

# **Instruction**

**- Analysis of CCA Method -**

**Aug. 31, 2014  
IISEE, BRI, Japan**

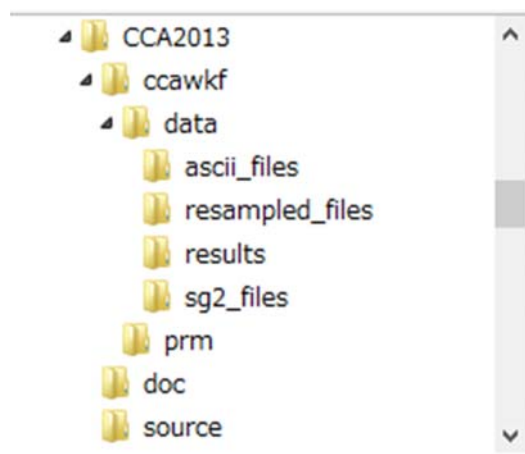
**By T.Yokoi**

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Note: This program package was developed on Linux: Ubuntu 12.04.1 LTS for 64bit PC using gfortran compiler.  
It has been tested also on Cygwin on Windows 8.1 (64bit) with re-compilation of the executable files.  
Operation on other OS may require additional revision or correction by users themselves.

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# Folder Structure



Every necessary programs and files are stored under the folder “CCA2013”. The command operation is 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 the instruction manual.

The subfolder “ccawkf” contains the subfolder “prm” for parameter files including script files of GNUPLOT and the subfolder “data” for data files including graphic ones.

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## Note: GNUPLOT scripts files

(For extension in future)

The folder “CCA2013” includes the files of GNUPLOT scripts.

\*.plt

and others under the subfolder ./ccawkf/prm/gnuplt\_scripts

These can be loaded on GNUPLOT as **load '????'**

In the version uploaded Sep. 2014, these have not been installed yet.

## Note: Executable files

The folder “CCA2013” 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.

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

Executable files must be stored in the folder CCA2013.

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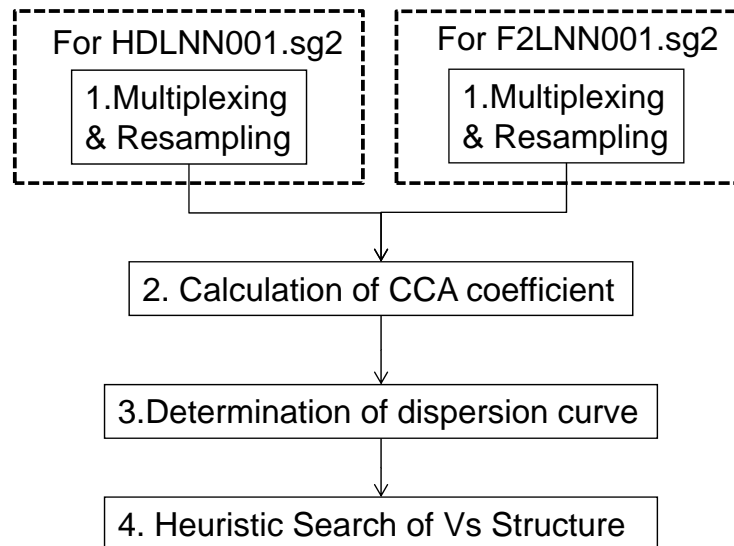
# Note: Example

An example that consists of two data sets is shown below.

HDLNN001.sg2: Huddle test data file

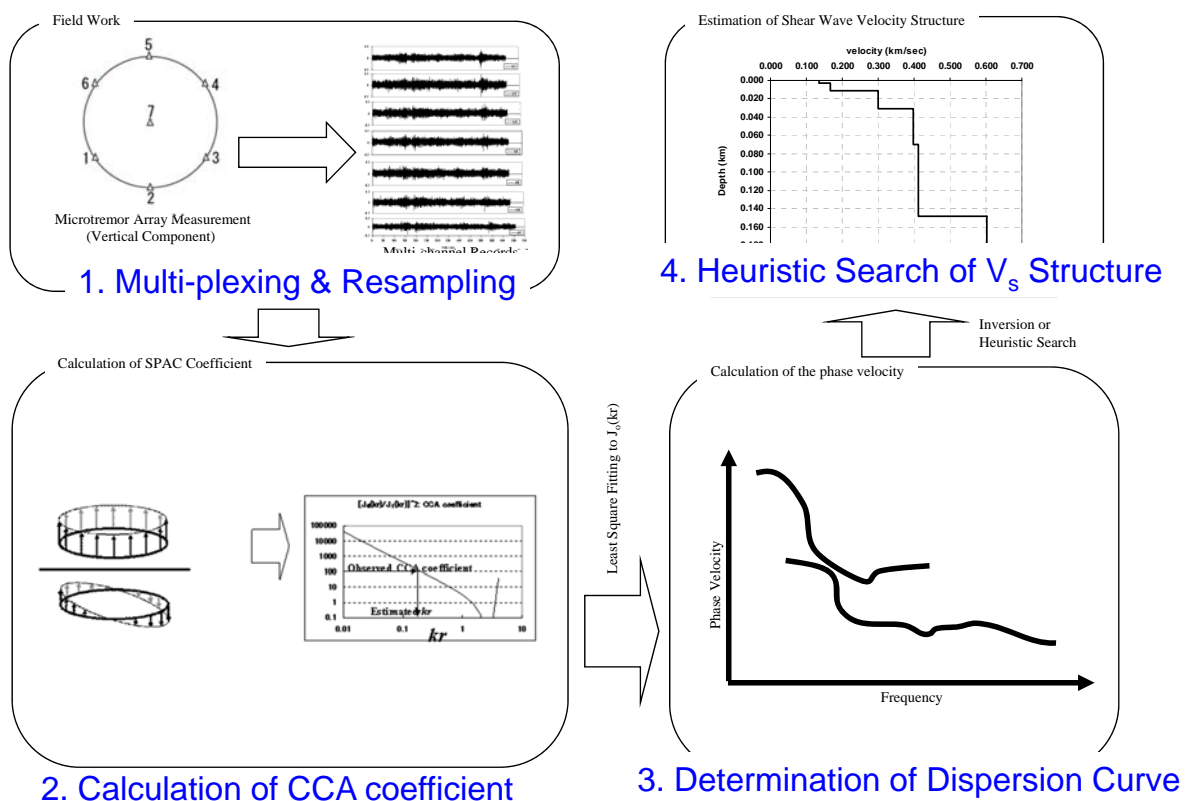
F2LNN001.sg2: 6 points circular array without the center

Both are the seg2 standard format file.



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## Procedures of analysis



# 1. Multiplexing & Resampling

## 1.1 Multiplexing

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

Jump to 1.2 if the field data files are of seg2 standard format.

Program used:

