Instructions for users

This document is to assist in using the modeling programs. These make the 3D modeling of the electric and magnetic fields of the *Marine Controlled Source Electromagnetic* (mCSEM) method, for a x-oriented electric dipole source. The modeling with the nodal methodology is found in the ***Fwd_mCSEM3D_nodal*** directory and with the vector one in ***Fwd_mCSEM3D_vector***. The programs were developed with the Fortran language. For correct execution, the following steps must be followed:

1 - MODEL:

1.1 – MESH:

The codes provided here make the 3D modeling of mCSEM fields with **unstructured tetrahedral meshes**. These programs are prepared to use meshes generated with the **Tetgen** program (http://wias-berlin.de/software/index.jsp?id=TetGen&lang=1), tested for version 5.1.

In the ***malha*** directory, present in both modeling programs, the files generated with Tetgen must be present. For example, if the user creates a model with the files *mcsem_canonical.poly* and *mcsem_canonical.mtr*, then for the correct execution of the programs, the ***malha*** directory must also contain the following files: mcsem_canonical.1.node, *mcsem_canonical.1.ele*, *mcsem_canonical.1.edge* and *mcsem_canonical.1.face.*

The meshes created for these programs must be built according to the following instructions: The values of the properties assigned to the mesh regions must be multiple numbers of 10 and follow an ascending sequence from it. For example, in the model in Fig. 1, which is widely used in the modeling of the mCSEM method, the first region that represents the **air** will have its elements (tetrahedrons) with properties equal to **10**, the second, which represents the **sea layer**, will have the property value equal to **20**, the third one representing a region below the water layer (**conductive half space**) will have the property value equal to **30** and the last one representing the **hydrocarbon reservoir** will have the property equal to **40**. In this model, the only region that represents a heterogeneity (source of secondary fields) is the reservoir (property 40), the others are associated with the 1D model that generates the primary fields. These property values can be assigned to the mesh regions as shown in Fig. 2, where a part of the "*mcsem_canonical.poly*" file that generated the model in Fig. 1 is shown.

The second model, shown in Fig. 3, has two regions of **heterogeneity** (sources of secondary fields). The first, which has a property value of 40, is an elevation of the conductive half space (**hill**), which has an electrical resistivity different from that of the sea layer. The second with 50, which represents the **reservoir**. The other regions, with properties 10, 20, and 30, represent air, sea and sediments, respectively. A part of the "*model_hill.poly*" file that generated the model in Fig. 3 can be seen in Fig. 4, where the region of attribution of model properties is shown.

It is important to inform that the assignment of these property values (10, 20, 30, 40, 50, ...) will not be the definitive values for those regions. The programs use these values as labels to assign the correct resistivities value to those regions, before generating the model fields. The numbering of these regions must always follow the following sequence: The air region must have the label 10, then the regions that are equivalent to the 1D model (air not included) must be numbered, with label values greater than the air (20 , 30, ...) and finally the regions of heterogeneities (..., 40, 50, ...). For example, the model in Fig. 1, with the exception of the air, has two layers, so the numbering of these regions must be 20 and 30, starting from the first layer that represents the sea layer. The same goes for the model in Fig. 3, if you create a 1D model with more layers, these regions must be numbered before numbering the heterogeneities. For example, imagine that the 1D model in the example has the structure of Fig. 5, so the numbering should follow the sequence shown there. Note that the numbering, starting in the air, starts to increase from the water layer and increases (always with multiples of 10), prioritizing the 1D layer model. In that model there are 4 layers (not including air) and a heterogeneity (reservoir) with label 50.

