

Magnetotelluric Impedance Tensor Tools (MITT)

User Guide

September, 2018

Ivan Romero-Ruiz¹ and Jaume Pous¹

¹ *Departament de Dinàmica de la Terra i de l'Oceà, Universitat de Barcelona, Martí i Franquès, s/n, 08028 Barcelona, Spain. (ivanromeroruiz@gmail.com; jpous@ub.edu)*

Introduction

This manual is a first draft to guide the practitioner through MITT program. MITT program is mainly constituted by four blocks: 1- Magnetotelluric impedance tensor representation (Apparent resistivity and phase curves, Impedance tensor and Mohr diagrams); 2-Probability Density Functions of different indexes which account for the dimensionality; 3- Perturbed Method to determine the 'Phase Sensitive strike angle' for 2D; 4- Galvanic Distortion tools for obtaining the galvanic distortion (with the exception of the gain) in a general 2D/3D case. Given that the distortion parameters cannot be determined, the method is based on a constrained stochastic heuristic method, which consists of exploring randomly the full space of the distortion parameters. The constraints imposed assume the 2D (or 1D) tendency for the shortest periods of the regional impedance tensor. In this way a unique solution fulfilling the constraints is obtained. The method is based on Romero-Ruiz and Pous (2018 a,b).

Requirements

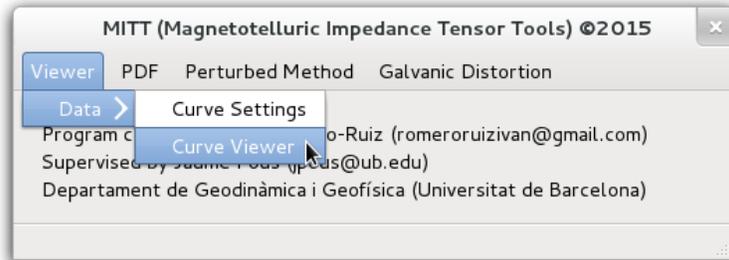
MITT program is constituted by a set of programs to analyze the impedance tensor, accordingly an edit file is needed. MITT program has been written in Python 2.7 and the following modules are required:

- PyQt: PyQt is one of the two most popular Python bindings for the Qt cross-platform GUI/XML/SQL C++ framework (<http://pyqt.sourceforge.net/>). We used PyQt4.
- Pygame: is a set of Python modules designed for writing games (<http://pygame.org>).
- NumPy: is the fundamental package for scientific computing with Python (<http://www.numpy.org/>).
- SciPy: is a Python-based ecosystem of open-source software for mathematics, science, and engineering (<http://www.scipy.org/>).
- matplotlib: is a plotting library which produces publication quality figures in a variety of hardcopy formats and interactive environments across platforms (<http://matplotlib.org/>).

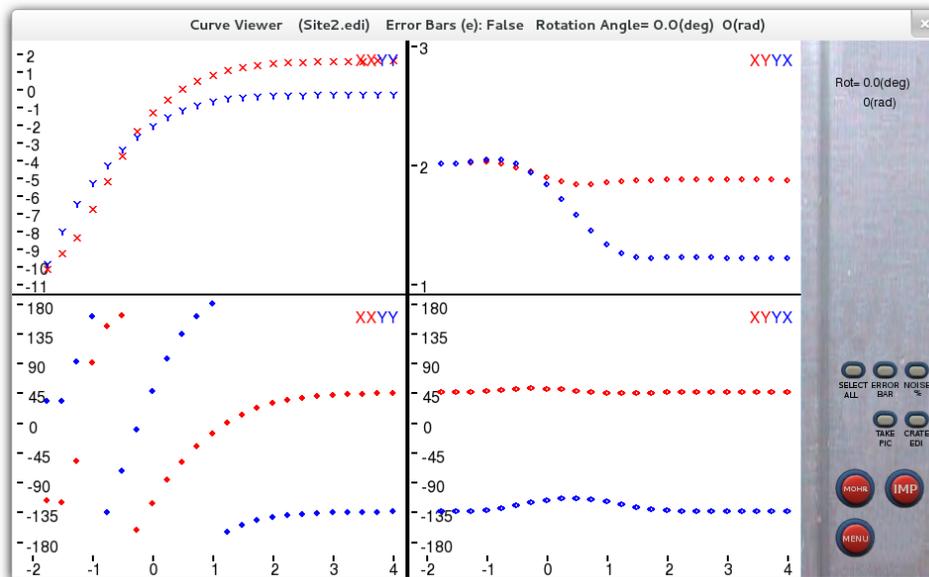
The program has only been tested in Linux OS.

Block 1: Magnetotelluric Impedance tensor representation

MITT allows to draw different representations of the impedance tensor. After launched the program (python GUIDIS.pyc) select the **Viewer** menu and then the **Viewer/Data/Curve Viewer** sub-menu.



Next choose the edi file in the EDIS folder. Taking Site2.edi the apparent resistivity curves and phases appear



Ordinates of upper panels are log of apparent resistivities (Ωm) and ordinates of lower panels are phases (deg). The abscissa are log of periods (s).

At the same time some information about the impedance tensor for each period appears in the terminal:

 (Site2)

=====
 PERIOD 0.017782794897 ** 1D Case **
 =====

Cl3 Clifford Algebra Decomposition:

$$1/2*[S1R + S1I e123 + D1R e1 + D1I e23 + S2R e2 + S2I e31 + D2R e12 - D2I e3] =$$

$$=1/2*[+8.993527e-05 -2.366346e-05e123 -0.00021656993e1 -0.00020995574e23 +0.2009e2 -0.0441e31 +237.4163e12 -237.2923e3]$$

Bahr Phase Sensitive Strike = 0.000760885978431 (-89.999239114)

$$\Lambda+ = 0.00368288357628 \quad N_i^{\wedge}R+N_i^{\wedge}I = 0.00368290247774 \quad \%1 = 5.13221868392e-06$$

$$\Lambda- = -0.00583892975665 \quad N_i^{\wedge}R-N_i^{\wedge}I = -0.00583889978983 \quad \%1 = 5.13224502373e-06$$

Index 1: atan(ϕ_{12}/ϕ_0) = 4.77612839034e-07

$$\Gamma+ = 2.79085489787e-07 \quad Q_i^{\wedge}R+Q_i^{\wedge}I = 2.79085489787e-07 \quad \%1 = 3.77481906692e-14$$

$$\Gamma- = 4.78531152373e-07 \quad Q_i^{\wedge}R-Q_i^{\wedge}I = 4.78531152373e-07 \quad \%1 = 3.78352154458e-14$$

Index 2: sqrt($\phi_1^2+\phi_2^2$)/ sqrt($\phi_{12}^2+\phi_0^2$) = 0.00103203952908

$$\Omega+ = 0.00103204245162 \quad P_i^{\wedge}R+P_i^{\wedge}I = 0.00103204228932 \quad \%1 = 1.57264073913e-07$$

$$\Omega- = 0.000660344496282 \quad P_i^{\wedge}R-P_i^{\wedge}I = 0.00066034460013 \quad \%1 = 1.57264049289e-07$$

Possible pair of triplets for ideal 1D :

$$(T_1, E_1, S_1) = (1.39505982302e-07, -8.89841666739e-07, -0.000330708901693)$$

$$(T_2, E_2, S_2) = (-7168151.38316, 1123795.43168, -3023.80732687)$$

C Matrix on Bahr Phase Sensitive Strike direction:

$$C11 = 0.999669236432 \quad C12 = -1.02968800716e-06$$

$$C21 = -7.50087500728e-07 \quad C22 = 1.0003306542$$

C Matrix on the current frame:

$$C11r = 1.00033065418 \quad C12r = 7.58871105577e-07$$

$$C21r = 1.03847161201e-06 \quad C22r = 0.999669236456$$

The dimensionality (1D, 2D or 3D case) refers to the values of Index1 and Index2:

$$Index1 \leq 0.05 \quad \text{and} \quad Index2 \leq 0.05 \quad \Rightarrow 1D$$