`multipx5.for +./ccawkf/prm/multipx5.prm`

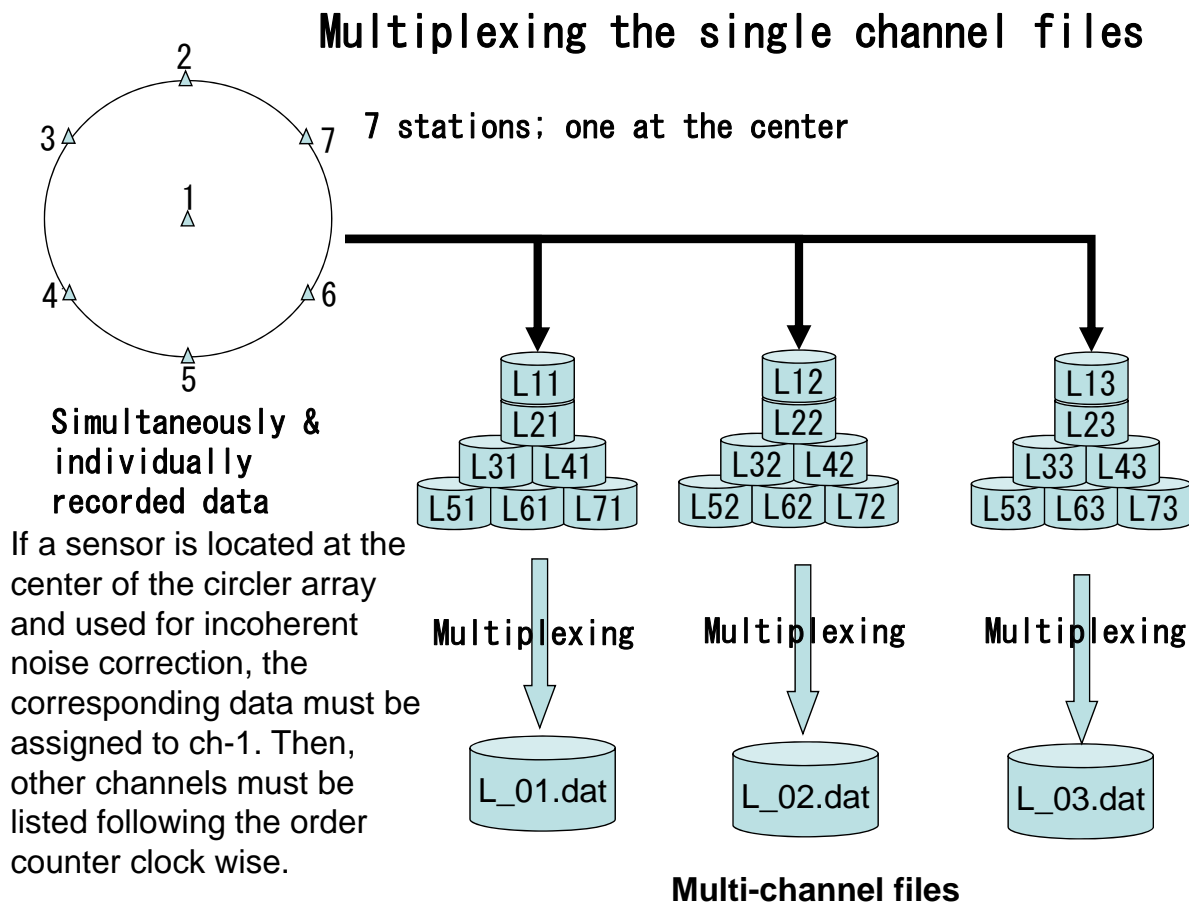
Store the input files in “./ccawkf/data/ascii\_files” the output files are created in the same folder.

### Terminology

#### **Multiplexing:**

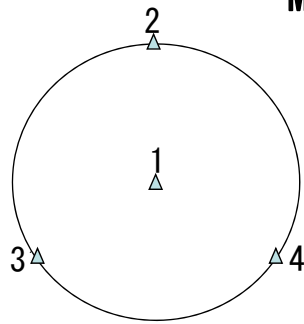
To sort the data individually stored in single channel files into a multi-channel file of the time-sequential format.

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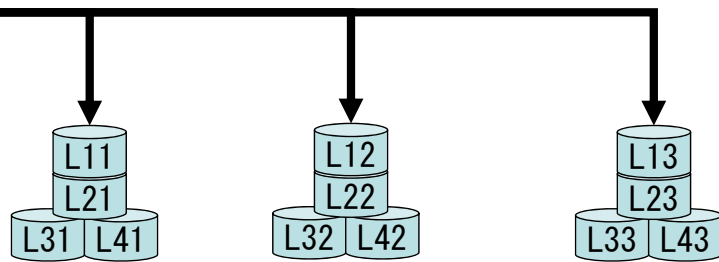
## Multiplexing the single channel files



4 stations; one at the center

**Simultaneously & individually recorded data**

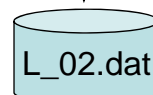
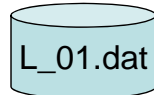
If a sensor is located at the center of the circular array and used for incoherent noise correction, the corresponding data must be assigned to ch-1. Then, other channels must be listed following the order counter clock wise.



**Multiplexing**

**Multiplexing**

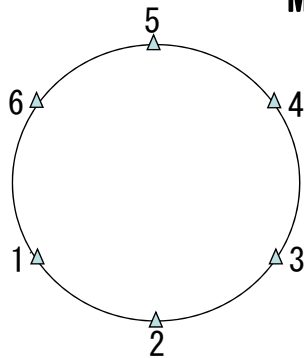
**Multiplexing**



**Multi-channel files**

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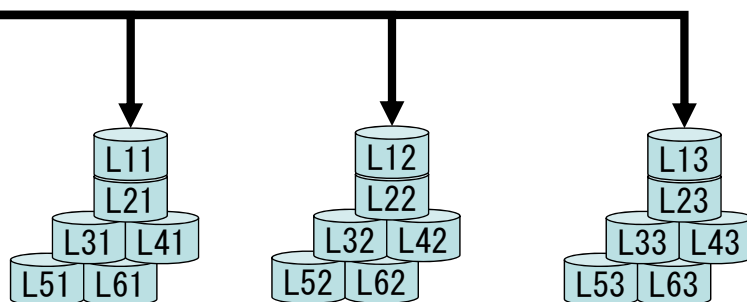
## Multiplexing the single channel files



6 stations without the center

**Simultaneously & individually recorded data**

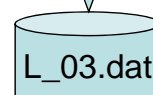
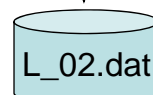
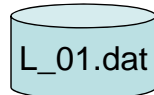
Stations must be listed following the order counter clock wise.



**Multiplexing**

**Multiplexing**

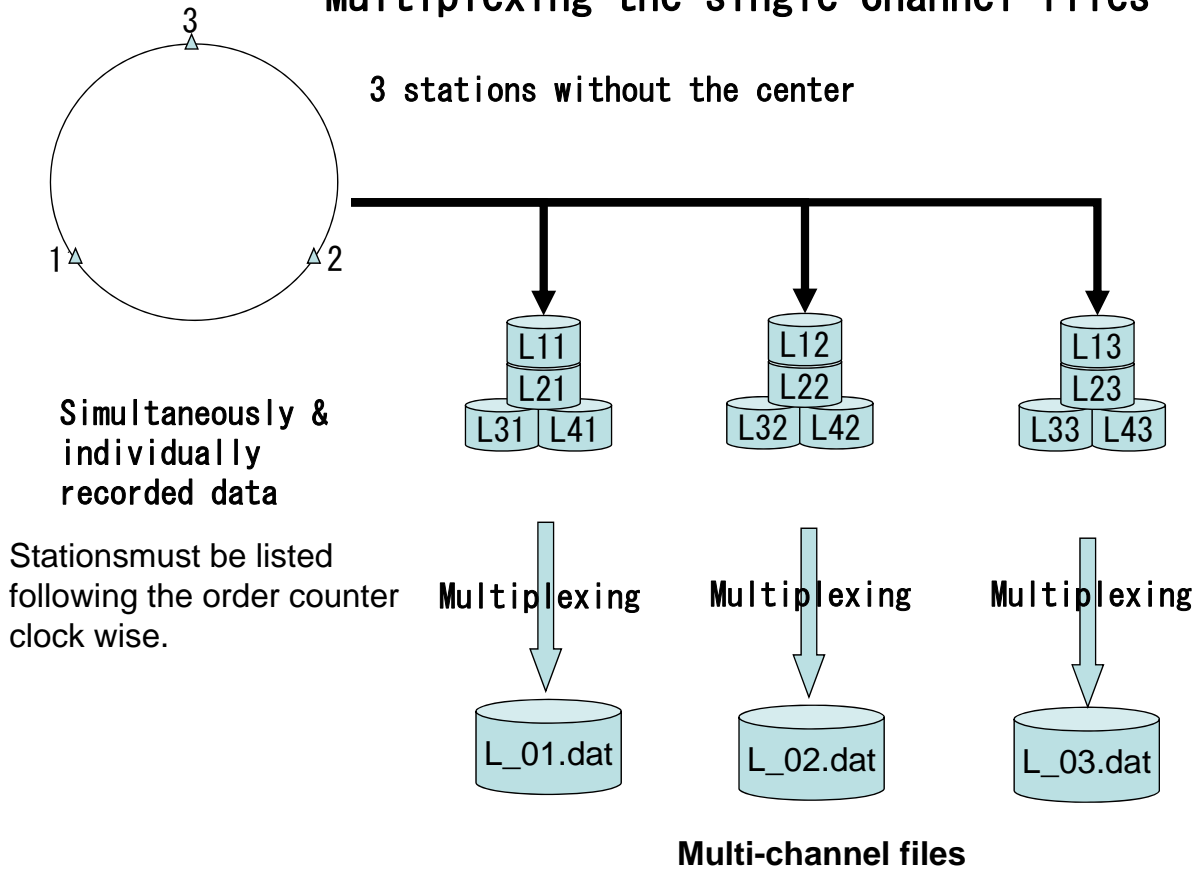
**Multiplexing**



**Multi-channel files**

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## Multiplexing the single channel files



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## Example for “multipx5.prm”

```

7 0.004           :Number of Channels,dt
0.0 65.532        :tst,tdur
1.e4              :scale(input data is divided by this scale)
4 .cdm            :nattach, cattach
2 D2              :n_out(A12),cout      (".dat" is attached)
Re_processing_Sep_08_2011 :comment(A50)
30 8              :number of measurement in the same array
configuration,ncfrm
ii155119 ii155118 ii155117 ii155116 ii155115 ii155114 ii155113 :file name
ii155219 ii155218 ii155217 ii155216 ii155215 ii155214 ii155213 :file name
ii155319 ii155318 ii155317 ii155316 ii155315 ii155314 ii155313 :file name
ii155419 ii155418 ii155417 ii155416 ii155415 ii155414 ii155413 :file name
...

