How to use FEMTIC

1. Serial calculation

1) Copy all input files to a work directory.
2) Write ‘1‘ below ‘NUM_THREADS‘ in ‘control.dat‘.
3) In the work directory, execute the following command.

```
femtic
```

2. Parallel calculation only using MPI

1) Copy all input files to a work directory.
2) Write ‘1‘ below ‘NUM_THREADS‘ in ‘control.dat‘.
3) In the work directory, execute the following command.

```
mpiexec –n [Number of MPI processes] femtic
```

3. Parallel calculation only using OpenMP

1) Copy all input files to a work directory.
2) Write number of threads below ‘NUM_THREADS‘ in ‘control.dat‘.

   < Example >

```
NUM_THREADS
4
```

3) In the work directory, execute the following command.

```
femtic
```

4. Hybrid MPI/OpenMP parallel calculation

1) Copy all input files to a work directory.
2) Write number of threads below ‘NUM_THREADS‘ in ‘control.dat‘.

   < Example >

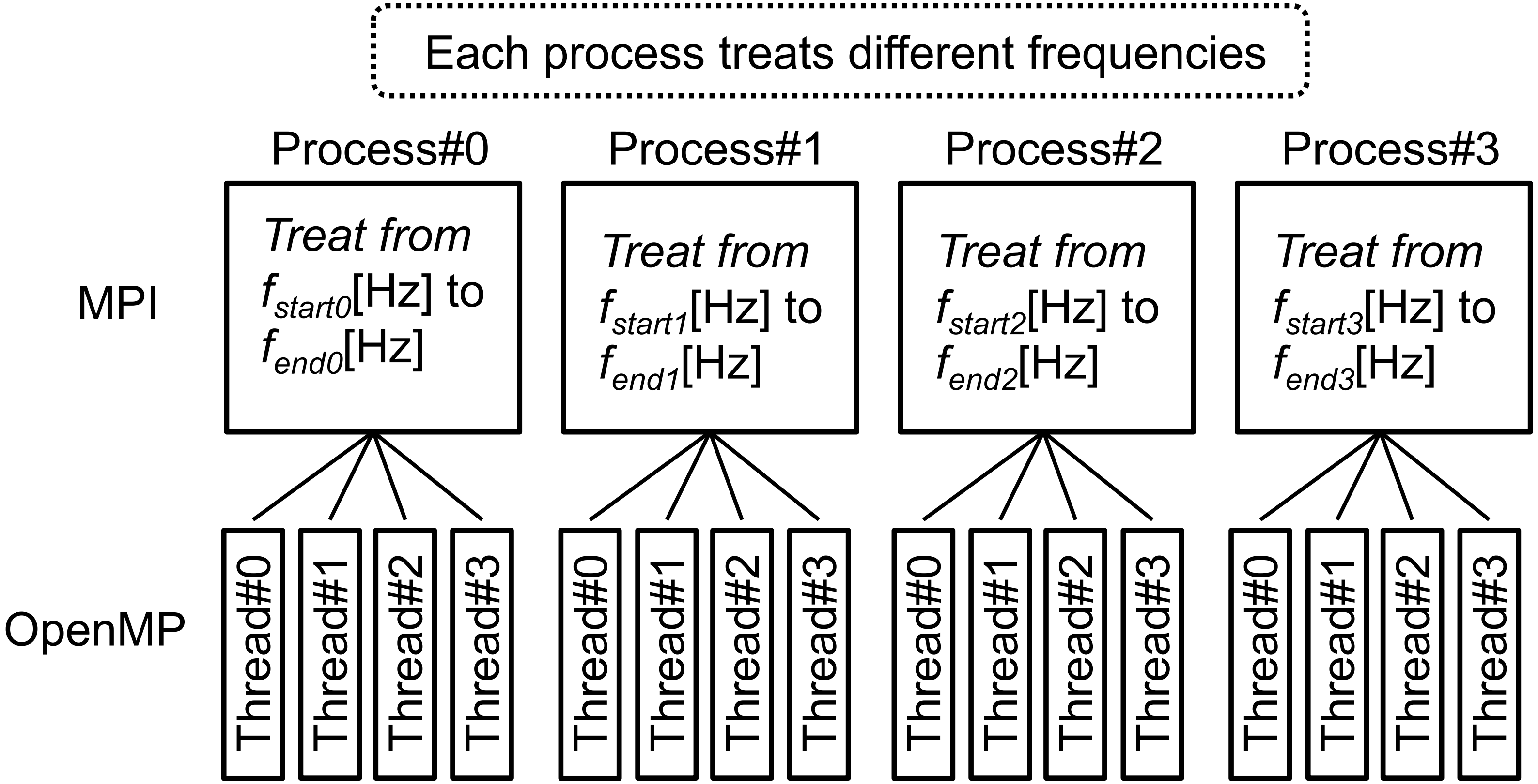
```
NUM_THREADS
4
```

1) In the work directory, execute the following command.

```
mpiexec –n [Number of MPI processes] femtic
```

OpenMP-MPI hybrid parallelization

OpenMP-MPI Hybrid parallelization speed up the forward and inversion calculation.



Each process treats different frequencies

	Process#0	Process#1	Process#2	Process#3
MPI	*Treat from* f_{start0}[Hz] to f_{end0}[Hz]	*Treat from* f_{start1}[Hz] to f_{end1}[Hz]	*Treat from* f_{start2}[Hz] to f_{end2}[Hz]	*Treat from* f_{start3}[Hz] to f_{end3}[Hz]
OpenMP	Thread#0 Thread#1 Thread#2 Thread#3	Thread#0 Thread#1 Thread#2 Thread#3	Thread#0 Thread#1 Thread#2 Thread#3	Thread#0 Thread#1 Thread#2 Thread#3

Following procedure are performed with multi-thread

- Making roughening matrix, Making coefficient matrix
- Making sensitivity matrix, etc

Input files

File name	Content
control.dat	Parameters controlling FEMTIC
mesh.dat	Data of computational mesh
resistivity_block_iter[Iter#].dat	Data of parameter cells and initial resistivity values
observe.dat	Observation data
distortion_iter[Iter#].dat	Initial parameters of galvanic distortion

In the file names, [Iter#] indicates the start number of the iteration.
The start number of the iteration can be specified in ‘ITERATION’ data in ‘control.dat’.

File format of control.dat (1/9)

This file contains the parameters controlling FEMTIC.

Keyword	Content	Data type	Option	Default	Example
MESH_TYPE	Type of element	Integer (0 or 1)	0: Brick hexahedral element 1: Tetrahedral element 2: Deformed non-conforming hexahedral element	0	MESH_TYPE 1
INV_METHOD	Type of inversion method	Integer (0 or 1)	0: Model space method 1: Data space method	0	INV_METHOD 0
DATA_SPACE_METHOD	Type of data-space method	Integer (1 or 2)	1: Inverse of roughening matrix ***R*** is used in the data-space method 2: Inverse of $\boldsymbol{R}^T\boldsymbol{R}$ matrix is used the in data-space method	1	DATA_SPACE_METHOD 1
NUM_THREADS	Number of threads	Integer greater than or equal to 1		1	NUM_THREADS 4
FWD_SOLVER	Mode of direct sparse solver *1)	Integer (0, 1 or 2)	0: In-core mode 1: Out-of-core mode is selected when the amount of the memory required by the direct solver is larger than that specified below 'MEM_LIMIT'; otherwise in-core mode is selected. 2: Out-of-core mode.	0	FWD_SOLVER 0

*1) In the in-core mode, all information required by the direct solver is stored in memory. On the other hand, in the out-of-core mode, some of the information are stored to and read from temporary data files at hard disk. Computational speed of the in-core mode is much higher than that of the out-of-core mode. However, the in-core mode requires much more memory than the out-of-core mode.

Type of element

1. Brick hexahedral element

   Topography/bathymetry cannot be incorporated.

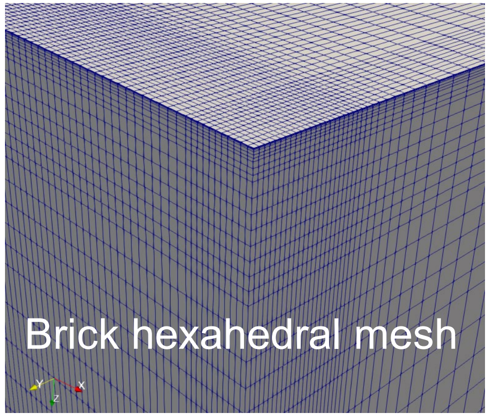
2. Tetrahedral element

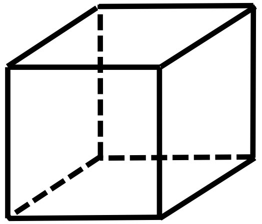
3. Non-conforming deformed hexahedral mesh

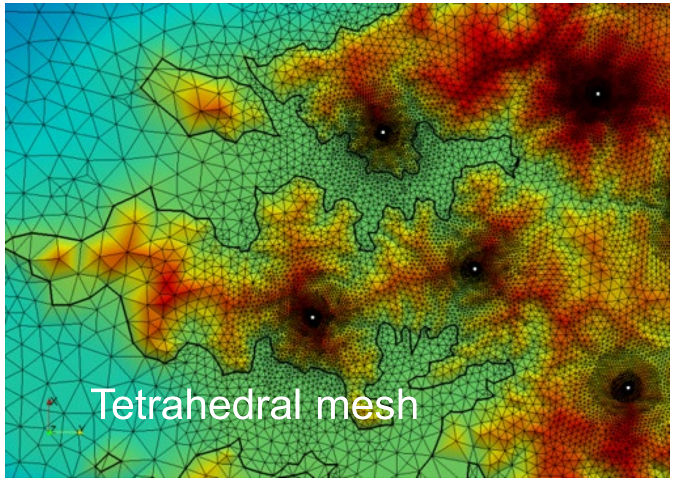
   Discretization method of non-conforming deformed hexahedral mesh is based on that of Grayver & Burg (2014).

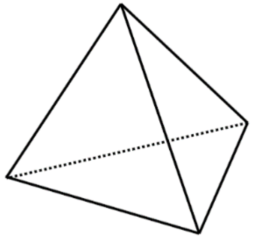
   In FEMTIC, the division number of one side can be double compared to the other side only in the horizontal direction.

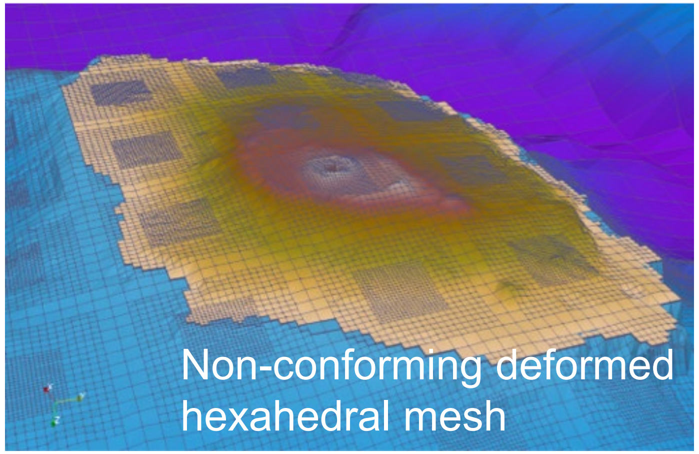
Grayver, a. V., & Burg, M. (2014). Robust and scalable 3-D geo-electromagnetic modelling approach using the finite element method. Geophysical Journal International. https://doi.org/10.1093/gji/ggu119

