BIDO version 3.0

This program is a modification of BIDO2.0 to process microtremor data In BIDO2.0, the cross spectral densities along a circle are weighted and averaged (Note 1). This process is based on an assumption that the microtremor power is uniform everywhere, and then, the analysis results are sensitive to slight differences in either instrumental responses or installation conditions. BIDO3.0 uses complex coherencies (Note 2), instead of cross spectra, to stabilize the analysis results. BIDO3.0 has the following limitations, however:

* It includes array processing methods for vertical component only (i.e., only the vertical SPAC, CCA and nc-CCA methods applicable).

* Preprocess option (e.g., band-pass filtering) is not available.

Except for the above change, the usage and the analysis procedure are the same as those of the BIDO2.0 (BIDO2.02). **The manual of the BIDO2.0** applies for the details.

In brief, the installation for linux/osx is as

cd src

Install_xxx.sh [HIT RETURN KEY]

Before doing this, edit the line including "export FC=gfotran" in the file "Install_xxx.sh" if you use linux or osx and if your laptop does not have the Fortran compiler "gfortran". For Windows 10, on the other hand, the source programs has been precompiled and no preparation (i.e., compiling the program) is needed.

To execute a test run of the program, type as

run.sh   demo/synth_SN100_18mGamR0.8RV0.1N4/param.sh   [HIT RETURN KEY]

The demo data included in the archive are the same as those included in the package of BIDO2.0. After running the program you can see some plots of the analysis results (Figure 1). The plotting software gnuplot is needed to see the analysis results for linux/osx. See **the manual of the BIDO2.0** for the details.

The general usage of this program is as

      1) run.sh [return key]

      2) run.sh paramfile [return key]

       (paramfile will be created automatically by running this file)

Before the analysis, you have to have all necessary input data files, each one containing waveform records from a single sensor and having a simple four-column or two-column format as follows:

    time [s]   z(UD)   x(EW)   y(NS)

or

    time [s]   z(UD)

(A space, a tab, or a comma may be used as a separator.)

There is no rule for naming the input data files, except that all of them should be placed in a single directory. The number of the input data files should be equal to the number of seismic sensors in your microtremor array.

After the data processing, in the same manner of the version 2.0, all analysis results are stored in a folder, named RESULT, which has been created beneath the data folder. The files of the analysis results includes updates from the version 2.0. The naming scheme for output files has been changed from that of the version 2.0. See Appendix 1-1 for descriptions of the individual files.

All the final analysis results are stored in the folder named ave (short for average). See Appendix 1-2 for descriptions of the individual files.

All files in the ave folder are statistical processings of individual analysis results that are stored (but finally deleted to save the HDD capacity) in folders with numerical names like 1, 2 and so forth. The numerically named folders contain not just the analysis results intended for statistical processing and storage in ave, but also a variety of input ad input log files that are normally not used unless you want to do in-depth analysis. See Appendix 1-3 for descriptions of the individual files.

(Note 1) In BIDO2.0, the cross spectral densities along a circle are weighted and averaged because we originally released the analysis code BIDO to demonstrate the performance of a general theory (Cho et al., 2006GJI) that involves the SPAC method as a special case (i.e., the program was developed for a development purpose). As the results, the specification of the data processing workflow of this code is not suited to the calculation of the complex coherencies; the SPAC coefficient in the SPAC method is defined in the Version 2 as a spectral ratio according to the formulation of Aki (1957BERI) (See **Section 5-4 of the manual for Ver. 2.0**).

(Note 2) Actually, BIDO3.0 was developed to examine the performance of the SPAC method for a practical purpose where the SPAC coefficient is defined as the real part of the complex coherency. See Cho and Iwata (2021)* for the details; it also includes the URL of the downloadable field data in a format that you can directly apply BIDO3.0.