```

## Format of the multiplexed files in ./ccawkf/data/ascii\_files:

Users who use single channel recorders must multiplex the record files in the following format.

```
7  5.000000E-02    1.000000    34800
comment
.000000 .8488064E-02 .2240569E-01 .7275309E+00 ...
.050000 .6672466E-02 .2059771E-01 .7258945E+00 ...
.100000 .6364370E-02 .2036088E-01 .7256799E+00 ...
.150000 .7738471E-02 .2166483E-01 .7272448E+00 ...
...
```

1st line: Number of channels,  $\Delta t$ (sec), scale, number of samples

2nd line: Comment (less than 81 characters)

3rd line: Time, 1st-ch sample, 2nd-ch sample, 3rd-ch sample, ....

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# 1. Multiplexing & Resampling

## 1.2 seg2 standard format

Program used:

seg2read.for +./ccawkf/prm/seg2read.prm

This procedure is prepared for the field data files of seg2 standard format

Store the input files in “./ccawkf/data/sg2\_files”, the output files are created in “./ccawkf/data/ascii\_files”.

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## Example for “./ccawkf/prm/seg2read.prm”

HDLNN0 :cname, '.sg2' is added for input seg2 format file.

01 01 :measurement numbering for starts and ends

0.E0 0 :scale factor, Gain of sensor V/(m/s)

6 :Channel number

Huddle Test,L22D,No\_Rs,No\_A\_amp,D\_amp=X1,F2LNN0,Mar.15,2012.

Explanation:

1st line : input file name (e.g., 'sxbg80'), '.sg2' is added for input file.

2nd line : measurement numbering for starts and ends

e.g., (00 03)==>from sxbg8000.sg2 to sxbg8003.sg2 for input

3rd line : Scale factor (=0,descaling factor in seg2 file is used),

Gain of sensor V/(m/s) (=0. results in voltage output)

4th line :mch=number of channel in use. Channels from 1 to mch are processed

5th line :Comment(A80)

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## Example for “./ccawkf/prm/seg2read.prm”

F2LNN0 :cname, '.sg2' is added for input seg2 format file.

01 01 :measurement numbering for starts and ends

0.E0 0 :scale factor, Gain of sensor V/(m/s)

6 :Channel number

LCCM,Field,r=2m,L22D,No\_Rs,No\_A\_amp,D\_amp=X1,F2LNN0,Mar.15,2012.

Explanation:

1st line : input file name (e.g., 'sxbg80'), '.sg2' is added for input file.

2nd line : measurement numbering for starts and ends

e.g., (00 03)==>from sxbg8000.sg2 to sxbg8003.sg2 for input

3rd line : Scale factor (=0,descaling factor in seg2 file is used),

Gain of sensor V/(m/s) (=0. results in voltage output)

4th line :mch=number of channel in use. Channels from 1 to mch are processed

5th line :Comment(A80)

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# Output files in ./ccawkf/data/ascii\_files

```
6 0.0080      0.1000E+01 225000
LCCM,Field,r=2m,L22D,No_Rs,No_A_amp,D_amp=X1,F2LNN
0.000000 -0.7149702E-04 -0.5138848E-04 -0.9086079E-04 -0.8415795E-04 -0.4840944E-04 -0.5436752E-04
0.008000 -0.1340569E-04 -0.3127994E-04 0.1079903E-03 0.2979042E-05 -0.1280988E-03 0.2830090E-04
0.016000 -0.8192366E-04 -0.1541654E-03 0.1437388E-03 -0.1861901E-04 -0.2211939E-03 -0.6404941E-04
0.024000 -0.4096183E-04 -0.1020322E-03 0.1377807E-03 0.5287800E-04 -0.1720397E-03 -0.4989896E-04
0.032000 -0.2234282E-04 0.2457710E-04 0.3932336E-03 0.4014260E-03 0.1415045E-04 -0.3872755E-04
.....
```

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## 1. Multiplexing & Resampling

### 1.3 Resampling & Screening

Program used:

resamplecca2.for +./ccawkf/prm/resamplecca2.prm

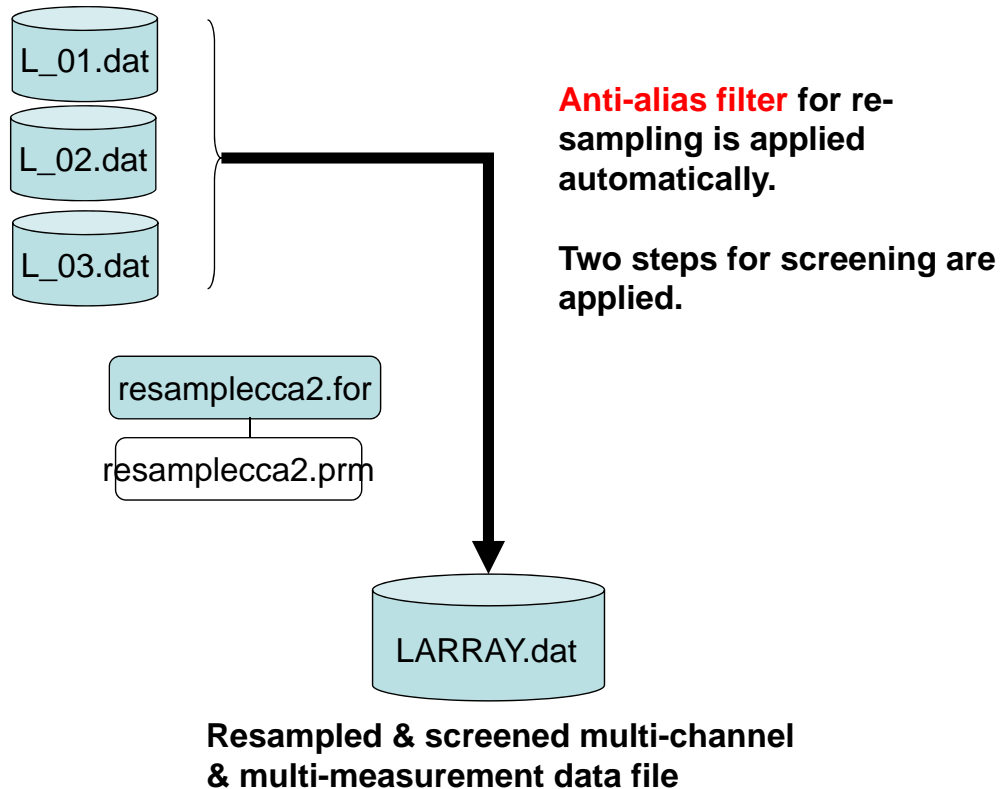
#### Terminology

##### 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 aliasing effect. Then, it is necessary to apply the digital anti-alias filter that has high cut characteristics before thinning out.