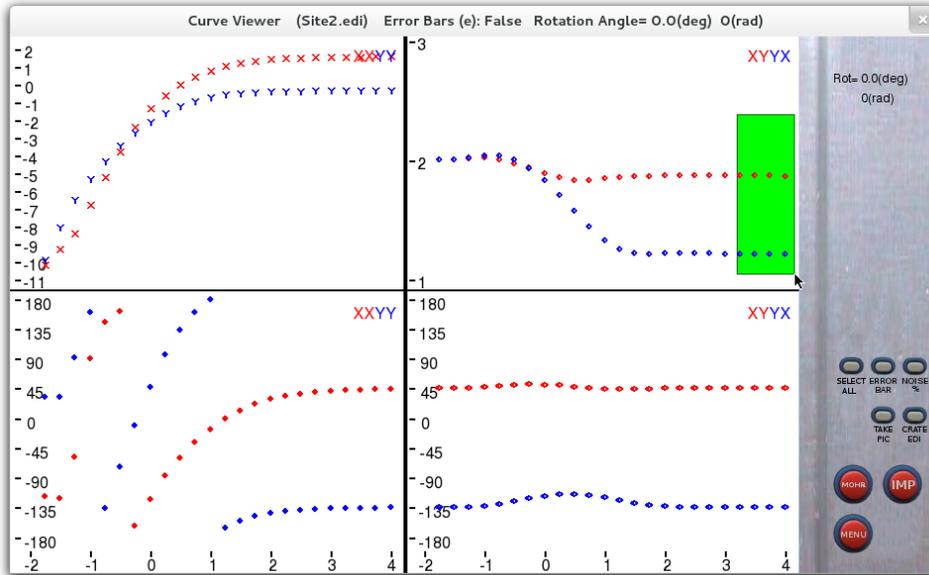
$$Index1 \leq 0.05 \quad \text{and} \quad Index2 > 0.05 \quad \Rightarrow 2D$$

$$Index1 > 0.05 \quad \Rightarrow 3D$$

These indexes are independent of the galvanic distortion and rotation. Accordingly, the dimensionality can be studied directly in a measured (distorted) impedance tensor. This dimensionality criteria refer only to the mathematical relationships of the impedance tensor at a given period. Accordingly, it does not refer to the dimensionality of the resistivity structure. Only if this dimensionality of a given period is the same as all the shorter periods or if it decreases steadily towards the shortest period, then this dimensionality coincides with the dimensionality of the resistivity structure.

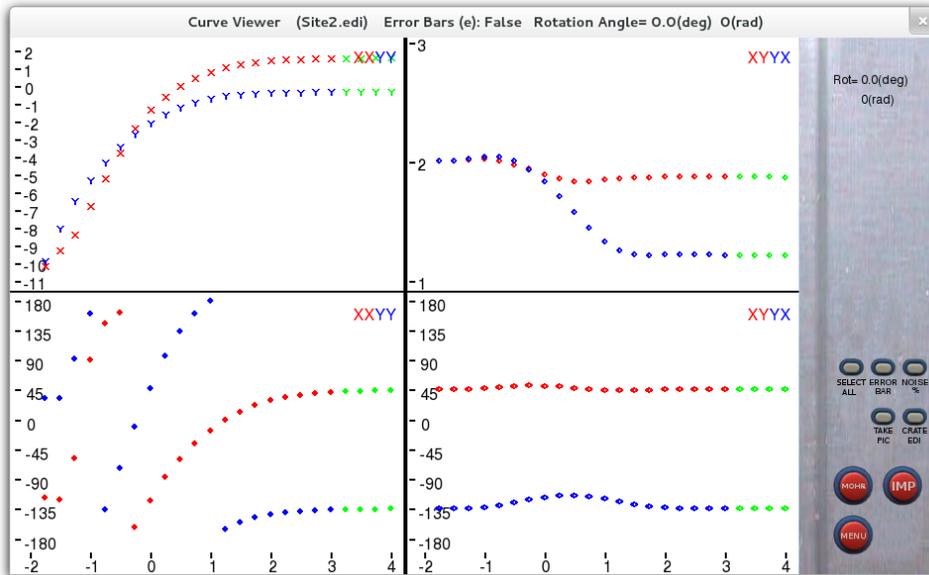
Selecting periods

In order to select a number of periods click the right button of the mouse one time and a green box appears. Drag the cursor to resize the green box and include the desired periods,



The last four periods included in the green box will be selected.

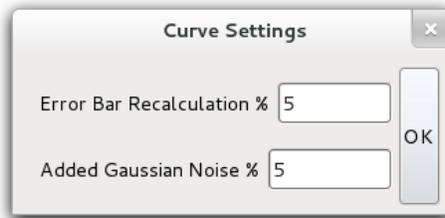
Then click one more time to select the periods included. The selection can be done in upper panels or lower panels.



The selected periods are shown in green.

By selecting periods, you specify which periods can be eliminated, depicted in Mohr diagrams or impedance tensor, as well as those periods in which the error bars can be recalculated and for which periods a Gaussian noise is added to the impedance tensor.

By selecting **Viewer/Data/Curve Settings** sub-menu, you may define the error bar recalculation (in %) and the Gaussian noise (in %) to be added to the impedance tensor.

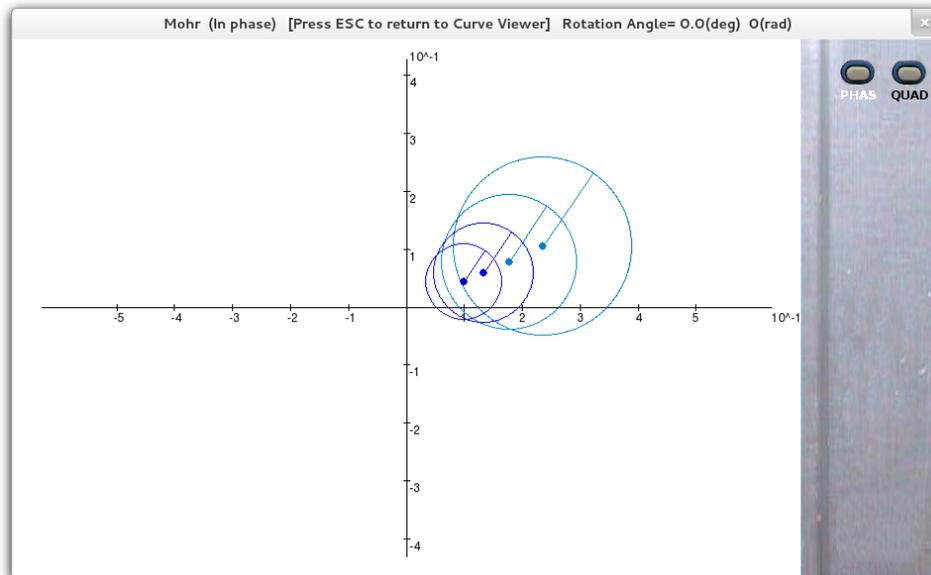


Once a selection of periods has been made, press key “w” to assign error bar to the selected periods and then key “q” (or button **NOISE %**) to add the Gaussian noise to the selected periods. **ERROR BAR** button shows the error bars. By clicking the button **MENU**, a list of the commands used by **Curve Viewer** sub-menu appears.

Curve Viewer sub-menu allows us to create a new edi file containing the current changes, such as noise, new error bars or rotation. The new edi file is created by clicking **CREATE EDI** button or pressing “o” key (an edi called filename_1.edi is created in /EDIS folder). When creating a new edi, all the selected periods are eliminated and the new picture is re-scaled. Accordingly, deselect previously the periods wanted in the new EDI file.

Mohr Diagrams

Click the **MOHR** button to see the Mohr diagrams for the selected periods. The buttons on the upper right side allow the quadrature and in phase diagrams. By pressing the “i” key, period and rotation marks appear. Only the selected periods are plotted and re-scaled.



Mohr diagram in phase.

Impedance Tensor

By clicking **IMP** button you see the representation of the real and imaginary parts of the impedance tensor plotted by components. Only the selected periods are plotted. The new picture is re-scaled, so that variations for larger periods can be observed.

General considerations

In all representations:

- rotation (spinning mouse wheel) and fine rotation (spinning mouse wheel + “f” key) can be interactively seen.
- by pressing the “p” key a picture is taken, and automatically saved in the /pictures folder.
- press the “esc” key to return to the previous image.

The recalculation error bar and the Gauss noise addition are applied to the selected periods.

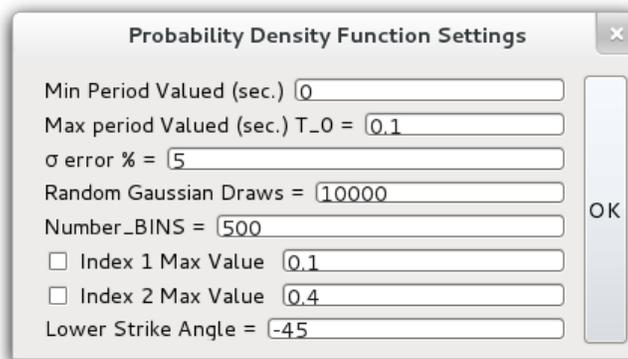
By creating an edi file, all selected periods are removed in the new edi file.

Block 2: Probability Density Function Estimation

Probability Density Function (PDF) menu contains two sub-menus, **Settings** and **Calculate**.

By clicking the **Calculate** sub-menu, Bahr's Phase sensitive Strike, Index 1 and Index 2 PDF plots appear. The PDF depends on the values introduced in the **Settings** sub-menu.

