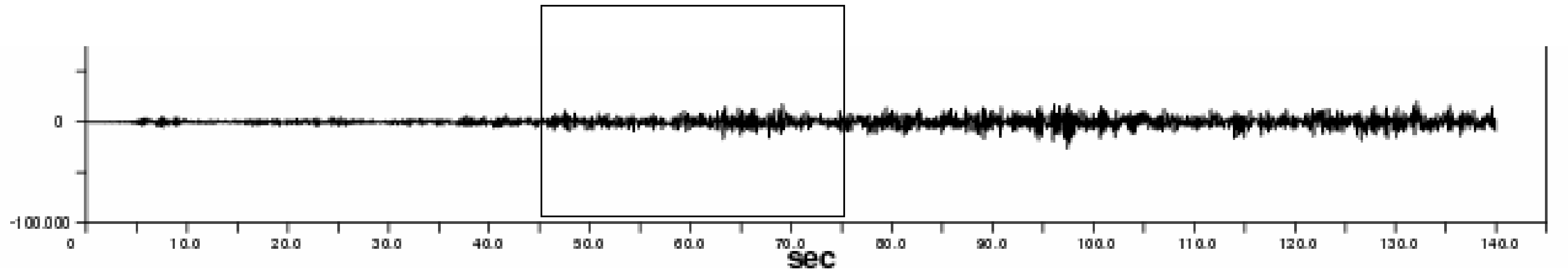
Anti-alias filter for re-sampling is applied automatically.

Two steps for screening are applied.

Resampled & screened multi-channel & multi-measurement data file

Screening: Step-1

Parameter: ajudge



If the maximum amplitude in a time block exceeds the product of the “ajudge” parameter to RMS amplitude of the same time block, this time block is not used in analysis.
This is a countermeasure against impulsive noise due to traffic, i. e., vehicles passing near by seismometers.
The bigger value of “ajudge” means looser screening. The smaller value means fewer available time blocks.

Screening: Step-2

Parameter: a_sgm

If the RMS amplitude in a time block deviates more than the "a_sgm" parameter multiplied to the standard deviation from the average, this time block is not used in analysis, where the average and the standard deviation are calculated over the all time blocks that survived in the screening Step-1.

This is a countermeasure against outliers.
The bigger value of "a_sgm" means looser screening. The smaller value means fewer available time blocks.

Warning:

Be sure to use the same resampling interval and the same block size, in case of the combination of arrays of various sizes. Otherwise, a heavy problem will take place in the further step of analysis, namely, the determination of dispersion curves.

The declared array size for input data in resample5.for and resample6.for is 750,000.
This gives the constraint: tdur/dt < or =750,000
Similarly nch< or =11
and number of data in one time block < or = 8192

It is recommendable to make a multiplexed data file for every 30 minutes or shorter duration, in order to avoid the problem due to the exceedance of input data quantity.

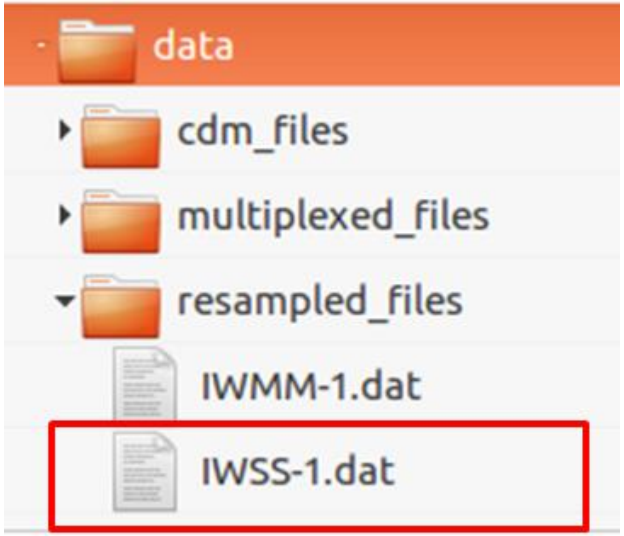
resample5.prm or resample6.prm

```
7 0.002 10          :nch,dt,number of Channels,dt,nskip
7.0 1.5             :ajudge,a_sgm
0.0  32.766         :tst,tdur
IWSS-1.dat          :output file name
1024                :number of data in one time block after resampling
30                  :number of measurement in the same array configuration
SS01.dat
SS02.dat
SS03.dat
…
SS30.dat
```

1st line: Channel number, sampling interval, skip data number
2nd line: ajudge, a_sgm: parameters for two step screening
3rd line: start time and duration for processing
4th line: Output file name
5th line: number of data in one time block after resampling.
resample5.for divides all the data into the time blocks that have this number of data allowing overlapping of 50 % between neighboring blocks.
6th line: number of measurement in the same array configuration.
Example1 is the single measurement case.
7th line: Input file name

Example of execution: Output file is stored in ‘./spacwkf/data/resampled_files’

```
~/SPAC2017$ ./resample5.exe
 ./spacwkf/prm/resample5.prm
  Working Folder=./spacwkf/prm/
 Band-Pass:fl=  0.100000001     fh=   20.2499981     fs=   22.4999981
  Nch=           7
  Nskip=          10  f(Nyquist)=   24.9999981      fs=   22.4999981
  ajudge=   7.00000000      a_sgm=   1.50000000
   0.00000000       32.7659988
  First screening (peak/rms<   7.00000000      ):
           1 -th measurement:./spacwkf/data/multiplexed_files/SS01.dat
           2  blocks remained among            2  blocks
...
 30 -th measurement:./spacwkf/data/multiplexed_files/SS30.dat
           2  blocks remained among            2  blocks
  Data stored in the temporary file
 ./spacwkf/data/resampled_files/IWSS-1.dat
  Second screening ({rms-average(rms)}/sigma<   1.50000000      ):
          27  blocks remained among           39  blocks
~/SPAC2017$
```



Resampled & screened multi-channel & multi-measurement data file

1st line:file parameters

```
       7      27      1024   (i8,f16.4, 7e15.7) mkine
       1              0.0000  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
       2              0.0200 -0.6542959E-10  0.6730985E-10  0.8688813E-11 -0.9121746E-10  0.3278066E-10  0.3681669E-10 -0.2157925E-10
     ...
    1024             20.4600  0.6798404E-01  0.8341893E-01  0.7360612E-01 -0.3876965E-01  0.1080229E+00 -0.9545929E-01 -0.1346539E+00
       1             10.2400 -0.1701506E+00  0.9676924E-01  0.3960467E-01 -0.3436972E+00  0.1931517E+00  0.1742720E-01  0.8249036E-01
     ...
    1024             30.7000 -0.4059438E-01  0.2059561E-02  0.2788787E-01 -0.1173913E+00  0.2213649E-01 -0.1785946E-01 -0.9963673E-01
       1              0.0000  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
     ...
```

(Lines 1 … 1024 after the first line: 1st block; next lines 1 … 1024: 2nd block)

The file includes mmblk=27 time blocks of nch=7 channel data.
Each time block is composed of nblk=1024 data.
Each line corresponds to a time step. The format used to store each line is cform3='(i8,f16.4, 7e15.7)'.
The unit for these data is "mkine".
These file parameters are stored in the 1st line.
As all of the data are delimited by space, this file can be read using free format.

For MM-1 array: resample6.prm

```
4 0.01  2                :nch,dt,number of Channels,dt,nskip
4.0 2.0                  :ajudge,a_sgm
0.0 163.83                 :tst,tdur
IWMM-1.dat                   :output file name
1024                     :number of data in one time block after resampling
21                      :number of measurement in the same array configuration
MM01.dat
…
MM21.dat
```

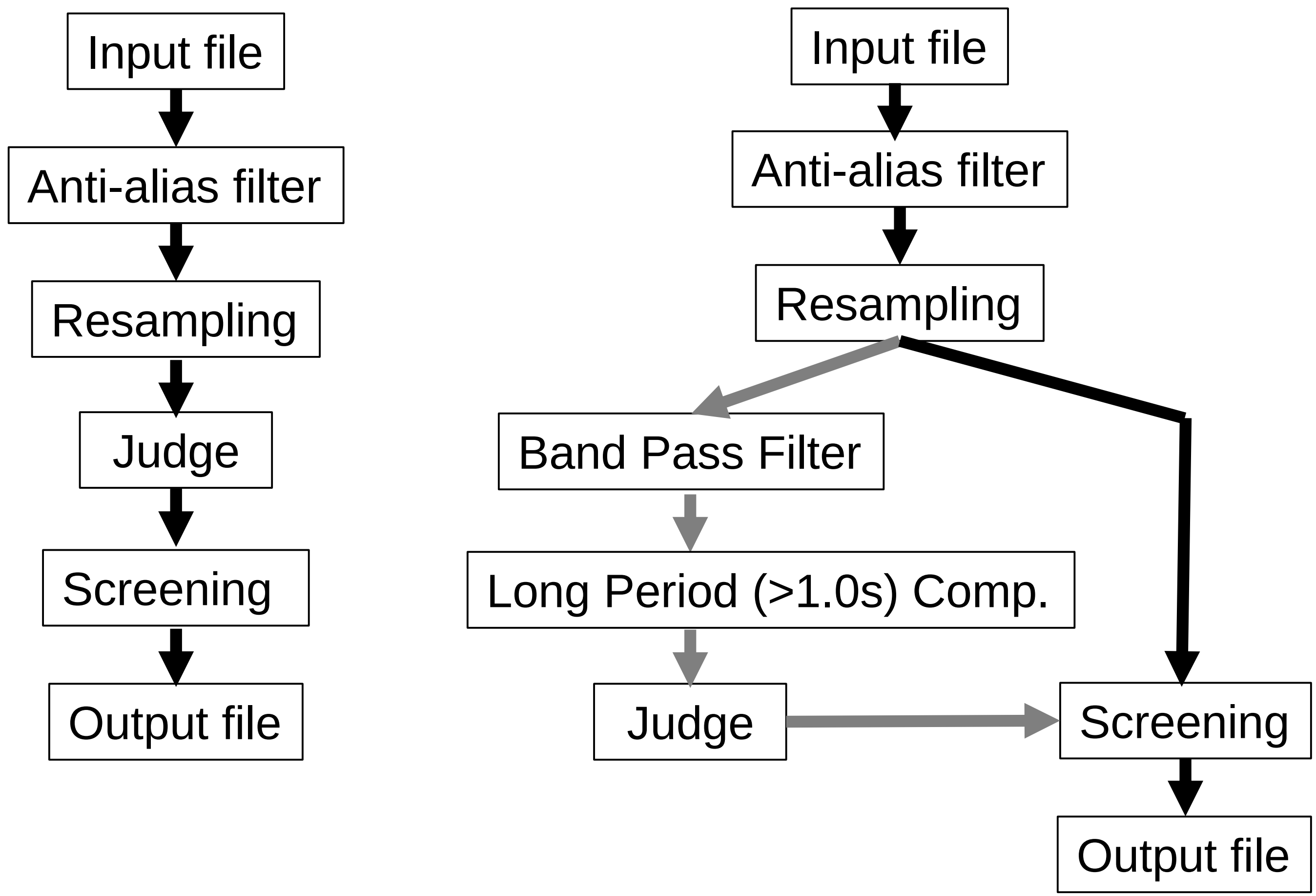
Execution:

```
~SPAC2017$ ./resample6.exe
 ./spacwkf/prm/resample6.prm
  Working Folder=./spacwkf/prm//
 Band-Pass:fl=  0.100000001     fh=   20.2500000     fs=   22.5000000
  Nch=           4
  Nskip=           2  f(Nyquist)=   25.0000000      fh=   20.2500000
  ajudge=   4.00000000      a_sgm=   2.00000000
   0.00000000       163.830002
  First screening (peak/rms<   4.00000000     ):
           1 -th measurement:./spacwkf/data/multiplexed_files/MM01.dat
 Band-Pass:fl1=   5.00000007E-02 fh1=   1.00000000     fs1=   1.50000000
          14  blocks remained among           14  blocks
…
 21 -th measurement:./spacwkf/data/multiplexed_files/MM21.dat
 Band-Pass:fl1=   5.00000007E-02 fh1=   1.00000000     fs1=   1.50000000
 14  blocks remained among           14  blocks
  Data stored in the temporary file
 ./spacwkf/data/resampled_files/IWMM-1.dat
  Second screening ({rms-average(rms)}/sigma<   2.00000000     ):
         280  blocks remained among          294  blocks
~SPAC2017$
```

What's special of resample6.exe in comparison with resample5.exe

resample5.exe

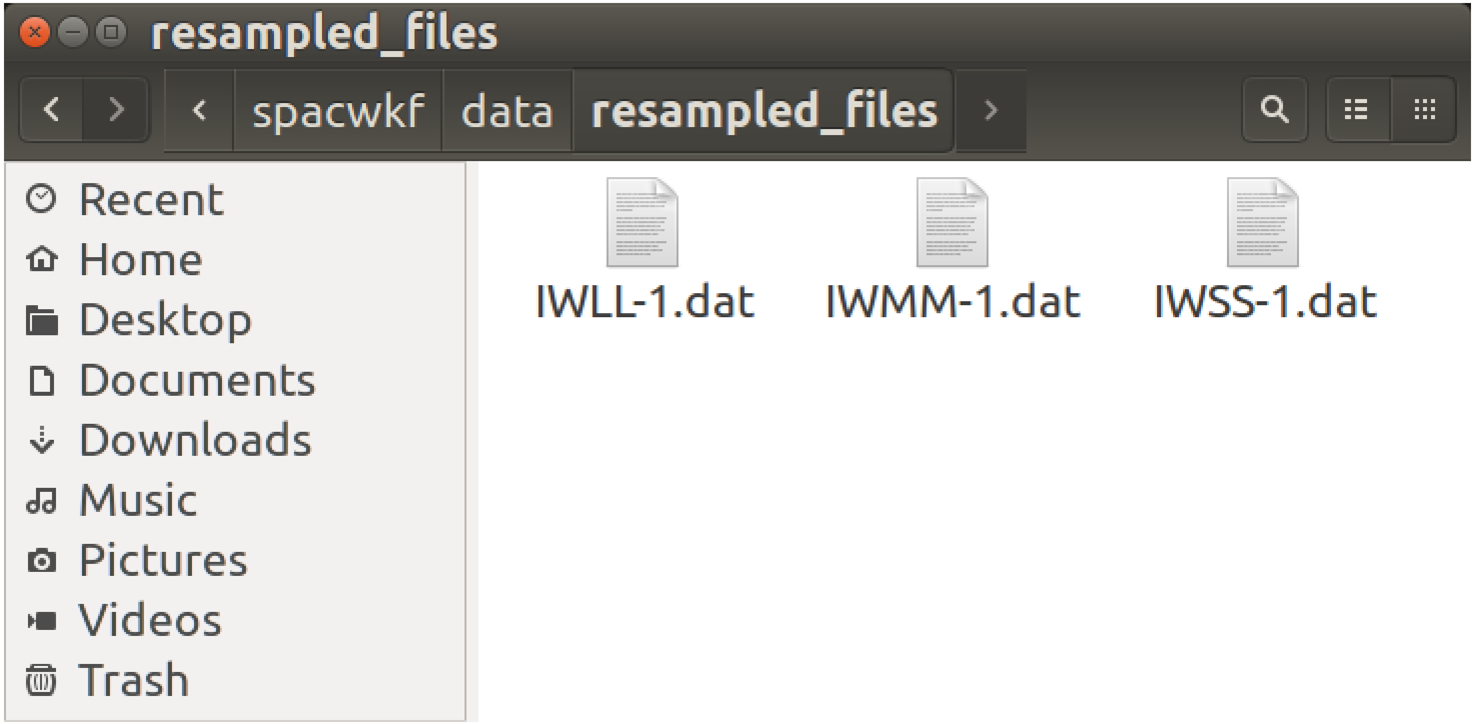
resample6.exe



For short period observation

For long period observation

```
Output files:
IWSS-1.dat ← resample5.exe
IWMM-1.dat ← resample6.exe
IWLL-1.dat ← resample6.exe

Resample6.prm is edited after obtaining IWMM-1.dat
```