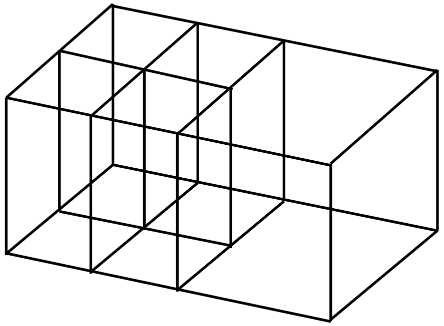

Brick hexahedral mesh


Brick hexahedral element


Tetrahedral mesh


Tetrahedral element


Non-conforming deformed hexahedral mesh


Non-conforming deformed hexahedral element

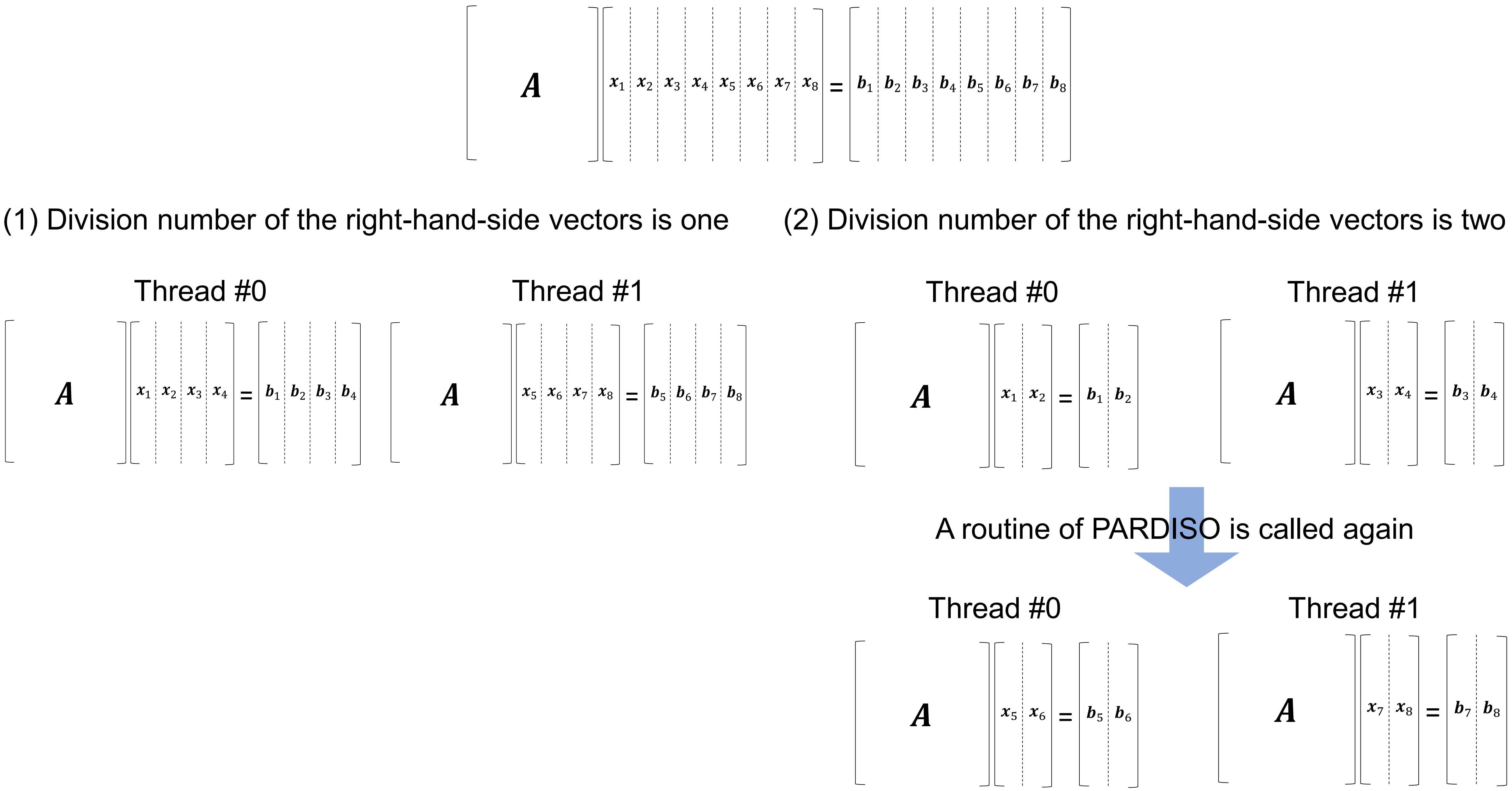
File format of control.dat (2/9)

Keyword	Content	Data type	Option	Default	Example
MEM_LIMIT	The maximum amount of memory (in MB) for direct sparse solver	Real number greater than 0		3000(MB)	MEM_LIMIT 3000
DIV_NUM_RHS_FWD	Division number of the right-hand-side vectors of the linear equation solved for the calculation of sensitivity matrix *1)	Integer greater than or equal to 1		1	DIV_NUM_RHS_FWD 1
DIV_NUM_RHS_INV	Division number of the right-hand-side vectors of the linear equation solved for the calculation of the updates of model parameters. This option is used only when the data-space method is selected *2)	Integer greater than or equal to 1		1	DIV_NUM_RHS_INV 1

*1) In calculating sensitivity matrix, a linear equation with multiple right-hand-sides is solved. When division number of the right-hand-side vectors is one, a routine of PARDISO is called one time to solve the linear equation. On the other hand, when the division number is more than one, that routine is called the specified times and the number of right-hand-side vectors at each time is inversely proportional to the division number as shown in the next slide. In general, the smaller the division number becomes, the faster the speed for solving a linear equation becomes. However, the smaller the division number is, the more memory is required.

*2) When the data-space method is used, a linear equation with multiple right-hand-sides is solved for the calculation of the updates of model parameters. When division number of the right-hand-side vectors is one, a routine of PARDISO is called one time to solve the linear equation. On the other hand, when the division number is more than one, that routine is called the specified times and the number of right-hand-side vectors at each time is inversely proportional to the division number as shown in the next slide. In general, the smaller the division number becomes, the faster the speed for solving a linear equation becomes. However, the smaller the division number is, the more memory is required.

Linear equation to be solved



$$\boldsymbol{A}\begin{bmatrix} \boldsymbol{x}_1 & \boldsymbol{x}_2 & \boldsymbol{x}_3 & \boldsymbol{x}_4 & \boldsymbol{x}_5 & \boldsymbol{x}_6 & \boldsymbol{x}_7 & \boldsymbol{x}_8 \end{bmatrix} = \begin{bmatrix} \boldsymbol{b}_1 & \boldsymbol{b}_2 & \boldsymbol{b}_3 & \boldsymbol{b}_4 & \boldsymbol{b}_5 & \boldsymbol{b}_6 & \boldsymbol{b}_7 & \boldsymbol{b}_8 \end{bmatrix}$$

(1) Division number of the right-hand-side vectors is one

Thread #0

$$\boldsymbol{A}\begin{bmatrix} \boldsymbol{x}_1 & \boldsymbol{x}_2 & \boldsymbol{x}_3 & \boldsymbol{x}_4 \end{bmatrix} = \begin{bmatrix} \boldsymbol{b}_1 & \boldsymbol{b}_2 & \boldsymbol{b}_3 & \boldsymbol{b}_4 \end{bmatrix}$$

Thread #1

$$\boldsymbol{A}\begin{bmatrix} \boldsymbol{x}_5 & \boldsymbol{x}_6 & \boldsymbol{x}_7 & \boldsymbol{x}_8 \end{bmatrix} = \begin{bmatrix} \boldsymbol{b}_5 & \boldsymbol{b}_6 & \boldsymbol{b}_7 & \boldsymbol{b}_8 \end{bmatrix}$$

(2) Division number of the right-hand-side vectors is two

Thread #0

$$\boldsymbol{A}\begin{bmatrix} \boldsymbol{x}_1 & \boldsymbol{x}_2 \end{bmatrix} = \begin{bmatrix} \boldsymbol{b}_1 & \boldsymbol{b}_2 \end{bmatrix}$$

Thread #1

$$\boldsymbol{A}\begin{bmatrix} \boldsymbol{x}_3 & \boldsymbol{x}_4 \end{bmatrix} = \begin{bmatrix} \boldsymbol{b}_3 & \boldsymbol{b}_4 \end{bmatrix}$$

A routine of PARDISO is called again

Thread #0

$$\boldsymbol{A}\begin{bmatrix} \boldsymbol{x}_5 & \boldsymbol{x}_6 \end{bmatrix} = \begin{bmatrix} \boldsymbol{b}_5 & \boldsymbol{b}_6 \end{bmatrix}$$

Thread #1

$$\boldsymbol{A}\begin{bmatrix} \boldsymbol{x}_7 & \boldsymbol{x}_8 \end{bmatrix} = \begin{bmatrix} \boldsymbol{b}_7 & \boldsymbol{b}_8 \end{bmatrix}$$

File format of control.dat (3/9)

Keyword	Content	Data type	Option	Default	Example
ELEC_FIELD	Type of the electric field used to calculate response functions	Integer (0, 1 or -1)	0: Horizontal electric field 1: Tangential electric field -1: Type of the electric field of each station is individually selected *2)	0	ELEC_FIELD 0
OWNER_ELEMENT	Type of owner element *1) of observation stations	Integer (0, 1 or -1)	0: Downward element 1: Upward element -1: Type of owner element of each station is individually selected *2)	0	OWNER_ELEMENT 0
RESISTIVITY_BOUNDS	Type of the method limiting subsurface resistivity to be estimated	Integer (0 or 1)	0: When a resistivity value is exceeds the upper limit or become less than the lower limit, the resistivity value is forced to be the upper limit or the lower limit, respectively. 1: The method proposed by Kim and Kim (2010) *3) is used.	0	RESISTIVITY_BOUNDS 0

*1) Owner element denotes the element in which the electric field and magnetic field of the observation station are interpolated.

*2) When this option is selected, you need to specify the type of the electric field and/or the owner element for each station in ‘observe.dat’.

*3) The method is described in detail in the next slide.

Kim, H. J., & Kim, Y. (2010). A unified transformation function for lower and upper bounding constraints on model parameters in electrical and electromagnetic inversion. Journal of Geophysics and Engineering, 8(1), 21–26. https://doi.org/10.1088/1742-2132/8/1/004

$$x = \frac{1}{n} ln\left(\frac{m - m_{min}}{m_{max} - m}\right)$$

$$m = log_{10}(\rho)$$
$$m_{min} = log_{10}(\rho_{min})$$
$$m_{max} = log_{10}(\rho_{max})$$

ρ : Resistivity (Ωm)
ρ_{min}: Lower limit of resistivity (Ωm)
ρ_{max}: Upper limit of resistivity (Ωm)

In the method proposed by Kim and Kim (2010), the range of resistivity is constrained by the above equation and parameter x.

Updates of parameter x (δx) is calculated by the following equation from the update of the common logarithm of resistivity (δm).

$$\delta x = \frac{\partial x}{\partial m}\delta m = \frac{m_{max} - m_{min}}{n(m_{max} - m)(m - m_{min})}\delta m$$

Next, the new resistivity is calculated from the previous values of x (x_{pre}) and δx by the equation below.

$$\rho = 10^m$$

$$m = \frac{m_{max} - m_{min}}{2}\tanh\left(\frac{nx}{2}\right) + \frac{m_{min} + m_{max}}{2} = \frac{m_{max} - m_{min}}{2}\tanh\left(\frac{n\left(x_{pre} + \delta x\right)}{2}\right) + \frac{m_{min} + m_{max}}{2}$$

Kim, H. J., & Kim, Y. (2010). A unified transformation function for lower and upper bounding constraints on model parameters in electrical and electromagnetic inversion. *Journal of Geophysics and Engineering*, *8*(1), 21–26. https://doi.org/10.1088/1742-2132/8/1/004

File format of control.dat (4/9)

Keyword	Content	Data type	Option	Default	Example
SMALL_VALUE	A small positive value used to regularize roughening matrix (Usui et al., 2017). This option is necessary only when the data-space method is selected.	Positive real number			SMALL_VALUE 1.0e-4
OUTPUT_PARAM	Number of output variables	Integer greater than or equal to 0			OUTPUT_PARAM 2 0 4
	Output variables for the visualization with ParaView *1)	Integer(s)			
OFILE_TYPE	Format of output file for ParaView	Integer (0 or 1)	0: VTK file format (ASCII) 1: Ensight Gold file format (binary)	1	OFILE_TYPE 1
MOVE_OBS_LOC	When you write this keyword, observation station is forced to be located at the center of the element face				MOVE_OBS_LOC

*1) Detail of this option is described in the next slide.

Format about the keyword ‘OUTPUT_PARAM’

Under the keyword, you write the number of output variables first.

Following the number, you need to write the index numbers of the variables needed.

The variables you selected are outputted by VTK file format (ASCII) or Ensight Gold file format (binary) depending on the setting of ‘OFILE_TYPE’.

The output files can be read and visualized by ParaView.

<Example>

By the following setting, the resistivity and sensitivity are only outputted.

```
OUTPUT_PARAM
2
0 4
```

Output file names of Ensight Gold file format

Index	Variable type	Output file name
0	Resistivity	Resistivity.iter[Iter#]
1	Electric field	ReE_Freq[Freq#]_ExPol.iter[Iter#] ImE_Freq[Freq#]_ExPol.iter[Iter#] ReE_Freq[Freq#]_EyPol.iter[Iter#] ImE_Freq[Freq#]_EyPol.iter[Iter#]
2	Magnetic field	ReH_Freq[Freq#]_ExPol.iter[Iter#] ImH_Freq[Freq#]_ExPol.iter[Iter#] ReH_Freq[Freq#]_EyPol.iter[Iter#] ImH_Freq[Freq#]_EyPol.iter[Iter#]
3	Electric current	Rej_Freq[Freq#]_ExPol.iter[Iter#] Imj_Freq[Freq#]_ExPol.iter[Iter#] Rej_Freq[Freq#]_EyPol.iter[Iter#] Imj_Freq[Freq#]_EyPol.iter[Iter#]
4	Sensitivity	Sensitivity.iter[Iter#] NormalizedSensitivity.iter[Iter#]
5	Sensitivity density	SensitivityDensity.iter[Iter#] NormalizedSensitivityDensity.iter[Iter#]

*1) When you select VTK file format (ASCII) as output file format, output variables are written in the files named as ‘result_[PE#]_iter[Iter#].vtk’.

*2) In the file names, [PE#] and [Iter#] indicate process number and iteration number, respectively.

File format of control.dat (5/9)

Keyword	Content	Data type	Option	Default	Example
DISTORTION	Treatment of galvanic distortion	Integer (0, 1, 2 or 3)	0: Distortion matrix is not estimated 1: Differences of distortion matrix and unit matrix are estimated. 2: Both gains and rotations are estimated*1). 3: Only gains are estimated.	None. You must write this keyword and an option.	DISTORTION 1
TRADE_OFF_PARAM	Trade-off parameters	Real positive value(s)	The number of option(s) depends on the option of the keyword 'DISTORTION'. If the option of 'DISTORTION' is '0', you should write only trade-off parameter α. If the option of 'DISTORTION' is '1' or '3', you should write trade-off parameters α and β. If the option of 'DISTORTION' is '2', you should write trade-off parameters α, β_1 andβ_2.	None. You must write this keyword and option(s).	TRADE_OFF_PARAM 1.0 0.1
ITERATION	Start and end iteration number	Two integers greater than or equal to 0	Start and end iteration number	None. You must write this keyword and options.	ITERATION 0 10
CONVERGE	Convergence threshold (%) of Gauss-Newton iteration	Real value greater than 0	If the change rates of the objective function and its respective terms of the current iteration from those of the previous iteration are less than the threshold value, the Gauss-Newton iteration is finished.	1.0	CONVERGE 1.0

*1) Distortion matrix is decomposed as Smith (1995)

Smith, J. T. (1995). Understanding telluric distortion matrices. Geophysical Journal International, 122(1), 219–226. https://doi.org/10.1111/j.1365-246X.1995.tb03549.x

Objective function

The form of objective function depends on the setting of ‘DISTORTION’.