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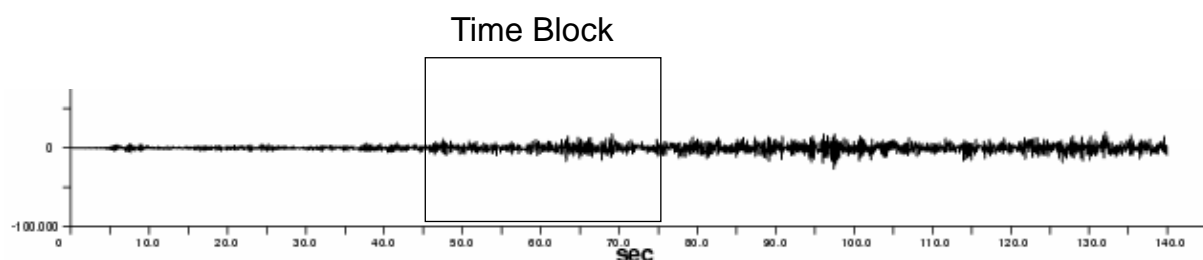
## Multi-channel data files from the same array configuration



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## Screening: Step-1

Parameter: *ajudge*



If the maximum amplitude in a time block exceeds the product of “*ajudge*” 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.

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## Screening: Step-2

Parameter: a\_sgm

If the RMS amplitude in a time block deviates more than a\_sgm X 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.

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## 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 problem will take place in the further step of analysis, namely, the determination of dispersion curves.

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Example of resamplecca2.prm:

```

7 0.0 0.05 1 :nch, ph0, dt,nskip
0 0.0 :nch_center,rr
4.0 2.0 :ajudge,a_sgm
0.0 1740.0 :tst,tdur
HDMTN0.dat :output file name
4096 :number of data in one time block after resampling
2 :number of measurement in the same array configuration
150.dat :input file name
153.dat :input file name

```

where

ph0: Azimuth from the center(1ch) to 2ch

nskip: skip number for resampling (1: no resampling, 2: resample at every two samples)

nch\_center: 0 (no sensor at the center) or 1 (1ch at the center)

rr: radius of circular array (m)

tst: start time of analysis (sec)

tdur: duration of time window for analysis (sec)

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### Example of Output (resampled) file format

HDMTN0.dat

1<sup>st</sup> line:file parameters

```

7 30 4096 0 .00 .00 (i6,f12.4, 7e15.7) :nch,mmbld,nblk,nch_center,ph0,rr,cform3
1 10.2400 0.4646236E-01 0.4119775E-01 -0.4262851E-02 0.2120773E-01 0.2454802E-01 0.1651071E-01 0.1690427E-01
2 10.2800 0.4383430E-01 0.3974453E-01 -0.2571377E-02 0.1386825E-01 0.1751127E-01 0.1511946E-01 0.1294782E-01
...
512 51.1600 0.2422718E-01 0.1534039E-01 0.2603670E-01 0.1417860E-01 0.2043526E-01 0.2110930E-01 0.2491470E-01
1 40.9600 -0.1647814E-01 -0.1781779E-01 -0.6996713E-02 -0.2801293E-01 -0.7406686E-02 -0.9947842E-02 -0.1166921E-01
...
512 61.4000 0.6565484E-02 0.1167425E-01 0.1688264E-01 0.2749743E-02 0.2582426E-02 0.5863708E-02 0.3238959E-02
1 51.2000 0.2494610E-01 0.1642562E-01 0.2538362E-01 0.1597471E-01 0.2079931E-01 0.2758794E-01 0.2056385E-01
...

```

The file include mmbld=30 time blocks of nch=7 channel data. Each time block is composed of nblk=4096 data.

Each line corresponds to a time step. The format used to store each line is cform3='(i6,f12.4, 7e14.7)'.

These parameters are stored in the 1<sup>st</sup> line.

As all of the data are delimited by space, this file can be read using free format.

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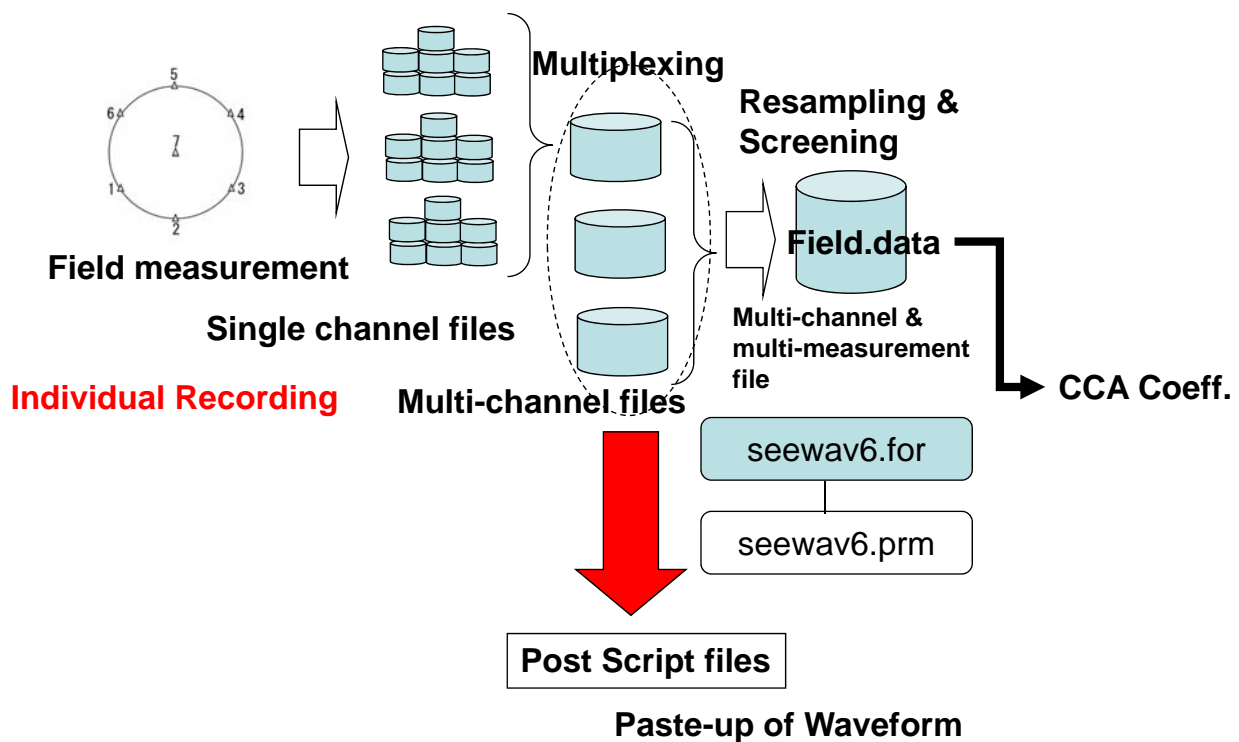
# 1. Multiplexing & Resampling

## 1.4 Plot Waveform

`seewav6.exe+ ./ccawkf/prm/seewav6.prm`

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### Flow of the data processing for the conventional CCA



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## Multi-channel file: SS01.dat

```

7 0.0020      0.1000E+01 16382
SS-1, Iwaki City Hall, Dec. 22, 2012
0.000000 -0.1479083E-03 -0.3292947E-04 -0.4525494E-04 0.2501947E-03 -0.1626334E-04 0.6159581E-04 -0.6209756E-04
0.002000 -0.1406819E-03 0.8416013E-05 -0.3367045E-04 0.1703026E-03 -0.4016794E-05 0.4109484E-04 -0.6437057E-04
0.004000 -0.1286992E-03 0.6413076E-04 -0.1699326E-04 0.1571616E-03 0.1541292E-04 0.3963208E-04 -0.7448299E-04
0.006000 -0.9073457E-04 0.1229303E-03 -0.7809489E-05 0.1588118E-03 0.4091091E-04 0.6388919E-04 -0.1350910E-03
0.008000 -0.8823746E-04 0.1375451E-03 0.1742737E-06 0.1593182E-03 0.7517333E-04 0.7343001E-04 -0.1661227E-
03...

```

↓  
F2LNN0.ps

seewav6.for

seewav6.prm

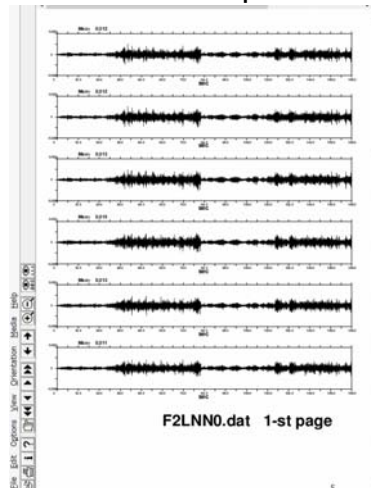


Figure in Multi-page Post Script file.  
Post Script file can be opened, for  
example, by “gv &”.

