# 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<br>2                                   |
| SAMPLING_FREQ | Sampling frequency (Hz)   | Positive real number |        |                              | SAMPLING_FREQ<br>32                            |
| NUM_THREADS   | Number of OpenMP threads  | Positive integer     |        |                              | NUM_THREADS<br>4                               |
| AZIMUTH       | Measurement direction<br>(clockwise angle (deg.) from the<br>north) of all channels including<br>remote reference data                | Real numbers         |        |                              | AZIMUTH<br>0.0 90.0<br>0.0 90.0<br>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<br>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 |

<sup>\*1)</sup> 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  | Ordinary robust remote reference method     RRMS estimator   | 0       | PROCEDURE<br>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       | <ul> <li>-1: Iterative re-weighted least square is not performed</li> <li>0: Huber weight</li> <li>1: Tukey's bi-weight (Bisquare weight)</li> <li>2: Thomson weight*3)</li> </ul> | 0 1     | MESTIMATORS<br>0 1           |

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

<sup>\*2)</sup> 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.

<sup>\*3)</sup> 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<br>1000  |
| PREWHITENING     | Detail of this option is described in a subsequent slide | Three integers   |  | Any pre-<br>whitening<br>is NOT<br>performed | PREWHITENING<br>0<br>10<br>5   |
| ROBUST_FILTER    | Detail of this option is described in a subsequent slide | Integers         |  | Robust<br>filter is not<br>applied           | ROBUST_FILTER 0 10 12 50 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<br>(down-sampling)<br>is not performed. | DECIMATION<br>32<br>100<br>0.5       |
| HIGH_PASS          | Cutoff frequency of high-pass filter (Hz)  | Positive real number                                |        | HPF is not applied                                 | HIGH_PASS<br>0.1                     |
| LOW_PASS           | Cutoff frequency of low-pass filter (Hz)   | Positive real number                                |        | LPF is not applied                                 | LOW_PASS<br>0.1                      |
| NOTCH              | Cutoff frequencies (Hz) following the number of them   | Integer and positive real numbers                   |        | Notch filters are not applied                      | NOTCH<br>6<br>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<br>and non-negative<br>real number |        | Coherence<br>thresholding is<br>not performed.     | COHERENCE_CRITERIA<br>10<br>0.3      |

<sup>\*1)</sup> The stopband frequency is the Nyquist frequency after decimation.

<sup>\*2)</sup> 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<br>Metronix<br>instruments      |                                      |  |                              | ATS_BINARY  |
| MFS_CAL            | Coil carburation files of Metronix instruments*2). | Characters<br>and/or real<br>numbers |  | Calibration is not performed | MFS_CAL<br>30.0<br>30.0<br>MFS06375.TXT<br>MFS06376.TXT<br>MFS06e549.TXT<br>MFS06e576.TXT |
| MTH5               | Read MTH5 files<br>(Peacock et al.,<br>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 <sub>x</sub> , E <sub>y</sub> , H <sub>z</sub> , H <sub>x</sub> , H <sub>y</sub> , H <sub>rx</sub> , H <sub>ry</sub> 1: E <sub>x</sub> , E <sub>y</sub> , H <sub>x</sub> , H <sub>y</sub> , H <sub>rx</sub> , H <sub>ry</sub> 2: H <sub>z</sub> , H <sub>x</sub> , H <sub>y</sub> , H <sub>rx</sub> , H <sub>ry</sub> | 0                            | ELOGMT_READ_OPTION<br>0   |

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

<sup>\*2)</sup> 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<br>1                                       |
| SEGMENT            | Segments lengths (section lengths) of the overlapped section averaging method and indexes of the Fourier transforms*2)         | Positive integers<br>(detail of this option<br>is described in a<br>subsequent slide) |        |   | SEGMENT<br>3<br>1024 3 2 3 4<br>512 2 3 4<br>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<br>operation<br>is not<br>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  |

<sup>\*1)</sup> 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)