Check the selected time blocks

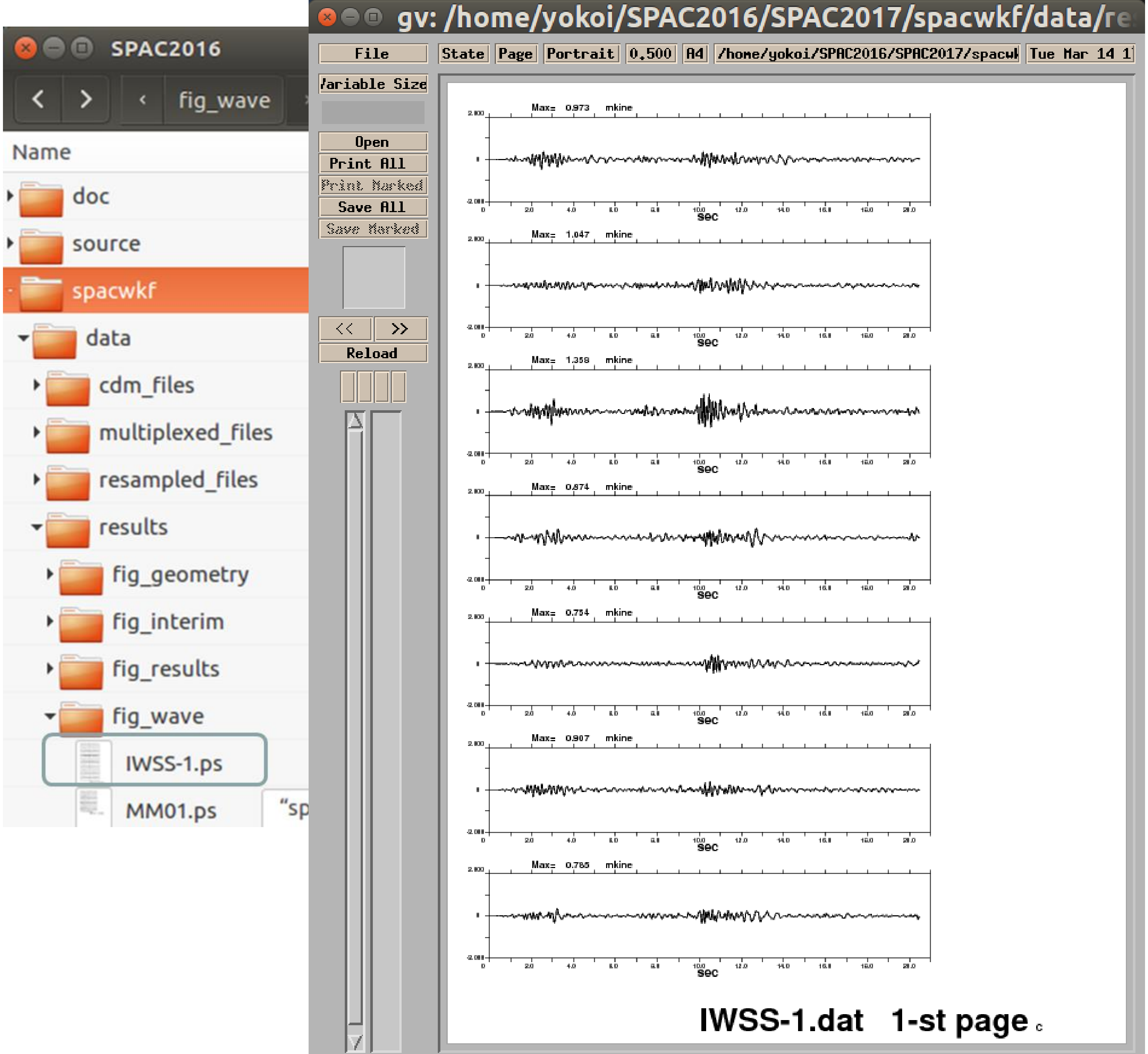
Parameter file:
./spacwkf/prm/seeblk1.prm

```
0  0.005 1.0 1.5 3     :nfilter,fl,fh,fs,nchara(=2:lowpass, =3:bandpass)
 1 10                  :n_mea,n_character
IWSS-1.dat
```

Example of execution: Output file is stored in ./spacwkf/data/results/fig_wave'

```
~SPAC2017$ ./seeblk1.exe
 ./spacwkf/prm/seeblk1.prm
 ./spacwkf/data/resampled_files/IWSS-1.dat
          28          10
          28          20
   4.42062318E-03   4.99999989E-03
./spacwkf/data/results/fig_wave/IWSS-1.ps
~SPAC2017$
```

Multi-page postscript files are created in ./spacwkf/data/results/fig_wave


SPAC2016
fig_wave
Name
doc
source
spacwkf
data
cdm_files
multiplexed_files
resampled_files
results
fig_geometry
fig_interim
fig_results
fig_wave
IWSS-1.ps
MM01.ps
gv: /home/yokoi/SPAC2016/SPAC2017/spacwkf/data/re
File
State
Page
Portrait
0.500
A4
/home/yokoi/SPAC2016/SPAC2017/spacwk
Tue Mar 14 1
Variable Size
Open
Print All
Print Marked
Save All
Save Marked
Reload
Max= 0.973 mkine
Max= 1.047 mkine
Max= 1.358 mkine
Max= 0.874 mkine
Max= 0.754 mkine
Max= 0.907 mkine
Max= 0.785 mkine
sec
IWSS-1.dat 1-st page

1.2 Calculation of Inter station Distance and Azimuth & Plot Geometry of array

Programs used:

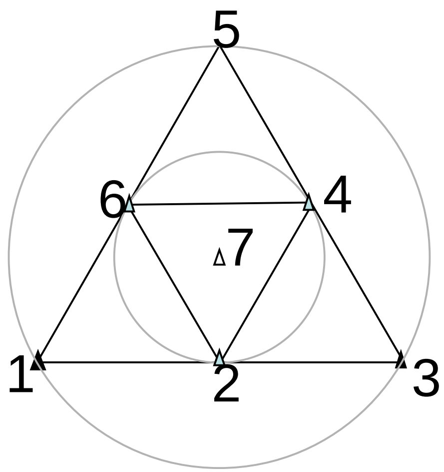
distazi.sh

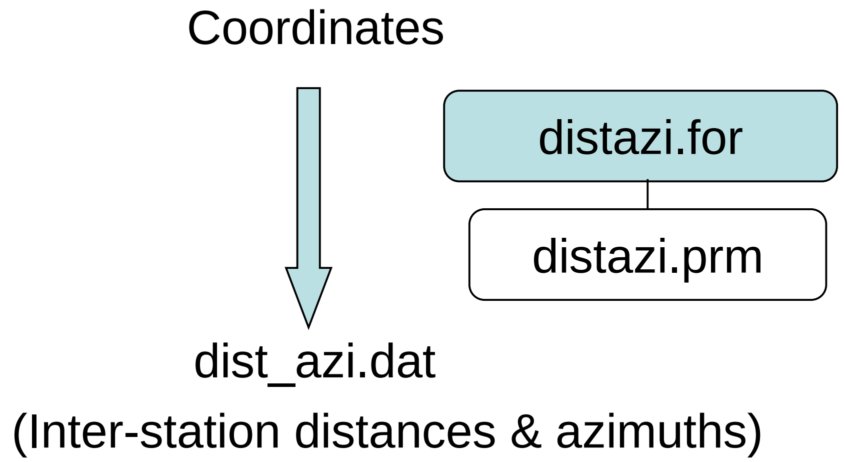
that controls:

distazi.exe + ./spacwkf/prm/distazi.prm

geometry.exe + ./spacwkf/prm/distazi.prm

A parameter file is used: temp0.dat





distazi.sh

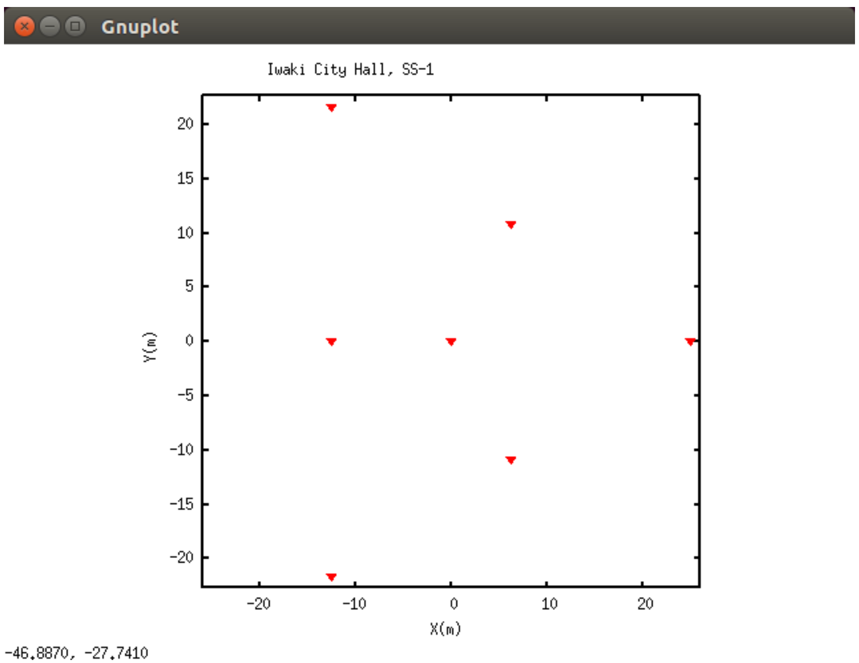
```
#!/bin/sh
rm ./spacwkf/data/results/temp0.dat
# rm ./spacwkf/data/results/distazi.dat
# rm ./spacwkf/prm/
./distazi.exe
./geometry.exe
gnuplot -e "
load 'geometry.plt' ;
pause -1
"
```

gnuplot is used for plotting.
If not yet installed,
sudo apt-get install gnuplot –x11

Example : SS-1 Array

distazi.prm

```
Iwaki City Hall, SS-1                         :Explanation (a45)
2                    :Type X-Y(=0), Lat-Long(=1),Dist-Angle(=2)
7   SS-1             :Number of stations, Title of figure
 25.0      90.0   1
 12.50     30.0   2
 25.0     -30.0   3
 12.50    -90.0   4
 25.00 -150.0   5
 12.50   150.0   6
  0.0       0.0   7
```



dist_azi.dat

```
Iwaki City Hall, SS-1
   7        :number of station
 id   st1   st2 distance  azimuth
   1     2     7   12.500 -150.000
   2     4     7   12.500   90.000
   3     6     7   12.500  -30.000
   4     1     2   21.651  -60.000
   5     1     6   21.651 -120.000
   6     2     3   21.651  -60.000
   7     2     4   21.651 -120.000
   8     2     6   21.651  180.000
   9     3     4   21.651  180.000
  10     4     5   21.651 -180.000
  11     4     6   21.651  120.000
  12     5     6   21.651   60.000
  13     1     7   25.000  -90.000
  14     3     7   25.000  150.000
  15     5     7   25.000   30.000
  16     1     4   37.500  -90.000
  17     2     5   37.500 -150.000
  18     3     6   37.500  150.000
  19     1     3   43.301  -60.000
  20     1     5   43.301 -120.000
  21     3     5   43.301 -180.000
```

The same image is saved simultaneously in a PostScript file in the subfolder “./spacwkf/data/results/fig_geometry/”.

distazi.prm

```
 Iwaki City Hall, SS-1                            :Explanation (a45)
 2                        :Type X-Y(=0), Lat-Long(=1),Dist-Angle(=2)
 7   SS-1                 :Number of stations, Title of figure
   25.0     90.0    1
   12.50    30.0    2
   25.0    -30.0    3
   12.50   -90.0    4
   25.00 -150.0    5
   12.50   150.0    6
    0.0      0.0    7
```

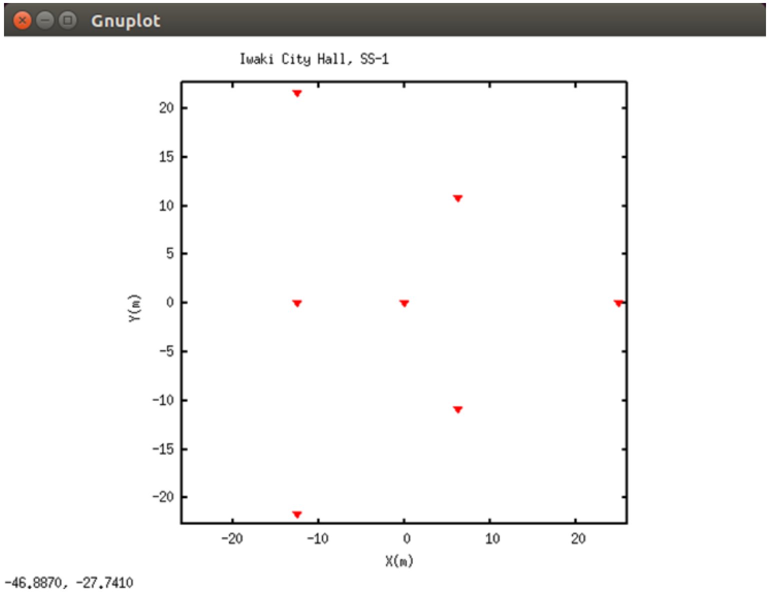
The 1st line & the 2nd parameter of the 3rd line are read and used later.

For Lat-Long (=1):
The statement for reading in distazi.for is:

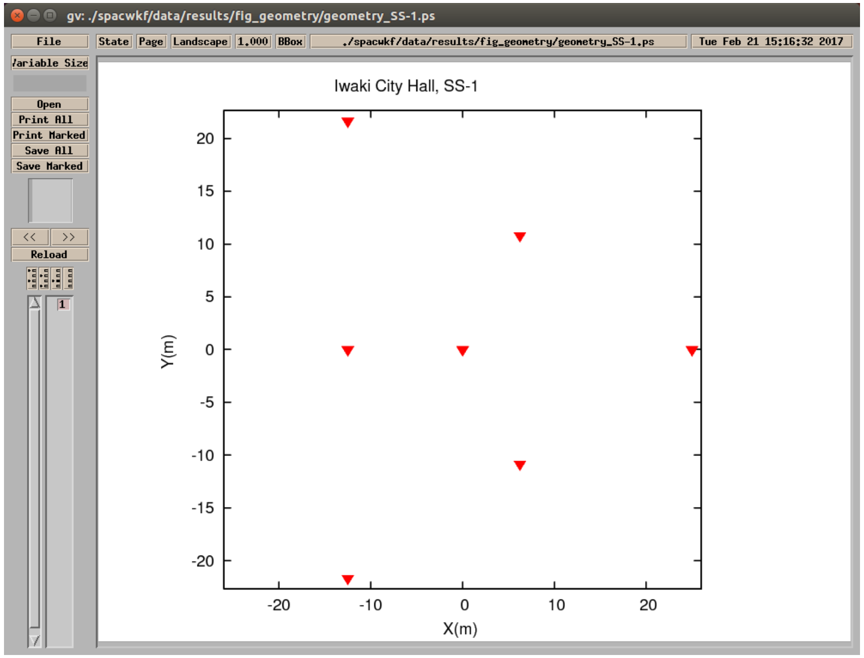
```
read(1,*)xla(ista),ylo(ista),id(ista)
```

Example of execution:

```
~SPAC2017$ ./distazi.sh
 Dist-Azimuth coordinates are selected
 X-axis toward East, Y-axis toward North.
      1    25.0    -0.0
      2     6.2    10.8
      3   -12.5    21.7
      4   -12.5    -0.0
      5   -12.5   -21.7
      6     6.3   -10.8
      7     0.0     0.0
          1           2   21.6506348      -59.9999962
...
          6           7   12.5000010      -30.0000038
 ./spacwkf/data/
 ./spacwkf/data/results/distazi.dat
   1    2    7   12.500 -150.000
...
  21    3    5   43.301 -180.000
Iwaki City Hall, SS-1
          7 SS-1
  25.0000000      -9.99999997E-07
  6.25000000       10.8253174
 -12.5000000       21.6506348
 -12.5000000      -9.99999997E-07
 -12.5000019      -21.6506348
  6.25000095      -10.8253174
  0.00000000       0.00000000

~SPAC2017$ gv &
```



Plot appears in a pop-up window



Automatically stored in a PS file, too.