By clicking sub-menu **settings**, a PDF dialog box opens:



Select the Min/ Max periods to be statistically analyzed. A selected number of Random Gaussian Draws are obtained with a standard deviation σ error %. Maximum values for the Index1 and Index2 can be selected for the random Gaussian draws.

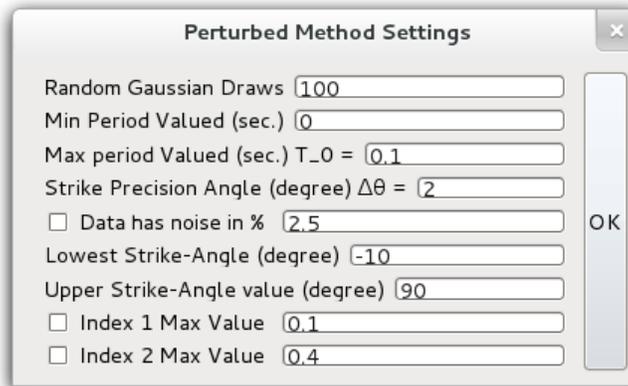
By clicking sub-menu **Calculate**, the program asks for an edi file and the probability density functions are depicted. Information about statistics being carried out are shown in the terminal.

Block 3: Perturbed Method

It provides, for the considered periods, an estimation of the Phase Sensitive Strike angle and a *Pseudoimpedance Tensor*, which is the impedance tensor “corrected” of noise, so that all the selected periods have the same Phase Sensitive Strike angle. The perturbed method applies a Gaussian perturbation (like a noise correction) to the impedance tensor.

The Perturbed Method menu contains two sub-menus: **Perturbed Method Settings** and **Regional Phase Sensitive Strike**.

In **Perturbed Method Settings** dialog box, *Min* and *Max* values select the range of periods, for which the impedance tensor has to be perturbed and the strike angle calculated. *Random Gaussian Draws* number is the number of random Gaussian perturbations. *Strike Precision angle* is the size of the segmentation in which all strike angles of the perturbed impedance tensor are considered to be the same. *Data noise %* is the size of the Gaussian perturbation (standard deviation in %). *Lowest Strike-Angle*, and *Upper Strike-Angle* are needed to apply the perturbed method.

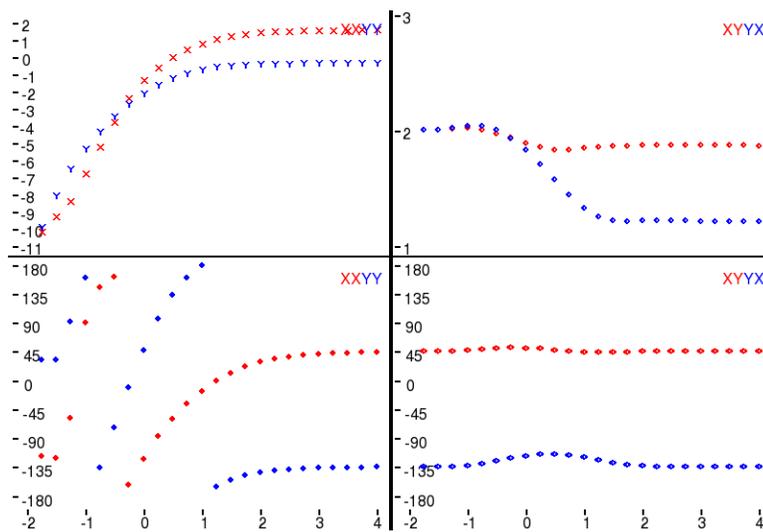


By selecting **Regional Phase Sensitive Strike** sub-menu, if the checking box *Data noise %* is activated in **Perturbed Method Settings**, the program will apply the perturbed method, otherwise the program will plot the rose diagram of the desired edi file. Index 1 and Index 2 are constraints defined in Romero-Ruiz and Pous (2018 a,b), which account for the “dimensionality”. When these indexes are checked, only the random draws fulfilling the constraints are saved. The terminal shows the average strike angle and its error (SIGMA) obtained after all the random draws, and the new components of the impedance tensor (Pseudoimpedance Tensor). These errors are a measure of the reliability of the strike obtained and, therefore, of the distortion parameters obtained in the next step.

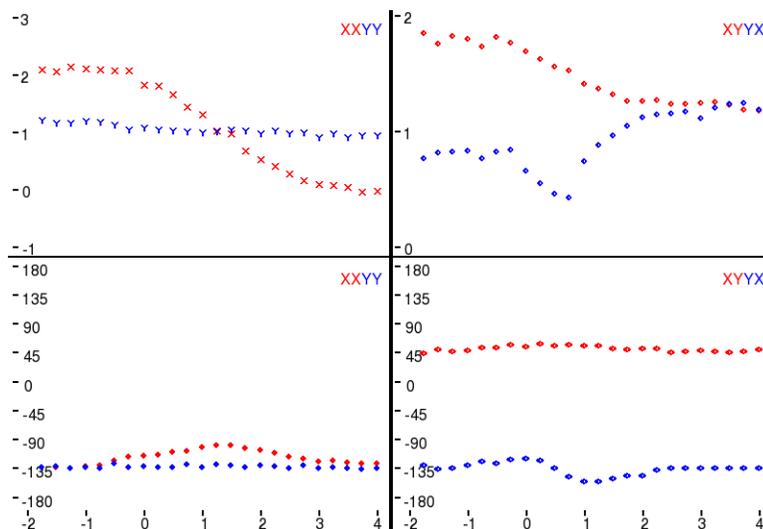
Block 4: Galvanic Distortion

The **Galvanic Distortion** menu has two sub-menus: Add or Remove GD sub-menu, which allows to add or remove a galvanic distortion, and **Search** sub-menu, which determines the galvanic distortion parameters, *twist* (t), *shear* (e) and *anisotropy* (s). The best way to show how this tool works is by showing an example. In the following section we are going to show the whole process step by step.

By using the sub-menu **Add or Remove GD/Settings (t,e,s) values** and the sub-menu **Add or Remove GD/Add** the current site 2.edi



is distorted by twist, shear and *anisotropy* ($t=-1.1$; $e=0.4$; $s=-0.3$), then rotated by 13° and perturbed by 5% of Gaussian noise, which results in:



Depicting this distorted, rotated and noisy site with **Viewer/Data/Curve Viewer** sub-menu, the terminal shows the following information for each period (only four periods shown here):

```

*****
              (Site2(-1.1+0.4-0.3)_rot13_p5)
*****

=====
PERIOD 0.017782794897 ** 2D Case **
=====

Cl3 Clifford Algebra Decomposition:
1/2*[ S1R + S1I e123 + D1R e1 + D1I e23 + S2R e2 + S2I e31 + D2R e12 - D2I e3] =
=1/2*[ -176.519810293 -178.038890372e123 -84.6111723612e1 -82.5781968278e23 +75.0233207239e2
+64.624144899e31 +128.533798716e12 -123.732549489e3]

Bahr Phase Sensitive Strike = 37.4188681018 ( -52.5811318982 )
  A+ = 5.4533621445   N_i^R+N_i^I = -2.40562094529 %1 = 1.44112620463
  A- = 0.0614570345849 N_i^R-N_i^I = 0.150024377584 %1 = 0.590353010794

Index 1: atan(phi_12/phi_0) = 0.00888539237385
  G+ = 2.88111833885   Q_i^R+Q_i^I = -2.81223481011 %1 = 1.97609139208
  G- = 0.0220313156849 Q_i^R-Q_i^I = 0.065567208966 %1 = 0.663988813428

Index 2: sqrt(phi_1^2+phi_2^2)/ sqrt(phi_12^2+phi_0^2) = 0.052674016489
  O+ = 1.33618145087   P_i^R+P_i^I = 1.00151480147 %1 = 0.250464971795
  O- = 0.0273775258291 P_i^R-P_i^I = 0.0342346370637 %1 = 0.200297471296

Possible pair of triplets for ideal 1D :
(T_1,E_1,S_1)=( 0.542163039391 , 3.3060819716 , -2.48100485856 )
(T_2=-1/T_1,E_2=-1/E_2,S_2)=( -1.84446361582 , -0.302472839025 , -0.403062491615 )

C Matrix on Bahr Phase Sensitive Strike direction:
C11 = 0.111666579638 C12 = 0.915446070736
C21 = -0.542278059215 C22 = 0.924891114164

C Matrix on the current frame:
C11r = 0.80471854955 C12r = 1.07251803225
C21r = -0.385206097704 C22r = 0.231839144253

=====
PERIOD 0.0316227732034 ** 2D Case **
=====

Cl3 Clifford Algebra Decomposition:
1/2*[ S1R + S1I e123 + D1R e1 + D1I e23 + S2R e2 + S2I e31 + D2R e12 - D2I e3] =
=1/2*[ -124.221888516 -129.011761922e123 -59.2011838924e1 -60.9216073515e23 +38.9433523729e2
+49.2465549781e31 +86.3058446397e12 -92.0562835311e3]

Bahr Phase Sensitive Strike = -64.5994994736 ( 25.4005005264 )
  A+ = 3.1311755513   N_i^R+N_i^I = -2.75726063515 %1 = 1.88058321546
  A- = -0.0982834535858 N_i^R-N_i^I = -0.283113666757 %1 = 0.652848077906

Index 1: atan(phi_12/phi_0) = 0.0131196123365
  G+ = 2.79292473424   Q_i^R+Q_i^I = -2.84076624416 %1 = 1.98315894171
  G- = -0.0125541406025 Q_i^R-Q_i^I = -0.037877468434 %1 = 0.668559142901

Index 2: sqrt(phi_1^2+phi_2^2)/ sqrt(phi_12^2+phi_0^2) = 0.0630501642085
  O+ = 1.25285621407   P_i^R+P_i^I = 0.962750340727 %1 = 0.231555600781
  O- = -0.0209518757262 P_i^R-P_i^I = -0.0258033998975 %1 = 0.188018795606

Possible pair of triplets for ideal 1D :
(T_1,E_1,S_1)=( 0.572194734293 , -2.32030814397 , 4.65568817446 )
(T_2=-1/T_1,E_2=-1/E_2,S_2)=( -1.747656768 , 0.430977240071 , 0.214791017467 )

C Matrix on Bahr Phase Sensitive Strike direction:
C11 = 0.94969914996 C12 = 0.762820720269
C21 = -0.713238205153 C22 = 0.0864137489333

C Matrix on the current frame:
C11r = 0.771649317983 C12r = 1.08820182653
C21r = -0.387857098888 C22r = 0.26446358091