0: Distortion matrix is not estimated

$$\phi(\boldsymbol{m}) = \phi_d(\boldsymbol{m}) + \alpha^2\phi_m(\boldsymbol{m})$$

$\phi_d(\boldsymbol{m})$: Data misfit
$\phi_m(\boldsymbol{m})$: Model roughness
α: Trade-off parameter

1: Differences of distortion matrix $\boldsymbol{C}$ and unit matrix are estimated

$$\phi(\boldsymbol{m}) = \phi_d(\boldsymbol{m}) + \alpha^2\phi_m(\boldsymbol{m}) + \beta^2\phi_c(\boldsymbol{m})$$

$\phi_d(\boldsymbol{m})$: Data misfit, $\phi_m(\boldsymbol{m})$: Model roughness

$$\phi_c(\boldsymbol{m}) = \sum_{i=1}^{\#sites}\left[|c'_{xx}|^2 + \left|c'_{xy}\right|^2 + \left|c'_{yx}\right|^2 + \left|c'_{yy}\right|^2\right]$$

α, β : Trade-off parameter

$$\boldsymbol{C}' = \boldsymbol{C} - \boldsymbol{I} = \begin{pmatrix} c_{xx} & c_{xy} \\ c_{yx} & c_{yy} \end{pmatrix} - \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} c'_{xx} & c'_{xy} \\ c'_{yx} & c'_{yy} \end{pmatrix}$$

2: Both gains and rotations are estimated

$$\phi(\boldsymbol{m}) = \phi_d(\boldsymbol{m}) + \alpha^2\phi_m(\boldsymbol{m}) + {\beta_1}^2\phi_{c1}(\boldsymbol{m}) + {\beta_2}^2\phi_{c2}(\boldsymbol{m})$$

$\phi_d(\boldsymbol{m})$: Data misfit, $\phi_m(\boldsymbol{m})$: Model roughness

$$\phi_{c1}(\boldsymbol{m}) = \sum_{i=1}^{\#site}\left[{G_x}^2 + {G_y}^2\right], \phi_{c2}(\boldsymbol{m}) = \sum_{i=1}^{\#site}\left[{\beta_x}^2 + {\beta_y}^2\right]$$

α, β_1, β_2 : Trade-off parameter

$$\boldsymbol{C} = \left(10^{G_x}\begin{pmatrix} cos\beta_x \\ sin\beta_x \end{pmatrix} \quad 10^{G_y}\begin{pmatrix} -sin\beta_y \\ cos\beta_y \end{pmatrix}\right)$$

3: Only gains are estimated.

$$\phi(\boldsymbol{m}) = \phi_d(\boldsymbol{m}) + \alpha^2\phi_m(\boldsymbol{m}) + \beta^2\phi_c(\boldsymbol{m})$$

$\phi_d(\boldsymbol{m})$: Data misfit, $\phi_m(\boldsymbol{m})$: Model roughness

$$\phi_c(\boldsymbol{m}) = \sum_{i=1}^{\#site}\left[{G_x}^2 + {G_y}^2\right]$$

α, β : Trade-off parameter

$$\boldsymbol{C} = \begin{pmatrix} 10^{G_x} & 0 \\ 0 & 10^{G_y} \end{pmatrix}$$

File format of control.dat (6/9)

Keyword	Content	Data type	Option	Default	Example
ROUGH_MATRIX	Way of making roughening matrix [1]	Integer (0, 1, 2 or -1)	0: Based on element 1: Based on parameter cell 2: Based on element (with weights based on area-volume ratio) -1: From external file 'roughening_matrix.dat' [2]	0	ROUGH_MATRIX 0
OUTPUT_ROUGH_MATRIX	Output roughening matrix as an external file [2] 'roughening_matrix.out'				OUTPUT_ROUGH_MATRIX
BOTTOM_RESISTIVITY	Give a resistivity below the bottom of mesh. By using this option, roughening matrix $\boldsymbol{R}$ will be regularized and then data-space inversion is stabilized	Positive real value			BOTTOM_RESISTIVITY 10.0
ALPHA_WEIGHT	Make regularization depend on directions [1]	Three non-negative values		1 1 1	ALPHA_WEIGHT 1 100 1

*1) Detail of this option is described in the following slides.

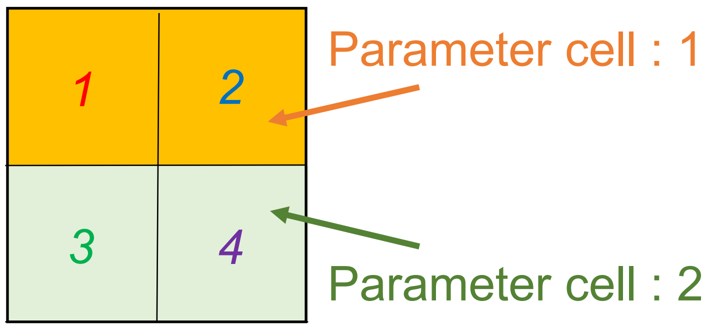
*2) Format of this file is explained in the later slides.

Way of making roughening matrix (1/2)

(1) Based on parameter cell

Roughening matrix is a Laplacian filter based on the relation of parameter cells

$$\boldsymbol{R} = \begin{array}{l|cc} & \textit{Column corresponding to parameter cell 1} & \textit{Column corresponding to parameter cell 2} \\ \hline \textit{Row corresponding to parameter cell 1} & 1 & -1 \\ \textit{Row corresponding to parameter cell 2} & -1 & 1 \end{array}$$



In this figure, different colors indicate different parameter cells and italic numbers indicate element numbers.
For simplified explanation, in this example, 2-D structure is treated.

(2) Based on element

* Because elements 1 and 2 (3 and 4) belong to parameter cell, differentiation between the two elements is not considered.

$$\begin{array}{l|cccc} & \textit{Column corresponding to element 1} & \textit{Column corresponding to element 2} & \textit{Column corresponding to element 3} & \textit{Column corresponding to element 4} \\ \hline \textit{Row corresponding to element 1} & 1 & 0 & -1 & 0 \\ \textit{Row corresponding to element 2} & 0 & 1 & 0 & -1 \\ \textit{Row corresponding to element 3} & -1 & 0 & 1 & 0 \\ \textit{Row corresponding to element 4} & 0 & -1 & 0 & 1 \end{array}$$

Components of roughening matrix are calculated from the components of the roughening matrix based on the relation of elements

$$\boldsymbol{R} = \begin{array}{l|cc} & \textit{Column corresponding to parameter cell 1} & \textit{Column corresponding to parameter cell 2} \\ \hline \textit{Row corresponding to parameter cell 1} & 2 & -2 \\ \textit{Row corresponding to parameter cell 2} & -2 & 2 \end{array}$$

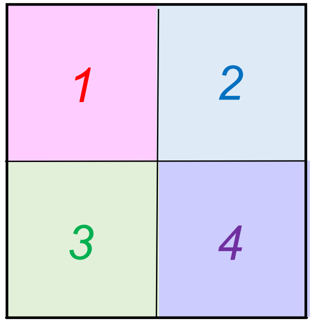
Way of making roughening matrix (2/2)

(3) Based on element (with weights based on area-volume ratio)

$$\boldsymbol{R} = \begin{array}{c|cccc} & \textit{Column corresponding to parameter cell 1} & \textit{Column corresponding to parameter cell 2} & \textit{Column corresponding to parameter cell 3} & \textit{Column corresponding to parameter cell 4} \\ \hline \textit{Row corresponding to parameter cell 1} & \frac{S_{1,2}+S_{1,3}}{V_1} & -\frac{S_{1,2}}{V_1} & -\frac{S_{1,3}}{V_1} & 0 \\ \textit{Row corresponding to parameter cell 2} & -\frac{S_{2,1}}{V_2} & \frac{S_{2,1}+S_{2,4}}{V_2} & 0 & -\frac{S_{2,4}}{V_2} \\ \textit{Row corresponding to parameter cell 3} & -\frac{S_{3,1}}{V_3} & 0 & \frac{S_{3,1}+S_{3,4}}{V_3} & -\frac{S_{3,4}}{V_3} \\ \textit{Row corresponding to parameter cell 4} & 0 & -\frac{S_{4,2}}{V_4} & -\frac{S_{4,3}}{V_4} & \frac{S_{4,2}+S_{4,3}}{V_4} \end{array}$$

V_X indicates the volume of element X.

$S_{X,Y}$ indicates the area of the face shared by element X and Y.



In this figure, different colors indicate different parameter cells and italic numbers indicate element numbers.

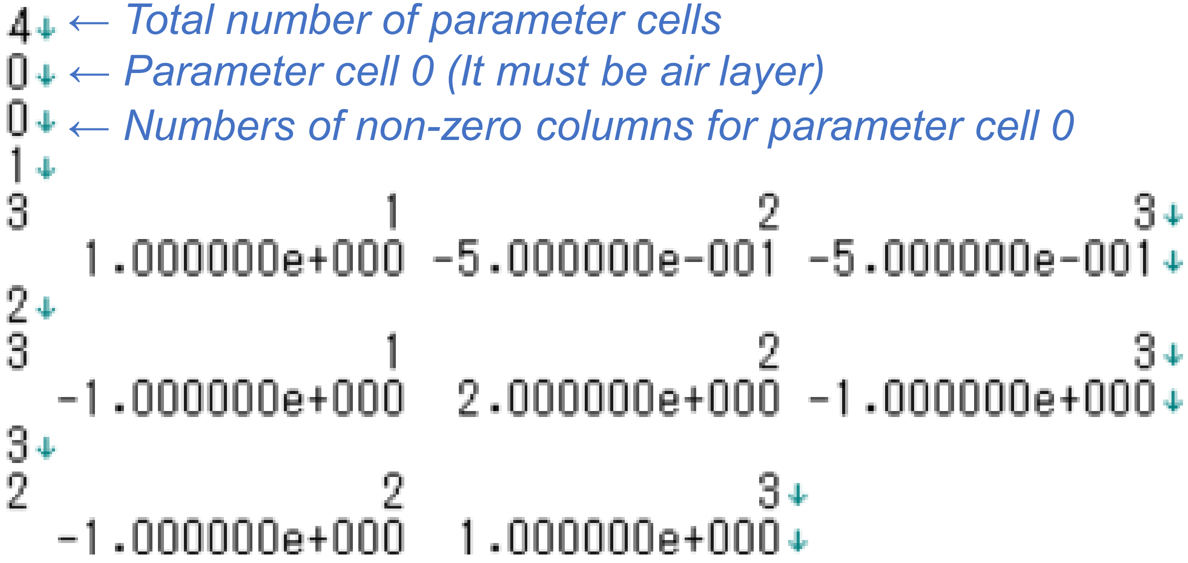
For simplified explanation, in this example, 2-D structure is treated.

In this example, respective elements have respective different parameter cells.

Format of ‘roughening_matrix.out’ and ‘roughening_matrix.dat’

Example

$$\begin{array}{lc}
 & \begin{array}{ccc} \textit{Column corresponding to parameter cell 1} & \textit{Column corresponding to parameter cell 2} & \textit{Column corresponding to parameter cell 3} \end{array} \\
\begin{array}{l} \textit{Row corresponding to parameter cell 1} \\ \textit{Row corresponding to parameter cell 2} \\ \textit{Row corresponding to parameter cell 3} \end{array} & \boldsymbol{R} = \begin{pmatrix} 1 & -0.5 & -0.5 \\ -1 & 2 & -1 \\ 0 & -1 & 1 \end{pmatrix}
\end{array}$$



`4↓` ← *Total number of parameter cells*
`0↓` ← *Parameter cell 0 (It must be air layer)*
`0↓` ← *Numbers of non-zero columns for parameter cell 0*
Parameter cell 1 → `1↓`
Numbers of non-zero columns for parameter cell 1 → `3 1 2 3↓`
Non-zero components for parameter cell 1 → `1.000000e+000 -5.000000e-001 -5.000000e-001↓`
Parameter cell 2 → `2↓`
Numbers of non-zero columns for parameter cell 2 → `3 1 2 3↓`
Non-zero components for parameter cell 2 → `-1.000000e+000 2.000000e+000 -1.000000e+000↓`
Parameter cell 3 → `3↓`
Numbers of non-zero columns for parameter cell 3 → `2 2 3↓`
Non-zero components for parameter cell 3 → `-1.000000e+000 1.000000e+000↓`