Output files

./spacwkf/data/results/distazi.dat

./spacwkf/data/results/geometry.dat

./spacwkf/prm/gnuplt_script/geometry_SS-1.plt

geometry.plt

Contents of ‘geometry.plt’

load './spacwkf/prm/gnuplt_script/geometry_SS-1.plt'

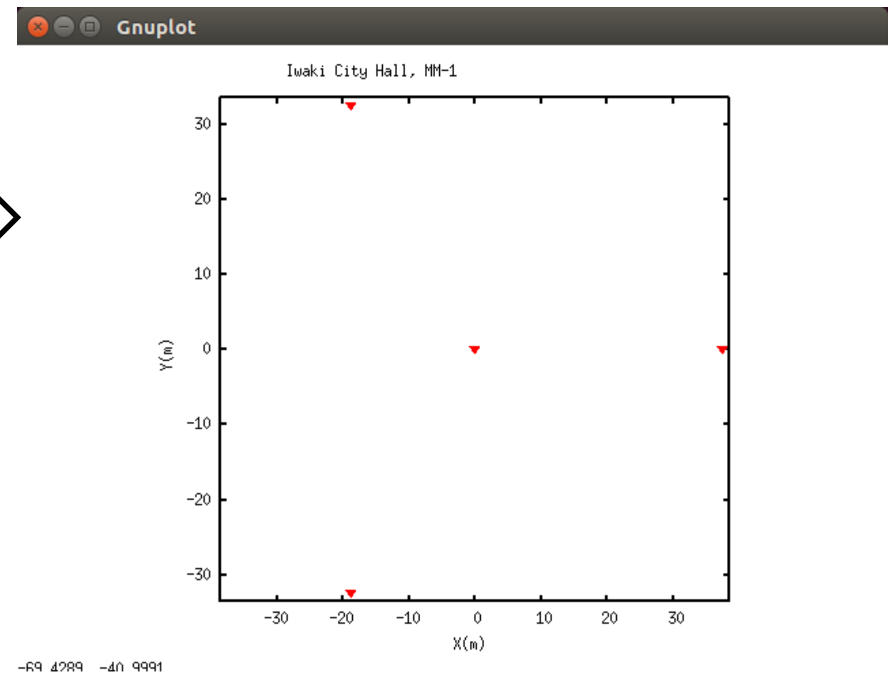
./spacwkf/data/results/fig_geometry/geometry_SS-1.ps

Example: MM-array

distazi.prm

```
Iwaki City Hall, MM-1                    :Explanation (a45)
2                  :Type X-Y(=0), Lat-Long(=1),Dist-Angle(=2)
4   MM-1           :Number of stations, Title of figure
  37.5    90.0   1
  37.5   -30.0   2
  37.5  -150.0   3
   0.0     0.0   4
```

Then run distazi.sh



distazi.dat

```
Iwaki City Hall, MM-1
    4      :number of station
       ID         X            Y
        1   37.500000   -0.000002
        2  -18.750000   32.475952
        3  -18.750002  -32.475952
        4    0.000000    0.000000
    id  st1  st2 distance  azimuth
    1    1    4   37.500  -90.000
    2    2    4   37.500  150.000
    3    3    4   37.500   30.000
    4    1    2   64.952  -60.000
    5    1    3   64.952 -120.000
    6    2    3   64.952 -180.000
```

2. Calculation of SPAC coefficient

Program used:

zcorrel.sh

that controls

zcorrel5_3.exe + ./spacwkf/prm/zcorrel5_3.prm

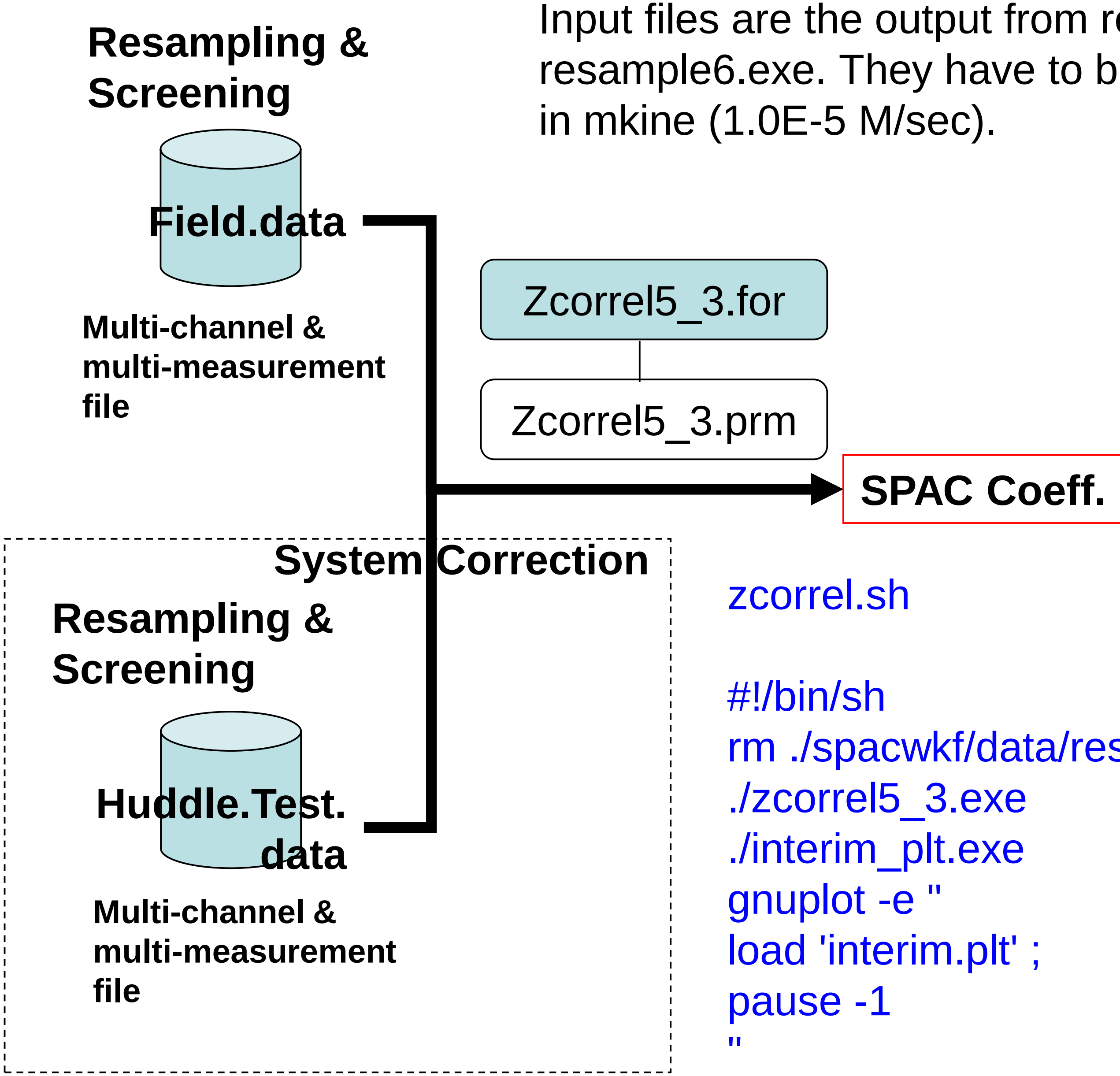
and

./interim_plt.exe + ./spacwkf/prm/zcorrel5_3.prm

for plotting the results

Calculation of SPAC coefficients

Input files are the output from resample5.exe or resample6.exe. They have to be velocity records in mkine (1.0E-5 M/sec).



zcorrel.sh

```
#!/bin/sh
rm ./spacwkf/data/results/temp*.dat
./zcorrel5_3.exe
./interim_plt.exe
gnuplot -e "
load 'interim.plt' ;
pause -1
"
```

zcorrel5_3.prm

```
Iwaki City Hall, SS-1
0.1 10.0 0.02 0.25  0 2 :fmin,fmax,dt,bw(>3.71/Td),n_huddle,nhide
HDSS-1.dat   1 1        :Huddle test file name (A12),n_coh_hud,n_pow_hud
IWSS-1.dat   1 1        :input file name (A12),n_coh,n_pow
 5
 3 27 47 67                              12.5
 9 12 16 23 24 26 34 45 46 56            21.65
 3 17 37 57                              25.0
 3 14 25 36                              37.5
 3 13 15 35                              43.3
 SPCSS1.dat              :output file name(a10)
```

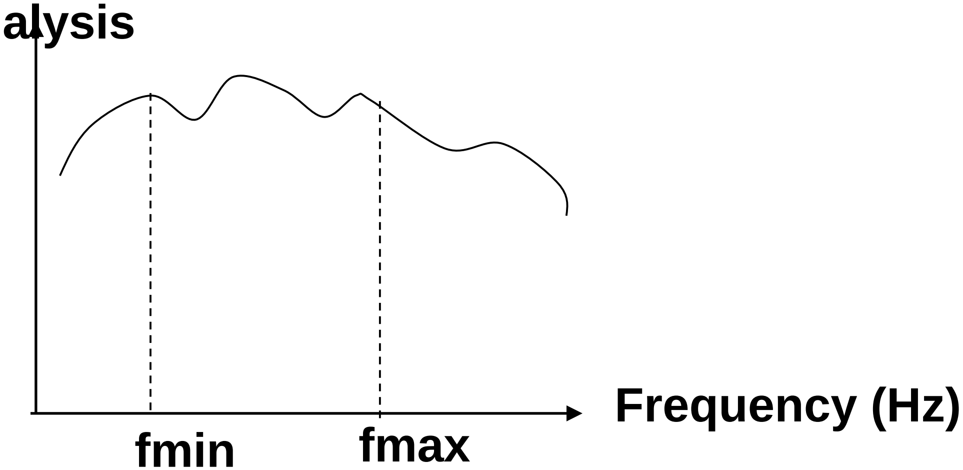
For the inter-station distance, 12.5m, 3 pairs namely stations (#2,#7),(#4,#7),(#6,#7) are averaged.

In the program nn=nn_org*nhide is conducted, where nn_org denotes length of a time block in the input data file. This means the zero padding in order to shorten the interval of frequency for the calculation of FFT.

1st line

Parameters: fmin, fmax, bw, n_huddle

Selection of frequency range for analysis



bw: bandwidth of Parzen Window that is used for smoothing the averaged cross- and auto- correlations. The bigger value of “bw” corresponds to smoother SPAC coefficient. bw=0.0 means exection without applying Parzen Window.

n_huddle: Flag for executing the system correction using the huddle test data (0= no effect, =1 conducting system correction). Correction using the huddle test data is usually not necessary when the array is composed of the seismographs of the same type.

2nd line
Parameters: Huddle test file name (A12),n_coh_hud,n_pow_hud

Resampled & screened Multi-channel & multi-measurement file of the huddle test data

***huddle*.dat**

Flag for outputing the coherence file of the huddle test data
0= no effect
1= output

***huddle*_coh.dat**

Flag for outputing the power spectra file of the huddle test data
0= no effect
1= output

***huddle*_psp.dat**

This line is read but not used in the analysis if n_huddle in the 1st line is “0”.

3rd line
Parameters: input file name (A12),n_coh,n_pow

Resampled & screened Multi-channel & multi-measurement file of the huddle test data

***Input*.dat**

Flag for outputing the coherence file of the huddle test data
0= no effect
1= output

***Input*_cor_coh.dat**

Flag for outputing the power spectra file of the huddle test data
0= no effect
1= output

***Input*_cor_psp.dat**

The coherence and the power spectra of the field data without the system correction are output as default.

***Input*_coh.dat**
***Input*_psp.dat**

Example of execution:

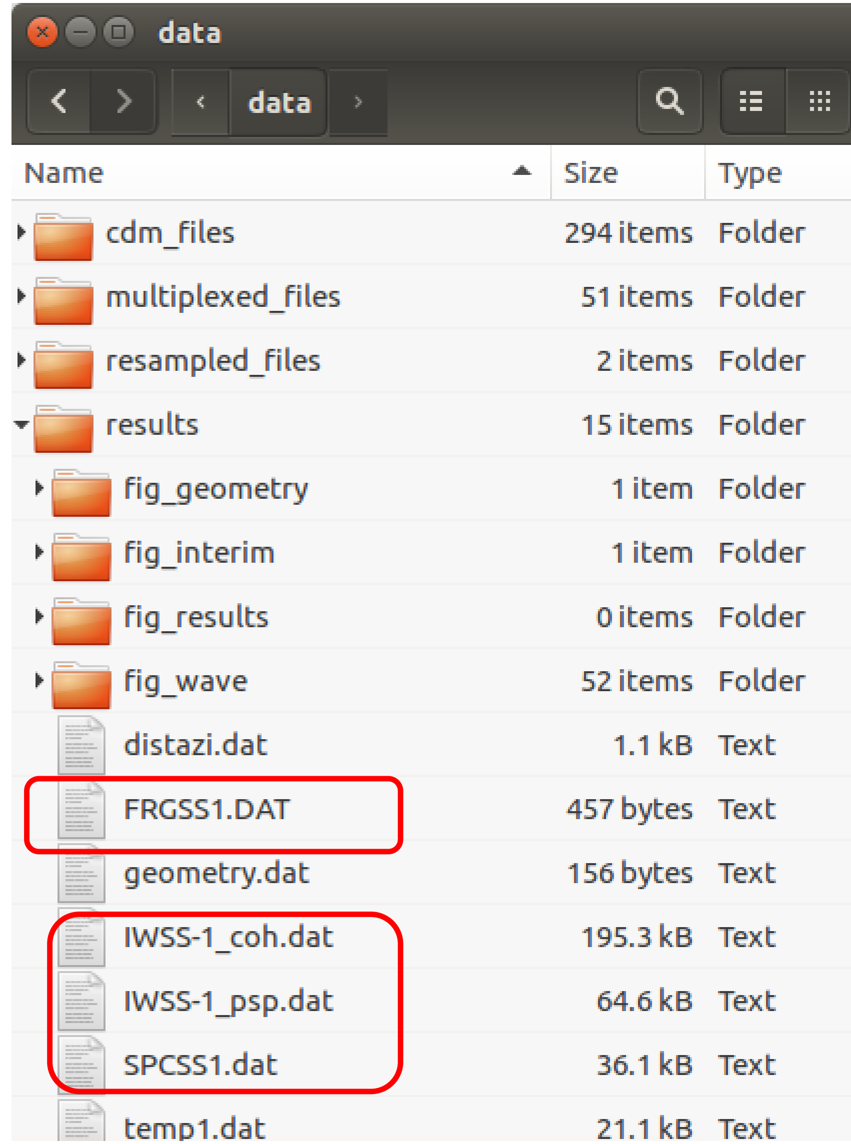
~SPAC2017$ sh ./zcorrel.sh

zcorrel5_3.exe

```
Program zcorrel5_3.for
./spacwkf/prm/zcorrel5_3.prm
 Huddle Test Skipped.
nn=  2048
        28          10
        28          20
 power and cross spectra for field data calculated.
Block Averaging has been done.
./spacwkf/data/results/IWSS-1_psp.dat
Output:./spacwkf/data/results/IWSS-1_psp.dat
./spacwkf/data/results/IWSS-1_coh.dat
./spacwkf/data/results/SPCSS1.dat
```