*Citing information added on April 2021: Cho, I., & Iwata, T. (2021). Limits and benefits of the spatial autocorrelation microtremor array method due to the incoherent noise, with special reference to the analysis of long wavelength ranges. Journal of Geophysical Research: Solid Earth, 126, e2020JB019850. https://doi.org/10.1029/2020JB019850
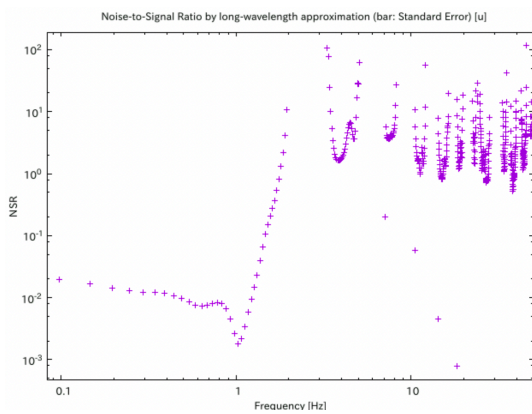
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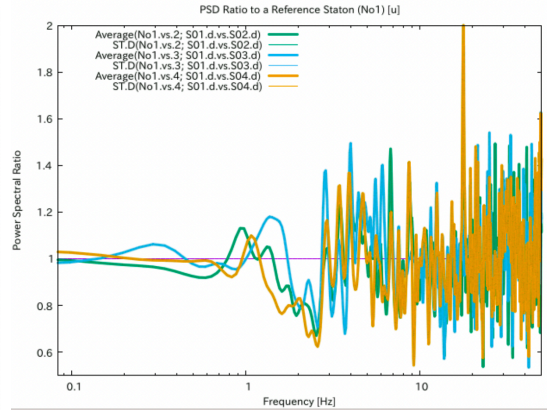
Ikuo Cho (**ikuo-chou@aist.go.jp**)
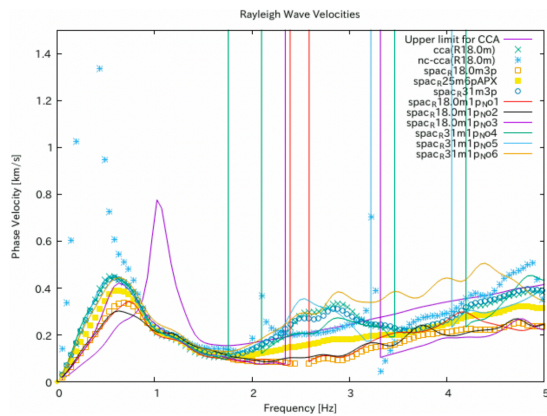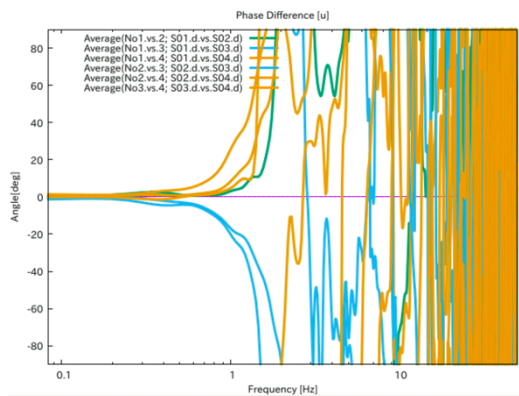
(a) Phase Velocities
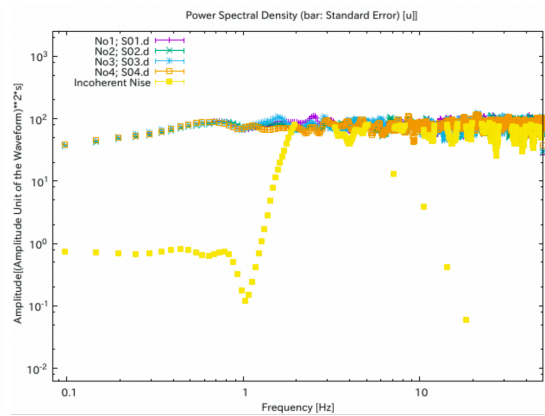
(b) Power Spectral Densities (PSD)

(c) Noise-to-Signal Ratios

(d) Power Spectrral Ratios

(e) Phase differences

Figure 1 Plots obtained by applying BIDO3.0 to the demo data. Note that the frequency range higher than about 2 Hz corresponds to a wavelength range shorter than 2r (r: array radius) so that the phase velocities in Panel (a) should not be interpreted in the frequency range higher than 2 Hz. This limitation comes from the calculation of the phase velocities in BIDO; See **Section 5-4 of the manual for Ver. 2.0**.

Also, note that Panel (a) includes the estimates of the upper limit of the analyzable ranges of the phase velocities and the noise compensated phase velocities (assigned as "nc-CCA"); Panel (b) includes the PSDs of the incoherent noise. These quantities are calculated based on the NSRs presented in Panel (c). The PSDs of the incoherent noise should be interpreted only in the frequency range lower than about 1 Hz. See Cho and Iwata (2020JGR) for details.