Option ALPHA_WEIGHT

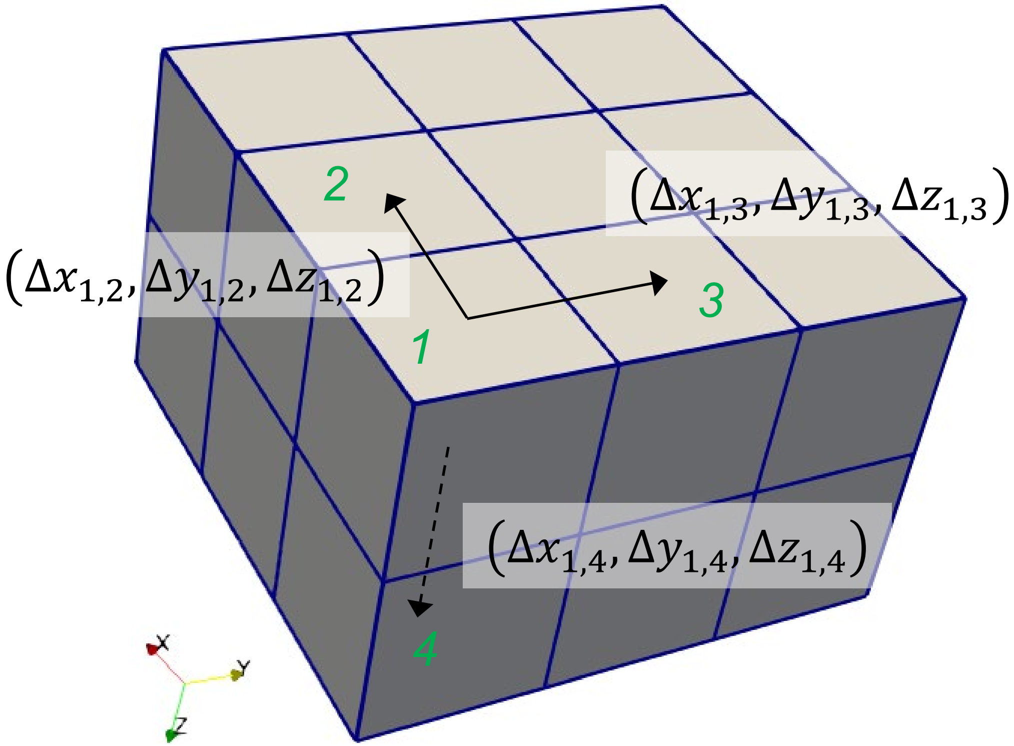
Three values under 'ALPHA_WEIGHT': $w_x \quad w_y \quad w_z$

Resultant weights:

$$w_{1,2} = \sqrt{\frac{\left(w_x \Delta x_{1,2}\right)^2 + \left(w_y \Delta y_{1,2}\right)^2 + \left(w_z \Delta z_{1,2}\right)^2}{\Delta x_{1,2}^2 + \Delta y_{1,2}^2 + \Delta z_{1,2}^2}}$$

$$w_{1,3} = \sqrt{\frac{\left(w_x \Delta x_{1,3}\right)^2 + \left(w_y \Delta y_{1,3}\right)^2 + \left(w_z \Delta z_{1,3}\right)^2}{\Delta x_{1,3}^2 + \Delta y_{1,3}^2 + \Delta z_{1,3}^2}}$$

$$w_{1,4} = \sqrt{\frac{\left(w_x \Delta x_{1,4}\right)^2 + \left(w_y \Delta y_{1,4}\right)^2 + \left(w_z \Delta z_{1,4}\right)^2}{\Delta x_{1,4}^2 + \Delta y_{1,4}^2 + \Delta z_{1,4}^2}}$$



Vectors connecting centers of adjacent elements

$(\Delta x_{1,2}, \Delta y_{1,2}, \Delta z_{1,2})$

$(\Delta x_{1,3}, \Delta y_{1,3}, \Delta z_{1,3})$

$(\Delta x_{1,4}, \Delta y_{1,4}, \Delta z_{1,4})$

Roughening matrix

$$\boldsymbol{R} = \begin{pmatrix} w_{1,2} + w_{1,3} + w_{1,4} & -w_{1,2} & -w_{1,3} & -w_{1,4} \\ -w_{1,2} & \ddots & & \\ -w_{1,3} & & & \\ -w_{1,4} & & & \\ & & & \end{pmatrix}$$

File format of control.dat (7/9)

Keyword	Content	Data type	Option	Default	Example
DIFF_FILTER	Type of norm	Integer (1 or 2)			DIFF_FILTER 1 0.01 1 5 10
	ε_1, ε_2	Positive real values			
	Maximum iteration number of iteratively reweighted least-squares algorithm	Positive real value			
	Convergence threshold (%) of IRLS algorithm	Real value greater than 0			

- ✓ If this option is used, difference filter is used for roughening matrix instead of Laplacian filter.
- ✓ L_1 norm can be used in addition to L_2 norm.
- ✓ When L_1 norm is selected, iteratively reweighted least-squares (IRLS) algorithm (Farquharson & Oldenburg, 1998) is used within the model update phase.
- ✓ Weight w multiplied to the roughening matrix (difference filter) is

$$w = \sqrt{0.5/d}$$

$$d = \min(\max(\varepsilon_1, |log_{10}(\rho) - log_{10}(\rho_{neib})|), \varepsilon_2)$$

- ✓ IRLS is stopped when the iteration number reaches the specified maximum value or change rate of the model roughness is less than the convergence threshold.
- ✓ To use this option, you need to select the data-space method, and the inverse of RTR matrix is used in the data-space method.

Example of difference filter with L_2 norm

```
INV_METHOD
1
DATA_SPACE_METHOD
2
DIFF_FILTER
2
0.01 2
1
1
```

Example of difference filter with L_1 norm

```
INV_METHOD
1
DATA_SPACE_METHOD
2
DIFF_FILTER
1
0.01 2
5
10
```

Farquharson, C. G., & Oldenburg, D. W. (1998). Non-linear inversion using general measures of data misfit and model structure. Geophysical Journal International, 134(1), 213–227. https://doi.org/10.1046/j.1365-246x.1998.00555.x

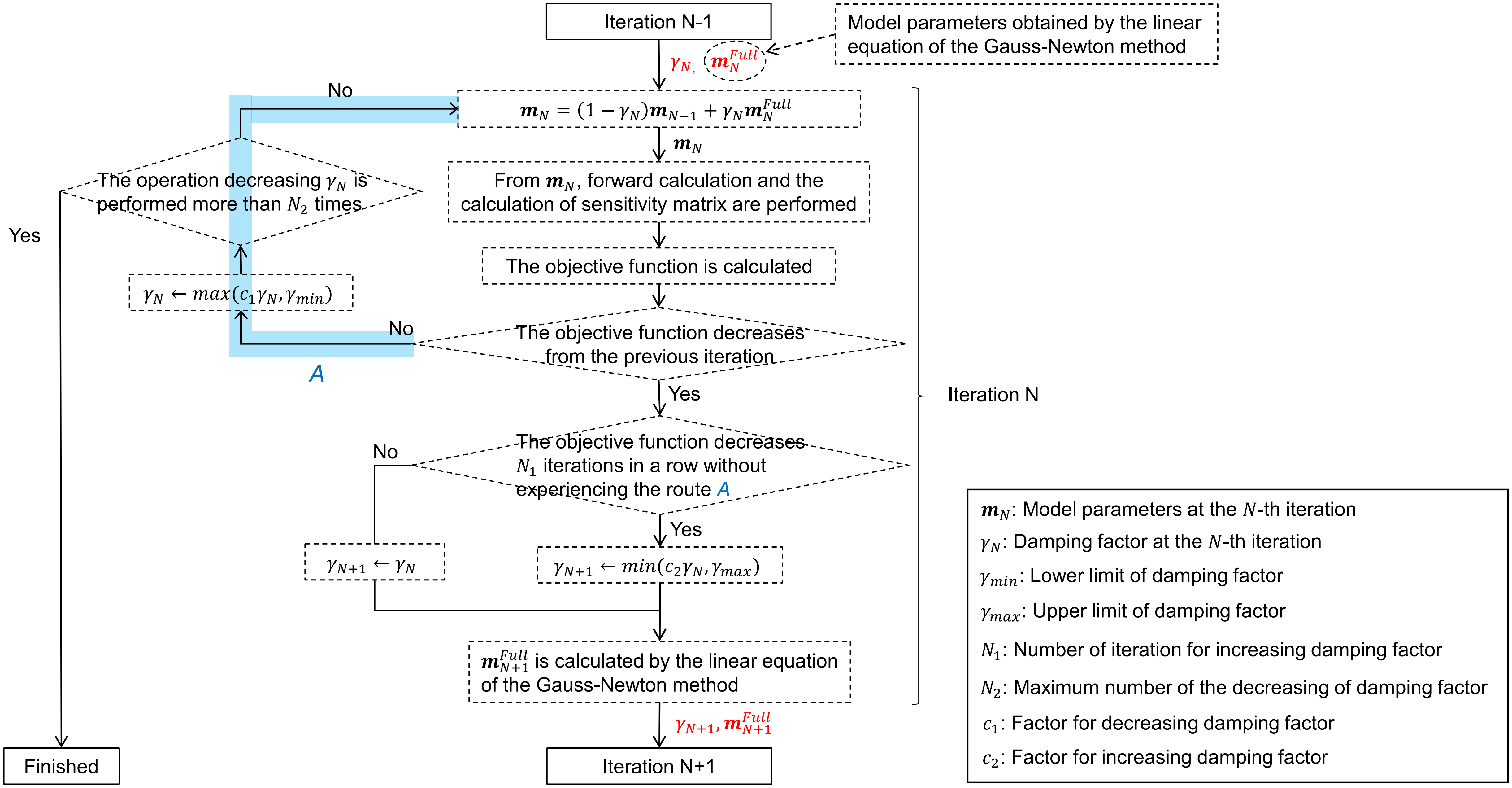
File format of control.dat (8/9)

Keyword	Content	Data type	Option	Default	Example
DECREASE_THRESHOLD	Threshold value for determining whether the objective function decreases. If the difference of the objective function of the current iteration and the previous iteration is less than the threshold value, the objective function is deemed to decrease.	Positive real value		0.001	DECREASE_THRESHOLD 0.001
STEP_LENGTH *1)	Initial damping factor	Positive real value		0.50	STEP_LENGTH 0.5 0.1 0.5 3 0.5 1.2
	Lower limit of damping factor	Positive real value		0.10	
	Upper limit of damping factor	Positive real value		1.00	
	Number of iteration for increasing damping factor	Positive integer		3	
	Factor for decreasing damping factor	Real value less than or equal to 1.0		0.50	
	Factor for increasing damping factor	Real value greater than or equal to 1.0		1.25	
RETRIAL	Maximum number of the decreasing of damping factor	Positive integer		5	RETRIAL 3

*1) Modification algorithm of the damping factor is shown as flow chart in the next slide.

File format of control.dat (9/9)

Keyword	Content	Data type	Option	Default	Example
APP_PHS_OPTION	Option about treatment of apparent resistivity and phase	Integer (0 or 1)	0:No special treatment 1:Impedance tensor is used instead of apparent resistivity and phase if the sign of the real part of impedance tensor component is different between observed and calculated responses. This treatment will improve the stabilization of the inversion using apparent resistivity and phase.	0	APP_PHS_OPTION 1
END	Indication of the end of controlling parameters				END


Iteration N-1
Model parameters obtained by the linear equation of the Gauss-Newton method
γ_N, $\boldsymbol{m}_N^{Full}$
$\boldsymbol{m}_N = (1-\gamma_N)\boldsymbol{m}_{N-1} + \gamma_N \boldsymbol{m}_N^{Full}$
$\boldsymbol{m}_N$
From $\boldsymbol{m}_N$, forward calculation and the calculation of sensitivity matrix are performed
The objective function is calculated
The objective function decreases from the previous iteration
No
A
Yes
$\gamma_N \leftarrow max(c_1\gamma_N, \gamma_{min})$
The operation decreasing γ_N is performed more than N_2 times
No
Yes
The objective function decreases N_1 iterations in a row without experiencing the route A
No
Yes
$\gamma_{N+1} \leftarrow \gamma_N$
$\gamma_{N+1} \leftarrow min(c_2\gamma_N, \gamma_{max})$
$\boldsymbol{m}_{N+1}^{Full}$ is calculated by the linear equation of the Gauss-Newton method
γ_{N+1}, $\boldsymbol{m}_{N+1}^{Full}$
Iteration N+1
Iteration N
Finished
$\boldsymbol{m}_N$: Model parameters at the N-th iteration
γ_N: Damping factor at the N-th iteration
γ_{min}: Lower limit of damping factor
γ_{max}: Upper limit of damping factor
N_1: Number of iteration for increasing damping factor
N_2: Maximum number of the decreasing of damping factor
c_1: Factor for decreasing damping factor
c_2: Factor for increasing damping factor

Recommended setting for initial trial

```
MESH_TYPE
2
OUTPUT_PARAM
1
0
DIV_NUM_RHS_FWD
10
INV_METHOD
1
SMALL_VALUE
1.0e-4
DISTORTION
0
TRADE_OFF_PARAM
10.0
ITERATION
0 20
STEP_LENGTH
0.5 0.1 0.8
2
0.6 1.2
END
```

File format of mesh.dat (for brick elements) (1/3)

HEXA						
Division number of the X direction (N_X)	*Division number of the Y direction (N_Y)*	*Division number of the Z direction (N_Z)*	*Division number of the air layer (N_{Air})*			
0	*X coordinate value of the 1st node*	*Y coordinate value of the 1st node*	*Z coordinate value of the 1st node*			
⋮						
$N_n - 1$	*X coordinate value of the N_n-th node*	*Y coordinate value of the N_n-th node*	*Z coordinate value of the N_n-th node*			
Number of elements (N_e)						
0	*Index of the adjacent element sharing face 0*	*Index of the adjacent element sharing face 1*	*Index of the adjacent element sharing face 2*	*Index of the adjacent element sharing face 3*		
	Index of the adjacent element sharing face 4	*Index of the adjacent element sharing face 5*	*Index of node 0*	*Index of node 1*	*Index of node 2*	*Index of node 3*
	Index of node 4	*Index of node 5*	*Index of node 6*	*Index of node 7*		
⋮						
$N_e - 1$	*Index of the adjacent element sharing face 0*	*Index of the adjacent element sharing face 1*	*Index of the adjacent element sharing face 2*	*Index of the adjacent element sharing face 3*		
	Index of the adjacent element sharing face 4	*Index of the adjacent element sharing face 5*	*Index of node 0*	*Index of node 1*	*Index of node 2*	*Index of node 3*
	Index of node 4	*Index of node 5*	*Index of node 6*	*Index of node 7*		