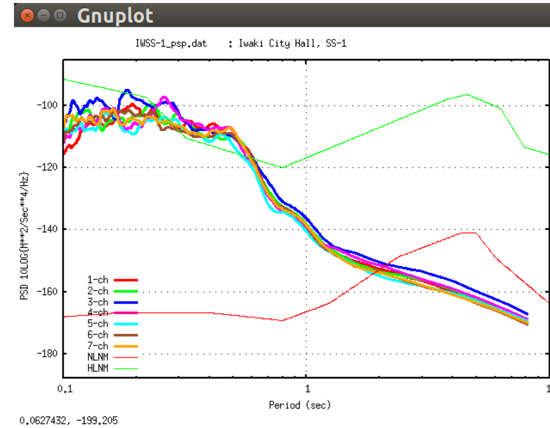
interim_plt.exe

Look the next page

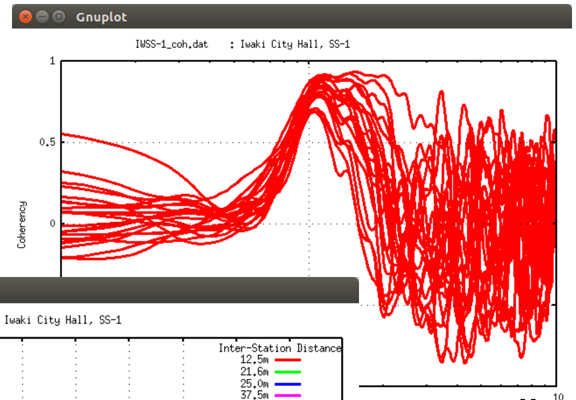


interim_plt.exe

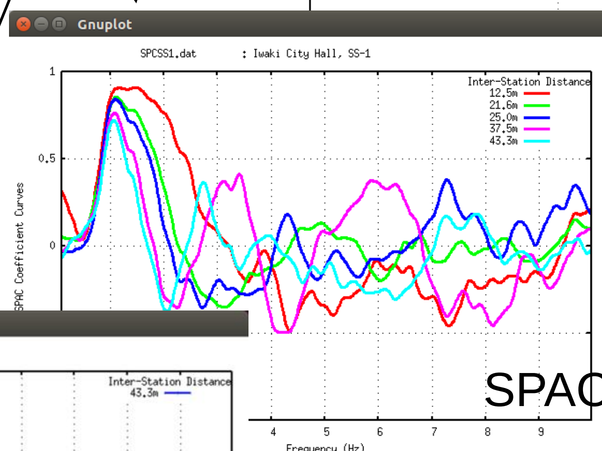
```
Iwaki City Hall, SS-1
Iwaki City Hall, SS-1
Hit return to continue
Hit return to continue
Hit return to continue
Hit return to continue
Hit return to continue
Hit return to continue
Hit return to continue

~SPAC2017$
```



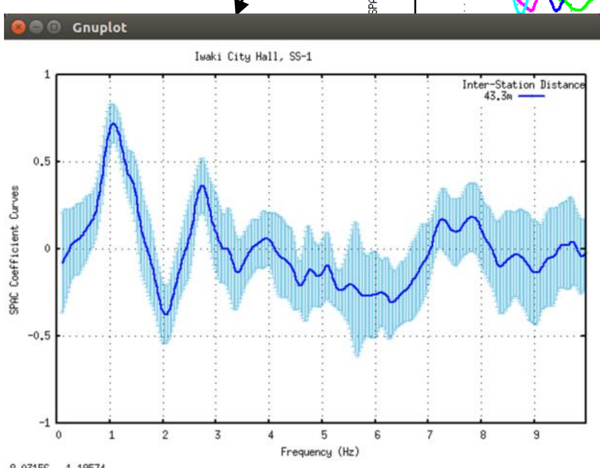
Power spectra



All Coherence functions



SPAC coefficients

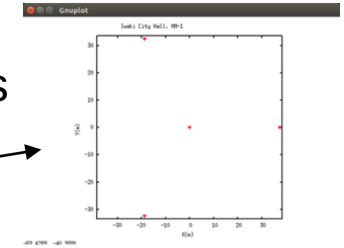


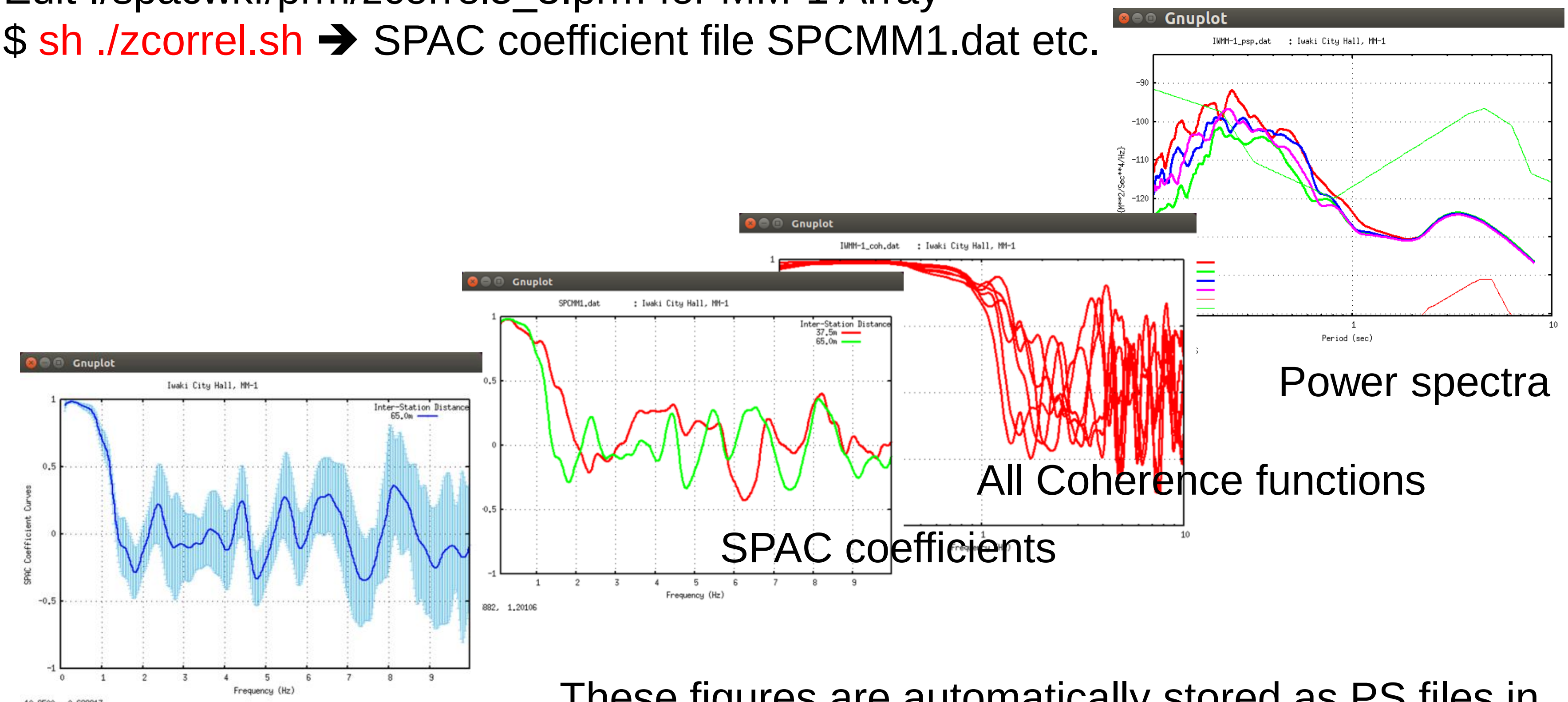
Individual SPAC function with error bar

These figures are automatically stored as PS files in ./spacwkf/data/results/fig_interim

Procedure for MM-1 Array

+ Edit ./spacwkf/prm/resample6.prm for MM-1 Array
+ $ ./resample5.exe ➔ resampled & screened file IWMM-1.dat
+ Edit ./spacwkf/prm/seewav6.prm for MM-1 Array
+ $ ./seewav6.exe ➔ Waveform plot files MM??.ps
+ Edit ./spacwkf/prm/distazi.prm for MM-1 Array
+ $ sh ./distazi.sh ➔geometry plot file geometry_MM-1.ps
+ Edit ./spacwkf/prm/zcorrel5_3.prm for MM-1 Array
+ $ sh ./zcorrel.sh ➔ SPAC coefficient file SPCMM1.dat etc.





Power spectra

All Coherence functions

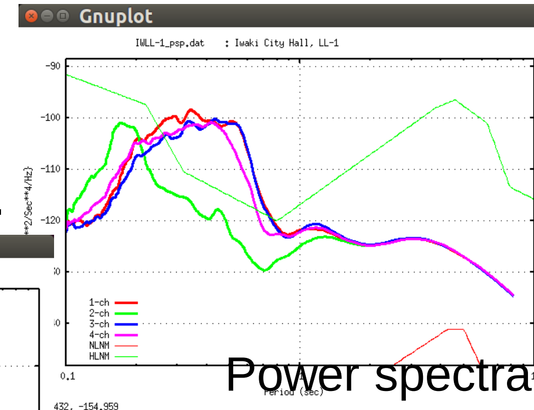
SPAC coefficients

Individual SPAC function with error bar

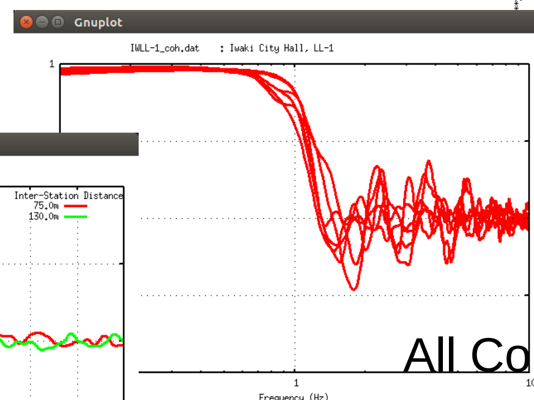
These figures are automatically stored as PS files in ./spacwkf/data/results/fig_interim

Procedure for LL-1 Array

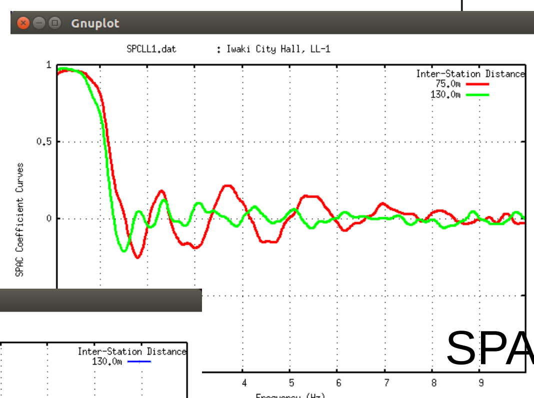
+ Edit ./spacwkf/prm/resample6.prm for LL-1 Array
+ $ ./resample6.exe ➔ resampled & screened file IWLL-1.dat
+ Edit ./spacwkf/prm/seewav6.prm for LL-1 Array
+ $ ./seewav6.exe ➔ Waveform plot files LL??.ps
+ Edit ./spacwkf/prm/distazi.prm for LL-1 Array
+ $ sh ./distazi.sh ➔geometry plot file geometry_LL-1.ps
+ Edit ./spacwkf/prm/zcorrel5_3.prm for LL-1 Array
+ $ sh ./zcorrel.sh ➔ SPAC coefficient file SPCLL1.dat etc.



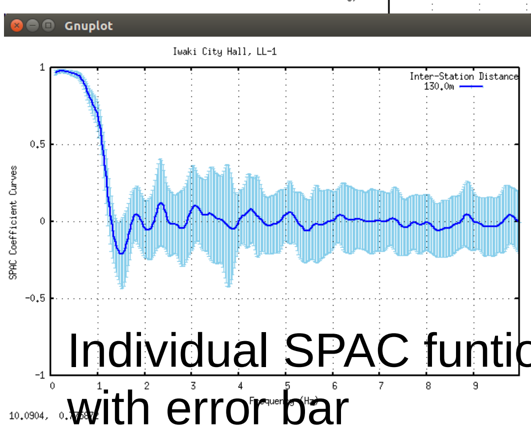
Power spectra



All Coherence functions



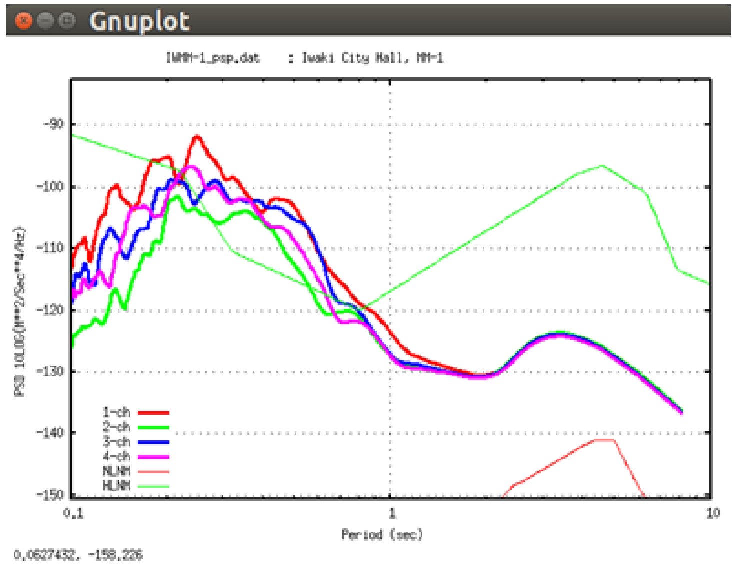
SPAC coefficients



Individual SPAC funtion with error bar

These figures are automatically stored as PS files in ./spacwkf/data/results/fig_interim

Power Spectra



10*Log$_{10}$ (Fourier Coefficient *Td* omg**2) of each frequency is plotted in PostScript file
spacwkf/data/results/fig_interim/IWMM-1_psp.ps
in the unit 10*Log10(M**2/Sec**4/Hz)
Also output into
spacwkf/data/results/IWMM-1_psp.dat
that is CSV format file.