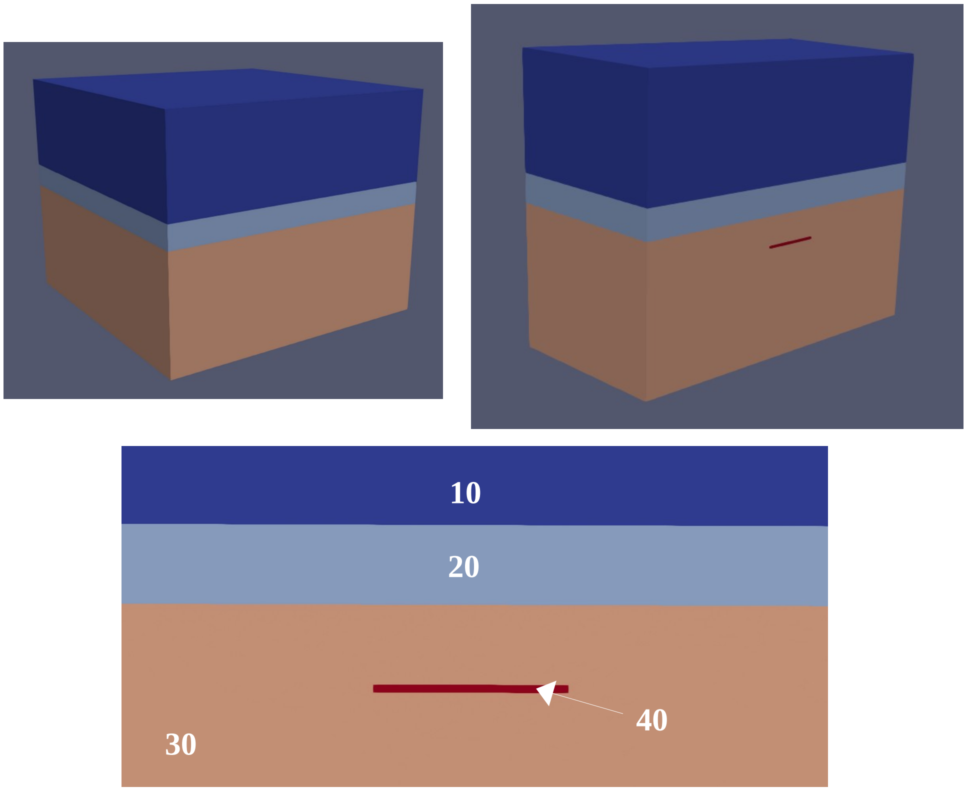
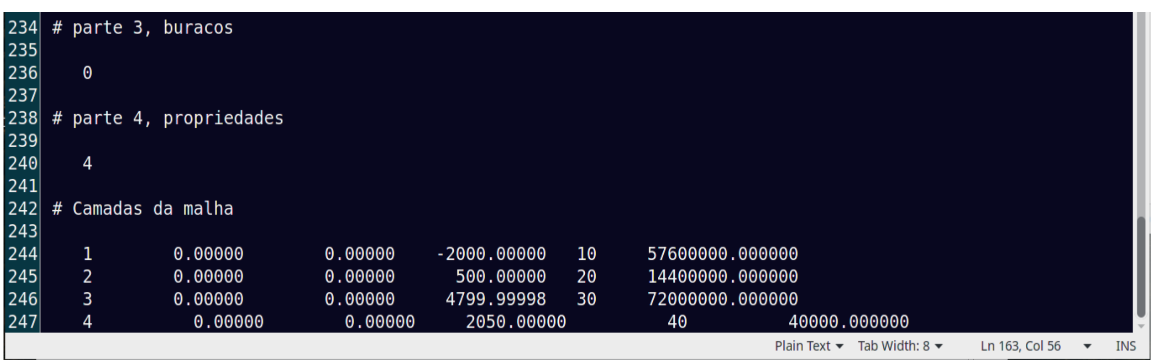


Figure 1: Example of a model for the correct execution of modeling programs ***Fwd_mCSEM3D_vector*** and ***Fwd_mCSEM3D_nodal***.



```
# parte 3, buracos

   0

# parte 4, propriedades

   4

# Camadas da malha

   1        0.00000        0.00000     -2000.00000    10      57600000.000000
   2        0.00000        0.00000       500.00000    20      14400000.000000
   3        0.00000        0.00000      4799.99998    30      72000000.000000
   4          0.00000        0.00000      2050.00000           40             40000.000000
```


Figure 2: Example of attribution of labels to the model in Fig. 1, in the properties region of the file “`mcsem_canonical.poly`”, which must be present in the ***malha*** directory, present in both modeling codes.