*1) $N_n = (N_X + 1)(N_Y + 1)(N_Z + 1)$

*2) $N_e = N_X N_Y N_Z$

File format of mesh.dat (for brick elements) (2/3)

Number of the element faces on the Y-Z plane (-X side) (N_{-YZ})

Element index of the 1st element face	*The 1st node index of the element face*	*The 2nd node index of the element face*	*The 3rd node index of the element face*	*The 4-th node index of the element face*
		⋮		
Element index of the N_{-YZ}-th element face	*The 1st node index of the element face*	*The 2nd node index of the element face*	*The 3rd node index of the element face*	*The 4-th node index of the element face*

Number of the element faces on the Y-Z plane (+X side) (N_{+YZ})

Element index of the 1st element face	*The 1st node index of the element face*	*The 2nd node index of the element face*	*The 3rd node index of the element face*	*The 4-th node index of the element face*
		⋮		
Element index of the N_{+YZ}-th element face	*The 1st node index of the element face*	*The 2nd node index of the element face*	*The 3rd node index of the element face*	*The 4-th node index of the element face*

Number of the element faces on the Z-X plane (-Y side) (N_{-ZX})

Element index of the 1st element face	*The 1st node index of the element face*	*The 2nd node index of the element face*	*The 3rd node index of the element face*	*The 4-th node index of the element face*
		⋮		
Element index of the N_{-ZX}-th element face	*The 1st node index of the element face*	*The 2nd node index of the element face*	*The 3rd node index of the element face*	*The 4-th node index of the element face*

File format of mesh.dat (for brick elements) (3/3)

Number of the element faces on the Z-X plane (-Y side) (N_{+ZX})

Element index of the 1st element face	*The 1st node index of the element face*	*The 2nd node index of the element face*	*The 3rd node index of the element face*	*The 4-th node index of the element face*
		⋮		
Element index of the N_{+ZX}-th element face	*The 1st node index of the element face*	*The 2nd node index of the element face*	*The 3rd node index of the element face*	*The 4-th node index of the element face*

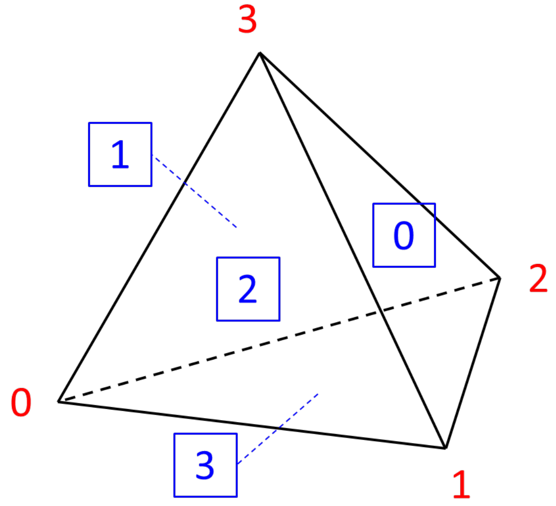
Number of the element faces on the X-Y plane (-Z side) (N_{-XY})

Element index of the 1st element face	*The 1st node index of the element face*	*The 2nd node index of the element face*	*The 3rd node index of the element face*	*The 4-th node index of the element face*
		⋮		
Element index of the N_{-XY}-th element face	*The 1st node index of the element face*	*The 2nd node index of the element face*	*The 3rd node index of the element face*	*The 4-th node index of the element face*

Number of the element faces on the X-Y plane (+Z side) (N_{+XY})

Element index of the 1st element face	*The 1st node index of the element face*	*The 2nd node index of the element face*	*The 3rd node index of the element face*	*The 4-th node index of the element face*
		⋮		
Element index of the N_{+XY}-th element face	*The 1st node index of the element face*	*The 2nd node index of the element face*	*The 3rd node index of the element face*	*The 4-th node index of the element face*

File format of mesh.dat (for tetrahedral elements) (1/3)



TETRA				
Number of nodes (N_n)				
0	*X coordinate value of the* 1*st node*	*Y coordinate value of the* 1*st node*	*Z coordinate value of the* 1*st node*	
⋮				
$N_n - 1$	*X coordinate value of the* N_n*-th node*	*Y coordinate value of the* N_n*-th node*	*Z coordinate value of the* N_n*-th node*	
Number of elements (N_e)				
0	*Index of the adjacent element sharing face 0*	*Index of the adjacent element sharing face 1*	*Index of the adjacent element sharing face 2*	*Index of the adjacent element sharing face 3*
	Index of node 0	*Index of node 1*	*Index of node 2*	*Index of node 3*
⋮				
$N_e - 1$	*Index of the adjacent element sharing face 0*	*Index of the adjacent element sharing face 1*	*Index of the adjacent element sharing face 2*	*Index of the adjacent element sharing face 3*
	Index of node 0	*Index of node 1*	*Index of node 2*	*Index of node 3*

File format of mesh.dat (for tetrahedral elements) (2/3)

Number of the element faces on the Y-Z plane (-X side) (N_{-YZ})	
Element index of the 1st element face	*Face index of the 1st element face*
⋮	
Element index of the N_{-YZ}*-th element face*	*Face index of the* N_{-YZ}*-th element face*
Number of the element faces on the Y-Z plane (+X side) (N_{+YZ})	
Element index of the 1st element face	*Face index of the 1st element face*
⋮	
Element index of the N_{+YZ}*-th element face*	*Face index of the* N_{+YZ}*-th element face*
Number of the element faces on the Z-X plane (-Y side) (N_{-ZX})	
Element index of the 1st element face	*Face index of the 1st element face*
⋮	
Element index of the N_{-ZX}*-th element face*	*Face index of the* N_{-ZX}*-th element face*
Number of the element faces on the Z-X plane (+Y side) (N_{+ZX})	
Element index of the 1st element face	*Face index of the 1st element face*
⋮	
Element index of the N_{+ZX}*-th element face*	*Face index of the* N_{+ZX}*-th element face*

File format of mesh.dat (for tetrahedral elements) (3/3)

Number of the element faces on the X-Y plane (-Z side) (N_{-XY})

Element index of the 1^{st} *element face*	*Face index of the* 1^{st} *element face*
⋮	
Element index of the N_{-XY}*-th element face*	*Face index of the* N_{-XY}*-th element face*

Number of the element faces on the X-Y plane (+Z side) (N_{+XY})

Element index of the 1^{st} *element face*	*Face index of the* 1^{st} *element face*
⋮	
Element index of the N_{+XY}*-th element face*	*Face index of the* N_{+XY}*-th element face*

Number of the element faces on the Earth's surface (N_{surf})

Element index of the 1^{st} *element face*	*Face index of the* 1^{st} *element face*
⋮	
Element index of the N_{surf}*-th element face*	*Face index of the* N_{surf}*-th element face*

File format of mesh.dat (for deformed non-conforming hexahedral elements) (1/4)

DHEXA			
Number of nodes (N_n)			
0	*X coordinate value of the 1st node*	*Y coordinate value of the 1st node*	*Z coordinate value of the 1st node*
		⋮	
$N_n - 1$	*X coordinate value of the N_n-th node*	*Y coordinate value of the N_n-th node*	*Z coordinate value of the N_n-th node*
Number of elements (N_e)			
Information about the 1st element 1)			
⋮			
Information about the N_e-th element 1)			

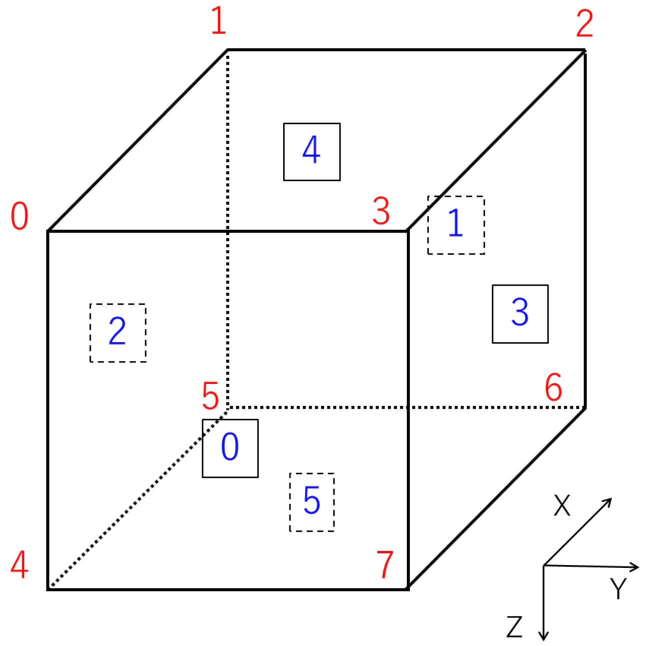
*1) The format of the information about element is described in the next slide

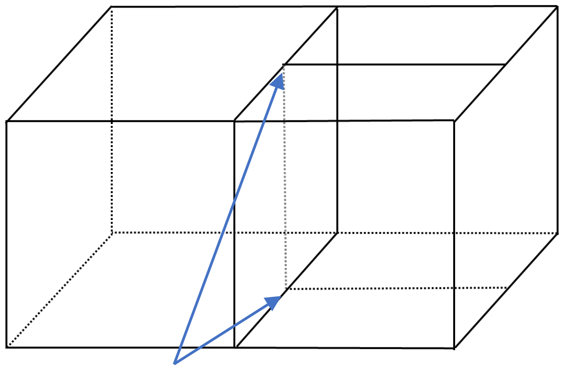
File format of mesh.dat (for deformed non-conforming hexahedral elements) (2/4)

The format of the information about element

Element Index	*Index of node 0*	*Index of node 1*	*Index of node 2*	*Index of node 3*	*Index of node 4*	*Index of node 5*	*Index of node 6*	*Index of node 7*

Total number of the adjacent elements sharing face 0	*The element index of the 1st adjacent element*	…	*The element index of the last adjacent element*
Total number of the adjacent elements sharing face 1	*The element index of the 1st adjacent element*	…	*The element index of the last adjacent element*
Total number of the adjacent elements sharing face 2	*The element index of the 1st adjacent element*	…	*The element index of the last adjacent element*
Total number of the adjacent elements sharing face 3	*The element index of the 1st adjacent element*	…	*The element index of the last adjacent element*
Total number of the adjacent elements sharing face 4	*The element index of the 1st adjacent element*	…	*The element index of the last adjacent element*
Total number of the adjacent elements sharing face 5	*The element index of the 1st adjacent element*	…	*The element index of the last adjacent element*





Hanging node

Total number of the adjacent elements is larger than 1 if there are hanging nodes on the face. If there is no adjacent element, that can occur at the outer boundary of the mesh, total number of the adjacent elements should be zero or a negative value.

File format of mesh.dat (for deformed non-conforming hexahedral elements) (3/4)

Number of the element faces on the Y-Z plane (-X side) (N_{-YZ})	
Element index of the 1st element face	*Face index of the 1st element face*
⋮	
Element index of the N_{-YZ}-th element face	*Face index of the N_{-YZ}-th element face*
Number of the element faces on the Y-Z plane (+X side) (N_{+YZ})	
Element index of the 1st element face	*Face index of the 1st element face*
⋮	
Element index of the N_{+YZ}-th element face	*Face index of the N_{+YZ}-th element face*
Number of the element faces on the Z-X plane (-Y side) (N_{-ZX})	
Element index of the 1st element face	*Face index of the 1st element face*
⋮	
Element index of the N_{-ZX}-th element face	*Face index of the N_{-ZX}-th element face*
Number of the element faces on the Z-X plane (+Y side) (N_{+ZX})	
Element index of the 1st element face	*Face index of the 1st element face*
⋮	
Element index of the N_{+ZX}-th element face	*Face index of the N_{+ZX}-th element face*

File format of mesh.dat (for deformed non-conforming hexahedral elements) (4/4)

Number of the element faces on the X-Y plane (-Z side) (N_{-XY})

Element index of the 1st element face	*Face index of the 1st element face*
⋮	
Element index of the N_{-XY}-th element face	*Face index of the N_{-XY}-th element face*