IWMM-1_psp.dat

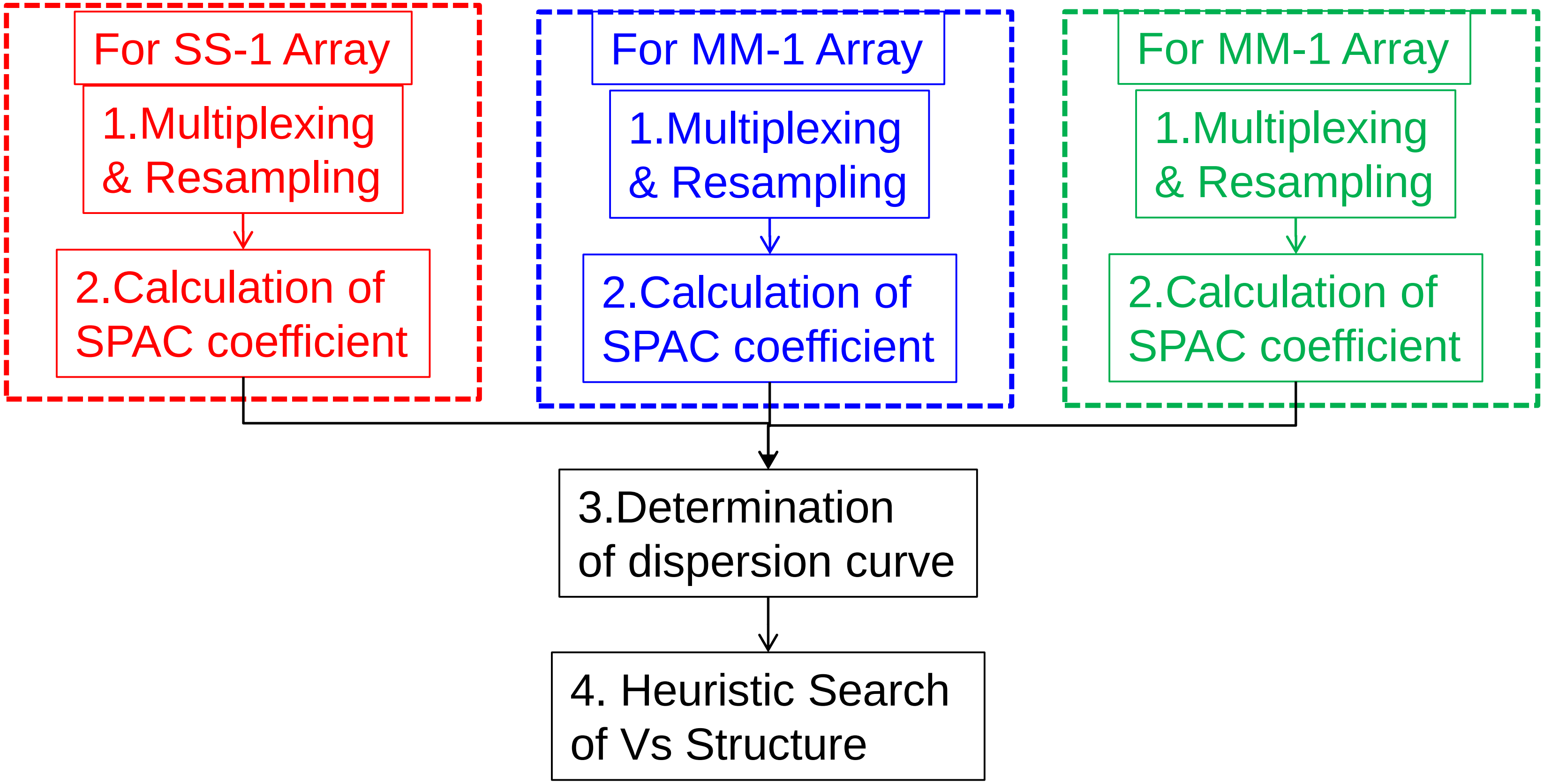
# Period	1-ch	2-ch	3-ch	4-ch Power Spc	1-ch	2-ch	3-ch	4-ch S.D.
0.100	-122.523	-121.038	-123.098	-122.525	-123.525	-121.061	-123.484	-122.815
0.100	-121.617	-120.174	-122.290	-121.659	-122.703	-120.218	-122.836	-122.091
0.101	-120.964	-119.546	-121.741	-121.039	-122.073	-119.536	-122.445	-121.599
…								

10*Log10 (Fourier Coefficient * Td * omg**2)

10*LOG10(sqrt(variance of Fourier Coefficient)*Td*omg**2)

where omg=2π/period
When Velocity Fourier Amplitude Spectral Density is required, type
./fourier.sh
in the folder SPAC2017. fourier_plt.exe convert the above mentioned psp to Fourier Amplitude Spectra.

Example: Up to this slide the red part of the below shown diagram has been performed for SS-1 Array (7 points). The next step is to do the same procedure for MM-1 Array (4 points), i.e., the blue part of the diagram below. Then, the green part.



SPCSS1.dat, SPCMM1.dat, SPCLL1.dat are used in the next step of analysis.

3. Determination of Dispersion Curve

Programs used:

cf_panel1.sh

that controls

cf_panel1.exe + cf_panel1.prm

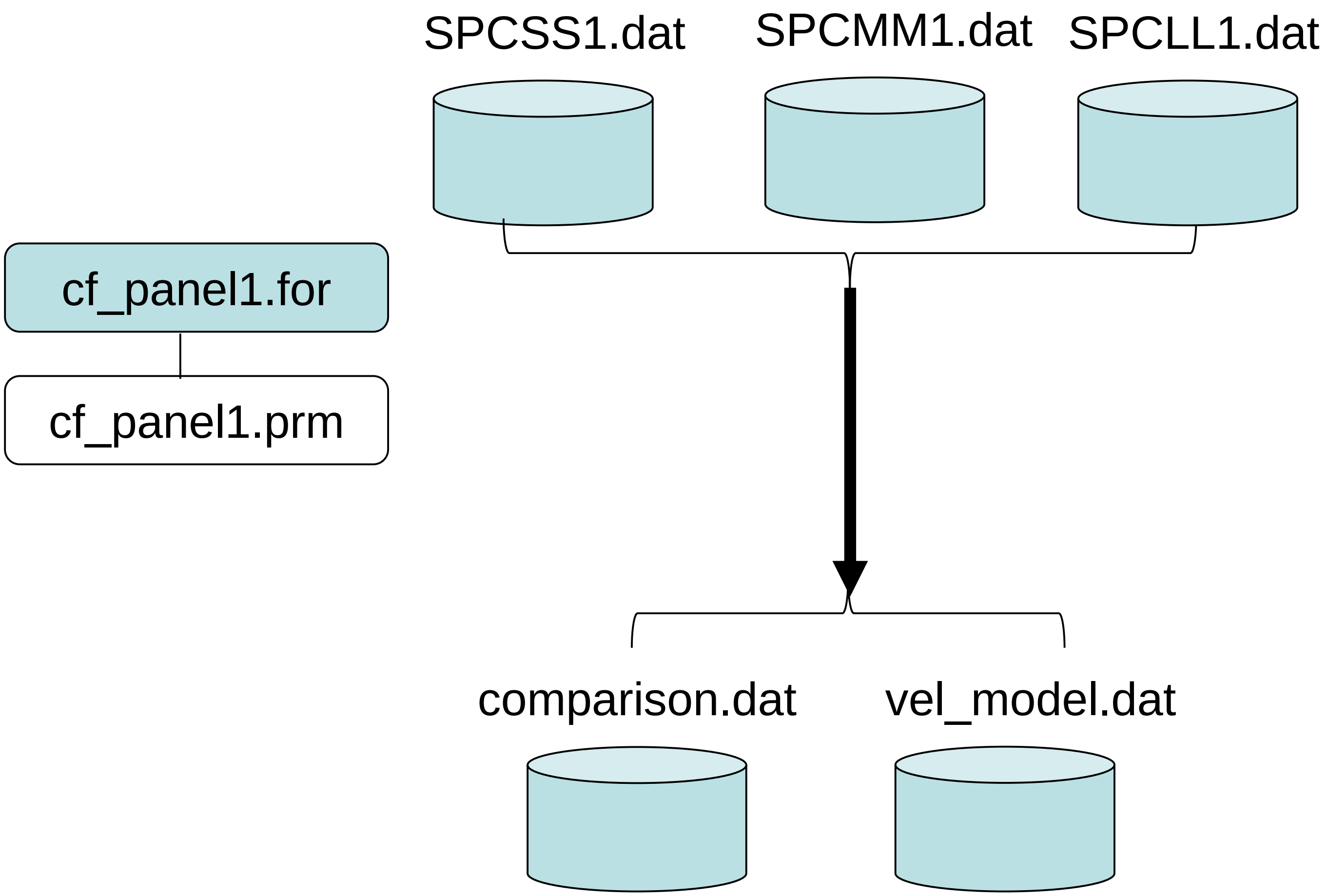
for fitting to Bessel function, plotting SPAC coefficient and determination of dispersion curve using the imaging technique.

For plotting

vel_model.sh

that controls

vel_model_plt.exe + vel_model_plt.prm



The same file name is used for every case

Determination of dispersion curve

1st step:

+ The fif-th order polynomial that approximates the inverse function of $J_o(x)$

$$y=-6.0803x^5+9.2477x^4-3.9322x^3+0.1815x^2-1.7079x+2.4121$$

is used to calculate the tentative values of the phase velocity $c(r,\omega)$, where $y=kr=r\omega/c(r,\omega)$, $x=\rho(r,\omega)$.

+ The wave lengths are estimated from the observed SPAC coefficients through this tentative phase velocity.

+ The frequency range for analysis is narrowed below the frequency that corresponds to the spacial Nyquist wave length, i.e., 2 times the minimum interstation distance.

+ The frequency range for analysis is again narrowed above the frequency of the maximum value of SAC coefficient curves.

2nd step:

+ Imaging technique is applied to determine the phase velocity of each frequency. The misfit function is set for the SPAC coefficient curves.

Example:

cf_panel1.prm

```
Iwaki city Hall (test data)    2017 version       :graph title(a50)
 0    1    0   0.1    :n_message,n_comparison(0=no, 1=yes),nfskip(0=no, 1=yes),aps
 0.10  5.0  100.0  1000.0 :fmin,fmax,vmin,vmax that specify the range of analysis
3                        :file number
SPCSS1.dat              :file name (a12)
   5                    :Number of Radius
  12.5  1.0               :Radius(m),Min and Max of the frequency(Hz) for fitting
  21.6  1.0
  25.0  1.0
  37.5  1.0
  43.3  1.0
SPCMM1.dat              :file name (a12)
   2                    :Number of Radius
  37.5                   :Radius(m),Min and Max of the frequency(Hz) for fitting
  65.0
SPCLL1.dat              :file name (a12)
   2                    :Number of Radius
  75.0                   :Radius(m),Min and Max of the frequency(Hz) for fitting
 130.0
```

SS-1-array

MM-1-array

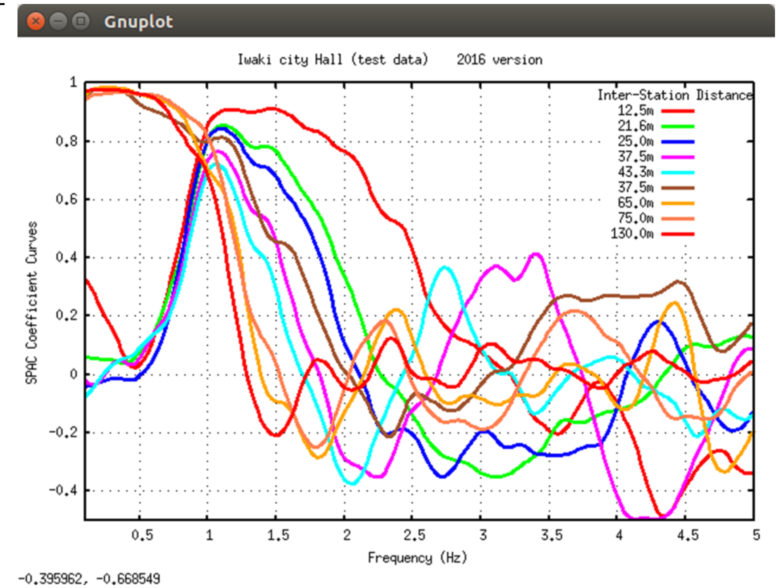
LL-1-array

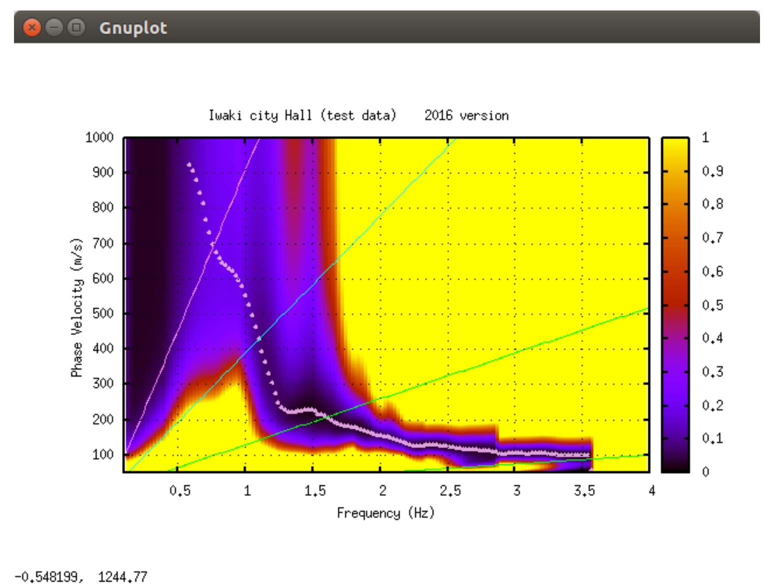
→ The list of inter-station distances must be coincident to the contents of the SPAC coefficient's file.

The minimum and maximum frequency for fitting can be specified, if not f_{min} and f_{max} in the 3rd line will be used in place of them.