Appendix 1-1 Analysis Results (Folder RESULT)

1, 2, ..., *n*, ...   Folder containing analysis results relevant to the *n*th **segment cluster**

ave   Folder containing data files used in gnuplot plots (files with **statistics of the analysis results** in folders 1, 2, ...)

array.png   Plot of the array geometry

center.d   Work file to store data to plot array geometry

circle.d   Work file to store data to plot array geometry

dummy   Used in gnuplot plots. A dummy data file that contains nothing

input.mkcrcle_center.z.d   Input data for the calculation of Fourier coefficients at the center (UD component)

input.mkcrcle_circle.z.d   Input data for the calculation of Fourier coefficients around the circle (UD component)

logfile.mkcrcle_center.z.d Execution log of the program to calculate Fourier coefficients at the center (UD component)

logfile.mkcrcle_circle.z.d   Execution log of the program to calculate Fourier coefficients around the circle (UD component)

message.sh   Work file that contains messages outputted during execution of the calculations plus a number of parameters

input.chk_seism.d   Work (input) file for a program that checks the coordinates of the array data

plot.gnplt   Macro to activate gnuplot (to plot analysis results)

wave.png   Plot of the waveforms

wavplot   Work directory to store data that are decimated to plot waveform data using gnuplot

plot_array.gnplt   Macro to activate gnuplot (to plot array geometry)

plot_wave.gnplt   Macro to activate gnuplot (to plot waveforms)

segment_3c.d   **Segment file** describing which segments were extracted from the three-component measurement data

segment_3c.d.gnpltdat   Work data file for drawing waveform data using gunplot

segment_z.d   **Segment file** describing which segments were extracted from the UD-component measurement data

segment_z.d.gnpltdat   Work data file for drawing waveform data using gunplot

seism.log   Execution log of the program to examine array geometry

Appendix 1-2 Analysis Results (Folder RESULT/ave)

PHASE1u_2u.d   Phase difference [degree] between two data described in the seismfile, which are assigned the numbers 1, 2, ... from top to bottom (see ave.info involved in the same folder for the correspondence between the number and the data). A mean angle is calculated by the vector sum of the data from all data blocks. The letters e, n and u denote the east-west. north-south, and up-down components, respectively.

PSDRATIO1u_2u.d   Power-spectral ratios of two data described in the seismfile, which are assigned the numbers 1, 2, ... from top to bottom (see ave.info involved in the same folder for the correspondence between the number and the data). The letters e, n and u denote the east-west. north-south, and up-down components, respectively.

SD1u_SD1u.d   Power-spectral density function. The data described in the seismfile are assigned the numbers 1, 2, ... from top to bottom (see ave.info involved in the same folder for the correspondence between the number and the data). The letters e, n and u denote the east-west. north-south, and up-down components, respectively.

ave.info   Rough explanation of how the analysis results were averaged

cmax_by_nsr.d   Upper limits of analyzable phase velocities (UD component) determined based on the analysis results of Noise-to-Signal Ratios (NSR)

nsr_cca.lwapx.d   NSRs (UD component) calculated based on the long-wavelength approximation of the CCA and SPAC coefficients

pow_noise.d, pow_singal.d   Power-spectral density of the incoherent noise and the coherent signal (UD component), which are estimated by using SD1u_SD1u.d and nsr_cca.lwapx.d.

spr_cca.d   CCA coefficient.

spr_spac_RXXmYp.d   SPAC coefficient that is defined as the real part of the average complex coherency. "XX" means the radius or the

distance between observation points. "Y" means the number of observation-point pairs to be averaged.

spr_spac_RXXmYp.d.img   Imaginary part of the average complex coherency

spr_spac_RXXmYpAPX.d   Approximated SPAC coefficient when the distances between two observation points are not uniform although the differences are small. "XX" means an average distance between observation points. "Y" means the number of observation-point pairs to be averaged (see Appendix 2).

spr_hv.d   Ratios of the power of horizontal motion (sum of the two horizontal-component powers) to the power of vertical motion

vel_cca.d   Phase velocities of Rayleigh waves according to the CCA method

vel_nc-cca.d Phase velocities of Rayleigh waves according to the nc-CCA method

vel_spac_RXXmYp.d   Phase velocities of Rayleigh waves according to the SPAC method (with the definition of the SPAC coefficient as the real part of the average complex coherency)

vel_spac_RXXmYpAPX.d   Phase velocities of Rayleigh waves corresponding to approximated SPAC coefficients (see the explanation of spr_spac_RXXmYpAPX.d and Appendix 2).