```

=====
 PERIOD 0.0562341454856 ** 1D Case **
 =====

Cl3 Clifford Algebra Decomposition:

$$1/2*[S1R + S1I e123 + D1R e1 + D1I e23 + S2R e2 + S2I e31 + D2R e12 - D2I e3] =$$

$$=1/2*[-104.537758425 -100.19858867e123 -54.2770337005e1 -51.4003937906e23 +35.5046643112e2$$

$$+37.9672329321e31 +70.5007465398e12 -70.8869005041e3]$$

Bahr Phase Sensitive Strike = -70.0865615298 (19.9134384702)

$$\Lambda+ = 2.69494778894 \quad N_i^R+N_i^I = -2.88253898824 \quad \%1 = 1.93492153963$$

$$\Lambda- = -0.0569845796942 \quad N_i^R-N_i^I = -0.174920348636 \quad \%1 = 0.674225553868$$

Index 1: atan(ϕ_{12}/ϕ_0) = 0.00974779237236

$$\Gamma+ = 2.64278767084 \quad Q_i^R+Q_i^I = -2.89628874495 \quad \%1 = 1.91247382549$$

$$\Gamma- = -0.022381062386 \quad Q_i^R-Q_i^I = -0.0692900199957 \quad \%1 = 0.67699443026$$

Index 2: sqrt($\phi_1^2+\phi_2^2$)/ sqrt($\phi_{12}^2+\phi_0^2$) = 0.025859272354

$$\Omega+ = 1.41359225631 \quad P_i^R+P_i^I = 1.03502151045 \quad \%1 = 0.26780759739$$

$$\Omega- = -0.00493450308241 \quad P_i^R-P_i^I = -0.00625600049723 \quad \%1 = 0.211236782254$$

Possible pair of triplets for ideal 1D :

$$(T_1, E_1, S_1) = (0.593769055171 , -1.99953414216 , 7.34897425266)$$

$$(T_2 = -1/T_1, E_2 = -1/E_1, S_2) = (-1.68415647682 , 0.500116491594 , 0.136073411829)$$

C Matrix on Bahr Phase Sensitive Strike direction:

$$C11 = 0.946979487751 \quad C12 = 0.853814652019$$

$$C21 = -0.608628965017 \quad C22 = 0.0616536513106$$

C Matrix on the current frame:

$$C11r = 0.765757198981 \quad C12r = 1.10888337887$$

$$C21r = -0.35356023817 \quad C22r = 0.242875940081$$

=====
 PERIOD 0.1 ** 1D Case **
 =====

Cl3 Clifford Algebra Decomposition:

$$1/2*[S1R + S1I e123 + D1R e1 + D1I e23 + S2R e2 + S2I e31 + D2R e12 - D2I e3] =$$

$$=1/2*[-73.3607431219 -77.1802717296e123 -34.7456696189e1 -37.7993162344e23 +26.2037419432e2$$

$$+26.607347104e31 +50.5323996418e12 -53.5240580004e3]$$

Bahr Phase Sensitive Strike = 3.83674538185 (-86.1632546181)

$$\Lambda+ = 3.10796409538 \quad N_i^R+N_i^I = -2.74661575353 \quad \%1 = 1.88373471161$$

$$\Lambda- = 0.0328231720242 \quad N_i^R-N_i^I = 0.0946533205114 \quad \%1 = 0.653227463687$$

Index 1: atan(ϕ_{12}/ϕ_0) = 0.0145445894111

$$\Gamma+ = 2.64655634126 \quad Q_i^R+Q_i^I = -2.8937300405 \quad \%1 = 1.91458301369$$

$$\Gamma- = -0.00316257671261 \quad Q_i^R-Q_i^I = -0.00978309728079 \quad \%1 = 0.676730525943$$

Index 2: sqrt($\phi_1^2+\phi_2^2$)/ sqrt($\phi_{12}^2+\phi_0^2$) = 0.0236993952802

$$\Omega+ = 1.29112047336 \quad P_i^R+P_i^I = 0.980689996634 \quad \%1 = 0.240434942465$$

$$\Omega- = -0.00291780091977 \quad P_i^R-P_i^I = -0.00361934221604 \quad \%1 = 0.193831158922$$

Possible pair of triplets for ideal 1D :

$$(T_1, E_1, S_1) = (0.750277267686 , 2.0656874802 , 12.4671012266)$$

$$(T_2 = -1/T_1, E_2 = -1/E_1, S_2) = (-1.33284059516 , -0.484100334434 , 0.0802111077647)$$

C Matrix on Bahr Phase Sensitive Strike direction:

$$C11 = -0.206347359917 \quad C12 = -0.4203437684$$

$$C21 = 1.05679584249 \quad C22 = -0.814809444417$$

C Matrix on the current frame:

$$C11r = -0.769593100351 \quad C12r = -1.09456941759$$

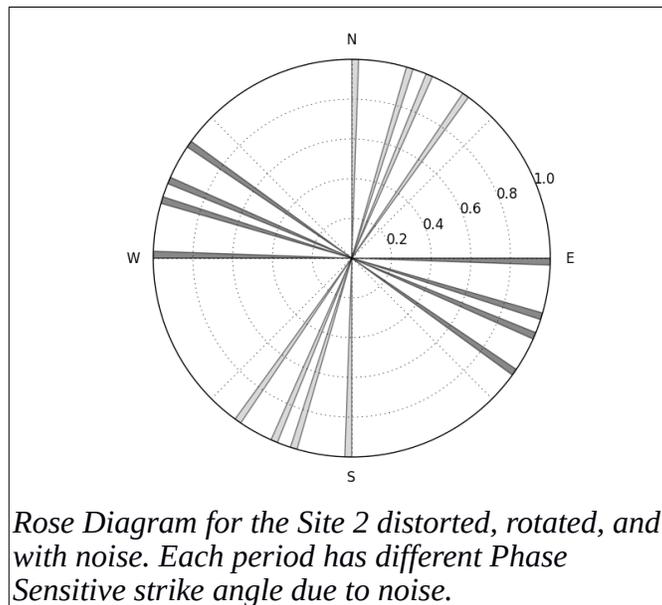
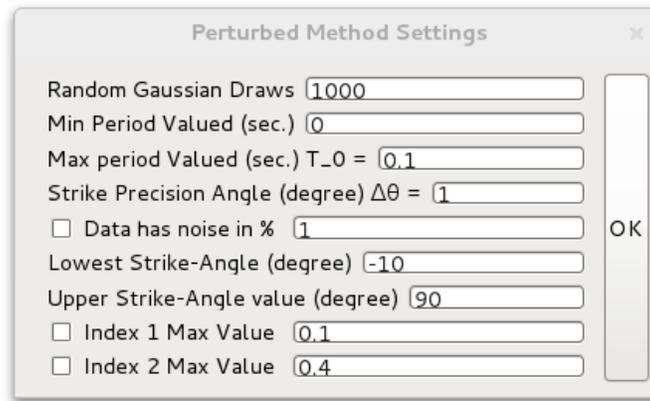
$$C21r = 0.382570193302 \quad C22r = -0.251563703982$$

