Input files

File name	Content
param.dat	Parameters controlling TRACMT. Lines prefixed with # are recognized as comment lines.
Arbitrary names	Time-series data

Output files

File name	Content
TRACMT.log	Execution logs
TRACMT.cvg	Detained information of computation processes
response_functions.csv	Resultant transfer function estimates and their error estimates
apparent_resistivity_and_phase.csv	Estimates of the apparent resistivity and phase and their error estimates (keyword “OUTPUT_RHOA_PHS” is required)

How to run TRACMT

You need to execute the following command in the directory where input files exist.

```
TRACMT
```

File format of param.dat (1/6)

Keyword	Content	Data type	Option	Default	Example
NUM_OUT	Number of output channels*1)	Positive Integer			NUM_OUT 2
SAMPLING_FREQ	Sampling frequency (Hz)	Positive real number			SAMPLING_FREQ 32
NUM_THREADS	Number of OpenMP threads	Positive integer			NUM_THREADS 4
AZIMUTH	Measurement direction (clockwise angle (deg.) from the north) of all channels including remote reference data	Real numbers			AZIMUTH 0.0 90.0 0.0 90.0 0.0 90.0
ROTATION	Rotation angle (deg.) (positive clockwise) of the coordinate system where transfer functions are estimated from the NS/EW coordinates	Real number		0	ROTATION 30
CAL_FILES	File names used for correcting instrumental calibration*1)	Characters		Calibration is not performed	CAL_FILES hz.cal hx.cal hy.cal hrx.cal hry,cal

*1) For example, when you estimate the impedance tensor from two electric field components and the magnetic field, the number of output channels is two. The file format of the correction file is shown in a subsequent slide.

File format of param.dat (2/6)

Keyword	Content	Data type	Option	Default	Example
PROCEDURE	Transfer function estimation method	Integer	0: Ordinary robust remote reference method 1: RRMS estimator	0	PROCEDURE 0
RRMS	Parameters of RRMS estimator	Detail of this option is described in a subsequent slide			RRMS 1 100 3 0.05 10 16 0.01
MESTIMATORS*1)	M-estimators used in the ordinary robust remote reference method*2)	Two integers for the first and second M-estimators	-1: Iterative re-weighted least square is not performed 0: Huber weight 1: Tukey's bi-weight (Bisquare weight) 2: Thomson weight*3)	0 1	MESTIMATORS 0 1

*1) To use the fast and robust bootstrap method, it is necessary to write the option as "1 -1".

*2) In the ordinary robust remote reference method, iterative re-weighted least square (IRWLS) is performed twice. In the first IRWLS, the scale of the residual magnitude is also updated as well as transfer functions, while the scale parameter is fixed in the second IRWLS.

If you write "-1 -1" in this option, the ordinary least square is performed.

*3) The severe weight function used in Chave & Thomson (1989, 2004)

File format of param.dat (3/6)

Keyword	Content	Data type	Option	Default	Example
ERROR_ESTIMATION	Error estimation method	Integer	0: Parametric approach 1: Fixed-weight bootstrap 2: Ordinary (strict) bootstrap 3: Fast and robust bootstrap 4: Fixed-weight Jackknife 5: Subset deletion Jackknife (Eisel & Egbert, 2001)	1	ERROR_ESTIMATION 1
BOOTSTRAP	Number of bootstrap samples	Positive integer		1000	BOOTSTRAP 1000
PREWHITENING	Detail of this option is described in a subsequent slide	Three integers		Any pre-whitening is NOT performed	PREWHITENING 0 10 5
ROBUST_FILTER	Detail of this option is described in a subsequent slide	Integers		Robust filter is not applied	ROBUST_FILTER 0 10 12 50 10 12 50 10 12 50 10 12 50 10 12 50 10 12 50

File format of param.dat (4/6)

Keyword	Content	Data type	Option	Default	Example
DECIMATION	Decimation interval, length of antialiasing (FIR) filter, and width between the passband and stopband*1) frequency in the logarithmic scale.	Two positive integers and one positive real number		Decimation (down-sampling) is not performed.	DECIMATION 32 100 0.5
HIGH_PASS	Cutoff frequency of high-pass filter (Hz)	Positive real number		HPF is not applied	HIGH_PASS 0.1
LOW_PASS	Cutoff frequency of low-pass filter (Hz)	Positive real number		LPF is not applied	LOW_PASS 0.1
NOTCH	Cutoff frequencies (Hz) following the number of them	Integer and positive real numbers		Notch filters are not applied	NOTCH 6 50 100 150 200 250 300
COHERENCE_CRITERIA	Number of segments used for calculating transfer functions followed by the threshold of squared coherence*1)	Positive integer and non-negative real number		Coherence thresholding is not performed.	COHERENCE_CRITERIA 10 0.3

*1) The stopband frequency is the Nyquist frequency after decimation.