* In the above data files, the frequency, the mean value through all data blocks (i.e., corresponding to alphanumeric directories), the standard deviation and the number of data blocks are laid out in the first, second, third and fourth columns, respectively. The "mean" means an arithmetic mean if not specified. The standard error is calculated by (the third column)/sqrt(the fourth column)

Appendix 1-3 Analysis Results (Folder with alphanumeric names)

infile.estspec.d   Input data for the estimation of spectra (array analysis)

infile.estspec_hv.d   Input data for the estimation of spectra (H/V)

infile.estspec_psd.d Input data for the estimation of spectra (power spectral densities)

logfile.estspec.d   Execution log of the program to estimate spectra (array analysis)

logfile.estspec_hv.d Execution log of the program to estimate spectra (H/V)

logfile.estspec_psd.d   Execution log of the program to estimate spectra (power spectral densities)

seism_coh.log   Logfile describing the exact value of the radius (distance) expression in the SPAC file (e.g., "XXm" of either spr_spac_RXXmYp.d or vel_spac_RXXmYp.d). The first and the second lows correspond to "XXm" and the exact value, respecrively. The nineth row represents "_RXXmYp".

seism_spacapx.log   Logfile describing the approximation condition: "radius_id" is the ID used for the file name; "radius_ave", "radius_std", "radius_cv", "radius_n" are an average radius, standard deviation, coefficient of variations, the number of radiuses averaged.

Appendix 2 Approximated SPAC coefficient when the distances between two observation points are not uniform

Assume that we want to apply the SPAC method but the distances between observation points are not uniform. In this case, an azimuthal average of the SPAC coefficients cannot be calculated in an ordinary sense. However, provided that the differences in the distances are small and the microtremor wavefield is close to isotropic, the azimuthal average of the N SPAC coefficients $\rho(f) = \frac{1}{N} \sum_{i=1}^{N} \rho_i(f)$ can be modeled as the zeroth order Bessel function of the first kind, of which argument is the product of an average distance $r = \frac{1}{N} \sum_{i=1}^{N} r_i$ and the wavenumber $k(f)$. i.e.,

$$\rho(f) = J_0[rk(f)].$$

The above equation makes the estimation of phase velocities more robust than the estimation based on the data from a two-point array only.

(Explanation)
When the microtremor wavefield is close to isotropic, the i-th SPAC coefficient can be approximated as

$$\rho_i(f) = J_0\big(r_i k(f)\big). \quad (1)$$

An average distance between two observation points r and the perturbation from the average value Δr_i are represented as

$$r = \frac{1}{N} \sum_{i=1}^{N} r_i \,, \Delta r_i = r_i - r. \quad (2)$$

An average SPAC coefficient is represented as

$$\rho(f) = \frac{1}{N} \sum_{i=1}^{N} \rho_i(f). \quad (3)$$

Substituting equations (1) and (2) into (3), we have

$$\rho(f) = \frac{1}{N} \sum_{i=1}^{N} J_0[(r + \Delta r_i)k(f)]. \quad (4)$$

Taking the Taylor expansion of the Bessel function $J_0[(r + \Delta r_i)k(f)]$ around r and ignoring the terms higher than the second term, by assuming Δr_i is small, we have

$$J_0[(r + \Delta r_i)k(f)] = J_0[rk(f)] - k(f)J_1[rk(f)]\Delta r_i. \quad (5)$$

Substituting equation (5) into (4) yields

$$\rho(f) = \frac{1}{N}\sum_{i=1}^{N} [J_0[rk(f)] - k(f)J_1[rk(f)]\Delta r_i]$$
$$= \frac{1}{N}\sum_{i=1}^{N} J_0[rk(f)] + \frac{k(f)J_1[rk(f)]}{N}\sum_{i=1}^{N}\Delta r_i$$
$$= J_0[rk(f)]. \quad (6)$$

Thus, we can obtain

$$\rho(f) = J_0[rk(f)],$$

where,

$$\begin{cases} \rho(f) = \dfrac{1}{N}\sum_{i=1}^{N} \rho_i(f), \\ r = \dfrac{1}{N}\sum_{i=1}^{N} r_i. \end{cases}$$