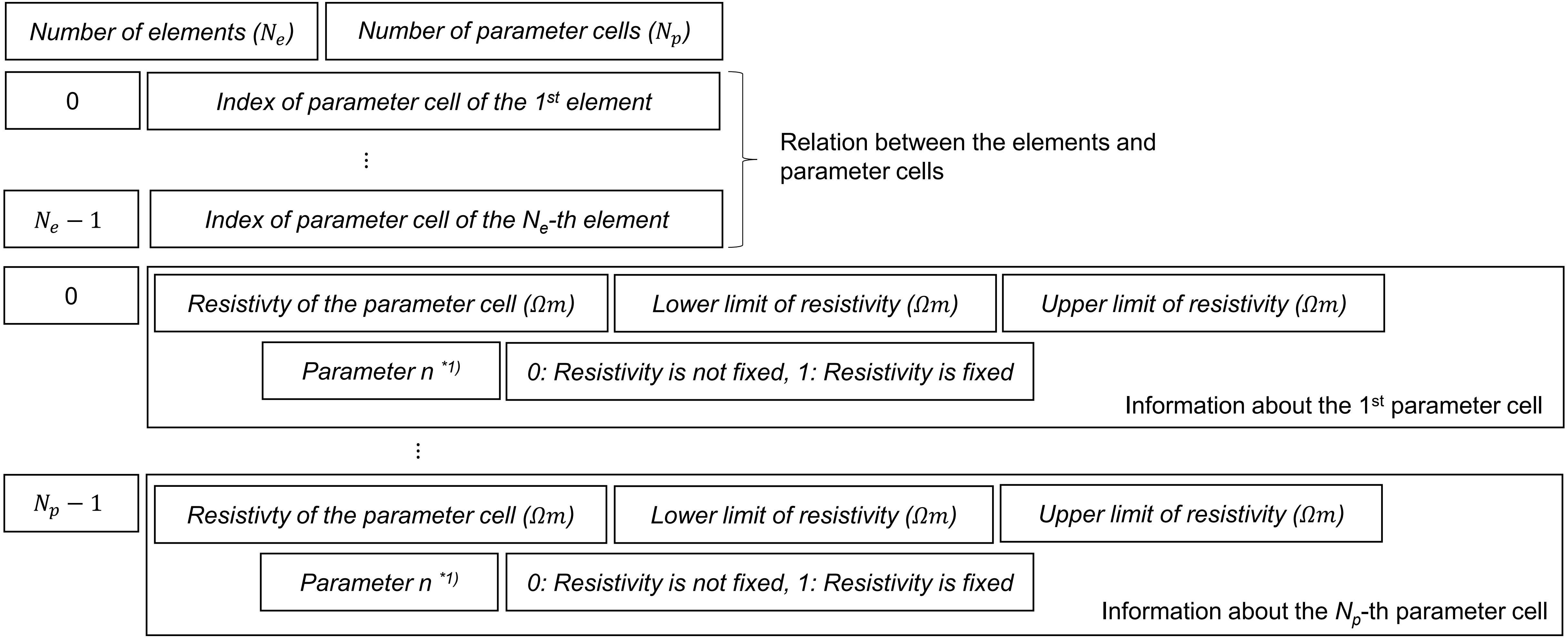
Number of the element faces on the X-Y plane (+Z side) (N_{+XY})

Element index of the 1st element face	*Face index of the 1st element face*
⋮	
Element index of the N_{+XY}-th element face	*Face index of the N_{+XY}-th element face*

Number of the element faces on the Earth's surface (N_{surf})

Element index of the 1st element face	*Face index of the 1st element face*
⋮	
Element index of the N_{surf}-th element face	*Face index of the N_{surf}-th element face*

resistivity_block_iter[Iter#].dat



Number of elements (N_e) *Number of parameter cells* (N_p)

0 *Index of parameter cell of the 1st element*

⋮

$N_e - 1$ *Index of parameter cell of the* N_e*-th element*

Relation between the elements and parameter cells

0 *Resistivty of the parameter cell* (Ωm) *Lower limit of resistivity* (Ωm) *Upper limit of resistivity* (Ωm)

Parameter n *1) *0: Resistivity is not fixed, 1: Resistivity is fixed*

Information about the 1st parameter cell

⋮

$N_p - 1$ *Resistivty of the parameter cell* (Ωm) *Lower limit of resistivity* (Ωm) *Upper limit of resistivity* (Ωm)

Parameter n *1) *0: Resistivity is not fixed, 1: Resistivity is fixed*

Information about the N_p-th parameter cell

*1) Parameter *n* is used only if the option of the keyword ‘RESISTIVITY_BOUNDS’ of control.dat is 1.

File format of observe.dat

The following response functions can be used as the observed data.

Impedance tensor

$$\begin{pmatrix} E_x \\ E_y \end{pmatrix} = \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix} \begin{pmatrix} H_x \\ H_y \end{pmatrix}$$

Vertical magnetic transfer function (Tipper)

$$H_z = \begin{pmatrix} T_{zx} & T_{zy} \end{pmatrix} \begin{pmatrix} H_x \\ H_y \end{pmatrix}$$

Horizontal magnetic transfer function between two sites

$$\begin{pmatrix} H_x{}^{Site1} \\ H_y{}^{Site1} \end{pmatrix} = \begin{pmatrix} T_{xx} & T_{xy} \\ T_{yx} & T_{yy} \end{pmatrix} \begin{pmatrix} H_x{}^{Site2} \\ H_y{}^{Site2} \end{pmatrix}$$

Phase tensor (Caldwell et al. 2004)

$$\begin{pmatrix} \Phi_{11} & \Phi_{12} \\ \Phi_{21} & \Phi_{22} \end{pmatrix} = \begin{pmatrix} Re(Z_{xx}) & Re(Z_{xy}) \\ Re(Z_{yx}) & Re(Z_{yy}) \end{pmatrix}^{-1} \begin{pmatrix} Im(Z_{xx}) & Im(Z_{xy}) \\ Im(Z_{yx}) & Im(Z_{yy}) \end{pmatrix}$$

Apparent resistivity

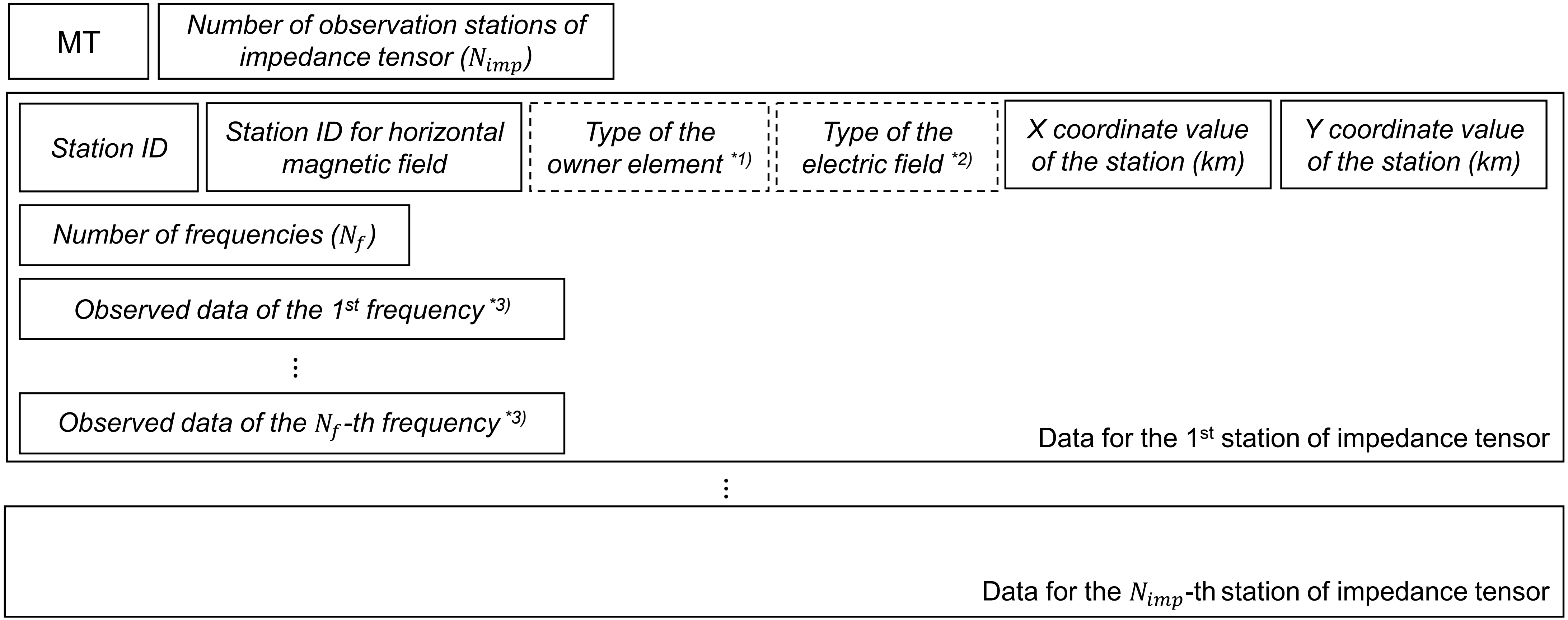
$$\rho_{a,ij} = \frac{1}{\omega\mu_0} \left| Z_{ij} \right|^2$$

Phase

$$\theta_{ij} = \begin{cases} Arctan\left(\frac{Im(Z_{ij})}{Re(Z_{ij})}\right) \; (Re(Z_{ij}) \geq 0) \\ Arctan\left(\frac{Im(Z_{ij})}{Re(Z_{ij})}\right) + \pi \; (Re(Z_{ij}) < 0 \; and \; Im(Z_{ij}) \geq 0) \\ Arctan\left(\frac{Im(Z_{ij})}{Re(Z_{ij})}\right) - \pi \; (Re(Z_{ij}) < 0 \; and \; Im(Z_{ij}) < 0) \end{cases}$$

Response functions must be written in SI units with $e^{-i\omega t}$ time dependence.

Impedance tensor (1/2)



MT

Number of observation stations of impedance tensor (N_{imp})

Station ID

Station ID for horizontal magnetic field

Type of the owner element [*1)]

Type of the electric field [*2)]

X coordinate value of the station (km)

Y coordinate value of the station (km)

Number of frequencies (N_f)

Observed data of the 1st frequency [*3)]

⋮

Observed data of the N_f-th frequency [*3)]

Data for the 1st station of impedance tensor

⋮

Data for the N_{imp}-th station of impedance tensor

*1) Type of the owner element (0: Downward element, 1: Upward element) is needed only if the option of the keyword ‘OWNER_ELEMENT’ in ‘control.dat’ is -1.

*2) Type of the electric field (0: Horizontal electric field, 1: Tangential electric field) is needed only if the option of the keyword ‘ELEC_FIELD’ in ‘control.dat’ is -1.

*3) The format of the observed data of each frequency is described in the next slide

Impedance tensor (2/2)

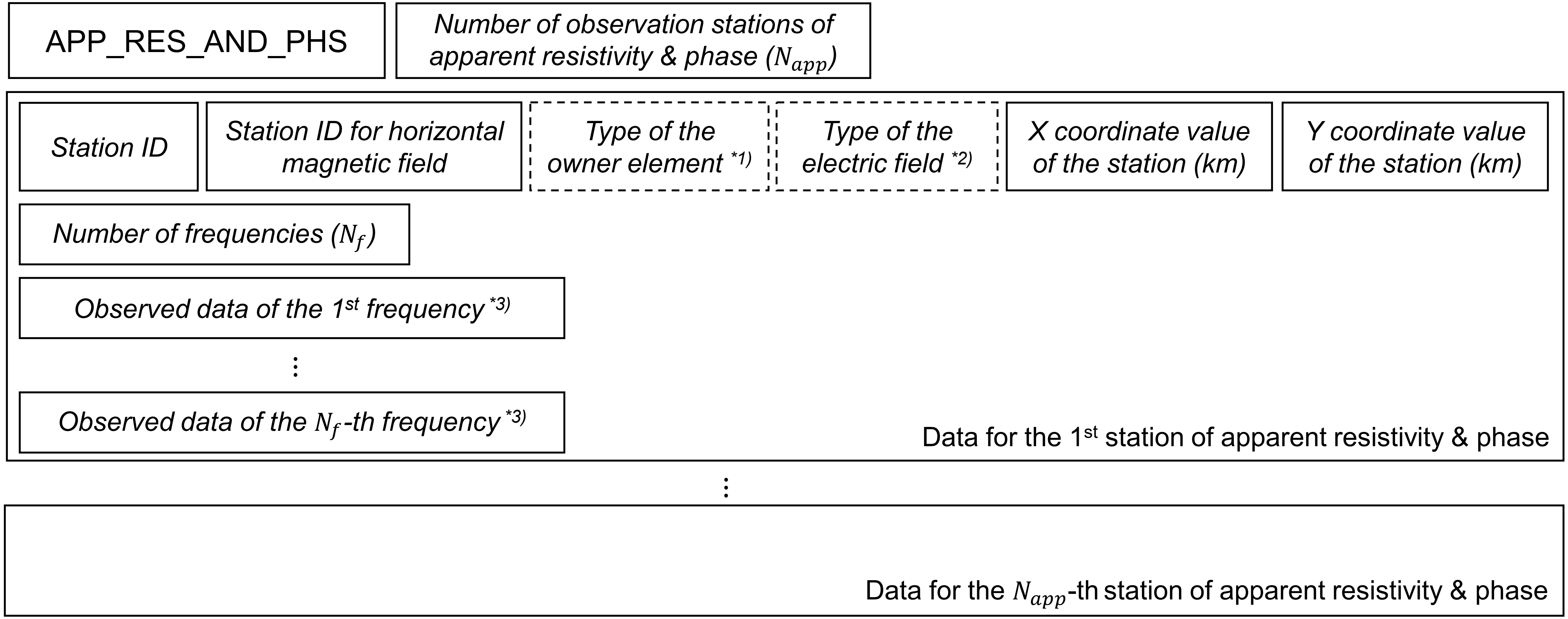
The format of the observed data of each frequency

Frequency(Hz) | *Re*(Z_{xx}) (V/A) | *Im*(Z_{xx}) (V/A) | *Re*(Z_{xy}) (V/A) | *Im*(Z_{xy}) (V/A) | *Re*(Z_{yx}) (V/A) | *Im*(Z_{yx}) (V/A) | *Re*(Z_{yy}) (V/A) | *Im*(Z_{yy}) (V/A)

SD of Re(Z_{xx}) | *SD of Im*(Z_{xx}) | *SD of Re*(Z_{xy}) | *SD of Im*(Z_{xy})

SD of Re(Z_{yx}) | *SD of Im*(Z_{yx}) | *SD of Re*(Z_{yy}) | *SD of Im*(Z_{yy})

Apparent resistivity & phase (1/2)



APP_RES_AND_PHS

Number of observation stations of apparent resistivity & phase (N_{app})

Station ID

Station ID for horizontal magnetic field

Type of the owner element [*1)]

Type of the electric field [*2)]

X coordinate value of the station (km)

Y coordinate value of the station (km)

Number of frequencies (N_f)

Observed data of the 1st frequency [*3)]

⋮

Observed data of the N_f-th frequency [*3)]

Data for the 1st station of apparent resistivity & phase

⋮

Data for the N_{app}-th station of apparent resistivity & phase

*1) Type of the owner element (0: Downward element, 1: Upward element) is needed only if the option of the keyword ‘OWNER_ELEMENT’ in ‘control.dat’ is -1.