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

#### Default setting:

RRMS

1

100

3

0.05

10

16

0.01

### **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<sup>1)</sup>

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 Recommended setting Are filtered time-series directly used for the transfer function estimation ROBUST FILTER 0: No 10 12 50 1: Yes 10 12 50 10 12 50 Parameters for the 1<sup>st</sup> channel 10 12 50 Maximum number of 10 12 50 The 1st threshold The 2<sup>nd</sup> threshold consecutive replacements 10 12 50 Parameters for the 2<sup>nd</sup> channel Number of data channels Maximum number of The 1st threshold The 2<sup>nd</sup> threshold consecutive replacements

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

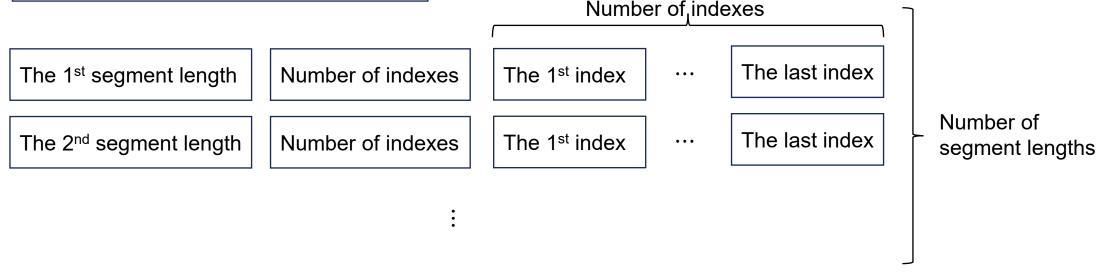
### **Keyword SEGMENT**

#### **SEGMENT**

Number of segment lengths

[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.



Frequency (Hz) for which the transfer function is estimated is determined from the segment length (L), index (i), and sampling interval ( $\Delta t$ ), 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 1<sup>st</sup> index The 2<sup>nd</sup> index 
$$f_1 = \frac{3}{128 \times 0.1} = 0.2344 \text{ (Hz)}$$
128 2 3 4  $f_2 = \frac{4}{128 \times 0.1} = 0.3125 \text{ (Hz)}$ 

### **Keyword DATA\_FILES**

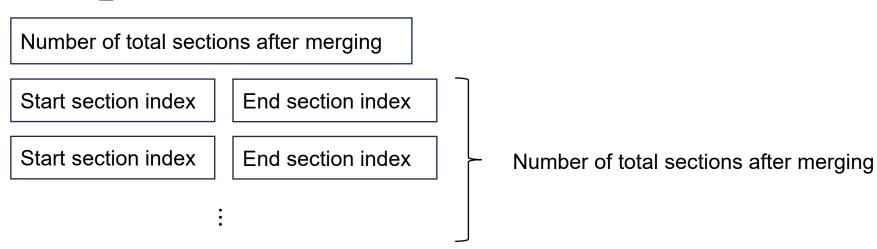
### DATA\_FILES

Information of the 1st section Number of data to be read File name of time series data Parameters for the 1<sup>st</sup> channel Number of channels (number of input variable Number of data to be skipped File name of time series data Parameters for the 2<sup>nd</sup> channel Number of data to be skipped Information of the 2<sup>nd</sup> section

Number of sections (specified in the keyword NUM\_SECTION)

### **Keyword MERGE\_SECTIONS**

### MERGE\_SECTIONS



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.

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

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

• • •

### 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 | Нх | Ну  | Hrx | Hry |     | (Number of output variables is 2) |
|                 | Hz | Нх | Ну | 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.

$$\begin{array}{ccc}
0 & 2 & 0 & 3 \\
0 & E_{x} \\
1 & E_{y}
\end{array} = \begin{pmatrix}
Z_{xx} & Z_{xy} \\
Z_{yx} & Z_{yy}
\end{pmatrix} \begin{pmatrix}
H_{x} \\
H_{y}
\end{pmatrix} \begin{pmatrix}
2 \\
H_{y}
\end{pmatrix} \begin{pmatrix}
3 \\
3 \\
1 & 2
\end{pmatrix}$$