Example of execution:

```
$ sh ./cf_panel1.sh
 n_message=  0 n_comparison=  1 nfskip=  0   0.200E+00
 Range of Analysis: from     0.10(Hz) to     5.00(Hz)
                and from    50.00(m/s) to  1000.00(m/s)
 Number of files=   3 for SPAC Coef. curves.
 1  SPCSS1.dat
 2  SPCMM1.dat
 3  SPCLL1.dat
 No. Distance min_fr  max_fr
            m      Hz      Hz
      1   12.50    1.47    3.56
      2   21.60    1.42    2.86
      3   25.00    1.10    2.32
      4   37.50    1.07    2.03
      5   43.30    1.05    1.93
      6   37.50    1.10    2.34
      7   65.00    0.24    1.81
      8   75.00    0.34    1.81
      9  130.00    0.17    1.51
 Range of analysis: fmin=  0.561999977      fmax=  3.56399989
 ./spacwkf/prm/gnuplt_script/SPAC_coef.plt
 ./spacwkf/prm/gnuplt_script/cf_panel1.plt
Hit return to continue
```





These figures are automatically stored as PS files in
./spacwkf/data/results/fig_results

Example of Output

vel_model.dat for the determined dispersion curve

```
#  freq.(Hz) Vel.(km/s)
     0.586      0.925      0.004
     0.610      0.907      0.004
     0.635      0.881      0.004
     0.659      0.845      0.004
     0.684      0.813      0.005
…
```

Standard Deviation

Comparison.dat

for checking the glade of fitting

```
…
6   37.500     0.071    -0.180     0.199
f=    1.953      Hz   160.00        =c
      r   SPAC_Coef.    Cal_Bessel    S.D.
      0.000              1.000
 1   12.500     0.777     0.783     0.076
 2   21.600     0.388     0.423     0.091
 3   25.000     0.176     0.272     0.205
 4   37.500    -0.241    -0.215     0.185
 6   37.500     0.047    -0.215     0.197
f=    1.977      Hz   157.00        =c
      r   SPAC_Coef.    Cal_Bessel    S.D.
…
```

Standard deviation of the observed SPAC coefficient

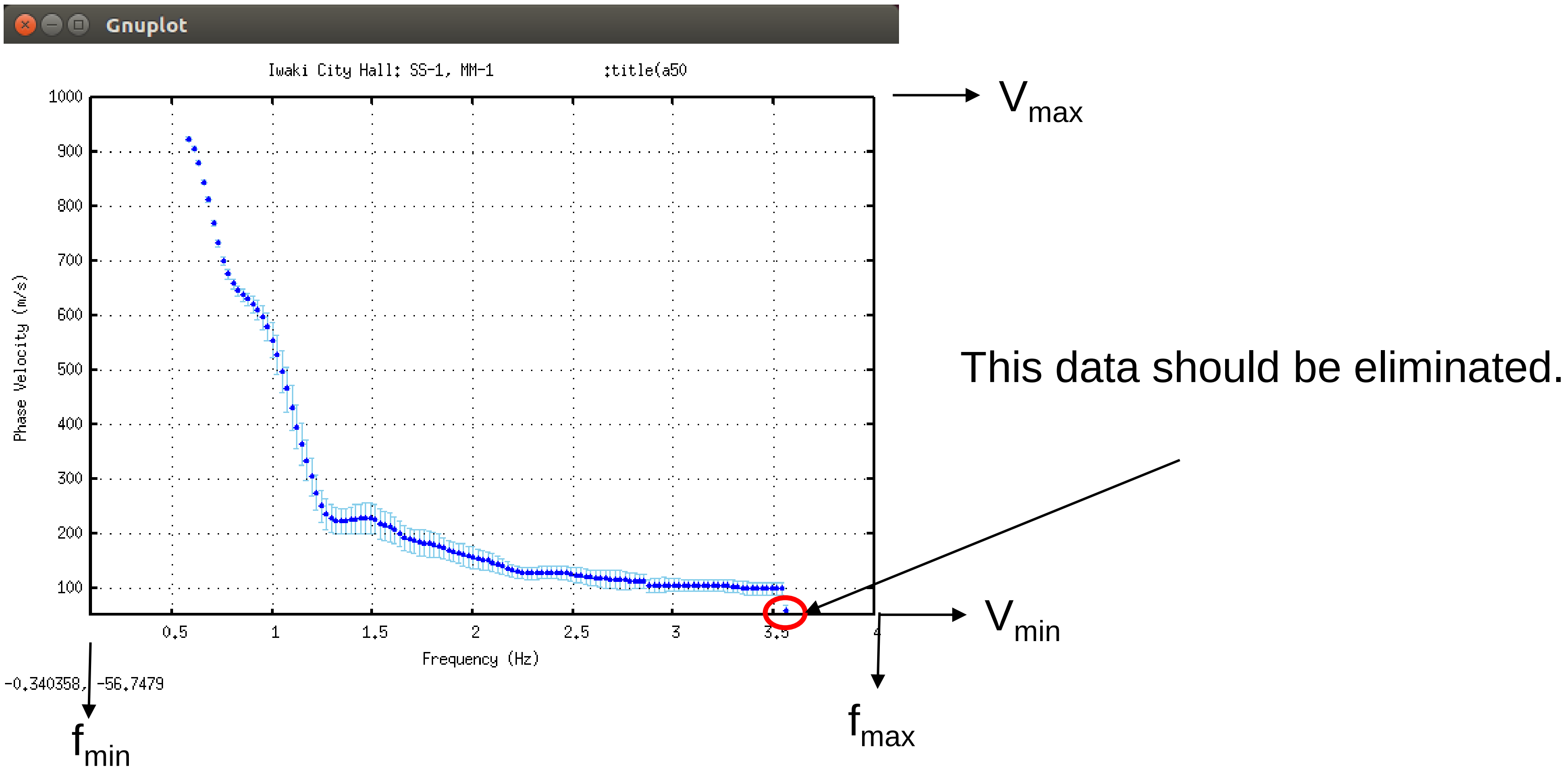
SPAC coefficient calculated using determined phse velocity

Observed SPAC coefficient

Inter-station distance

Plot the determined dispersion curve:
Execution: After editing ./spacwkf/prm/vel_model_plt.prm
for the graph title, [fmin,fmax] and [vmin, vmax]

~SPAC2017$ sh ./vel_model.sh
./spacwkf/prm/gnuplt_script/vel_model.plt



This figure is automatically stored as PS files in
./spacwkf/data/results/fig_results

./spacwkf/prm/vel_model_plt.prm

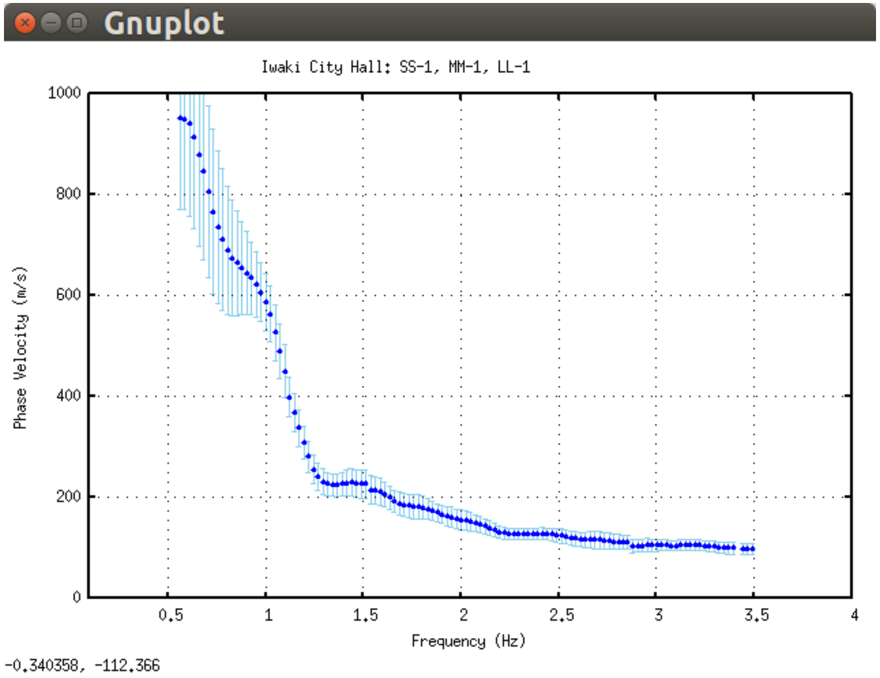
```
Iwaki City Hall: SS-1, MM-1, LL-1                :title(a50)
  0.1    4.0                       : fmin,fmax
  0.  1000.                        : vmin,vmax
 1                                 : n_mod
```

1st line: title of phase velocity plot
2nd line: fmin and fmax for plotting
3rd line: vmin and vmax for plotting
4th line: n_mod

=1: wavelength/3 – Vs will be plotted in Vs structure plot
otherwise not plotted.

File: vel_model.dat

- [fmin, fmax] described in vel_model_plt.prm and used by vel_model_plt.exe and cf_panel.exe are not reflected to the contents of the file vel_model.dat.
- It is recommendable to edit vel_model.dat manually to select the frequency range used in the next step.
- Don't leave a blank line at the end of the file vel_model.dat after editing.
- Run vel_model_plt.exe after editing it.➔ *sh ./vel_model.sh*



Plot the SPAC coefficient curve fitting:

Execution:

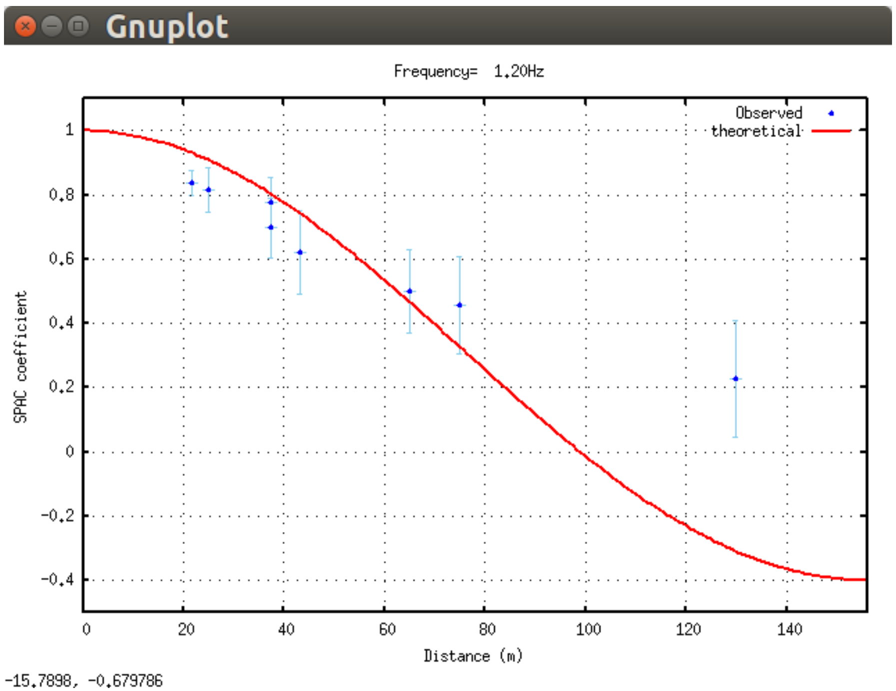
$ sh ./comparison.sh

…

Type in the frequency that you want to select.

…

./spacwkf/prm/gnuplt_script/comparison.plt



Simultaneously the same imge is saved in a PostScript file:

./spacwkf/data/results/fig_results/comparison.ps

4. Heuristic Search of Vs Structure

Programs used:

inversion.sh

that controls

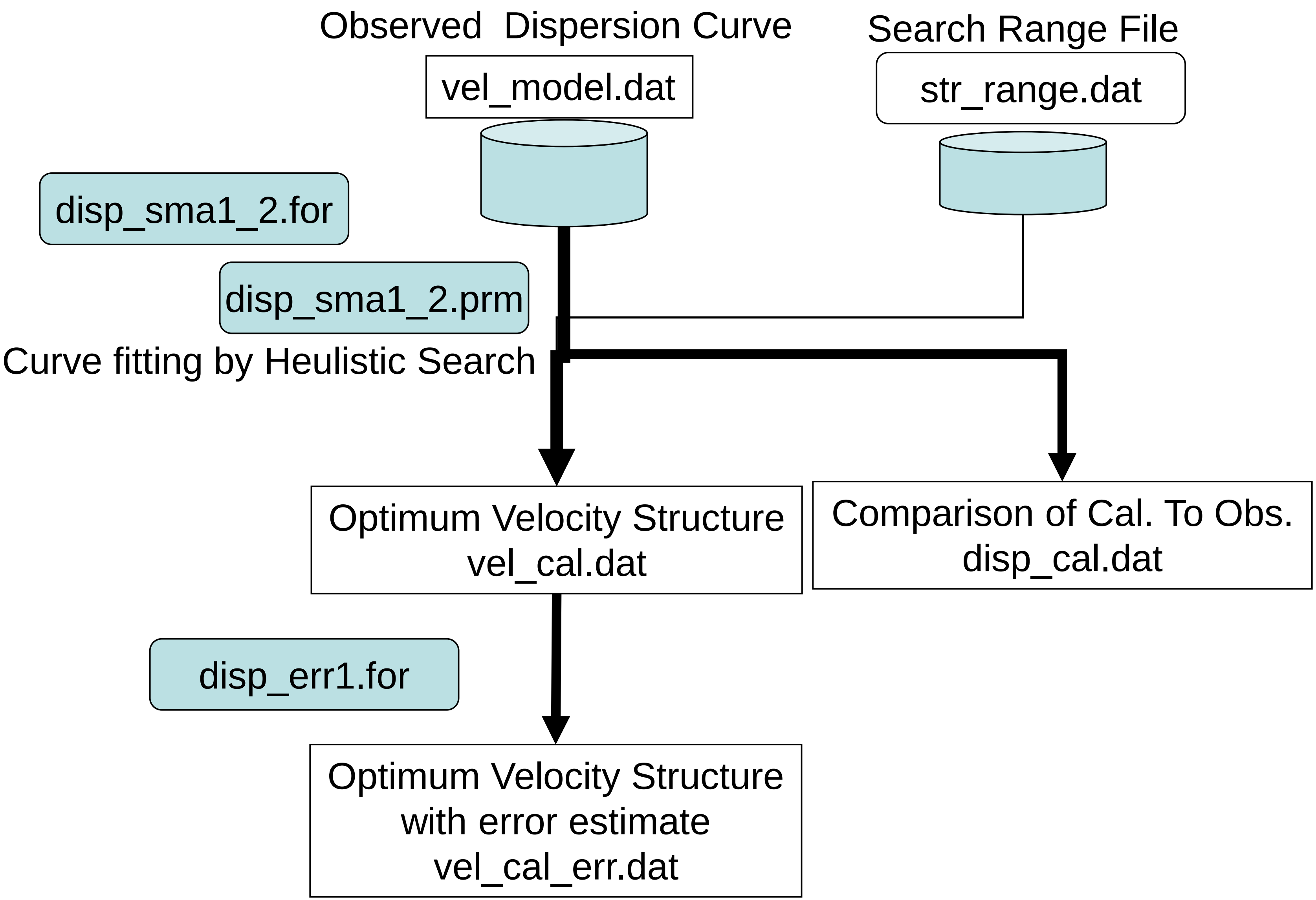
disp_sma1_2.for + ./spacwkf/prm/disp_sma1_2.prm

./disp_err1.exe

results.sh

that controls

./results_plt.exe


Observed Dispersion Curve
vel_model.dat
Search Range File
str_range.dat
disp_sma1_2.for
disp_sma1_2.prm
Curve fitting by Heulistic Search
Optimum Velocity Structure
vel_cal.dat
Comparison of Cal. To Obs.
disp_cal.dat
disp_err1.for
Optimum Velocity Structure
with error estimate
vel_cal_err.dat

inversion.sh

```
#!/bin/sh
rm ./spacwkf/data/results/temp*.dat
./disp_sma1_2.exe
./disp_err1.exe
```

results.sh

```
#!/bin/sh
./results_plt.exe
gnuplot -e "load 'results.plt’ ; pause -1"
```

disp_sma1_2.for

Combination of the Down Hill Simplex Method (Nelder & Mead (1965)) and the Very Fast Simulated Annealing method (Ingber, 1989).