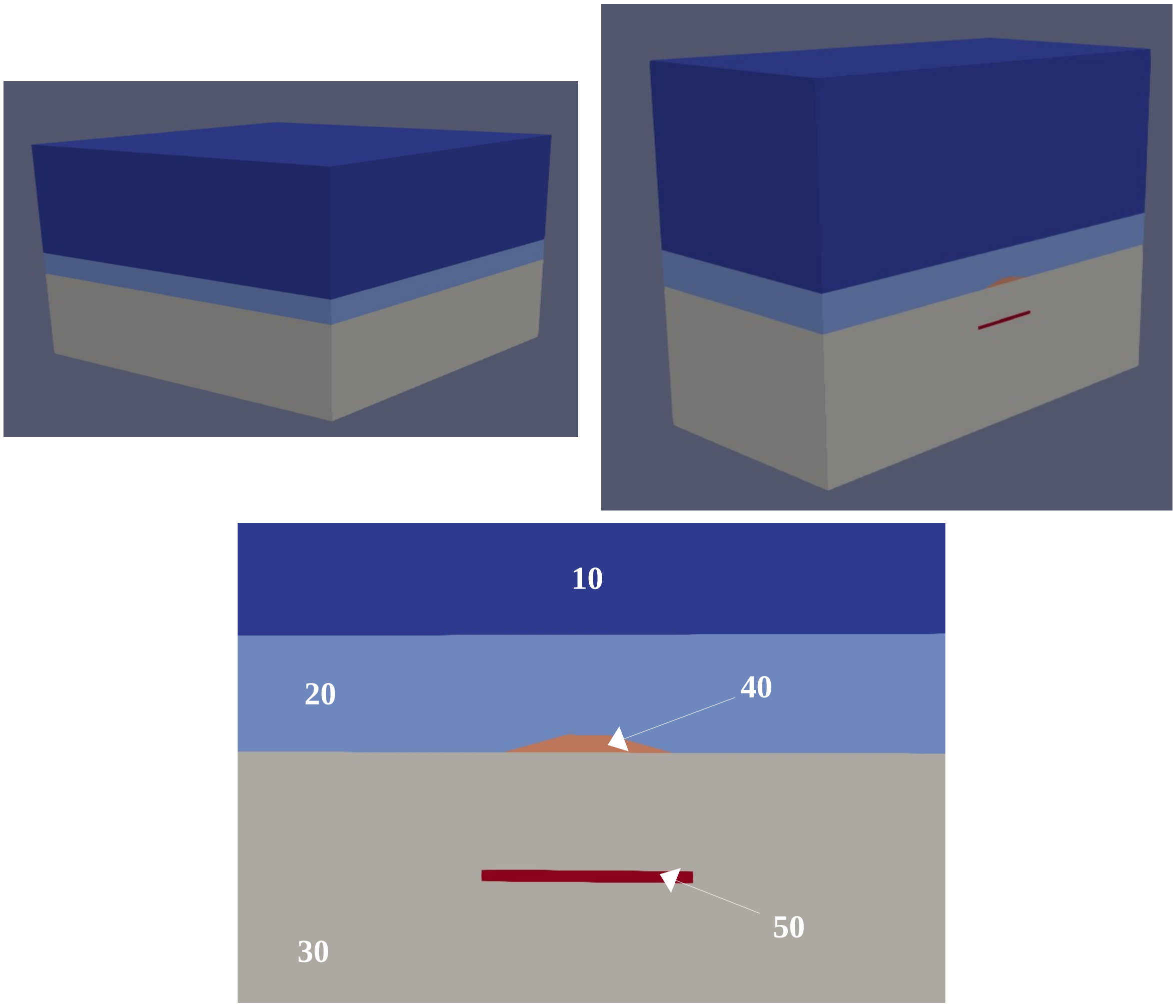


Figure 3: Second example model for running on modeling codes ***Fwd_mCSEM3D_vector*** and ***Fwd_mCSEM3D_nodal***.

```
# Buracos na malha

 0


# Atribuicao de propriedades

 5
 1        0.00000          0.00000      -2500.00000    10    36000000.0000000000
 2        0.00000          0.00000        500.00000    20    14400000.0000000000
 3        0.00000          0.00000       2500.00000    30    36000000.0000000000
 4        0.00000          0.00000        950.00000    40       25600.0000000000
 5        0.00000          0.00000       2050.00000    50       40000.0000000000

```

Figure 4: Example of attribution of labels to the model in Fig. 3, in the properties region of the file "`model_hill.poly`", which must be present in the ***malha*** directory, present in both modeling codes.