### How to read .ats files of Metronix instruments

```
ATS_BINARY
MFS_CAL
30.0
30.0
                           If you write a real number instead of a character, this number is recognized as a
MFS06375.TXT
                           dipole length (km) of an electric field channel, and the data at the channel is divided
MFS06376.TXT
                           by the real number in the calibration stage.
MFS06e549.TXT
MFS06e576.TXT
DATA FILES
691200
063 V01 C00 R008 TEx BL 32H.ats
063 V01_C01_R008_TEy_BL_32H.ats
063 V01 C02 R008 THx BL 32H.ats
                                        You can write .ats file directly if you use the keyword "ATS BINARY".
0
063 V01 C03 R008 THy BL 32H.ats
0
382 V01 C02 R069 THx BL 32H.ats
382 V01 C03 R069 THy BL 32H.ats
0
              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
              /schedule_01/hy
sample2.mth5
150000
```

Names of MTH5 files

Group names of each channel

File extensions should be 'mth5'.

### How to read .dat files of ELOG-MT

### 0: $E_x$ , $E_y$ , $H_z$ , $H_x$ , $H_y$ , $H_{rx}$ , $H_{ry}$ **ELOGMT\_BINARY** $\longrightarrow 1: E_x, E_y, H_x, H_y, H_{rx}, H_{ry}$ **ELOGMT\_READ\_OPTION** 2: $H_z$ , $H_x$ , $H_y$ , $H_{rx}$ , $H_{ry}$ 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

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.

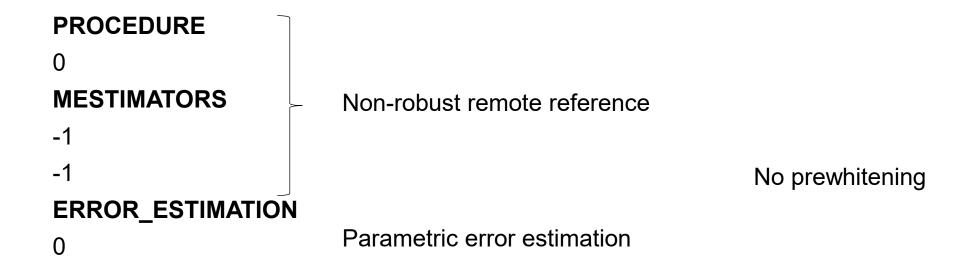
### Tradeoff between robustness and calculation speed

There are tradeoffs between robustness/accuracy and calculation speed

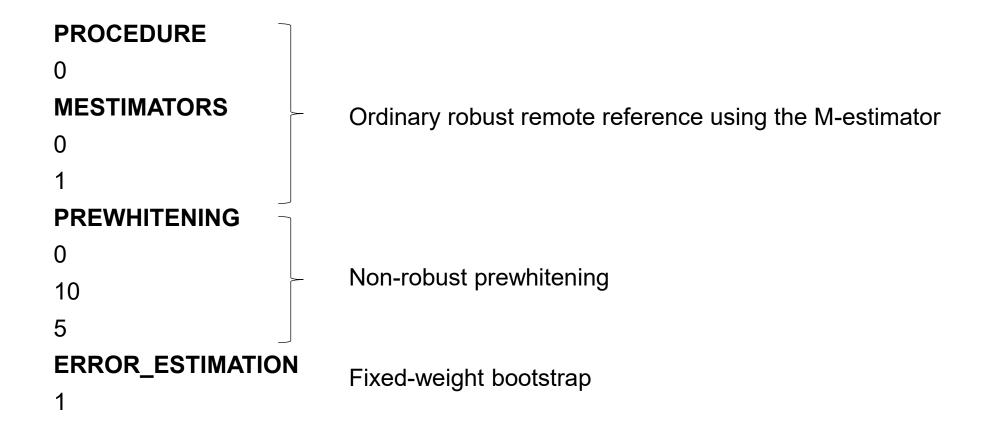
|                              |                             |  | Robust / Accurate           |
|------------------------------|-----------------------------|--|-----------------------------|
| Prewhitening                 | No prewhitening             | Non-robust prewhitening                | Robust prewhitening         |
| Transfer function estimation | Non-robust remote reference | Ordinary robust remote reference       | RRMS estimator              |
| Uncertainty estimation       | Parametric Parametric       | Fixed-weight bootstrap  Fast and robus | Ordinary (strict) bootstrap |
|                              | Fast                        |  |                             |

<sup>\*1)</sup> 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)**



### **Example of parameter setting (2) (Intermediate case)**



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