These short periods are 2D (1D) and, therefore the method can be applied. The first and the second periods are indicated as 2D, but note Index1 and Index2 almost fulfill the condition of 1D. In addition, note the significant variation in the Phase Sensitive Strike, together with the slight variation of the “C Matrix on the current frame” (the difference in sign is only due to the “complementary angle”). This

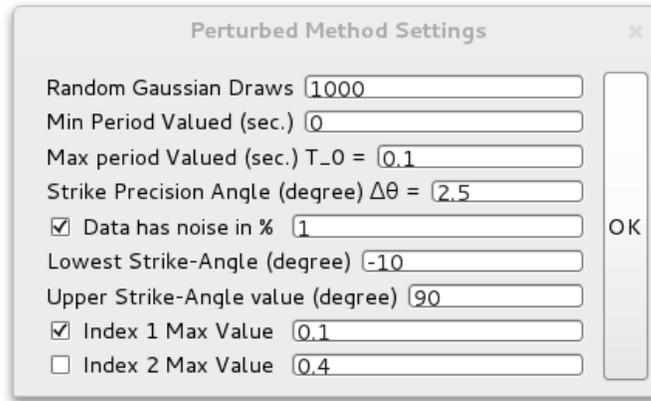
happens typically in 1D cases. In order to show how the program works in a 2D case, higher periods between 0.3s and 2s, which are really 2D, will be considered later, allowing to compare the results.

Perturbed Method

Leaving non-checked the “Data has noise %” checkbox in **Perturbation Method Settings**, the rose diagram for these periods is depicted with a 1° segment precision. That is

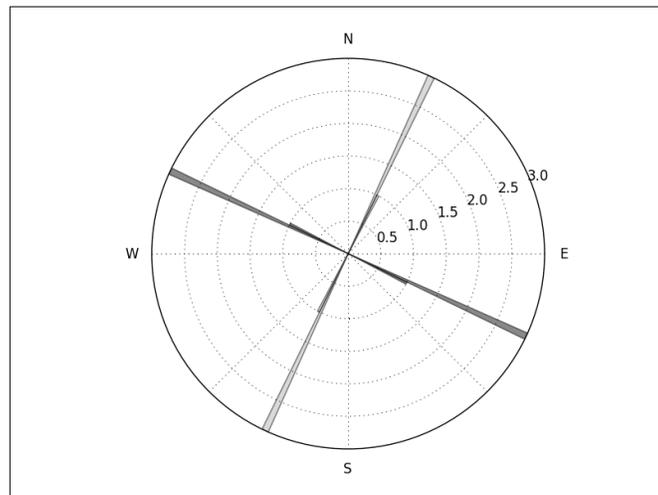


Next, we start the Perturbed method with the following settings. Note the “Data has noise %” checkbox is checked.



The results are shown in terminal. The Phase Sensitive Strike angle obtained is $27.67^\circ \pm 2.9^\circ$ and a new file in the EDIS folder appear (Site2(-1.1+0.4-0.3)_rot13_p5_ZP-1.0p_A5.0_I1-0.1.edi). It is labeled with _ZP to denote the *pseudo impedance tensor* corrected from noise.

Plotting the rose diagram of this edi file (*Data has noise % not checked*):



Note the Pseudoimpedance Tensor gives a unique Phase Sensitive strike within the Strike Precision Angle ($\Delta\theta$). To continue the process the edi file should be rotated to the Phase Sensitive strike angle. However, in 1D case to continue with the process to find the galvanic distortion parameters any angle can be used due to the independence of the regional impedance tensor with rotation (1D case). The galvanic distortion parameters obtained at different angles are connected by rotations. Therefore, all the galvanic distortion parameters coincide when derotating by the corresponding angle.

Galvanic Distortion Correction

In this example, only one period is considered to correct the galvanic distortion. Accordingly, we chose the lowest period 0.0178s. First, we rotate to the Phase Sensitive strike specific for 0.0178s, which is -61.36o (shown in the terminal when depicting the site with **Curve Viewer**). In case of choosing more periods, the Phase Sensitive Strike angle obtained in the Perturbed Method should be chosen. By plotting the rotated site, the following information appears in the terminal:

```
*****
                               (Site2(-1.1+0.4-0.3)_rot13_p5_ZP-1.0p_A5.0_I1-0.1_rot-61,36)
*****

=====
PERIOD 0.01782794897  ** 2D Case **
=====

Cl3 Clifford Algebra Decomposition:
1/2*[ S1R + S1I e123 + D1R e1 + D1I e23 + S2R e2 + S2I e31 + D2R e12 - D2I e3] =
=1/2*[ -175.897395184 -178.869923131e123 -18.3335267286e1 -8.7913655836e23 -110.479295888e2 -105.864788848e31
+128.673850168e12 -123.86449744e3]

Bahr Phase Sensitive Strike = -89.9931650765 ( 0.00683492354294 )
  Λ+ = 0.252467874318      N_i^R+N_i^I = 0.248988701141 %1 = 0.0137806569913
  Λ- = 0.0817751077668    N_i^R-N_i^I = 0.0829020224774 %1 = 0.0135933319463

Index 1: atan(φ_12/φ_0) = 0.00728181494971
  Γ+ = 2.88595084285      Q_i^R+Q_i^I = -2.81107929461 %1 = 1.9740565407
  Γ- = 0.0259159609247    Q_i^R-Q_i^I = 0.0770755330966 %1 = 0.66375891436

Index 2: sqrt(φ_1^2+φ_2^2)/ sqrt(φ_12^2+φ_0^2) = 0.0505101189784
  Ω+ = 1.33774948756      P_i^R+P_i^I = 1.00211518772 %1 = 0.250894732505
  Ω- = 0.02047408425      P_i^R-P_i^I = 0.0256109241412 %1 = 0.200572219217

Possible pair of triplets for ideal 1D :
(T_1,E_1,S_1)=( 0.54443154247 , 2.44185800462 , -3.40323544641 )
(T_2=-1/T_1,E_2=-1/E_2,S_2)=( -1.83677822094 , -0.409524222174 , -0.293838030235 )

C Matrix on Bahr Phase Sensitive Strike direction:
C11 = 0.0742880254355      C12 = 0.783977202246
C21 = -0.673433640786     C22 = 0.962469826589

C Matrix on the current frame:
C11r = 0.0742748511213     C12r = 0.783871247761
C21r = -0.67353959527     C22r = 0.962483000903

=====
PERIOD 0.0316227732034  ** 2D Case **
=====

Cl3 Clifford Algebra Decomposition:
1/2*[ S1R + S1I e123 + D1R e1 + D1I e23 + S2R e2 + S2I e31 + D2R e12 - D2I e3] =
=1/2*[ -124.16938737 -129.308103307e123 -0.961995103e1 -8.3265709707e23 -70.6510110782e2 -78.2347556149e31
+86.4168118562e12 -92.1629679921e3]

Bahr Phase Sensitive Strike = -1.29152587775 ( 88.7084741223 )
  Λ+ = 0.120220963134      N_i^R+N_i^I = 0.120046741878 %1 = 0.0014491753483
  Λ- = -0.0926801225469    N_i^R-N_i^I = -0.0928144322958 %1 = 0.00144707827813

Index 1: atan(φ_12/φ_0) = 0.0131770472694
  Γ+ = 2.79524383155      Q_i^R+Q_i^I = -2.83990363302 %1 = 1.98427418418
  Γ- = -0.0112164532156    Q_i^R-Q_i^I = -0.0338285656854 %1 = 0.668432492234

Index 2: sqrt(φ_1^2+φ_2^2)/ sqrt(φ_12^2+φ_0^2) = 0.0627519878205
  Ω+ = 1.25234874733      P_i^R+P_i^I = 0.962534647975 %1 = 0.231416448469
  Ω- = -0.0230713726496    P_i^R-P_i^I = -0.0284104677695 %1 = 0.187927040244

Possible pair of triplets for ideal 1D :
```

(T_1,E_1,S_1)=(0.562145568671 , -2.3963064463 , 4.15921801396)
(T_2=-1/T_1,E_2=-1/E_2,S_2)=(-1.77889866207 , 0.417308897009 , 0.240429810759)

C Matrix on Bahr Phase Sensitive Strike direction:
C11 = 0.950304841915 C12 = 0.733494027053
C21 = -0.742632174522 C22 = 0.0860504100835

C Matrix on the current frame:
C11r = 0.0866953919595 C12r = 0.762102420203
C21r = -0.714023781373 C22r = 0.949659860039

=====
PERIOD 0.0562341454856 ** 1D Case **
=====

Cl3 Clifford Algebra Decomposition:
1/2*[S1R + S1I e123 + D1R e1 + D1I e23 + S2R e2 + S2I e31 + D2R e12 - D2I e3] =
=1/2*[-104.413811244 -100.532784989e123 -0.6926742584e1 -4.0035464995e23 -64.5372790293e2 -64.248455269e31
+70.5344952347e12 -71.0143048114e3]