*2) If the squared coherence is lower than the threshold, all segments used for calculating the corresponding transfer functions are excluded in the transfer function estimation.

File format of param.dat (5/6)

Keyword	Content	Data type	Option	Default	Example
ATS_BINARY	Read .ats files of Metronix instruments				ATS_BINARY
MFS_CAL	Coil carburation files of Metronix instruments*2).	Characters and/or real numbers		Calibration is not performed	MFS_CAL 30.0 30.0 MFS06375.TXT MFS06376.TXT MFS06e549.TXT MFS06e576.TXT
MTH5	Read MTH5 files (Peacock et al., 2022)				MTH5
ELOGMT_BINARY	Read .dat files of ELOG-MT				ELOGMT_BINARY
ELOGMT_READ_OPTION	Components that are read from .dat files	Integer	0: E_x, E_y, H_z, H_x, H_y, H_{rx}, H_{ry} 1: E_x, E_y, H_x, H_y, H_{rx}, H_{ry} 2: H_z, H_x, H_y, H_{rx}, H_{ry}	0	ELOGMT_READ_OPTION 0

*1) The file format of the calibration files are shown in a subsequent slide. Carburation files for the remote reference data are also required.

*2) If you write a real number instead of a character, this number is recognized as a dipole length (m) of an electric field channel.

File format of param.dat (6/6)

Keyword	Content	Data type	Option	Default	Example
NUM_SECTION	Number of time-series data files for each channel	Positive Integer			NUM_SECTION 1
SEGMENT	Segments lengths (section lengths) of the overlapped section averaging method and indexes of the Fourier transforms*2)	Positive integers (detail of this option is described in a subsequent slide)			SEGMENT 3 1024 3 2 3 4 512 2 3 4 256 2 3 4
DATA_FILES	File names of time-series data and numbers of data to be read	Detail of this option is described in a subsequent slide			Detail of this option is described in the next slide
MERGE_SECTIONS	Merge time-series of different files into a continuous time-series. (detail of this option is described in a subsequent slide)	Integers.		Merge operation is not performed	MERGE_SECTIONS 2 0 2 3 5
OUTPUT_TIME_SERIES	Output input time-series data to csv files				
OUTPUT_RHOA_PHS	Output apparent resistivity and phase to a csv file in addition to the impedance tensor*1)				
END	End of controlling parameters				END

*1) Apparent resistivity (Ohm-m) is calculated assuming that the units of the electric and magnetic field is mV/km and nT, respectively.

Keyword RRMS

RRMS

Are initial candidate sets of the ISTFs randomly selected for each frequency?

0: No. TFs at the previous (lower) frequency are used as an initial candidate set.

1: Yes.

Number of the initial candidate sets of the ISTFs (positive integer)

Maximum number of iteration of the first parameter updates (positive integer)

Convegence criteria of the first parameter updates (positive real number)

Maximum number of the candidate sets of the second parameter updates (positive integer)

Maximum number of iteration of the second parameter updates (positive integer)

Convegence criteria of the second parameter updates (positive real number)

Default setting:

RRMS
1
100
3
0.05
10
16
0.01

Convegence criteria means the threshold of the change rates of weighted norm of each residual and the robust scale of the Mahalanobis distance.

Keyword PREWHITENING

PREWHITENING

Prewhitening method

-1: Pre-computed AR coefficients are specified

0: Non-robust prewhitening

1: Robust prewhitening

Maximum degrees of the AR model used for prewhitening[1)]

Number of initial candidates (it is used only in the robust prewhitening)

If you do not write this keyword, any pre-whitening is not performed

1) I recommend you use a higher value than five.