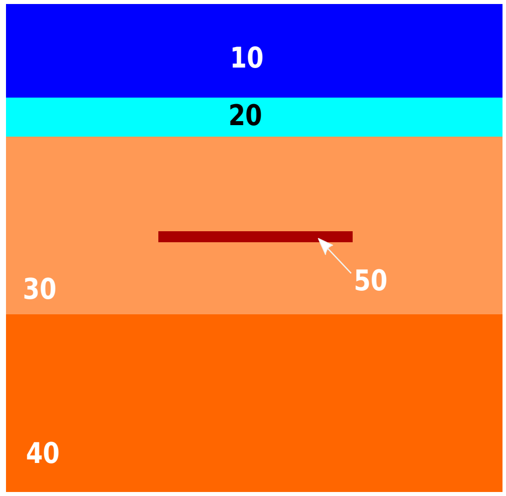
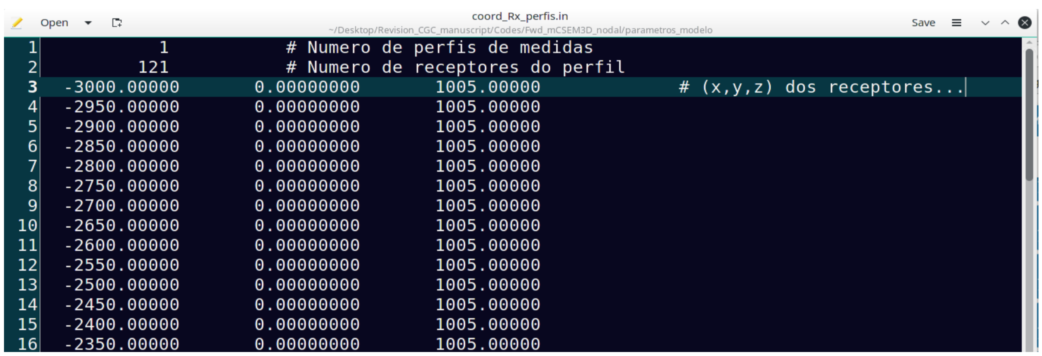


Figure 5: Example with the presence of a layer more than the model in Fig. 1 and how the attribution of labels to its regions should be done.

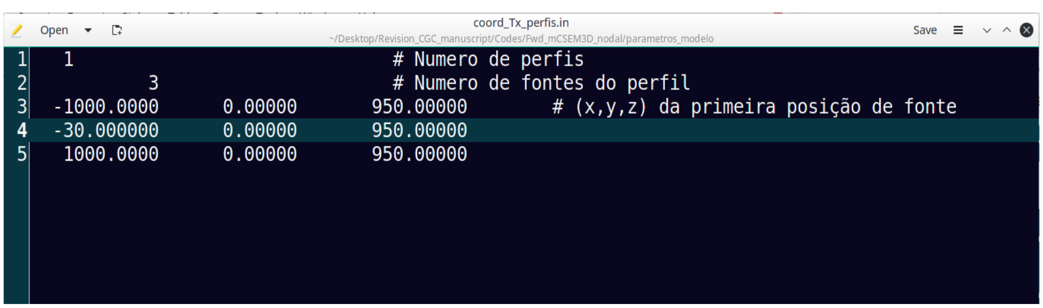
1.2 – POSITIONS OF SOURCES AND RECEIVERS:

a)




```
1                 1        # Numero de perfis de medidas
2               121        # Numero de receptores do perfil
3   -3000.00000    0.00000000    1005.00000        # (x,y,z) dos receptores...
4   -2950.00000    0.00000000    1005.00000
5   -2900.00000    0.00000000    1005.00000
6   -2850.00000    0.00000000    1005.00000
7   -2800.00000    0.00000000    1005.00000
8   -2750.00000    0.00000000    1005.00000
9   -2700.00000    0.00000000    1005.00000
10  -2650.00000    0.00000000    1005.00000
11  -2600.00000    0.00000000    1005.00000
12  -2550.00000    0.00000000    1005.00000
13  -2500.00000    0.00000000    1005.00000
14  -2450.00000    0.00000000    1005.00000
15  -2400.00000    0.00000000    1005.00000
16  -2350.00000    0.00000000    1005.00000
```

b)




```
1   1                                   # Numero de perfis
2           3                           # Numero de fontes do perfil
3   -1000.0000     0.00000    950.00000        # (x,y,z) da primeira posição de fonte
4   -30.000000     0.00000    950.00000
5   1000.0000      0.00000    950.00000
```