Bahr Phase Sensitive Strike = -1.24182958898 (88.758170411)
 $\Lambda^+ = 0.0730953250689$ $N_i^{\wedge R} + N_i^{\wedge I} = 0.0730464384293$ %1 = 0.000668806652054
 $\Lambda^- = -0.0515460990911$ $N_i^{\wedge R} - N_i^{\wedge I} = -0.051580573465$ %1 = 0.000668359648675

Index 1: atan(ϕ_{12}/ϕ_0) = 0.00968292353391
 $\Gamma^+ = 2.64317841329$ $Q_i^{\wedge R} + Q_i^{\wedge I} = -2.89599214926$ %1 = 1.91270220258
 $\Gamma^- = -0.0208851808307$ $Q_i^{\wedge R} - Q_i^{\wedge I} = -0.0646531604228$ %1 = 0.676965817384

Index 2: sqrt($\phi_1^2 + \phi_2^2$) / sqrt($\phi_{12}^2 + \phi_0^2$) = 0.0261796840829
 $\Omega^+ = 1.41399100137$ $P_i^{\wedge R} + P_i^{\wedge I} = 1.03520586821$ %1 = 0.267883694303
 $\Omega^- = -0.008509815672$ $P_i^{\wedge R} - P_i^{\wedge I} = -0.0107894565321$ %1 = 0.21128412291

Possible pair of triplets for ideal 1D :
(T_1,E_1,S_1)=(0.537048259371 , -2.17179325468 , 4.15587593916)
(T_2=-1/T_1,E_2=-1/E_2,S_2)=(-1.86203005512 , 0.460448985116 , 0.240623159748)

C Matrix on Bahr Phase Sensitive Strike direction:
C11 = 0.96282381913 C12 = 0.736915516505
C21 = -0.726551924633 C22 = 0.0452561118837

C Matrix on the current frame:
C11r = 0.0454625333792 C12r = 0.746437940972
C21r = -0.717029500165 C22r = 0.962617397634

=====
PERIOD 0.1 ** 1D Case **
=====

Cl3 Clifford Algebra Decomposition:
1/2*[S1R + S1I e123 + D1R e1 + D1I e23 + S2R e2 + S2I e31 + D2R e12 - D2I e3] =
=1/2*[-73.7741160823 -76.8581650436e123 -2.9604179299e1 -2.310501931e23 -44.1509436125e2 -45.5178619109e31
+50.6661929479e12 -53.5407649617e3]

Bahr Phase Sensitive Strike = 88.4738100096 (-1.52618999041)
 $\Lambda^+ = 0.11821489119$ $N_i^{\wedge R} + N_i^{\wedge I} = 0.11781253591$ %1 = 0.00340359218493
 $\Lambda^- = 0.0162366026122$ $N_i^{\wedge R} - N_i^{\wedge I} = 0.016291865386$ %1 = 0.00339204704014

Index 1: atan(ϕ_{12}/ϕ_0) = 0.0139086426947
 $\Gamma^+ = 2.65230828483$ $Q_i^{\wedge R} + Q_i^{\wedge I} = -2.89158910833$ %1 = 1.91724936893
 $\Gamma^- = -0.0066578772067$ $Q_i^{\wedge R} - Q_i^{\wedge I} = -0.0205742807085$ %1 = 0.676398032329

Index 2: sqrt($\phi_1^2 + \phi_2^2$) / sqrt($\phi_{12}^2 + \phi_0^2$) = 0.0180460404354
 $\Omega^+ = 1.29177442134$ $P_i^{\wedge R} + P_i^{\wedge I} = 0.981003698246$ %1 = 0.240576619233
 $\Omega^- = 0.00633573471029$ $P_i^{\wedge R} - P_i^{\wedge I} = 0.00785996434725$ %1 = 0.1939232253

Possible pair of triplets for ideal 1D :
(T_1,E_1,S_1)=(0.549438651913 , 2.32157727043 , -4.17257399992)
(T_2=-1/T_1,E_2=-1/E_2,S_2)=(-1.82003941026 , -0.430741639632 , -0.239660219332)

C Matrix on Bahr Phase Sensitive Strike direction:
C11 = 0.0706441964795 C12 = 0.740706576654

C21 = -0.736019228107 C22 = 0.95112504996

C Matrix on the current frame:

C11r = 0.071393576048 C12r = 0.764145563248
C21r = -0.712580241513 C22r = 0.950375670392

Note that after this rotation, the Phase Sensitive Strike, for the considered periods, must be approximately zero.

The program allows to use different constraints which the regional impedance tensor (free of galvanic distortion) should fulfill for the short periods, between T_{min} and T_{max} :

- Off-diagonal components of the regional impedance tensor fulfill $Z_{xy} > 0$ and $Z_{yx} < 0$.
- The diagonal apparent resistivities should be lower than the specified value.
- Values for t and e may be specified from the terminal information above, which makes the search faster. From the two possible triplets (t, e, s) for the ideal 1D case, appearing in the terminal, it is recommended to select that with the lower anisotropy s parameter absolute value (specified in green above).
- Indexes γ , λ and ϵ are expected to be lower than the specified values.

These indexes are defined in Romero-Ruiz and Pous (2018 a,b).

By clicking the sub-menu Galvanic Distortion/Search (t, e, s) /Search Settings a dialog box is opened. The range of short periods fulfilling the conditions (2D or 1D) should be specified (T_{min} and T_{max}).

Although the user may choose any constraints, two sets are mainly considered :

- 1) The basic constraints are: (a) Off-diagonal constraint $Z_{xy} > 0$ and $Z_{yx} < 0$; (b) Prescribed t and e values; (c) γ and ϵ being lower than the specified values (as small as possible, usually less than 0.01). This set allows to determine the galvanic distortion parameters directly on the measured direction instead of the strike direction. Thus, we shall determine the galvanic distortion parameters from the original edi file (without any rotation).

It is necessary to determine a first approximation for prescribed t and e values, for this reason we make a first search with constraints (a) and (c) with $\gamma=0.08$ and $\epsilon=0.08$ (even $\gamma=0.05$ and $\epsilon=0.05$).

Galvanic Distortion Search Settings

Low limit period T_{min} 0

High Limit period T_{max} 0.02

(t, e, s) max value 6 Sphere Radi 50

Constraints:

$Z_{xy} > 0$ and $Z_{yx} < 0$ for $T_{min} < T < T_{max}$

ρ_{xx} and ρ_{yy} high limit $T_{min} < T < T_{max}$ 1

Prescribed t and e : 0 and 0

$\gamma = 0.08$ $\lambda = 0.01$

s known: 0 $\epsilon = 0.08$

Some other Consider

ρ_{xy} and ρ_{yx} max values < 1000

No phases greater than 90 degrees

Curve slope condition (-45,45) degrees

OK STOP

Once a prescribed values for t and e are obtained, we may apply all the constraints of the first set.

Galvanic Distortion Search Settings

Low limit period T_min 0

High Limit period T_max 0.02

(t,e,s) max value 6 Sphere Radi 50

Constraints:

Zxy>0 and Zyx <0 for Tmin< T < T_max

ρ_{xx} and ρ_{yy} high limit Tmin< T < T_max 1

Prescribed t and e : -1.3299916 and 0.4442669

$\gamma = 0.001$ $\lambda = 0.01$

s known : 0 $\epsilon = 0.008$

Some other Consider

ρ_{xy} and ρ_{yx} max values < 1000

No phases greater than 90 degrees

Curve slope condition (-45,45) degrees

OK STOP

- 2) The basic constraints are: (a) Off-diagonal constraint $Z_{xy} > 0$ and $Z_{yx} < 0$; (b) Prescribed t and e values; (c) diagonal apparent resistivities that should be lower than the prescribed value; (d) ϵ being lower than the specified value (as small as possible).