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## seewav6. prm

dtl denotes the time duration that corresponds  
to 1cm along the time axis.  
In one page,  $28 \cdot \text{dtl}/\text{dt}$  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.

```

6
0 0.1 8. 9.5
6.0
1 10
HDLNNO. dat

```

F2LNN0. dat

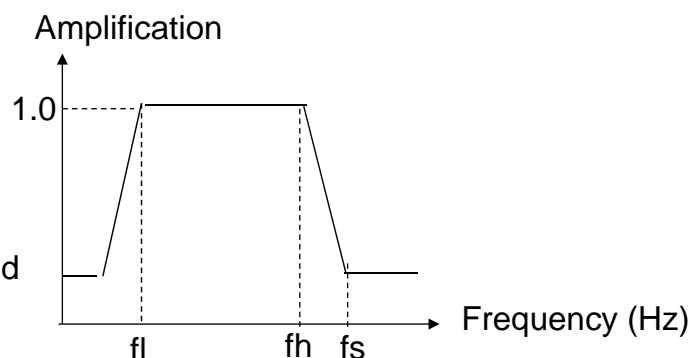
```

:nch
:nbandpass, fl, fh, fs
:dtl (sec/cm)
:n_mea, n_character

```

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

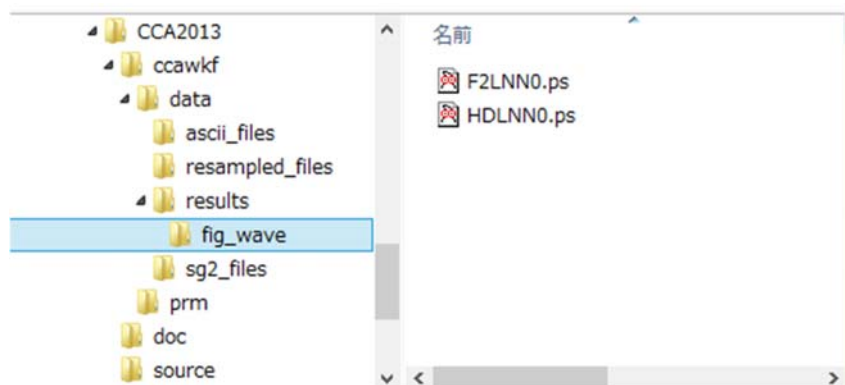
### Band Pass Filter



This BPF does not affect to the data files.<sup>28</sup>

Example of execution:

```
$ ./seewav6.exe  
./ccawkf/prm/seewav6.prm  
./ccawkf/data/multiplexed_files/HDLNN0.dat  
./ccawkf/data/results/fig_wave/HDLNN0.ps  
...  
./ccawkf/data/multiplexed_files/F2LNN0.dat  
./ccawkf/data/results/fig_wave/F2LNN0.ps  
~/CCA2013  
$
```



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## 2. Calculation of CCA coefficient

## 3. Dispersion Curve

Program used:

pwrcrs3.for + ./ccawkf/prm/pwrcrs3.prm

### Terminology

#### **Huddle test:**

**Common input motion recording to determine the difference of the system characteristics among the recording system and/or channels.**

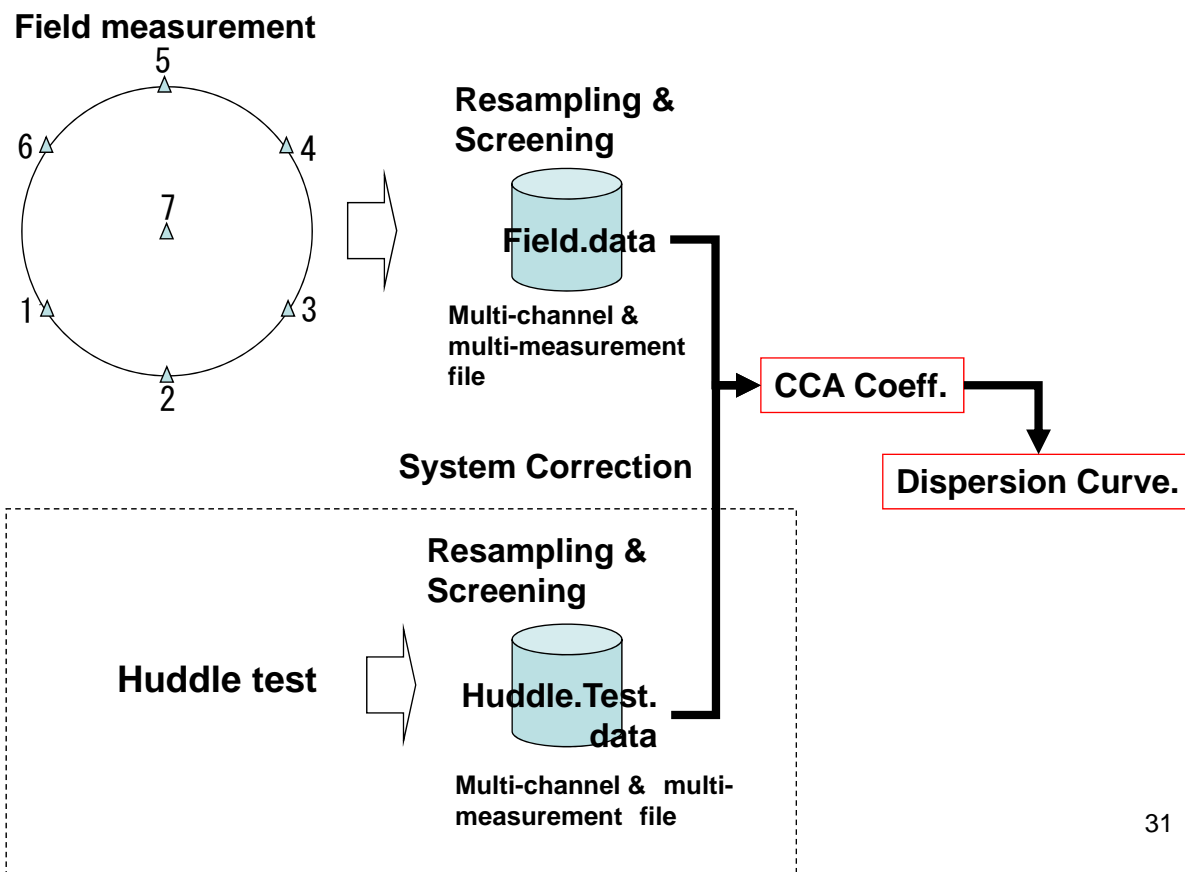
**The seismometers used in field measurement are put close each other like a huddle and simultaneous recording is conducted.**

#### **System correction:**

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

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# Flow of the data processing for CCA



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## Example of pwrhrs3.prm:

```

0.1 20.0 0.008 0.23 1 0.0 :fmin,fmax,dt,bw,n_huddle,smthf
HDLNN0.dat 1 1 :File name of Huddle Test data (A12) for input,coherence,power spectra,phase lag
F2LNN0.dat 1 1 :File name of Field data (A12) for input,coherence, power spectra,phase lag output
0 :n_cor_center
  
```

where

```

fmin, fmax : minimum and maximum frequencies for analysis
bw         : band width of Parzen window
n_huddle   :flag for system correction using huddle test data (0:no, 1:yes)
smthf      : smoothing parameter
coherence & power spectra output flag : (0:no output , 1:yes)
n_cor_center : flag for correction using sensor at the center.
  