DHSM: Down Hill Simplex Method (Nelder & Mead (1965))
An efficient algorithm to find "local minimum".
Faster than Geiger's method. Partial derivatives are not necessary.
Result is controlled by given initial values and easily captured by local minimum.
Example of application to the microtremor array: Ohori et al(2002)

VFSA: Very Fast Simulated Annealing method (Ingber, 1989)
One of the heuristic search methods.
Analogy of cooling and crystallization process of metals.
Results can escape from local minimum and can get global minimum with some probability.
Time consuming due to the probabilistic search for each parameter.
Example of application to the microtremor array & appropriate values of parameters for this purpose: Yamanaka (2004)

Example: disp_sma1_2.prm

```
 1 1. 0.6 1.3 10000  5  :idum,t0,a,c,ntemp,j0
 0.0015                 :eps0
   1    1               :n_roh,n_vp
   1    0    1           :ini_flg,ndsp_flg,n_err
   0    1               :kflg,jflg
   0    0               :n_vs,n_th
str_range.dat           :File name for the initial velocity model (a25).
vel_model.dat            :File name for the obseved dispersion relation (a25).
vel_cal.dat             :File name for the estimated velocity structure (a25)
disp_cal.dat            :File name for the calculated dispersion relation (a25)
```

Control parameter for the simulated annealing method

idum :Random seed (integer): As the result may depend on the initial velocity model given by random number, it is strongly recommended for users to apply this program several times with various values of random seed and to grasp the scatter of result.

t0, a,c :Initial Temperature, Coefficients for T=T0*exp(-c*k**a), where k is iteration number. T0=1.0, a=0.6 & c=1.3 are of the fastest schedule

ntemp :Maximum number of temparature change

j0 :Number of iteration for each temperature

threshold for conversion

eps0 : threshold of misfit function

flags for roh and vp

n_vp : 1=by Ludwig et al(1970): vp=1.11*vs+1.29; 0=fixed to the initial values

n_roh : 1=by Kitzunezaki et al(1990): roh=1.2475+0.399*vp-0.026*vp**2; 0=fixed to the initial values

flags for output to Display

ini_flg : Initial Velocity Structure Model. 1=yes

ndsp_flg : Observed Dispersion Relation . 1=yes

n_err : Error at each iteration, 1=yes

kflg : Missfit at each temp. change, 1=yes

jflg : Missfit at each itration with the same temp. 1=yes

n_vs : Vs value (n_vs=layer number, 0=no output)

n_th : Thickness value (n_th=layer number, 0=no output)

n_err :

Example: str_range.dat 🡐 Initial Search Range

```
Iwaki City, S-M-L 22/12/2012  :Model(a30)
        6                     :IL(I5),Layer Number
1.9   1.5    0.005  0.300  0.10 0.11 :density,Vp,hmin,hmax,vmin,vmax
1.9   1.5    0.005  0.300  0.10 0.20 :density,Vp,hmin,hmax,vmin,vmax
1.9   1.5    0.005  0.300  0.20 0.40 :density,Vp,hmin,hmax,vmin,vmax
1.9   1.5    0.005  0.300  0.40 0.70 :density,Vp,hmin,hmax,vmin,vmax
1.9   1.5    0.005  0.300  0.70 1.00 :density,Vp,hmin,hmax,vmin,vmax
2.0   1.70   998.0 999.0   0.80 3.20
```

(hmin, hmax) : Search range for layer thickness.
(vmin, vmax) : Search range for Vs (Shear Wave Velocity)

Example of execution(1): inversion.sh

Opening

```
$ sh ./inversion.sh
+----------------------------------------------------+
+                                                    +
+                    Disp_sma1                       +
+                                                    +
+ Program to obtain the optimum undeground velocity +
+ structure for the given dispersion relation of    +
+ Rayleigh wave.                                     +
+                                                    +
+ The used method is a combination of the down hill +
+ simplex method (Nelder & Mead (1965)) and the     +
+ very fast simulated annealing method (Ingber      +
+ (1989)).                                           +
+                                                    +
+ The subroutine DSPRAY and DSPMRX published in     +
+ "Seismological Algorithm" are used directly.      +
+ AMOEBA and AMOTRY published in "Numerical Recipe" +
+ are also used, but with significant modification  +
+ for the adaptation with the very fast simulated   +
+ annealing method.                                  +
+                                                    +
+ By the combination with the down hill simplex     +
+ method, the very fast simulated annealing method  +
+ is gotten much faster.                             +
+                                                    +
+                                       July 6, 2005+
+    CopyRight by Toshiaki Yokoi, IISEE, BRI, Japan.+
+----------------------------------------------------+
./spacwkf/data/results/progress.dat
./spacwkf/prm/disp_sma1_2.prm
./spacwkf/prm/str_range.dat
 Initial values randomly produced
```

Interim output (./spacwkf/data/results/progress.dat)

Input files (./spacwkf/prm/disp_sma1_2.prm, ./spacwkf/prm/str_range.dat)

Example of execution(2):

```
 Range of random fluctuation
Thicknes Density      Vp      Vs    Thickness          Vs
 0.005   1.755   1.401   0.100   0.005   0.300   0.100   0.110
   0.005   1.756   1.401   0.100   0.005   0.300   0.100   0.200
   0.009   1.795   1.522   0.209   0.005   0.300   0.200   0.400
   0.051   1.915   1.912   0.560   0.005   0.300   0.400   0.700
   0.242   1.962   2.069   0.702   0.005   0.300   0.700   1.000
 999.000   2.517   4.505   2.896 998.000 999.000   0.800   3.200
 ./spacwkf/data/results/vel_model.dat
    5    0.0121746268
   10    0.0121746268
   15    0.0121746268
...
 5945    0.0019684711
 ./spacwkf/data/results/vel_cal.dat
       Thicknes(Km) Density(g/cm^3)     Vp(Km/sec)     Vs(Km/sec)
 1       0.009639       1.755468       1.401007       0.100006
    2       0.015666       1.755969       1.402541       0.101389
    3       0.005149       1.859092       1.727209       0.393882
    4       0.151553       1.958929       2.059392       0.693146
    5       0.294746       1.961781       2.069172       0.701957
    6     999.000000       2.131174       2.684224       1.256057
 ./spacwkf/data/results/disp_cal.dat
 ./spacwkf/data/results/err_estm.dat
```

Initial model selected using random number with in the given initial search range

Input file (Dispersion Curve)

Iterations (Number , Misfit func.)

Output file

Optimum Solution

Output files

Output-1

progress.dat: Structure Models of every j0 iterations are stored.

err_estm.dat: Data for error estimation (Next Step) are stored.

Output-2

vel_cal.dat: Optimum Solution

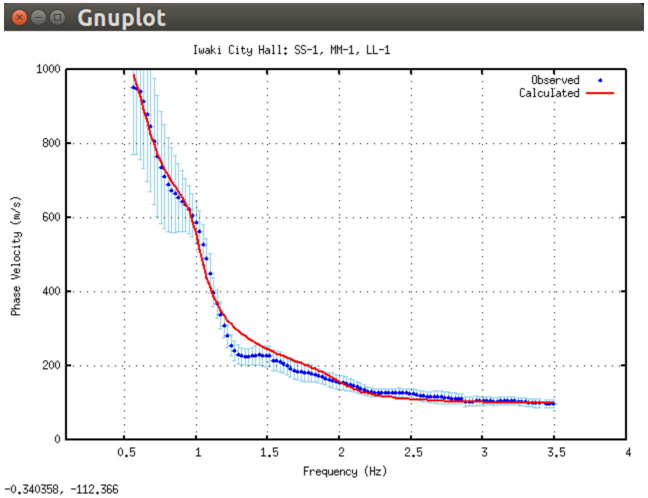
	Thicknes(Km)	Density(g/cm^3)	Vp(Km/sec)	Vs(Km/sec)
1	0.025384	1.755899	1.402329	0.101197
2	0.027954	1.894825	1.843926	0.499032
3	0.021701	1.923736	1.940100	0.585676
4	0.280051	1.958322	2.057313	0.691273
5	0.157091	1.979442	2.130108	0.756854
6	999.000000	2.122137	2.649509	1.224783

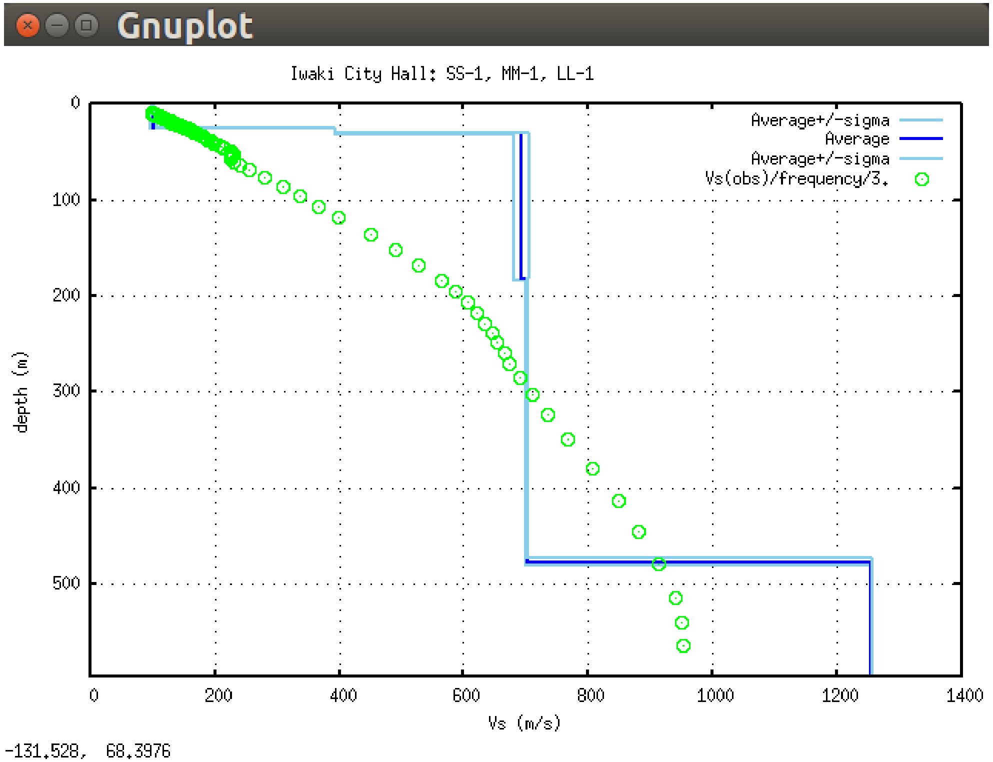
disp_cal.dat: Observed & Calculated Dispersion Curves

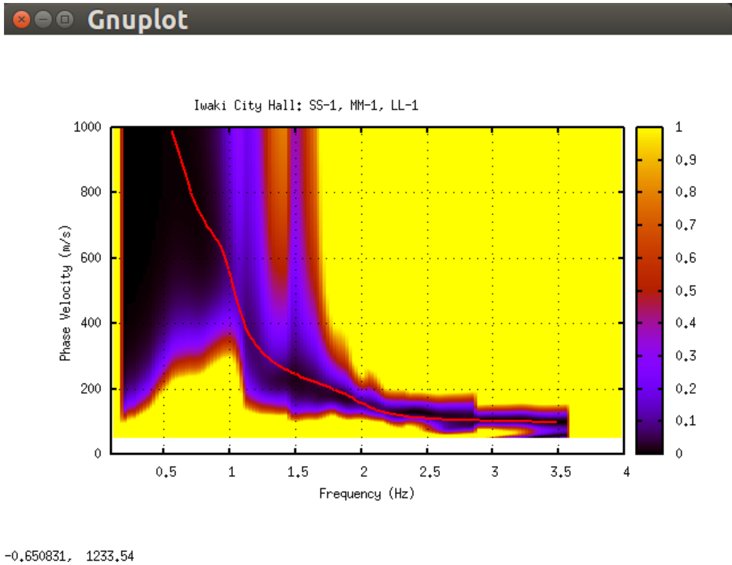
#	Frequency(Hz)	Observed Velocity	Calculated Velocity	
	0.562	0.918	0.944	0.003
	0.586	0.916	0.915	0.003
	0.610	0.905	0.884	0.004
	0.635	0.875	0.851	0.004
	0.659	0.849	0.820	0.004
	0.684	0.815	0.791	0.005
	0.708	0.769	0.766	0.005
	0.732	0.733	0.744	0.006
	0.757	0.700	0.724	0.007
	0.781	0.676	0.706	0.007
	0.806	0.659	0.690	0.008
	...			

Graphical Output: *sh ./results.sh*

./spacwkf/prm/gnuplt_script/disp_cal.plt
./spacwkf/prm/gnuplt_script/cal_cf_panel.plt
./spacwkf/prm/gnuplt_script/vs_structure.plt
Hit return to continue
Hit return to continue



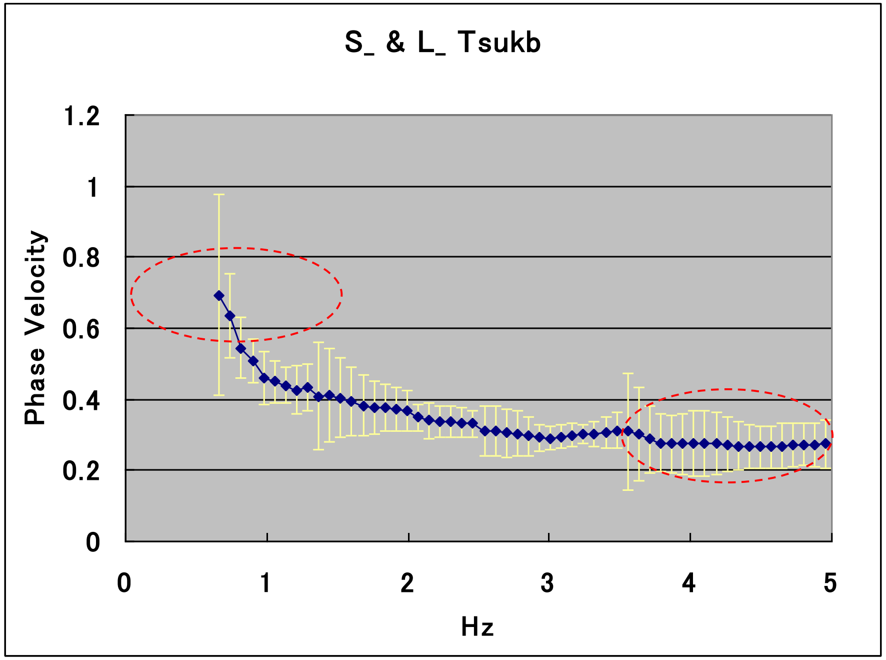




Set n_mod=0 in ‘vel_model_plt.prm’ to eliminate green circles.

These figures are automatically stored as PS files in ./spacwkf/data/results/fig_results

A way to find the optimum solution
- Explanation using another example -



In the highest frequency range, the phase velocity is about 0.3 (Km/sec).

At the lowest frequency 0.664 (Hz) the phase velocity estimated is 0.695 (Km/sec). Then, the corresponding wave length is about 1 (Km) and the expected explored depth very roughly estimated may be about 250 (m).