Galvanic Distortion Search Settings

Low limit period T_min 0

High Limit period T_max 0.02

(t,e,s) max value 6 Sphere Radi 50

Constraints:

Zxy>0 and Zyx <0 for Tmin< T < T_max

ρ_{xx} and ρ_{yy} high limit Tmin< T < T_max 0.1

Prescribed t and e : -1.83677 and -0.40952

$\gamma = 0.01$ $\lambda = 0.01$

s known : 0 $\epsilon = 0.001$

Some other Consider

ρ_{xy} and ρ_{yx} max values < 1000

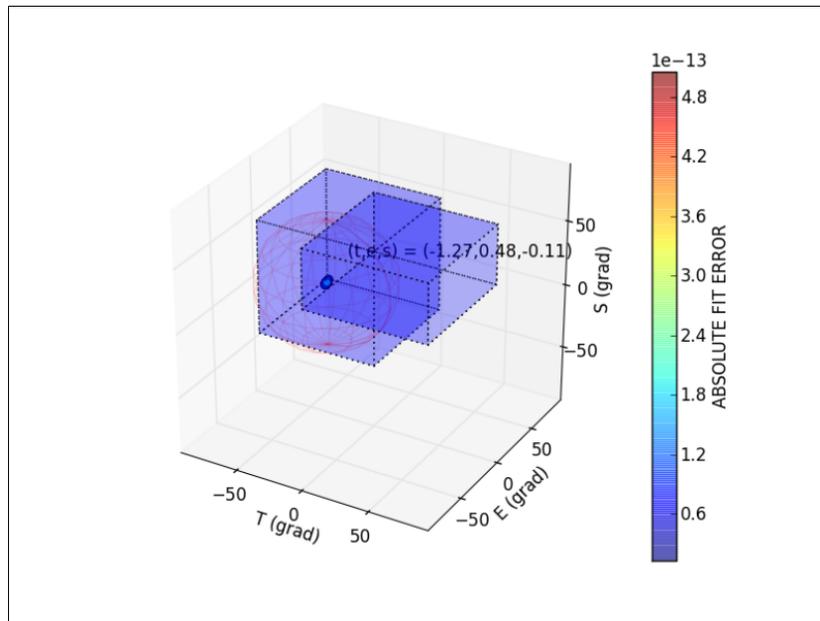
No phases greater than 90 degrees

Curve slope condition (-45,45) degrees

OK STOP

Once entering the selected inputs, click OK and then click sub-menu **Galvanic Distortion/Search (t,e,s)/Search**, to start the search.

By using the first set of constraints above, once the process ends, click **Galvanic Distortion/Search/Plotting Results** sub-menu and select Site2(-1.1+0.4-0.3)_rot13,006_p5.edi (instead Site2(-1.1+0.4-0.3)_rot13,006_p5_ZP-1.0p_A5.0_I1-0.1_rot-61,36.edi) file to obtain the figure:



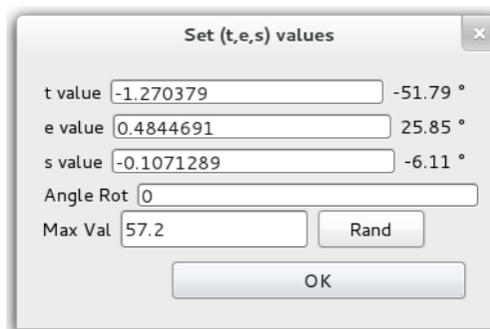
In the terminal, the obtained distortion parameter values appear:

_/SOLUTIONS \

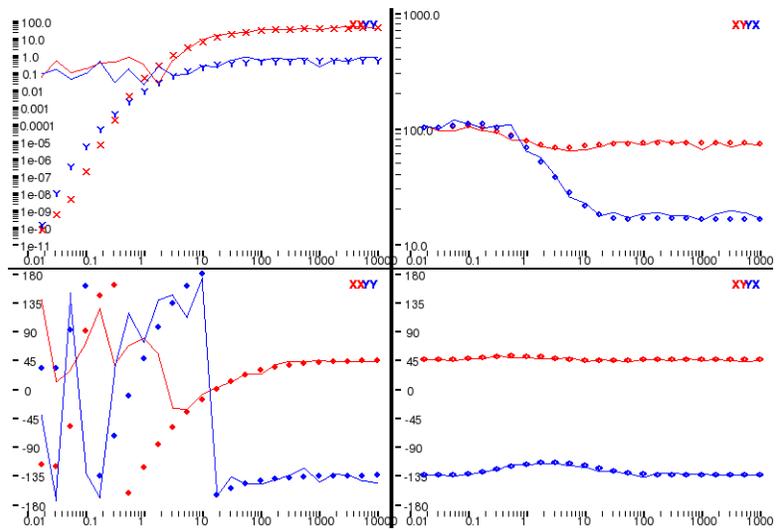
(t,e,s) = (-1.270379 , 0.4844691 , -0.1071289)

(θt,θe,θs) = (-51.7913575 , 25.848755 , -6.1147128) +-(0.4367361 , 0.634059 , 0.8999332)

In order to correct the galvanic distortion and obtain the regional impedance tensor, click the sub-menu **Galvanic Distortion/Add or Remove GD/Settings (t,e,s) values**

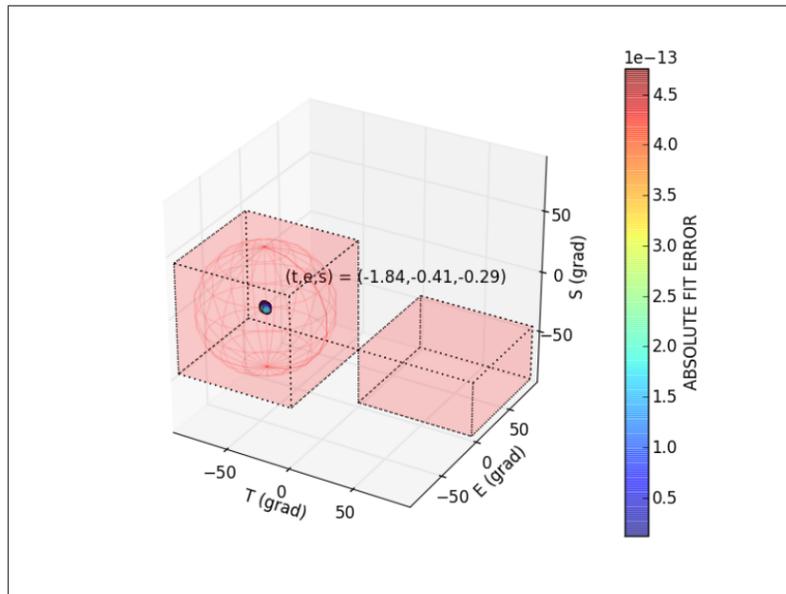


then click Galvanic Distortion/Add or Remove GD/Remove to create an edi file corrected of galvanic distortion. This edi file correspond to axes rotated (13o). In order to compare with the original synthetic Site2 (not rotated), the current edi must be rotated to -13o resulting:



Solid line: corrected of distortion. Dots: original site 2.

In the case of the second set of constraints, once the process ends, click **Galvanic Distortion/Search/Plotting Results** and select Site2(-1.1+0.4-0.3)_rot13_p5_ZP-1.0p_A5.0_I1-0.1_rot-61,36.edi file to obtain the figure:



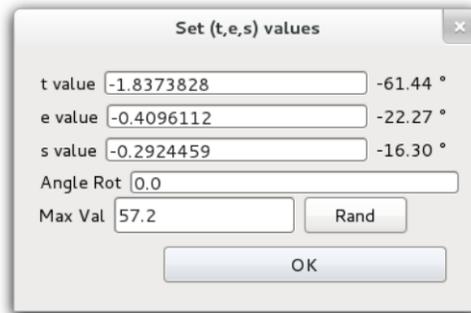
The obtained values are shown in the terminal:

```

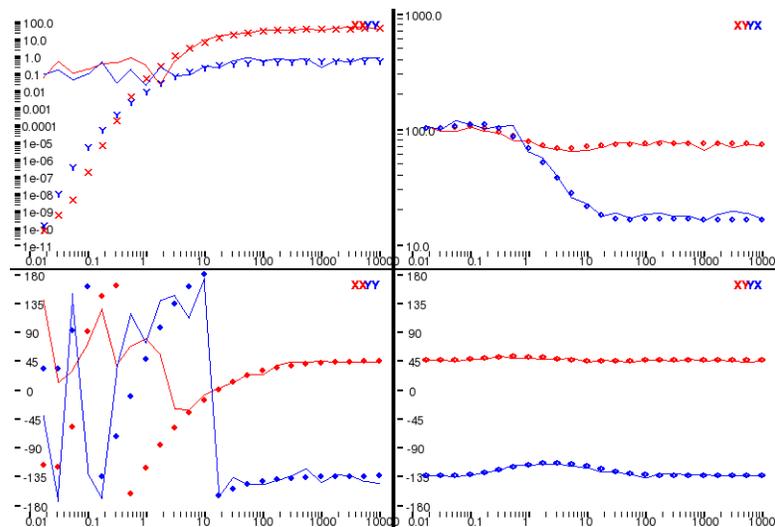
/SOLUTIONS\
(t,e,s) = ( -1.8373828 , -0.4096112 , -0.2924459 )
(θt,θe,θs) = ( -61.4426507 , -22.2745543 , -16.301344 ) +-( 0.5839794 , 0.5092479 , 1.2116853 )

```

In order to correct the galvanic distortion and obtain the regional impedance tensor in the Phase Sensitive Strike direction (-61.36o), click the sub-menu **Galvanic Distortion/Add or Remove GD/Settings (t,e,s) values**



then click **Galvanic Distortion/Add or Remove GD/Remove** to create an edi file corrected of galvanic distortion. This edi file correspond to axes rotated (-61.36o). In order to compare with the original synthetic Site2 (not rotated), the current edi must be rotated to 48.36o (= 61.36o-13o) resulting:



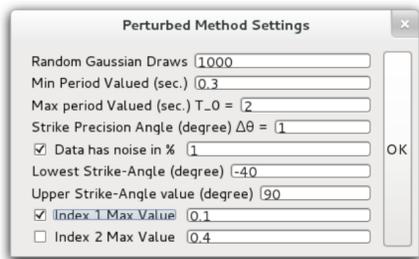
Solid line: corrected of distortion. Dots: original site 2.