*2) Type of the electric field (0: Horizontal electric field, 1: Tangential electric field) is needed only if the option of the keyword ‘ELEC_FIELD’ in ‘control.dat’ is -1.

*3) The format of the observed data of each frequency is described in the next slide

Apparent resistivity & phase (2/2)

The format of the observed data of each frequency

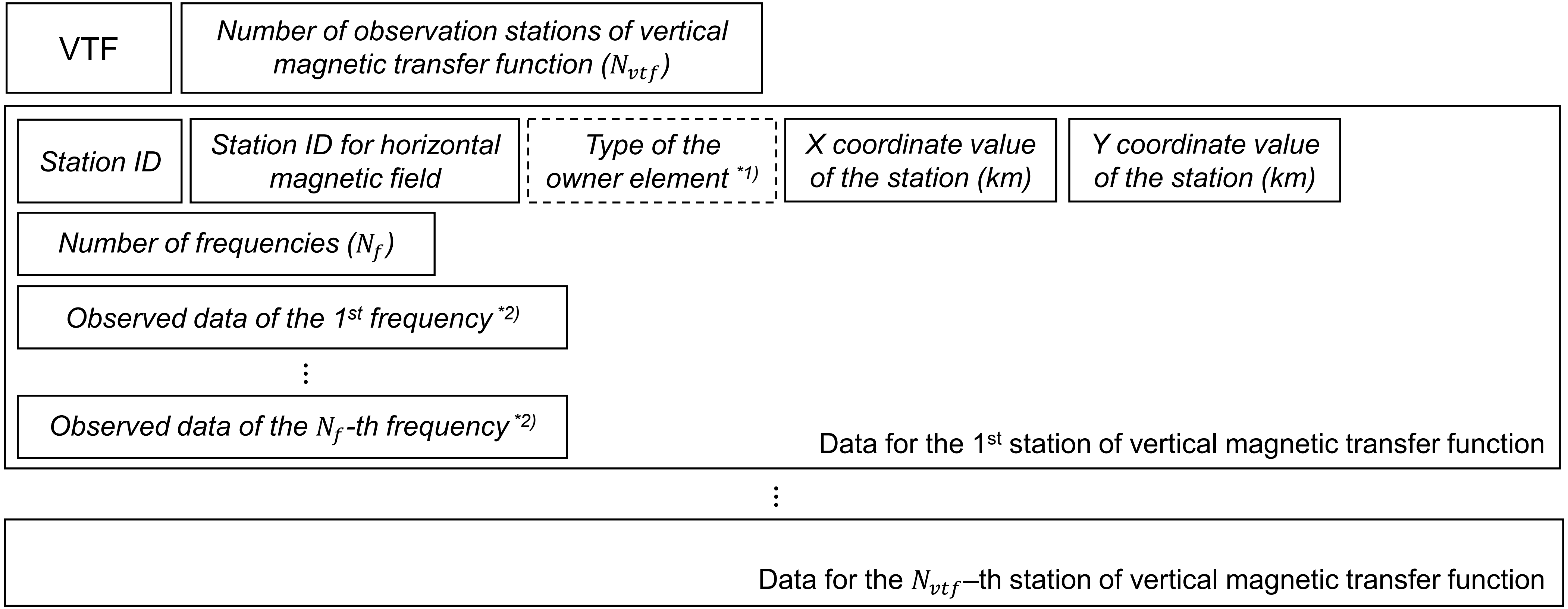
Frequency(Hz) $\rho_{a,xx}$ $(\Omega\mathrm{m})$ θ_{xx} $(deg.)$ $\rho_{a,xy}$ $(\Omega\mathrm{m})$ θ_{xy} $(deg.)$ $\rho_{a,yx}$ $(\Omega\mathrm{m})$ θ_{yx} $(deg.)$ $\rho_{a,yy}$ $(\Omega\mathrm{m})$ θ_{yy} $(deg.)$

SD of $\rho_{a,xx}$ *SD of* θ_{xx} *SD of* $\rho_{a,xy}$ *SD of* θ_{xy}

SD of $\rho_{a,yx}$ *SD of* θ_{yx} *SD of* $\rho_{a,yy}$ *SD of* θ_{yy}

If SD is negative, the corresponding component is not used in the inversion.

Vertical magnetic transfer function (1/2)



VTF

Number of observation stations of vertical magnetic transfer function (N_{vtf})

Station ID

Station ID for horizontal magnetic field

Type of the owner element *1)

X coordinate value of the station (km)

Y coordinate value of the station (km)

Number of frequencies (N_f)

Observed data of the 1st frequency *2)

⋮

Observed data of the N_f-th frequency *2)

Data for the 1st station of vertical magnetic transfer function

⋮

Data for the N_{vtf}–th station of vertical magnetic transfer function

*1) Type of the owner element (0: Downward element, 1: Upward element) is needed only if the option of the keyword ‘OWNER_ELEMENT’ in ‘control.dat’ is -1.

*2) The format of the observed data of each frequency is described in the next slide

Vertical magnetic transfer function (2/2)

The format of the observed data of each frequency

Frequency(Hz)	*Re*(T_{zx})	*Im*(T_{zx})	*Re*(T_{zy})	*Im*(T_{zy})	*SD of Re*(T_{zx})	*SD of Im*(T_{zx})	*SD of Re*(T_{zy})	*SD of Im*(T_{zy})

Horizontal magnetic transfer function (1/2)

HTF | *Number of observation stations of horizontal magnetic transfer function (N_{htf})*

Station ID for the output-side horizontal magnetic field | *Station ID for the input-side horizontal magnetic field* | *Type of the owner element* *1) | *X coordinate value of the station (km)* | *Y coordinate value of the station (km)*

Number of frequencies (N_f)

Observed data of the 1st frequency *2)

⋮

Observed data of the N_f-th frequency *2)

Data for the 1st station of horizontal magnetic transfer function

⋮

Data for the N_{htf}–th station of horizontal magnetic transfer function

*1) Type of the owner element (0: Downward element, 1: Upward element) is needed only if the option of the keyword ‘OWNER_ELEMENT’ in ‘control.dat’ is -1.

*2) The format of the observed data of each frequency is described in the next slide

Horizontal magnetic transfer function(2/2)

The format of the observed data of each frequency

Frequency(Hz) | Re(T_{xx}) | Im(T_{xx}) | Re(T_{xy}) | Im(T_{xy}) | Re(T_{yx}) | Im(T_{yx}) | Re(T_{yy}) | Im(T_{yy})

SD of Re(T_{xx}) | SD of Im(T_{xx}) | SD of Re(T_{xy}) | SD of Im(T_{xy})

SD of Re(T_{yx}) | SD of Im(T_{yx}) | SD of Re(T_{yy}) | SD of Im(T_{yy})

Phase tensor (1/2)

PT

Number of observation stations of phase tensor (N_{pt})

Station ID

Station ID for horizontal magnetic field

Type of the owner element *1)

Type of the electric field *2)

X coordinate value of the station (km)

Y coordinate value of the station (km)

Number of frequencies (N_f)

Observed data of the 1st frequency *3)

⋮

Observed data of the N_f-th frequency *3)

Data for the 1st station of phase tensor

⋮

Data for the N_{pt}–th station of phase tensor

*1) Type of the owner element (0: Downward element, 1: Upward element) is needed only if the option of the keyword ‘OWNER_ELEMENT’ in ‘control.dat’ is -1.

*2) Type of the electric field (0: Horizontal electric field, 1: Tangential electric field) is needed only if the option of the keyword ‘ELEC_FIELD’ in ‘control.dat’ is -1.

*3) The format of the observed data of each frequency is described in the next slide

Phase tensor (2/2)

The format of the observed data of each frequency

Frequency(Hz)	Φ_{11}	Φ_{12}	Φ_{21}	Φ_{22}	*SD of Re*(Φ_{11})	*SD of Im*(Φ_{12})	*SD of Re*(Φ_{21})	*SD of Im*(Φ_{22})

Indication of the end of observation data

Observation data of impedance tensor

Observation data of apparent resistivity & phase

Observation data of vertical magnetic transfer function

Observation data of horizontal magnetic transfer function

Observation data of phase tensor

END

Keyword ‘END’ must be written at the end of observation data

File format of distortion_iter[Iter#].dat (1/3)

When keyword ‘DISTORTION’ is 1 (differences of distortion matrix and unit matrix are estimated),

Total number of observation stations of the impedance tensor and the apparent resistivity & phase (N)

Station ID	c'_{xx}	c'_{xy}	c'_{yx}	c'_{yy}	*0: Distortion matrix is not fixed, 1: Distortion matrix is fixed*

Data for the 1st station

⋮

Data for the *N*-th station

Distortion matrix: $\boldsymbol{Z}_{observed} = \begin{pmatrix} c_{xx} & c_{xy} \\ c_{yx} & c_{yy} \end{pmatrix} \boldsymbol{Z}_{regional}$

$$\underbrace{\begin{pmatrix} c'_{xx} & c'_{xy} \\ c'_{yx} & c'_{yy} \end{pmatrix}}_{\text{Model parameters}} = \begin{pmatrix} c_{xx} & c_{xy} \\ c_{yx} & c_{yy} \end{pmatrix} - \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \in \mathbb{R}^{2\times 2}$$

File format of distortion_iter[Iter#].dat (2/3)

When keyword ‘DISTORTION’ is 2 (both gains and rotations are estimated),

Total number of observation stations of the impedance tensor and the apparent resistivity & phase (N)

Station ID | G_x | G_y | $\beta_x(deg.)$ | $\beta_y(deg.)$ | *0: Distortion matrix is not fixed, 1: Distortion matrix is fixed*

Data for the 1st station

⋮

Data for the *N*-th station

Distortion matrix is decomposed as Smith (1995)

Distortion matrix: $$\boldsymbol{Z}_{observed} = \left(10^{G_x} \begin{pmatrix} cos\beta_x \\ sin\beta_x \end{pmatrix} \quad 10^{G_y} \begin{pmatrix} -sin\beta_y \\ cos\beta_y \end{pmatrix} \right) \boldsymbol{Z}_{regional}$$

Smith, J. T. (1995). Understanding telluric distortion matrices. Geophysical Journal International, 122(1), 219–226. https://doi.org/10.1111/j.1365-246X.1995.tb03549.x

File format of distortion_iter[Iter#].dat (3/3)

When keyword ‘DISTORTION’ is 3 (only gains are only estimated),

Total number of observation stations of the impedance tensor and the apparent resistivity & phase (N)

Station ID G_x G_y *0: Distortion matrix is not fixed, 1: Distortion matrix is fixed*

Data for the 1st station

⋮

Data for the *N*-th station

Distortion matrix: $\boldsymbol{Z}_{observed} = \begin{pmatrix} 10^{G_x} & 0 \\ 0 & 10^{G_y} \end{pmatrix} \boldsymbol{Z}_{regional}$

Output files

File name	Content
femtic_[PE#].log	Log information about calculation
femtic.cnv	Convergence of Gauss-Newton iteration
result_[PE#]_iter[Iter#].csv	Calculated response functions and observed response functions
resistivity_block_iter[Iter#].dat	Resistivity values obtained by the inversion
distortion_iter[Iter#].dat	Parameters of galvanic distortion obtained by the inversion

In the file names, [PE#] and [Iter#] indicate process number and iteration number, respectively.

Output files for the visualization with ParaView (1/4)

These output files can be read and visualized by ParaView (http://www.paraview.org/).

File name	Content
obs_loc.vtk	Locations of the observation stations used in the inversion
induction_arrow_[PE#]_iter[Iter#].vtk	Induction vector (Parkinson convention) at each station of the vertical magnetic transfer function
result.case	EnSight Gold case file
Mesh.geo	EnSight Gold geometry file
BlockIDs	IDs of parameter cells (EnSight Gold variable file format)
Resistivity.iter[Iter#]	Resistivity values (EnSight Gold variable file format)
ReE_Freq[Freq#]_ExPol.iter[Iter#]	Real part of the electric field for the Ex-polarization (EnSight Gold variable file format)
ImE_Freq[Freq#]_ExPol.iter[Iter#]	Imaginary part of the electric field for the Ex-polarization (EnSight Gold variable file format)

*1) In the file names, [PE#] and [Iter#] indicate process number and iteration number, respectively.

Output files for the visualization with ParaView (2/4)

These output files can be read and visualized by ParaView (http://www.paraview.org/).

File name	Content
ReE_Freq[Freq#]_EyPol.iter[Iter#]	Real part of the electric field for the Ey-polarization (EnSight Gold variable file format)
ImE_Freq[Freq#]_EyPol.iter[Iter#]	Imaginary part of the electric field for the Ey-polarization (EnSight Gold variable file format)
ReH_Freq[Freq#]_ExPol.iter[Iter#]	Real part of the magnetic field for the Ex-polarization (EnSight Gold variable file format)
ImH_Freq[Freq#]_ExPol.iter[Iter#]	Imaginary part of the magnetic field for the Ex-polarization (EnSight Gold variable file format)
ReH_Freq[Freq#]_EyPol.iter[Iter#]	Real part of the magnetic field for the Ey-polarization (EnSight Gold variable file format)
ImH_Freq[Freq#]_EyPol.iter[Iter#]	Imaginary part of the magnetic field for the Ey-polarization (EnSight Gold variable file format)
Rej_Freq[Freq#]_ExPol.iter[Iter#]	Real part of the electric current density for the Ex-polarization (EnSight Gold variable file format)

*1) In the file names, [PE#] and [Iter#] indicate process number and iteration number, respectively.