Examples of Search Range

str_range.dat (4 layer model for exploration from surface to the seismic bedrock)

```
Yamanaka (2001)                        :Model(a30)
    4                                  :IL(I5),Layer Number
1.8 1.956 0.001 0.05  0.4  0.9 :density,Vp,hmin,hmax,vmin,vmax
2.0 2.400 0.001 0.30  0.7  1.3
2.3 2.955 0.010 0.30  1.2  1.8
2.5 4.842 998.0 999.0 2.6  3.6
```

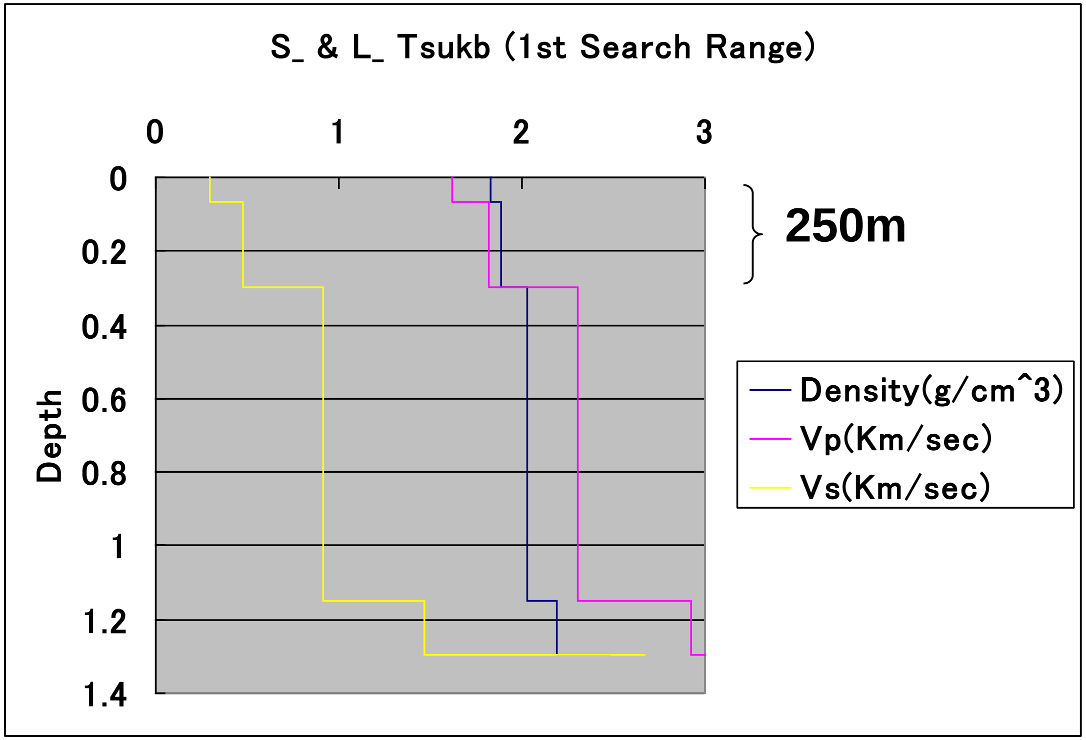
str_range.dat(4 layer model for exploration from surface to the engineering bedrock)

```
Engineering Bedrock                    :Model(a30)
    6                                  :IL(I5),Layer Number
1.5 1.5  0.0   0.03  0.08 0.15 :density,Vp,hmin,hmax,vmin,vmax
1.5 1.5  0.001 0.03  0.10 0.15
1.5 1.5  0.001 0.03  0.08 0.15
1.6 1.5  0.001 0.03  0.15 0.25
1.7 1.6  0.001 0.03  0.25 0.35
1.8 1.8  998.0 999.0 0.35 0.8
```

1st Search Range

```
S_ & L_ Tsukb                           :Model(a30)
    5                                   :IL(I5),Layer Number
1.5    1.6    0.001  0.2    0.2   0.5  :density,Vp,hmin,hmax,vmin,vmax
1.8    1.956  0.01   1.0    0.4   0.9
2.0    2.4    0.1    1.0    0.7   1.3
2.3    2.955  0.1    1.0    1.2   1.8
2.5    3.2    998.0  999.0  2.6   3.6
```

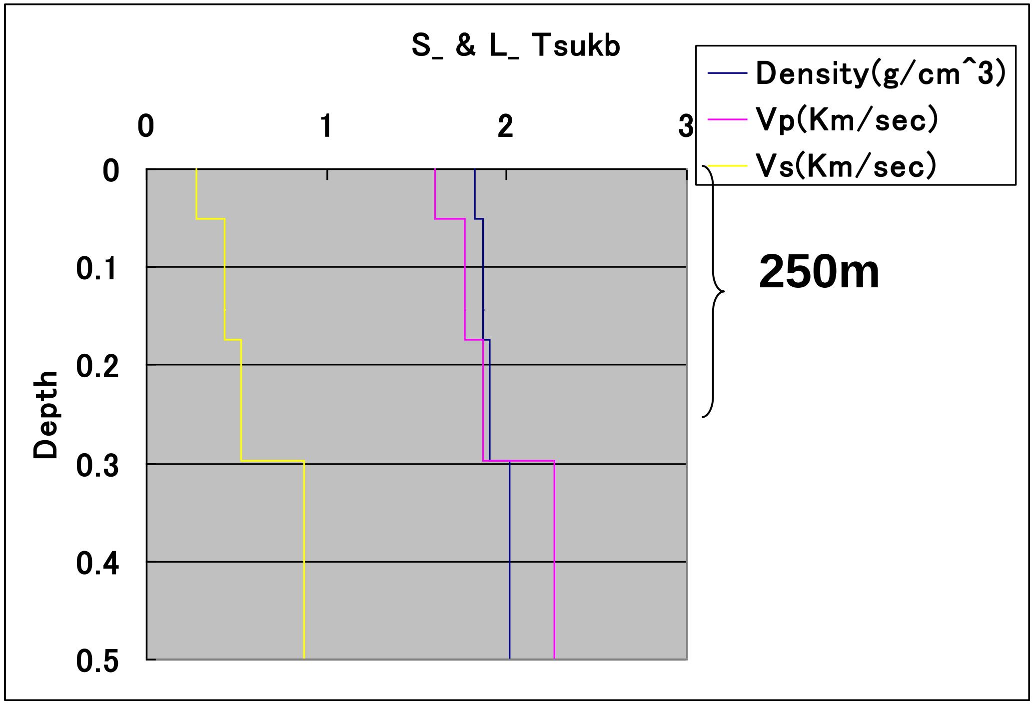
eps=0.01



2nd Search Range

```
S_ & L_ Tsukb                              :Model(a30)
    5                                      :IL(I5),Layer Number
1.5   1.6    0.001 0.2   0.2  0.4  :density,Vp,hmin,hmax,vmin,vmax
1.5   1.6    0.001 0.2   0.3  0.5
1.5   1.6    0.001 0.2   0.3  0.5
1.5   1.6    0.001 0.2   0.4  0.6
1.8   1.956  998.0 999.0 0.5  0.9
```

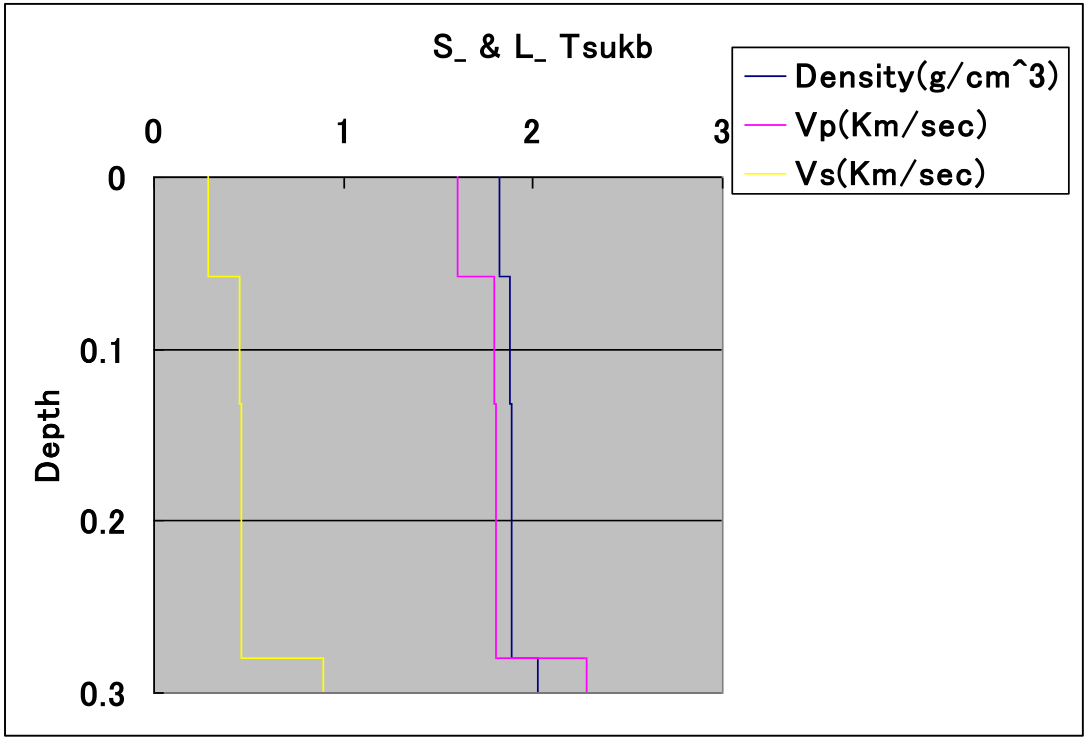
eps=0.0065



3rd Search Range

```
S_ & L_ Tsukb                              :Model(a30)
    4                                      :IL(I5),Layer Number
1.5   1.6    0.001 0.2   0.2  0.4  :density,Vp,hmin,hmax,vmin,vmax
1.5   1.6    0.001 0.2   0.3  0.5
1.5   1.6    0.001 0.2   0.4  0.6
1.8   1.956  998.0 999.0 0.5  0.9
```

eps=0.0065



disp_sma1_2.prm

```
 1 1.  0.6 1.3 500   5   :idum,t0,a,c,ntemp,j0
 0.0065                       :eps0
    1     1                   :n_roh,n_vp
    1     0     1             :ini_flg,ndsp_flg,n_err
    0     1                   :kflg,jflg
    0     0                   :n_vs,n_th
str_range.dat                 :File name for the initial velocity model (a25).
vel_model.dat                 :File name for the obseved dispersion relation (a25).
vel_cal.dat                   :File name for the estimated velocity structure (a25)
disp_cal.dat                  :File name for the calculated dispersion relation (a25
```

c idum :Random seed (integer)
c t_0 :Initial Temperature
c a,c :Coefficients for $T=T_0*exp(-c*k**a)$, where k is iteration number

<The optimum schedule is given t_0=1.0, a=0.6, c=1.3 (Yokoi(2006)).>

c ntemp :Maximum number of temparature change
c j0 :Number of iteration for each temperature
c threshold for conversion
c eps0 : averaged deviation

disp_sma1_2.prm (continuation)

```
c flags for roh and vp
c  n_vp     : 1=by Kitzunezaki et al(1990), vp=1.11*vs+1.29
c                  0=fixed to the initial values
c  n_roh    : 1=by Ludwig et al(1970), roh=1.2475+0.399*vp-0.026*vp**2
c                  0=fixed to the initial values
c flags for output to Display
c  ini_flg  : Initial Velocity Structure Model               1=yes
c  ndsp_flg : Observed Dispersion Relation                   1=yes
c  n_err    : Error at each iteration                        1=yes
c  kflg     : Missfit at each temp. change                   1=yes
c  jflg     : Missfit at each itration with the same temp.  1=yes
c  n_vs     : Vs value        (n_vs=layer number, 0=no output)
c  n_th     : Thickness value (n_th=layer number, 0=no output)
```

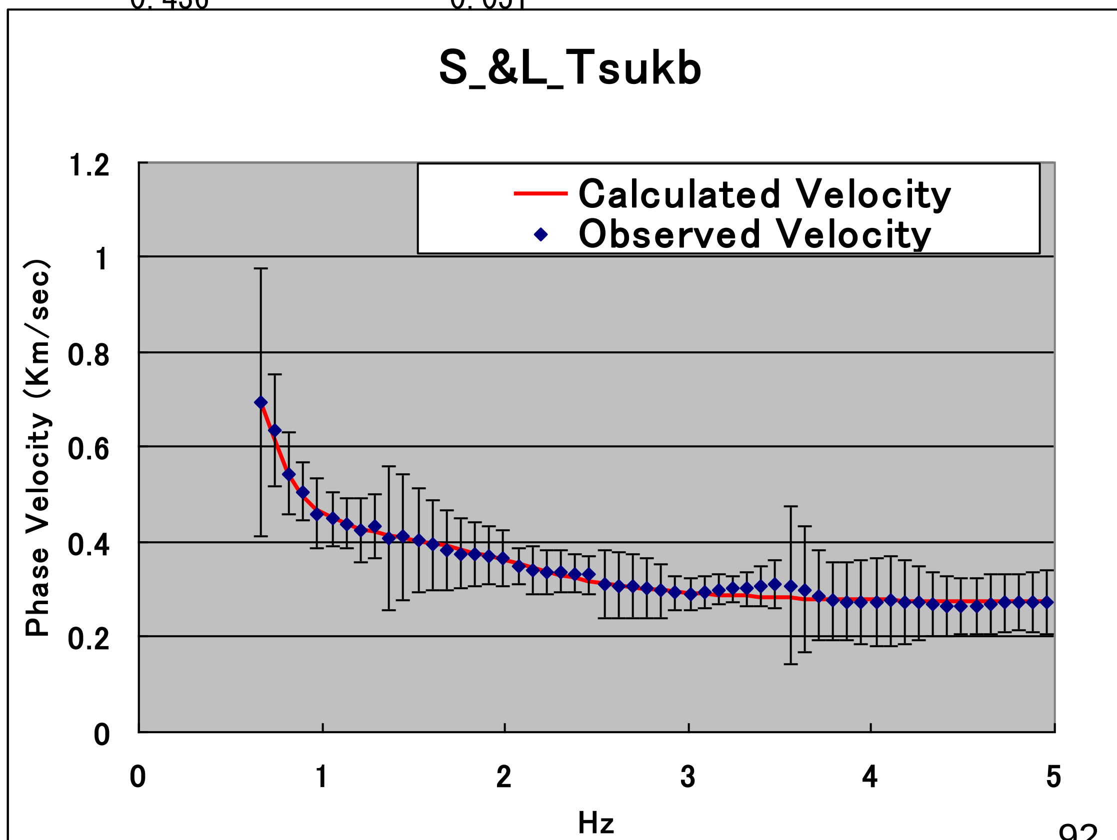
```
S_ & L_ Tsukb                           :Model(a30)
    4                                   :IL(I5),Layer Number
1.5   1.6    0.001 0.2   0.2  0.4 :density,Vp,hmin,hmax,vmin,vmax
1.5   1.6    0.001 0.2   0.3  0.5
1.5   1.6    0.001 0.2   0.4  0.6
1.8   1.956  998.0 999.0 0.5  0.9
```

	Thicknes(Km)	Density(g/cm^3)	Vp(Km/sec)	Vs(Km/sec)
1	0.057347	1.820632	1.604092	0.282966
2	0.074116	1.878893	1.791601	0.451893
3	0.147796	1.882880	1.804653	0.463651
4	999.000000	2.021464	2.277869	0.889972

Comparison of Cal. to Obs.

<u>disp_cal.dat</u>

Frequency(Hz)	Observed Velocity	Calculated Velocity	
0.664	0.694	0.698	0.281
0.742	0.636	0.618	0.118
0.820	0.545	0.543	0.085
0.898	0.507	0.496	0.061
0.977	0.460	0.467	0.074
1.055	0.449	0.449	0.058
1.133	0.440	0.436	0.051
1.211	0.426		
1.289	0.434		
1.367	0.408		
1.445	0.411		
1.523	0.405		
1.602	0.394		
1.680	0.382		
1.758	0.376		
1.836	0.375		
1.914	0.372		
1.992	0.367		
2.070	0.350		
2.148	0.341		
2.227	0.337		
2.305	0.338		
2.383	0.334		
2.461	0.331		
2.539	0.312		
2.617	0.309		
2.695	0.306		
2.773	0.303		
2.852	0.297		
2.930	0.293	0.294	0.037
3.008	0.291	0.292	0.033



Determined Velocity Structure

vel_cal.dat

	Thicknes(Km)	Density(g/cm^3)	Vp(Km/sec)	Vs(Km/sec)
1	0.057347	1.820632	1.604092	0.282966
2	0.074116	1.878893	1.791601	0.451893
3	0.147796	1.882880	1.804653	0.463651
4	999.000000	2.021464	2.277869	0.889972