Note that both set of constraints reproduce similar results. Differences with Site2 (dots) are due to the added noise. The first set of constraints has the advantage of determining the galvanic distortion parameters in the measured direction and any rotation is required. In cases of highly noisy data, the perturbed method used in this first set of constraints would allow a correction of those periods which do not fulfill the 2D (1D) criteria due to the noise.

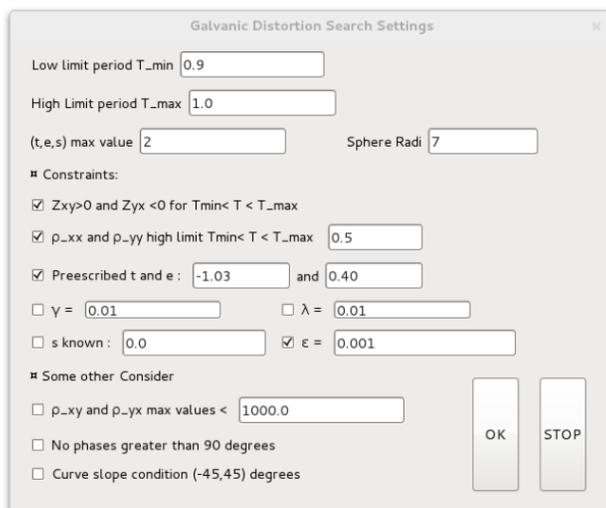
In the sub-menu Galvanic Distortion/Add or Remove GD/Settings (t,e,s) values by specifying Angle Rot the terminal shows the distortion matrix in the current frame (C Matrix), and the distortion matrix rotated to the specified Angle Rot (C Matrix rotated).

Repetition with a new selection of the short periods

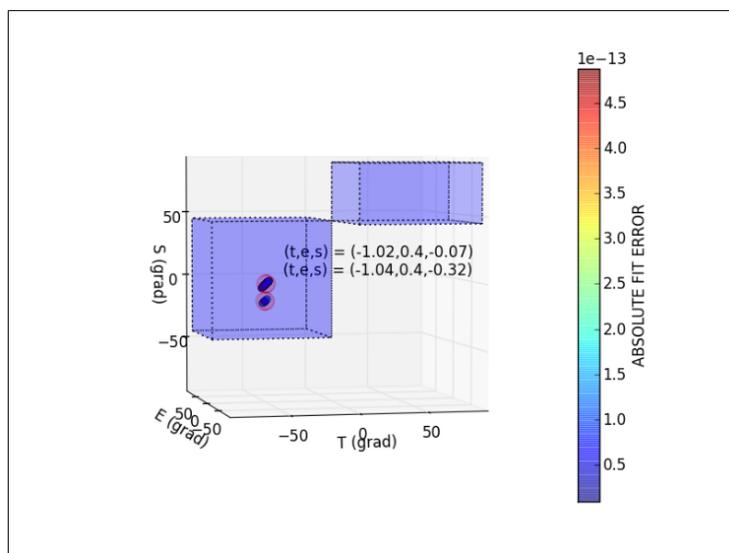
In the case with $T_{min}=0.3s$ and $T_{max}=2s$, which are really 2D, the Perturbation Method with the settings:



results in the Phase Sensitive Strike angle -16.33° . Considering only one period, 1s for example, the Phase Sensitive Strike angle given in terminal is 74.32° . This angle and its complementary, -15.68° , can be selected. If the complementary is chosen, the prescribed e value changes its sign. In order illustrate it we proceed rotating by, -15.68° . Starting the Galvanic Distortion Search with settings:



The Plotting Results are:



And the terminal shows:

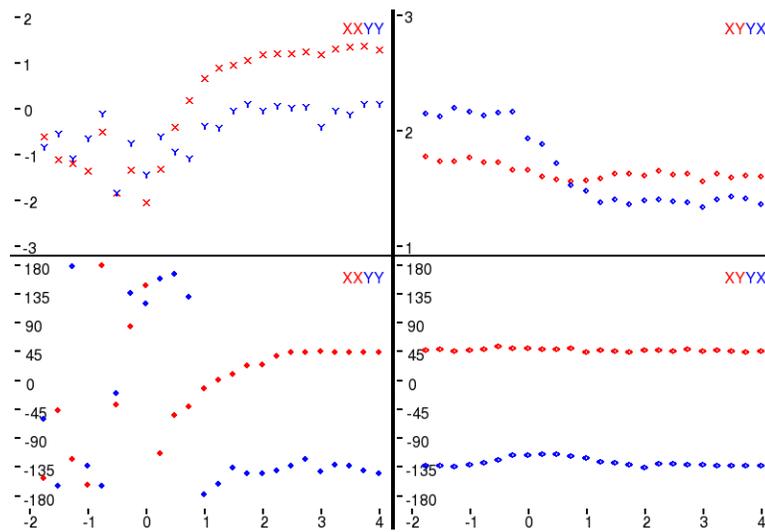
```

/SOLUTIONS\
(t,e,s) = ( -1.0159245 , 0.3985394 , -0.072834 )
( $\theta_t, \theta_e, \theta_s$ ) = ( -45.4525904 , 21.7292317 , -4.1657234 ) +-( 1.1801291 , 0.2082965 , 1.1074383 )
(t,e,s) = ( -1.0434373 , 0.3965492 , -0.3161543 )
( $\theta_t, \theta_e, \theta_s$ ) = ( -46.2177518 , 21.6307627 , -17.5445762 ) +-( 0.9038443 , 0.5272168 , 0.7013945 )

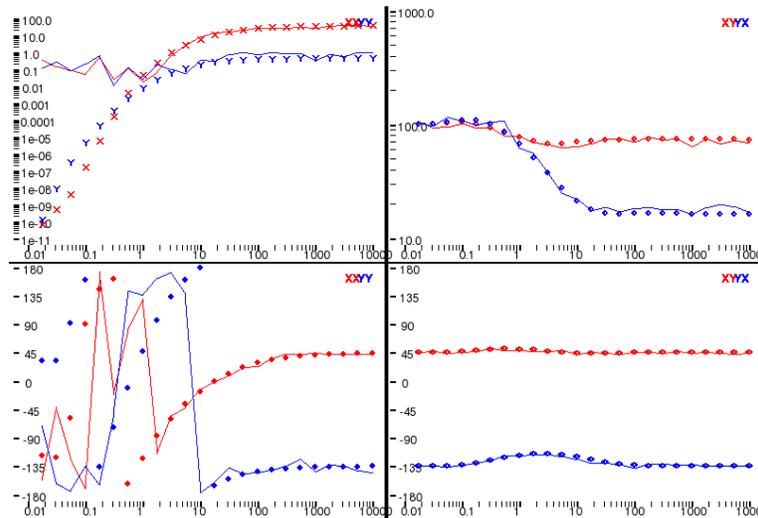
```

The terminal gives two possible solutions because of the 2D case of this period (Romero-Ruiz and Pous 2018 a,b). By plotting the corrected edis for both triplets, the right solution is identified:

For the triplet $(t,e,s) = (-1.0159245, 0.3985394, -0.072834)$ the regional impedance tensor rotated to 2.68 (15.68o-13o) is:



Clearly, this is not the solution because this case does not fulfill the 2D (1D) tendency for the shortest periods. For the triplet $(t,e,s) = (-1.0434373, 0.3965492, -0.3161543)$ the regional impedance tensor rotated to 2.68 (15.68o-13o) is the solid line below:



Solid line: corrected of distortion. Dots: original site 2.

Dots are the original Site2 rotated to 13° . It is clear this last triplet is the correct solution.

REFERENCES

Romero-Ruiz, I. and Pous, J. (2018 a). The magnetotelluric impedance tensor through Clifford algebras: Part I — theory. *Geophysical Prospecting*, submitted.

Romero-Ruiz, I. and Pous, J. (2018 b). The magnetotelluric impedance tensor through Clifford algebras: Part II — a constrained stochastic heuristic method for recovering the magnetotelluric regional impedance tensor in 2D/3D case. *Geophysical Prospecting*, submitted.