Keyword ROBUST_FILTER

ROBUST_FILTER

Are filtered time-series directly used for the transfer function estimation

0: No

1: Yes

Parameters for the 1st channel

The 1st threshold	The 2nd threshold	Maximum number of consecutive replacements

Parameters for the 2nd channel

The 1st threshold	The 2nd threshold	Maximum number of consecutive replacements

⋮

Number of data channels

Recommended setting

ROBUST_FILTER
0
10 12 50
10 12 50
10 12 50
10 12 50
10 12 50
10 12 50

If you do not write this keyword, robust filter is not applied in the prewhitening

Keyword SEGMENT

[NOTE]
- Segment length should be a power of two.
- I recommend you use three or higher as indexes if the prewhitening is performed and otherwise use seven or higher.

SEGMENT

Number of segment lengths

Number of indexes

The 1st segment length	Number of indexes	The 1st index	⋯	The last index
The 2nd segment length	Number of indexes	The 1st index	⋯	The last index
⋮				

Number of segment lengths

Frequency (Hz) for which the transfer function is estimated is determined from the segment length (*L*), index (*i*), and sampling interval (*Δt*), as follows.

$$f = \frac{i}{L\Delta t}$$

For example, the following setting leads to the transfer functions at 0.2344 and 0.3125 (Hz) if the sampling interval is 0.1 (sec).

Segment length	*Number of indexes*	*The 1st index*	*The 2nd index*
128	2	3	4

$$f_1 = \frac{3}{128 \times 0.1} = 0.2344\ (\mathrm{Hz})$$

$$f_2 = \frac{4}{128 \times 0.1} = 0.3125\ (\mathrm{Hz})$$

Keyword DATA_FILES

DATA_FILES

Information of the 1st section

Number of data to be read

File name of time series data

Number of data to be skipped

Parameters for the 1st channel

File name of time series data

Number of data to be skipped

Parameters for the 2nd channel

⋮

Number of channels
(number of input variable + 4)

Information of the 2nd section

⋮

Number of sections
(specified in the keyword
NUM_SECTION)

Keyword MERGE_SECTIONS

MERGE_SECTIONS

Number of total sections after merging

Start section index	End section index
Start section index	End section index
⋮	

Number of total sections after merging

For example, following setting merges the data from the section #0 to the section #3 into a section without gap.

```
MERGE_SECTIONS
1
0 3
```

Format of the files for correcting instrumental characteristics

Constant multiplication factor (A)		
Number of frequencies		
Frequency (Hz)	Real part of the correction function $C(f)$	Imaginary part of the correction function $C(f)$
Frequency (Hz)	Real part of the correction function $C(f)$	Imaginary part of the correction function $C(f)$
	⋮	

$\}$ Number of frequencies

Instrumental characteristics are corrected in the frequency domain by multiplying *A* and *C(f)*.

The correction function is interpolated for the frequency at which *C(f)* is not specified.

$$A \times C(f_1)E_x(f_1) \rightarrow E_x(f_1)$$

$$A \times C(f_2)E_x(f_2) \rightarrow E_x(f_2)$$

$$\cdots$$

File format of output file

The resultant transfer functions are outputted to csv files with headers such as “resp_real_0_2”, “resp_imag_0_2”, “coherence_0_2+3”, and “dresp_0_2”.

The number of header indicates index of channels. For example,

	Channel indexes							
	0	1	2	3	4	5	6	
	Ex	*Ey*	*Hz*	*Hx*	*Hy*	*Hrx*	*Hry*	(Number of output variables is 3)
Variables	*Ex*	*Ey*	*Hx*	*Hy*	*Hrx*	*Hry*		(Number of output variables is 2)
	Hz	*Hx*	*Hy*	*Hrx*	*Hry*			(Number of output variables is 1)

resp_real_i_j: Real parts of the transfer function relating channel #i to channel #j

resp_imag_i_j : Imaginary parts of the transfer function relating channel #i to channel #j

coherence_i_*: Squared coherence for channel#i

dresp_i_j: Standard error for the transfer function relating channel #i to channel #j

For example, if the output variables are Ex and Ey, resp_real_0_3 and resp_imag_0_3 are real and imaginary components of the Z_{xy} component of the impedance tensor.