```

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# CCA coefficient

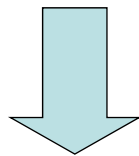
calculated in the frequency domain

$$\begin{aligned}
 & n\_huddle=0 \\
 & s_{CCA}(r, \omega) \approx \frac{\sum_{m=1}^M \sum_{m'=1}^M E[C_{m,m'}(r, \omega)]}{\sum_{m=1}^M \sum_{m'=1}^M E[C_{m,m'}(r, \omega)] \exp\{-i(\theta_m - \theta_{m'})\}} \approx \frac{J_0^2(r\omega/c)}{J_1^2(r\omega/c)} \\
 & n\_huddle=1 \\
 & \left\{ \begin{aligned}
 s_{CCA}(\omega) &= \frac{\sum_{i=1}^M \sum_{k=1}^M R_{ik}(\omega)}{\sum_{i=1}^M \sum_{k=1}^M R_{ik}(\omega) \exp\{-j(\theta_i - \theta_k)\}} \\
 R_{ik}(\omega) &= \frac{C_{00}^{obs}(\omega) E[C_{ik}^{obs}(\omega)] \overline{Cor_{ik}^{huddle}(\omega)}}{\sqrt{E[C_{ii}^{obs}(\omega)] E[C_{kk}^{obs}(\omega)]}} \\
 \overline{Cor_{ik}^{huddle}(f)} &= \exp \left\{ jE \left[ Arg \left( \frac{\sqrt{C_{ii}^{huddle}(f)} \cdot C_{kk}^{huddle}(f)}{C_{ik}^{huddle}(f)} \right) \right] \right\}
 \end{aligned} \right.
 \end{aligned}$$

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## KR derived from CCA coefficient

$$s(r, \omega) = \frac{J_0^2(r\omega/c)}{J_1^2(r\omega/c)}$$



Long wavelength approximation  
(Small value of  $kr$ ) (Cho et al, 2006)

$$c(\omega) = \frac{r\omega}{2} \sqrt{s(r, \omega) + 2}$$

Improved approximation: Yokoi (2012)

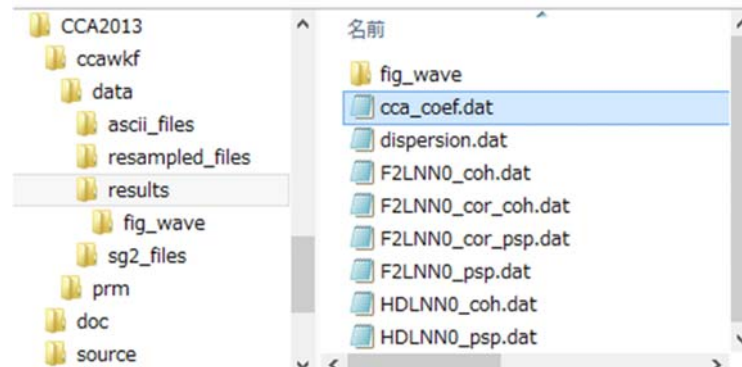
$$c(\omega)/r\omega = 1.0003 \left( \frac{\sqrt{s(r, \omega) + 0.97221}}{2.0003} + 0.0015245 \right) - 0.0138$$

Estimate  $c(\omega)$  using the relation  $KR = 2\pi R/c(\omega)$

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# Output Files

## in ./ccawkf/data/results



cca\_coef.dat : calculated CCA coefficient  
 dispersion.dat : estimated dispersion curve  
 F2LNN0\_coh.dat : coherence among the channels  
 F2LNN0\_cor\_coh.dat : coherence corrected by huddle test  
 (not created if n\_huddle=0 in pwrhrs3.prm)  
 F2LNN0\_psp.dat : power spectra of all channels  
 F2LNN0\_cor\_psp.dat : power spectra corrected by huddle test  
 (not created if n\_huddle=0 in pwrhrs3.prm)  
 HDLNN0\_coh.dat : coherence among the channel for huddle test  
 HDLNN0\_psp.dat : power spectra of huddle test

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## cca\_coef.dat

```

Freq.      ALL      Z0/ALL      Z1/ALL      Z0/Z1      Azi      err/N  2.000  0.100  20.000 :Radius, fmin, fmax
0.061      0.159723E-08  0.892037E+00  0.375753E-01  0.237400E+02-0.208969E+03  0.000000E+00
0.122      0.711724E-09  0.837860E+00  0.448491E-01  0.186818E+02-0.208319E+03  0.000000E+00
0.183      0.270016E-09  0.715646E+00  0.634022E-01  0.112874E+02-0.207233E+03  0.000000E+00
0.244      0.137192E-09  0.605082E+00  0.853591E-01  0.708867E+01-0.200393E+03  0.000000E+00
0.305      0.988401E-10  0.564597E+00  0.901056E-01  0.626595E+01-0.198077E+03  0.000000E+00
0.366      0.883166E-10  0.586148E+00  0.816502E-01  0.717877E+01-0.197768E+03  0.000000E+00
0.427      0.824325E-10  0.629496E+00  0.727541E-01  0.865239E+01-0.198016E+03  0.000000E+00
0.488      0.788436E-10  0.664547E+00  0.698261E-01  0.951718E+01-0.197850E+03  0.000000E+00
.....

```

1<sup>st</sup> line : titles of columns (Freq.,All, Zo/ALL, Z1/ALL, Z0/Z1,Azi,err/N), radius,fmin,fmax

Freq. : frequency

ALL : All power spectra

Z0/ALL :

Z1/ALL :

Z0/Z1 : CCA coefficient

azi : azimuth estimated from array analysis

err/N : actually not used

Z0: numerator of CCA coefficient

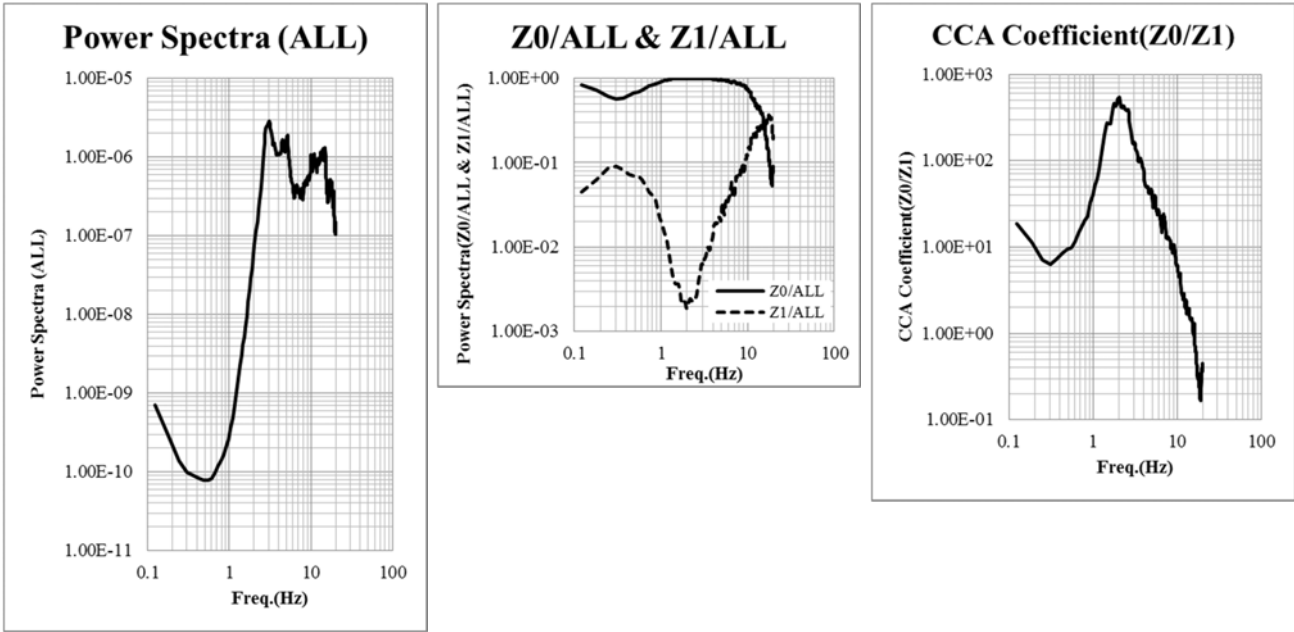
power of zero order component of Fourier expansion over azimuth

Z1: denominator of CCA coefficient

power of first order component of Fourier expansion over azimuth

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# cca\_coef.dat

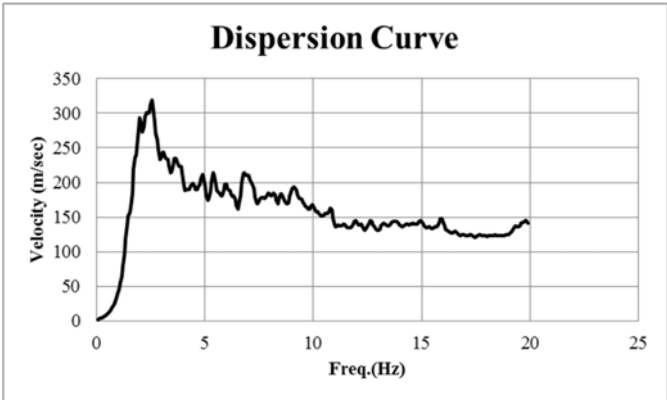


The format of the file is CSV and readable using MicroSoft Excel.