Output files for the visualization with ParaView (3/4)

These output files can be read and visualized by ParaView (http://www.paraview.org/).

File name	Content
Imj_Freq[Freq#]_ExPol.iter[Iter#]	Imaginary part of the electric current density for the Ex-polarization (EnSight Gold variable file format)
Rej_Freq[Freq#]_EyPol.iter[Iter#]	Real part of the electric current density for the Ey-polarization (EnSight Gold variable file format)
Imj_Freq[Freq#]_EyPol.iter[Iter#]	Imaginary part of the electric current density for the Ey-polarization (EnSight Gold variable file format)
Sensitivity.iter[Iter#]	Sensitivity (EnSight Gold variable file format) calculated as $$s_i = \sum_{j}^{N_d} \left| \frac{1}{\sigma_j} \frac{\partial d_j}{\partial\, log(\rho_i)} \right|$$ N_d : Number of the observation data *2) d_j : The *j*-th data σ_j : Standard deviation of the *j*-th data ρ_i : Resistivity at the *i*-th parameter cell
NormalizedSensitivity.iter[Iter#]	Normalized sensitivity (EnSight Gold variable file format) calculated as $$\overline{s_i} = s_i / \max_i s_i$$

*1) In the file names, [PE#] and [Iter#] indicate process number and iteration number, respectively.

*2) Real part and imaginary part of each response function are treated as different data.

Output files for the visualization with ParaView (4/4)

These output files can be read and visualized by ParaView (http://www.paraview.org/).

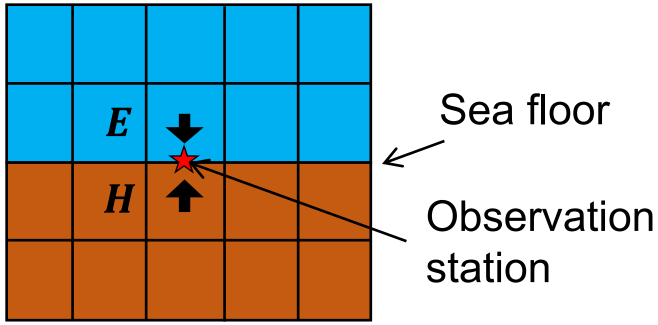
File name	Content
SensitivityDensity.iter[Iter#]	Sensitivity density (EnSight Gold variable file format) calculated as $$s'_i = \frac{1}{V_i} \sum_{j}^{N_d} \left| \frac{1}{\sigma_j} \frac{\partial d_j}{\partial\, log(\rho_i)} \right|$$ N_d : Number of the observation data *2) d_j : The *j*-th data σ_j : Standard deviation of the *j*-th data ρ_i : Resistivity at the *i*-th parameter cell V_i : Volume of the *i*-th parameter cell
NormalizedSensitivityDensity.iter[Iter#]	Normalized sensitivity (EnSight Gold variable file format) calculated as $$\overline{s'}_i = s'_i / \max_i s'_i$$
result_[PE#]_iter[Iter#].vtk	Output variables specified in ‘OUTPUT_PARAM’ (VTK file format (ASCII))

*1) In the file names, [PE#] and [Iter#] indicate process number and iteration number, respectively.

*2) Real part and imaginary part of each response function are treated as different data.

Things to be careful when seafloor MT data is used

- For seafloor MT stations, it is better to interpolate the electric field and the magnetic field from the upper-side and lower-side elements, respectively (Usui et al., 2018).
- However, the use of different elements for interpolating the electric field and the magnetic field needs a bit tricky setting.
- The required setting is as follows.



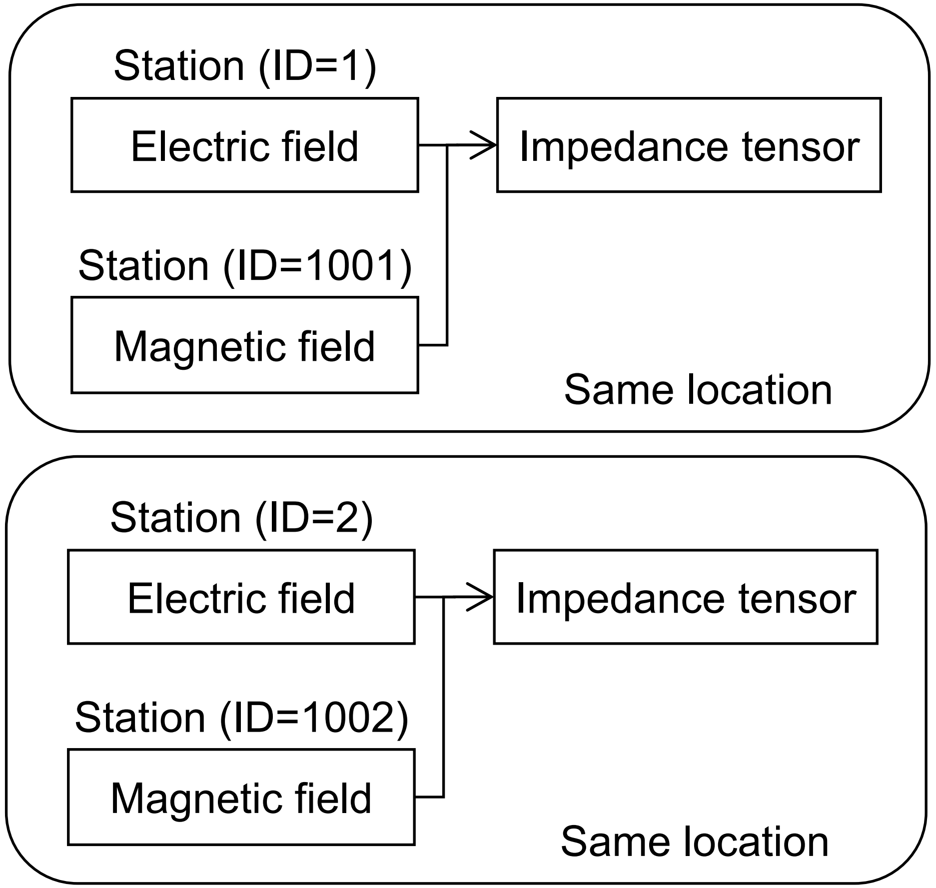
1. Set the option of the keyword ‘OWNER_ELEMENT’ of ‘control.dat’ to -1. By this setting, type of owner element can be individually selected for each element.
2. In ‘observe.dat’, add the dummy stations of the vertical magnetic transfer function or the horizontal magnetic transfer function at the same locations as seafloor MT stations. (If actually there are stations of the vertical magnetic transfer function or the horizontal magnetic transfer function on the same locations as the MT stations, you need not to add new dummy stations.)
3. For the dummy stations of magnetic transfer functions in ‘observe.dat’, set ‘Type of the owner element’ to 0 (element just below the seafloor is used for calculating the magnetic field)
4. For the seafloor MT stations in ‘observe.dat’, set ‘Type of the owner element’ to 1 (element just above the seafloor is used for calculating the electric field) and set ‘Station ID for horizontal magnetic field’ to the ID of the dummy station at the same location.

Things to be careful when seafloor MT data is used: Example

MT 2
1 1001 1   1.020000E+00 2.005000E+00
12
[*Observed data of the 1st frequency*]
…
[*Observed data of the 12-th frequency*]
2 1002 1   1.003330E+01 -9.004900E+01
12
[*Observed data of the 1st frequency*]
…
[*Observed data of the 12-th frequency*]

VTF 2
1001 1001 0   1.020000E+00 2.005000E+00
0
1002 1002 0   1.003330E+01 -9.004900E+01
0

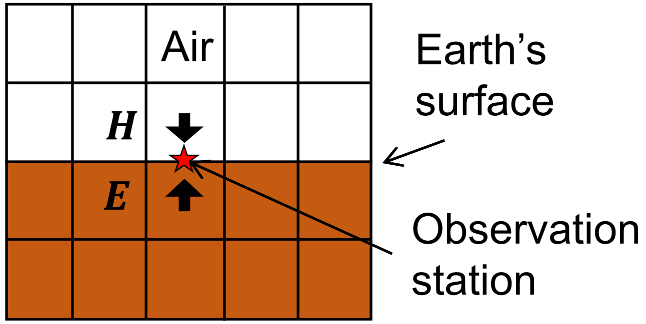
Dummy stations



Station (ID=1)
Electric field
Impedance tensor
Station (ID=1001)
Magnetic field
Same location

Station (ID=2)
Electric field
Impedance tensor
Station (ID=1002)
Magnetic field
Same location

How to improve response functions at high frequencies



- For land MT stations, it is better to interpolate the electric field and the magnetic field from the lower-side and upper-side elements, respectively.
- This is because the change of the magnetic field is smaller in the upper-side (in the air).
- Otherwise, it is possible that the amplitude of the impedance tensor is overestimated unless the size of the element just below MT station is not sufficiently small.
- The recommended setting is as follows.

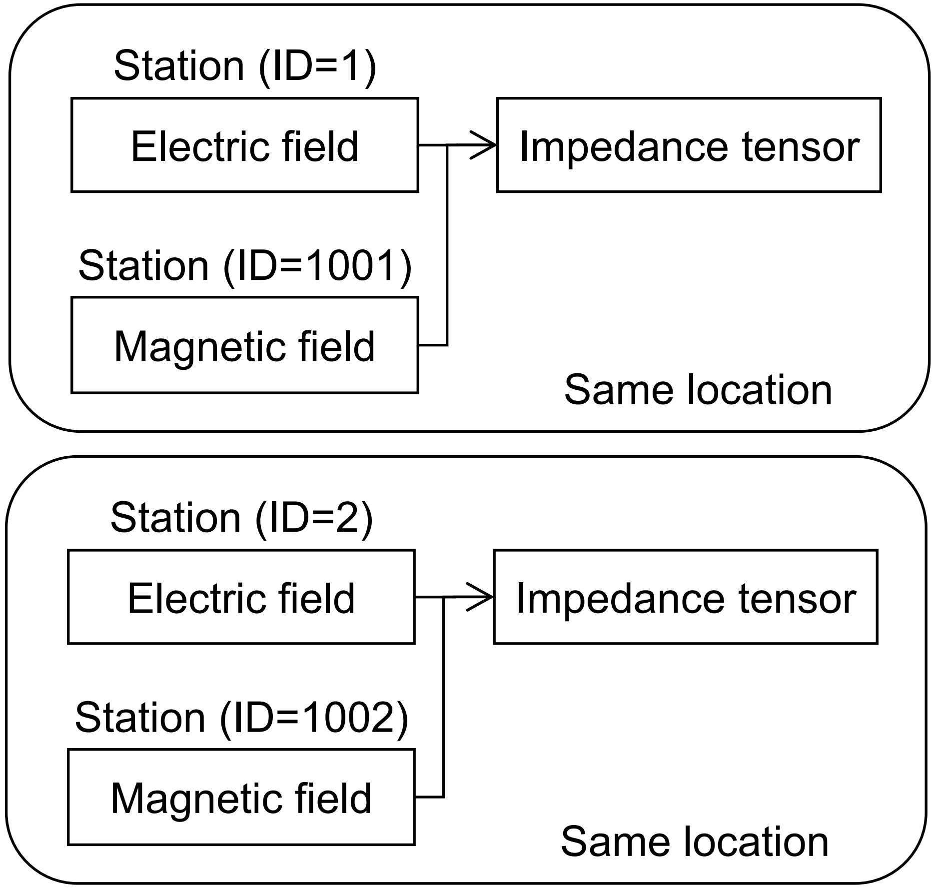
1. Set the option of the keyword 'OWNER_ELEMENT' of 'control.dat' to -1. By this setting, type of owner element can be individually selected for each element.
2. In 'observe.dat', add the dummy stations of the vertical magnetic transfer function or the horizontal magnetic transfer function at the same locations as land MT stations. (If actually there are stations of the vertical magnetic transfer function or the horizontal magnetic transfer function on the same locations as the MT stations, you need not to add new dummy stations.)
3. For the dummy stations of magnetic transfer functions in 'observe.dat', set 'Type of the owner element' to 1 (element just above the Earth's surface is used for calculating the magnetic field)
4. For the land MT stations in 'observe.dat', set 'Type of the owner element' to 0 (element just below the Earth's surface is used for calculating the electric field) and set 'Station ID for horizontal magnetic field' to the ID of the dummy station at the same location.

How to improve response functions at high frequencies: Example

MT 2
1 1001 0   1.020000E+00 2.005000E+00
12
[*Observed data of the 1st frequency*]
…
[*Observed data of the 12-th frequency*]
2 1002 0   1.003330E+01 -9.004900E+01
12
[*Observed data of the 1st frequency*]
…
[*Observed data of the 12-th frequency*]

VTF 2
1001 1001 1   1.020000E+00 2.005000E+00
0
1002 1002 1   1.003330E+01 -9.004900E+01
0

Dummy stations



Station (ID=1)
Electric field
Impedance tensor
Station (ID=1001)
Magnetic field
Same location

Station (ID=2)
Electric field
Impedance tensor
Station (ID=1002)
Magnetic field
Same location