$$\begin{array}{c} 0 \\ 1 \end{array} \begin{pmatrix} E_x \\ E_y \end{pmatrix} = \begin{array}{cc} \text{0\_2} & \text{0\_3} \\ \multicolumn{2}{c}{\begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix}} \\ \text{1\_2} & \text{1\_3} \end{array} \begin{pmatrix} H_x \\ H_y \end{pmatrix} \begin{array}{c} 2 \\ 3 \end{array}$$

How to read .ats files of Metronix instruments

```
ATS_BINARY
MFS_CAL
30.0
30.0
MFS06375.TXT
MFS06376.TXT
MFS06e549.TXT
MFS06e576.TXT
DATA_FILES
691200
063_V01_C00_R008_TEx_BL_32H.ats
0
063_V01_C01_R008_TEy_BL_32H.ats
0
063_V01_C02_R008_THx_BL_32H.ats
0
063_V01_C03_R008_THy_BL_32H.ats
0
382_V01_C02_R069_THx_BL_32H.ats
0
382_V01_C03_R069_THy_BL_32H.ats
0
```

If you write a real number instead of a character, this number is recognized as a dipole length (km) of an electric field channel, and the data at the channel is divided by the real number in the calibration stage.

You can write .ats file directly if you use the keyword “ATS_BINARY”.

File extensions should be ‘ats’.

How to read MTH5 files

MTH5
CAL_FILES
....

You need to prepare calibration files for each channel following the format written in Page 16.

DATA_FILES
750000
sample1.mth5 /schedule_01/ex
0
sample1.mth5 /schedule_01/ey
0
sample1.mth5 /schedule_01/hx
0
sample1.mth5 /schedule_01/hy
0
sample2.mth5 /schedule_01/hx
150000
sample2.mth5 /schedule_01/hy
150000

Names of MTH5 files

Group names of each channel

File extensions should be ‘mth5’.

How to read .dat files of ELOG-MT

ELOGMT_BINARY

ELOGMT_READ_OPTION

1

DATA_FILES

115200

D:Site1/20221023/20221023-010000_32Hz.dat

0

D:Site1/20221023/20221023-010000_32Hz.dat

0

D:Site1/20221023/20221023-010000_32Hz.dat

0

D:Site1/20221023/20221023-010000_32Hz.dat

0

D:Site2/20221023/20221023-010000_32Hz.dat

0

D:Site2/20221023/20221023-010000_32Hz.dat

0

0: E_x, E_y, H_z, H_x, H_y, H_{rx}, H_{ry}
1: E_x, E_y, H_x, H_y, H_{rx}, H_{ry}
2: H_z, H_x, H_y, H_{rx}, H_{ry}

You can write .dat file directly if you use the keyword "ELOGMT_BINARY".

If your compiler supports C++17, you can use the following function by activating preprocessor "_USE_FILESYSTEM" in compiling.

If you write "*.dat" under the directory name, all data files (of corresponding sampling frequency) under the directory are automatically read.

Tradeoff between robustness and calculation speed

There are tradeoffs between robustness/accuracy and calculation speed

Robust / Accurate

Prewhitening	No prewhitening	Non-robust prewhitening	Robust prewhitening
Transfer function estimation	Non-robust remote reference	Ordinary robust remote reference	RRMS estimator
Uncertainty estimation	Parametric	Fixed-weight bootstrap	Ordinary (strict) bootstrap

← Fast and robust bootstrap*1) →

Fast

*1) The fast and robust bootstrap method can provide standard errors comparable to those obtained by the ordinary bootstrap method as fast as the fixed-weight bootstrap method unless the uncertainty of the transfer function is significantly large.

Example of parameter setting (1) (Fast but not robust case)

PROCEDURE

0

MESTIMATORS

-1

-1

ERROR_ESTIMATION

0

Non-robust remote reference

No prewhitening

Parametric error estimation

Example of parameter setting (2) (Intermediate case)

PROCEDURE
0
MESTIMATORS
0
1

Ordinary robust remote reference using the M-estimator

PREWHITENING
0
10
5

Non-robust prewhitening

ERROR_ESTIMATION
1

Fixed-weight bootstrap

Example of parameter setting (3) (robust but not efficient case)

PROCEDURE	RRMS estimator
1	
PREWHITENING	
1	
10	Robust prewhitening
5	
ERROR_ESTIMATION	
3	Fast and robust bootstrap