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# dispersion.dat

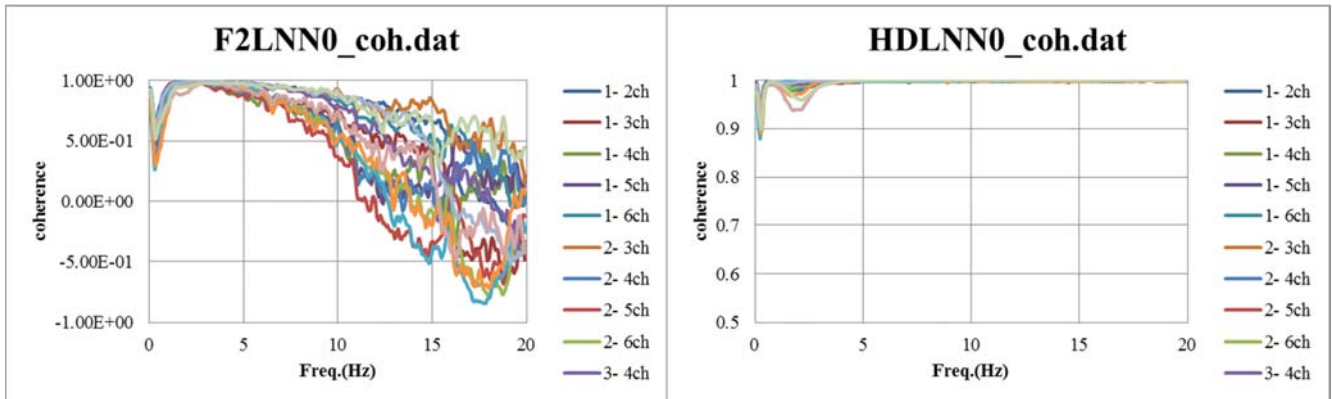
Frequency	Velocity	Azimuth	KR
0.061	1.897	-208.969	0.404
0.122	3.382	-208.319	0.454
0.183	4.001	-207.233	0.575
0.244	4.319	-200.393	0.71
0.305	5.113	-198.077	0.75
...			



The format of the file is CSV and readable using MicroSoft Excel.

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# F2LNN0\_coh.dat HDLNN0\_coh.dat



# F2LNN0\_cor\_coh.dat HDLNN0\_cor\_coh.dat

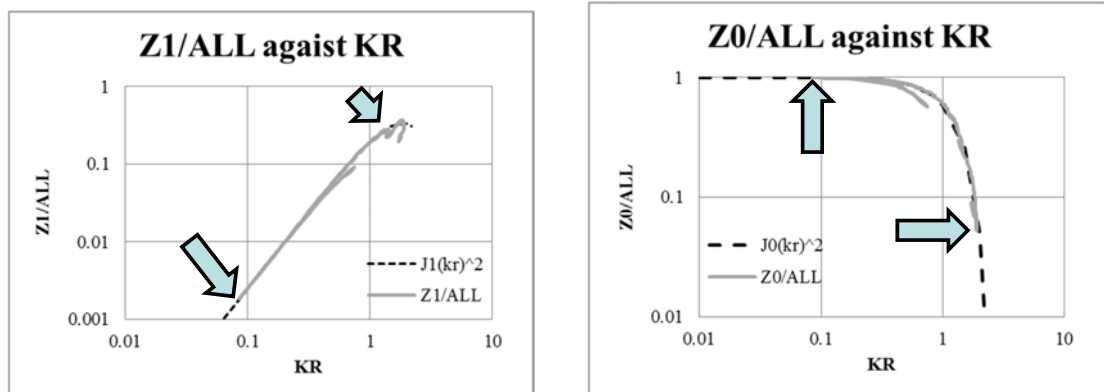
The format of the file is CSV and readable using MicroSoft Excel.

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## Quality Control

Using the values of KR in the file “dispersion.dat”, Z0/ALL and Z1/ALL in the file “cca\_coef.dat” are compared with the theoretical  $J_0(kr)^2$  and  $J_1(kr)^2$ , respectively, using MicroSoft Excel.

Arrows indicate the limit of the range of KR for analysis, where the observed curves run off from the theoretical ones.



The format of the file is CSV and readable using MicroSoft Excel.

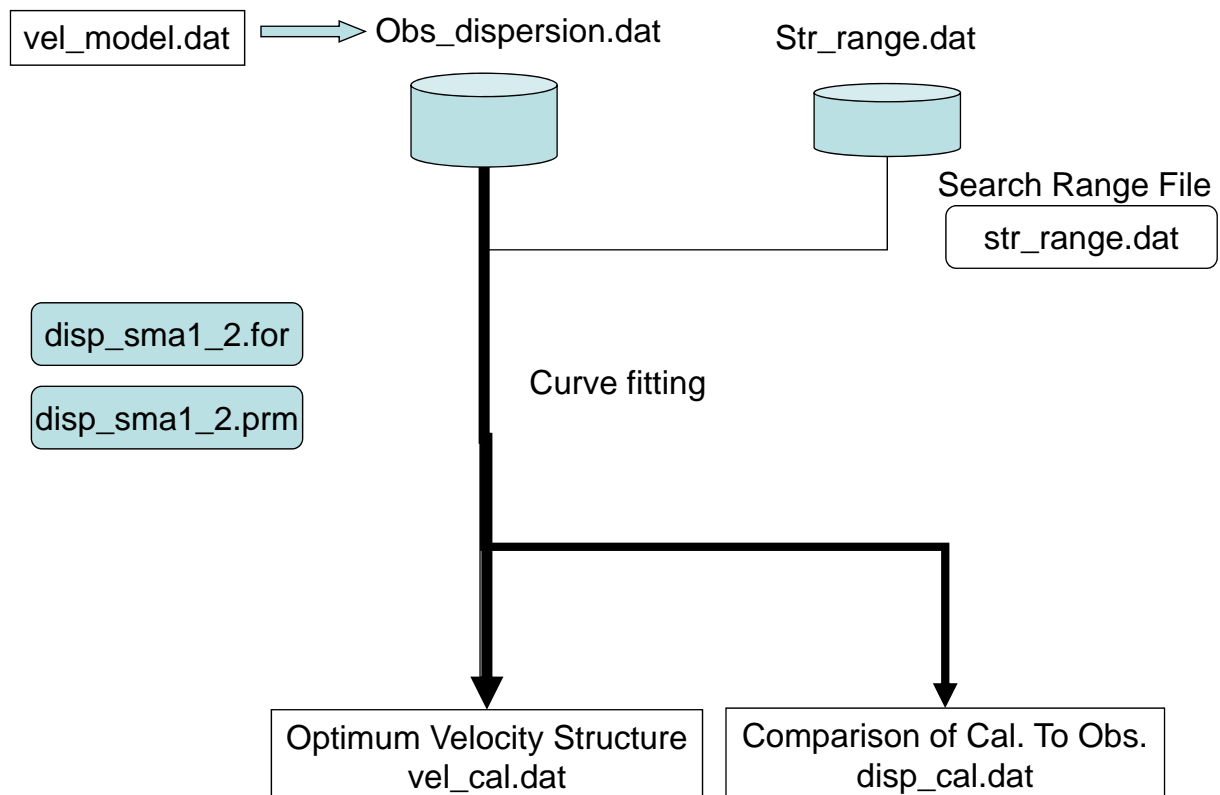
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## 4. Heuristic Search of Vs Structure

Programs used:

disp\_sma1\_2.for + disp\_sma1\_2.prm

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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.