Figure 6: Examples of files `coord_Tx_perfis.in` (figure b)) and `coord_Rx_perfis.in`, (figure a)) where the positions of the sources and receivers are placed, respectively.

The positions of sources and receivers, for the calculation of the secondary and primary electric and magnetic fields, can be informed in the files `coord_Tx_perfis.in` and `coord_Rx_perfis.in`, present in the directory ***parametros_modelo***, contained in the two modeling programs. They are written as shown in Fig. 6. The first line of both indicates the number of measurement profiles. The second, in the file `coord_Rx_perfis.in`, indicates the number of receivers of the first (and only) profile and in the file `coord_Tx_perfis.in`, the number of positions of sources of the same measurement profile. From the third line onwards, in the file `coord_Rx_perfis.in` , the coordinates (x,y,z) of the positions of the receivers are informed and in the file `coord_Tx_perfis.in`, the coordinates (x,y,z) of the positions of the field sources. In the example in Fig. 6, the model has only one measurement profile that has 121 receivers and 3 source positions. If you want to create a file with more than one measurement profile, follow the sequence below:

In the file *coord_Rx_perfis.in:*

```
Np              # Number of measurement profiles
nRx1              # Number of receivers from the first profile
x1   y1   z1      # Coordinates of the first receiver of the first profile
x2   y2   z2
x3   y3   z3
x4   y4   z4
.
.
.

nRx2              # Number of receivers from the second profile
x1   y1   z1      # Coordinates of the first receiver of the second profile
x2   y2   z2
x3   y3   z3
x4   y4   z4
.
.
.

nRx3              # Number of receivers from the third profile
x1   y1   z1      # Coordinates of the first receiver of the third profile
x2   y2   z2
x3   y3   z3
x4   y4   z4
.
.
.
```

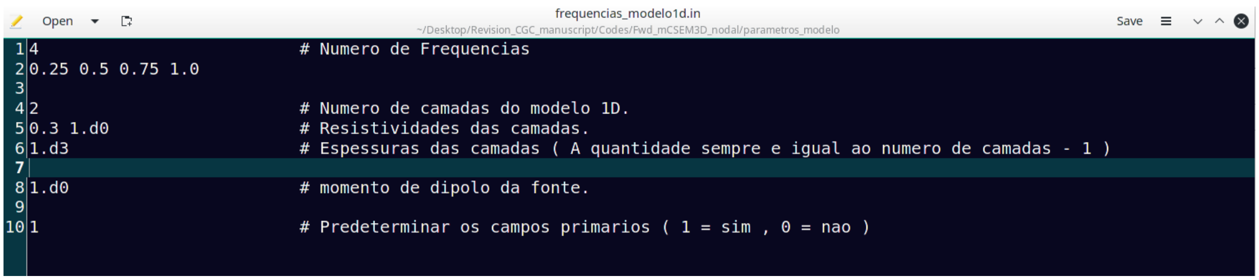
In the file *coord_Tx_perfis.in:*

```
Np              # Number of measurement profiles
nTx1              # Number of sources from the first profile
x1   y1   z1      # Coordinates of the first source of the first profile
x2   y2   z2
x3   y3   z3
x4   y4   z4
.
.
.

nTx2              # Number of sources from the second profile
x1   y1   z1      # Coordinates of the first source of the second profile
x2   y2   z2
x3   y3   z3
x4   y4   z4
.
.
```

```
.

nTx3                # Number of sources from the third profile
x1  y1  z1          # Coordinates of the first source of the third profile
x2  y2  z2
x3  y3  z3
x4  y4  z4
.
.
.
```

2 – 1D MODEL AND HETEROGENEITIES:

2.1 – 1D MODEL:



```
frequencias_modelo1d.in
~/Desktop/Revision_CGC_manuscript/Codes/Fwd_mCSEM3D_nodal/parametros_modelo
4                          # Numero de Frequencias
0.25 0.5 0.75 1.0

2                          # Numero de camadas do modelo 1D.
0.3 1.d0                   # Resistividades das camadas.
1.d3                       # Espessuras das camadas ( A quantidade sempre e igual ao numero de camadas - 1 )

1.d0                       # momento de dipolo da fonte.

1                          # Predeterminar os campos primarios ( 1 = sim , 0 = nao )
```

Figure 7: Example of the file `frequencias_modelo1d.in`, where the 1D model is configured and the frequencies that will be calculated in the primary and secondary fields.

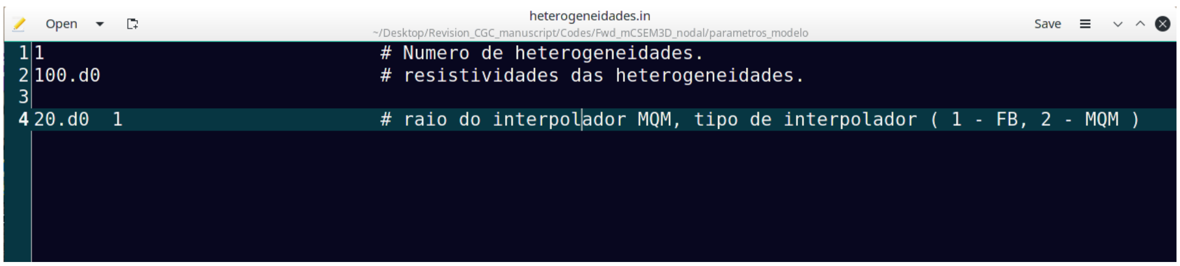
In the `frequencias_modelo1d.in` file, shown in Fig. 7, contained in the ***parametros_modelo*** directory, it is possible to configure the information of the 1D modeling and also choose the number of frequencies to generate the fields (primary and secondary). In the example in Fig. 7, the fields will be generated for 4 frequencies (line 1), which are `0.25, 0.5, 0.75` and `1.0 Hz` (line 2). The 1D model will have two layers (line 4), their resistivities will be `0.3` and `1 Ohm-m` (line 5). The thickness of the first layers must always be informed, the last will always be an infinite semi-space and its thickness is not informed. As in the model in Fig.7 there are only two layers, only the thickness of the first layer is informed, which is `1000 m` (line 6). In line 8, the dipole moment of the source is informed, which in the case of the example is `1 Am`. In line 10, the first number informs whether the primary field of the model is to be pre-calculated. With a value of 1, it is calculated and with a value of 0, no. If the modeling is done more than once with the same model, it is enough to pre-calculate the primary fields once.

2.2 - RESISTIVITIES OF HETEROGENEITIES AND CHOICE OF THE INTERPOLATOR:

In the file `heterogeneidades.in` (Fig. 8), present in the directory paramatros_modelo, we assign values for the resistivities of the model heterogeneities and choose the interpolator for the field measurements in the positions of the receivers. In the example in Fig. 8, the model has 1 heterogeneity (line 1) and its resistivity is `100 Ohm-m`. The file in Fig. 8 could be used in the model in Fig. 1, which has only one heterogeneity with a resistivity value of `100 Ohm-m`. For the model in Fig. 3, the file heterogeneidades.in could be edited as follows:

```
2                 # number of heterogeneities
1.d0 100.d0       # resistivities of heterogeneities
20.d0 1           # radius for interpolator MQM, interpolator type ( 1-FB,  2-MQM )
```