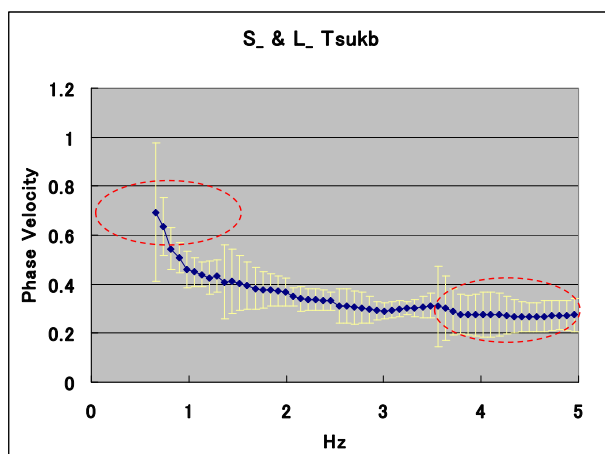
Analogy of cooling and crystallization process of metals.

**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)

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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).

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## 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)

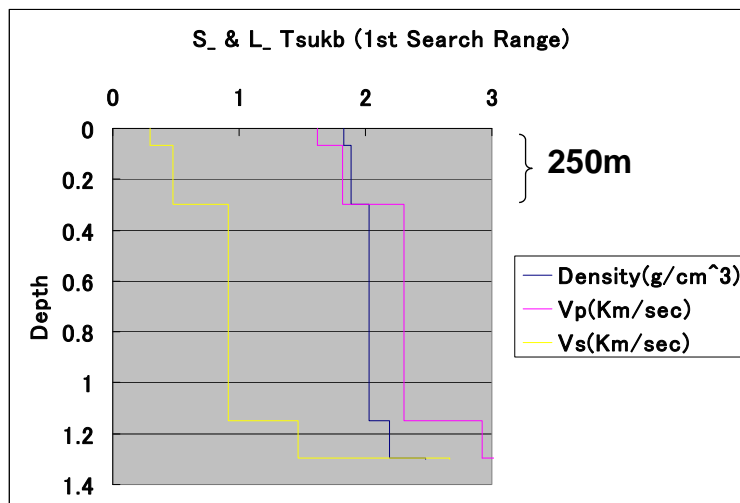
Engineering Bedrock	:Model (a30)
6	:IL (I5), Layer Number
1.5 1.5 0.0 0.03 0.08 0.15	:density, Vp, hmin, hmax, vmin, vmax
1.5 1.5 0.001 0.03 0.10 0.15	
1.5 1.5 0.001 0.03 0.08 0.15	
1.6 1.5 0.001 0.03 0.15 0.25	
1.7 1.6 0.001 0.03 0.25 0.35	
1.8 1.8 998.0 999.0 0.35 0.8	

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## 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

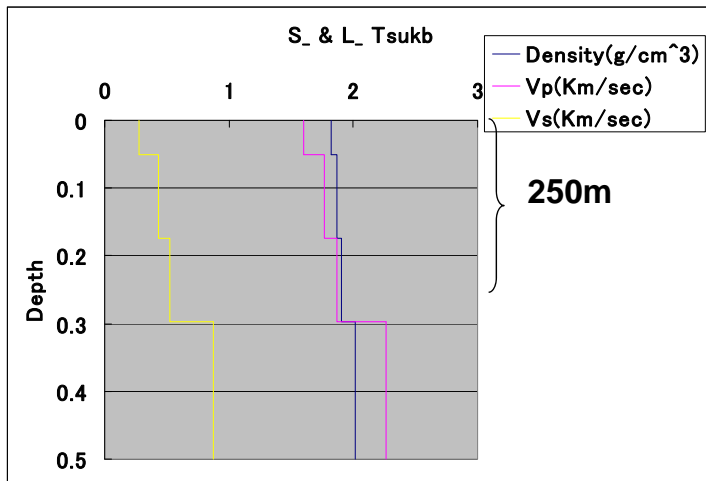


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## 2nd Search Range

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

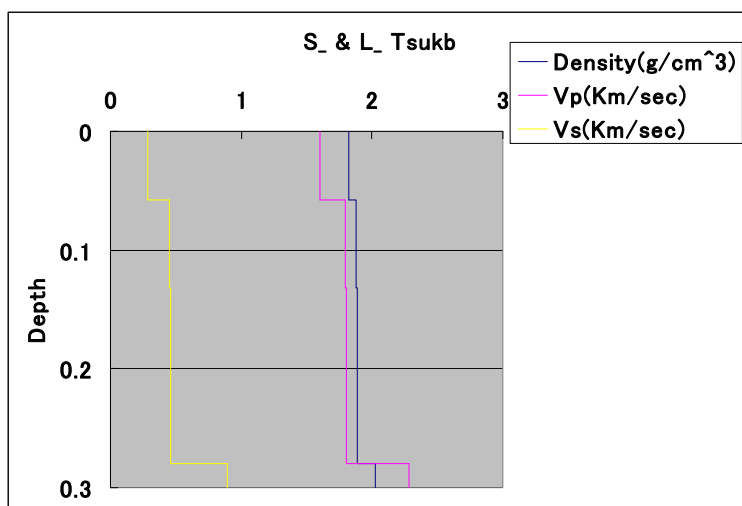


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## 3rd Search Range

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



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## 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 :k_flg,j_flg
0 0 :n_vs,n_th
str_range.dat :File name for the initial velocity model (a25).
vel_model.dat :File name for the observed 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 t0 :Initial Temperature
c a,c :Coefficients for  $T=T_0 \cdot \exp(-c \cdot k \cdot a)$ , 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 temperature change
c j0 :Number of iteration for each temperature
c threshold for conversion
c eps0 : averaged deviation
```

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## disp\_sma1\_2.prm (continuation)

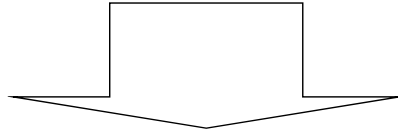
```
c flags for roh and vp
c n_vp : 1=by Kitzunezaki et al(1990),  $vp=1.11 \cdot vs+1.29$ 
c : 0=fixed to the initial values
c n_roh : 1=by Ludwig et al(1970),  $roh=1.2475+0.399 \cdot vp-0.026 \cdot vp^2$ 
c : 0=fixed to the initial values
c flags for output to Display
c ini_flg : Initial Velocity Structure Model 1=yes
c ndsp_flg : Observed Dispersion Relation 1=yes
c n_err : Error at each iteration 1=yes
c k_flg : Missfit at each temp. change 1=yes
c j_flg : Missfit at each iteration 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  
4

:Model (a30)

: 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	



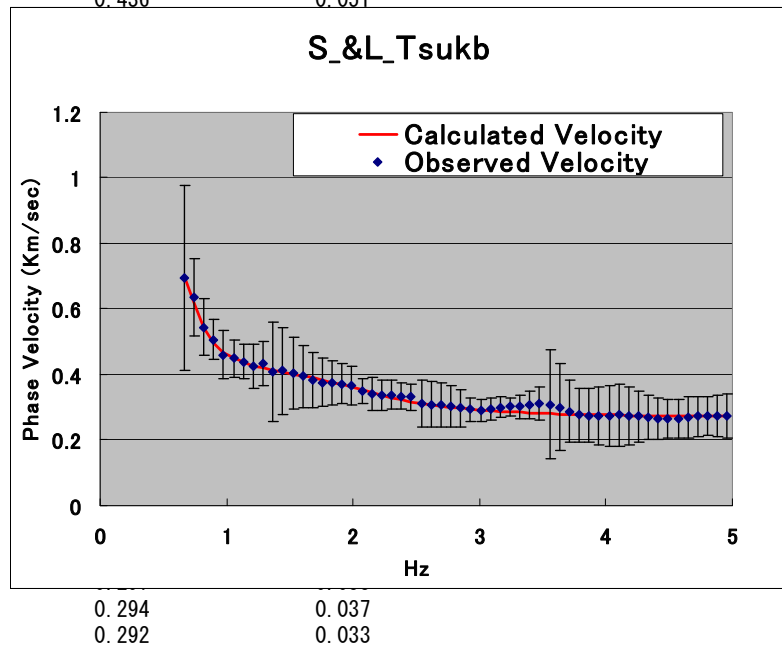
	Thicknes (Km)	Density (g/cm^3)	Vp (Km/sec)	Vs (Km/sec)
1	0.057347	1.820632	1.604092	0.282966
2	0.074116	1.878893	1.791601	0.451893
3	0.147796	1.882880	1.804653	0.463651
4	999.000000	2.021464	2.277869	0.889972

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Comparison of Cal. to Obs.

disp\_cal.dat

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		
3.008	0.291		



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