In this case there are two heterogeneities, the first with `1 Ohm-m` (hill) and the second with `100 Ohm-m` (reservoir), the chosen interpolator is FB, due to the value 1 in line 4. In line 4, some information is passed to the program regarding the choice of the interpolator that will be used to calculate the secondary fields in the measurement positions, contained in the file *coord_Rx_perfis.in*. In the programs it is possible to choose two types of interpolators. The first, here called **FB**, searches which element (tetrahedron) contains a certain measurement position and then interpolates the components of the secondary fields with the linear base functions of that element, at that position. The second is an interpolator that uses the *Moving Least Squares* technique, here called **MQM**, and calculates each component of the secondary fields at the measurement positions, with the information contained in a spherical region of radius *r*, centered on the measurement position. In Fig. 8, line 4 of the file *heterogeneidades.in*, the first value is the radius used by the **MQM** interpolator. If the numbering that is there is 1, the chosen interpolator will be **FB**, if it is 2, it will be **MQM**.




```
1 1                          # Numero de heterogeneidades.
2 100.d0                     # resistividades das heterogeneidades.
3
4 20.d0  1                   # raio do interpolador MQM, tipo de interpolador ( 1 - FB, 2 - MQM )
```

Figure 8: Example of the file *heterogeneidades.in*, where the resistivities of the heterogeneities are assigned and the interpolator that will be used to calculate the secondary fields in the receiver positions is chosen.

3 - COMPILING THE CODE:

Your computer must have the **MPI** (Message Passing interface) libraries installed, configured with the intel **fortran** compiler, with the **Pardiso** libraries included. To compile the codes contained in the ***Fwd_mCSEM3D_nodal*** directory, for example, and generate the executable **mcsem3D.nod**, it is necessary to use the `Make_compile` file contained therein. To do this, just open a command line, in the directory, and type:

make -f Make_compile

The same goes for the ***Fwd_mCSEM3D_vector*** directory, where the executable **mcsem3D.vec** will be generated.

4 - RUNNING THE CODES:

To run the executable present in the ***Fwd_mCSEM3D_vector*** directory, for example, just type the following command in a terminal:

mpiexec -n np ./mcsem3D.vec model

where *np* is the number of MPI processes and *model* is the name of the *model.poly* file contained in the ***malha*** directory. Remembering that the files *modelo.1.ele*, *modelo.1.node*, *modelo.1.edge*, *modelo.1.face*, among others generated with Tetgen, they must be contained in the same directory. The same goes for the executable present in the ***Fwd_mCSEM3D_nodal*** directory.

The programs are parallelized with the MPI libraries in the number of frequencies, so if your computer has computational capacity it is possible to calculate them in parallel. For example, if the model that you want to generate the data will calculate the fields for 4 frequencies, then it is possible to calculate them with 4 MPI processes, using the following command (in the vector code formulation):

```
mpiexec -n 4 ./mcsem3D.vec model
```

5 - DATA OUTPUT:

In the ***output*** directory are the files `Eprimario.dat`, `Esecundario.dat`, `Hprimario.dat` and `Hsecundario.dat` which are the outputs of the programs. These files keep the primary and secondary, Electrical and Magnetic fields generated with the modeling. These files have the fields distributed following the sequence: Frequency, profile, source and receivers. For example, considering the case of a model with 2 frequencies, 2 measurement profiles, 2 field sources and 10 receivers in each profile, the `Esecundario.dat` file, for example, would have the following structure:

```
# frequency 1, profile 1, source 1 (This line does not exist in the file...)
real Ex1   imag Ex1   real Ey1   imag Ey1   real Ez1   imag Ez1          # receiver 1
real Ex2   imag Ex2   real Ey2   imag Ey2   real Ez2   imag Ez2          # receiver 2
real Ex3   imag Ex3   real Ey3   imag Ey3   real Ez3   imag Ez3          # receiver 3
   .       .       .       .       .       .
   .       .       .       .       .       .
   .       .       .       .       .       .
real Ex10   imag Ex10   real Ey10 imag Ey10   real Ez10   imag Ez10      # receiver 10

# frequency 1, profile 1, source 2 (This line does not exist in the file...)
real Ex1   imag Ex1   real Ey1   imag Ey1   real Ez1   imag Ez1          # receiver 1
real Ex2   imag Ex2   real Ey2   imag Ey2   real Ez2   imag Ez2          # receiver 2
real Ex3   imag Ex3   real Ey3   imag Ey3   real Ez3   imag Ez3          # receiver 3
   .       .       .       .       .       .
   .       .       .       .       .       .
   .       .       .       .       .       .
real Ex10   imag Ex10   real Ey10 imag Ey10   real Ez10   imag Ez10      # receiver 10

# frequency 1, profile 2, source 1 (This line does not exist in the file...)
real Ex1   imag Ex1   real Ey1   imag Ey1   real Ez1   imag Ez1          # receiver 1
real Ex2   imag Ex2   real Ey2   imag Ey2   real Ez2   imag Ez2          # receiver 2
real Ex3   imag Ex3   real Ey3   imag Ey3   real Ez3   imag Ez3          # receiver 3
   .       .       .       .       .       .
   .       .       .       .       .       .
   .       .       .       .       .       .
real Ex10   imag Ex10   real Ey10 imag Ey10   real Ez10   imag Ez10      # receiver 10

# frequency 1, profile 2, source 2 (This line does not exist in the file...)
real Ex1   imag Ex1   real Ey1   imag Ey1   real Ez1   imag Ez1          # receiver 1
real Ex2   imag Ex2   real Ey2   imag Ey2   real Ez2   imag Ez2          # receiver 2
real Ex3   imag Ex3   real Ey3   imag Ey3   real Ez3   imag Ez3          # receiver 3
   .       .       .       .       .       .
   .       .       .       .       .       .
   .       .       .       .       .       .
real Ex10   imag Ex10   real Ey10 imag Ey10   real Ez10   imag Ez10      # receiver 10

# frequency 2, profile 1, source 1 (This line does not exist in the file...)
real Ex1   imag Ex1   real Ey1   imag Ey1   real Ez1   imag Ez1          # receiver 1
real Ex2   imag Ex2   real Ey2   imag Ey2   real Ez2   imag Ez2          # receiver 2
real Ex3   imag Ex3   real Ey3   imag Ey3   real Ez3   imag Ez3          # receiver 3
   .       .       .       .       .       .
   .       .       .       .       .       .
   .       .       .       .       .       .
real Ex10   imag Ex10   real Ey10 imag Ey10   real Ez10   imag Ez10      # receiver 10
```

frequency 2, profile 1, source 2 (This line does not exist in the file...)
```
real Ex1   imag Ex1   real Ey1   imag Ey1   real Ez1   imag Ez1            # receiver 1
real Ex2   imag Ex2   real Ey2   imag Ey2   real Ez2   imag Ez2            # receiver 2
real Ex3   imag Ex3   real Ey3   imag Ey3   real Ez3   imag Ez3            # receiver 3
   .       .        .        .        .       .
   .       .        .        .        .       .
   .       .        .        .        .       .
real Ex10  imag Ex10  real Ey10 imag Ey10  real Ez10  imag Ez10      # receiver 10
```

frequency 2, profile 2, source 1 (This line does not exist in the file...)
```
real Ex1   imag Ex1   real Ey1   imag Ey1   real Ez1   imag Ez1            # receiver 1
real Ex2   imag Ex2   real Ey2   imag Ey2   real Ez2   imag Ez2            # receiver 2
real Ex3   imag Ex3   real Ey3   imag Ey3   real Ez3   imag Ez3            # receiver 3
   .       .        .        .        .       .
   .       .        .        .        .       .
   .       .        .        .        .       .
real Ex10  imag Ex10  real Ey10 imag Ey10  real Ez10  imag Ez10      # receiver 10
```

frequency 2, profile 2, source 2 (This line does not exist in the file...)
```
real Ex1   imag Ex1   real Ey1   imag Ey1   real Ez1   imag Ez1            # receiver 1
real Ex2   imag Ex2   real Ey2   imag Ey2   real Ez2   imag Ez2            # receiver 2
real Ex3   imag Ex3   real Ey3   imag Ey3   real Ez3   imag Ez3            # receiver 3
   .       .        .        .        .       .
   .       .        .        .        .       .
   .       .        .        .        .       .
real Ex10  imag Ex10  real Ey10 imag Ey10  real Ez10  imag Ez10      # receiver 10
```

5 – TEST MODEL:

In the ***malha*** directory of the modeling programs are the files `model_hill.poly` and `model_hill.mtr`, which generate the mesh of the model in Fig. 3. In this there is only one measurement profile, with 131 receivers and a source position at `(0,0,800) m`. The fields were generated for the frequency `0.25 Hz`. The files `frequencias_modelo1d.in`, `heterogeneidades.in`, `coord_Rx_perfis.in` and `coord_Tx_perfis.in` are configured for this model.