

Magnetotellurics Impedance Tensor Tools (MITT)

User Guide

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Introduction

This manual is a first draft to guide the practitioner through MITT program. MITT program is mainly constituted by four blocks: 1- Magnetotellurics 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 parameters, *twist, shear and anisotropy* (with the exception of the gain) in a general 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 (2015).

Requirements

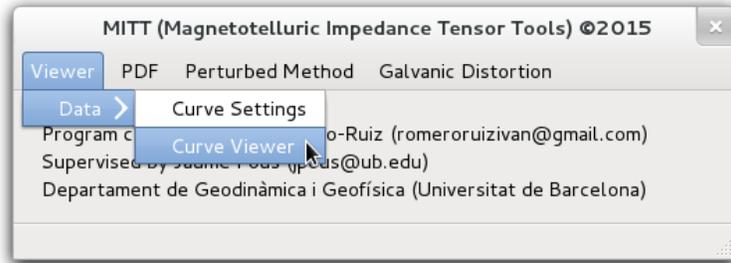
MITT program is constituted by a set of programs to analyze the impedance tensor, therefore an edi file is needed. MITT program has been written in Python 2.7 and the following modules are required:

- 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/>).

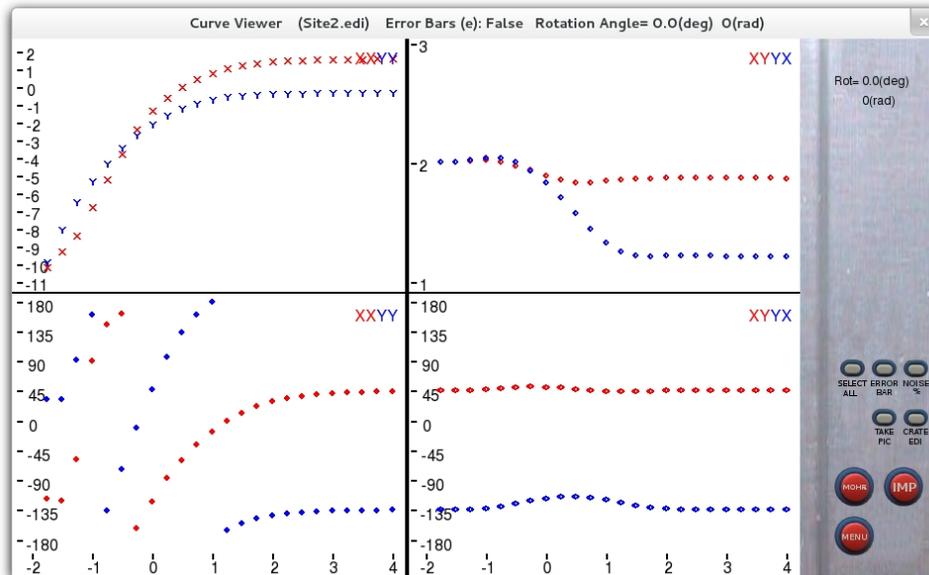
The program has only been tested in Linux OS.

Block 1: Magnetotellurics Impedance tensor representation

MITT allows to draw different representations of the impedance tensor. After launching 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 the following 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)
 $\Lambda+ = 0.00368288357628$ $N_{i^{\wedge}R}+N_{i^{\wedge}I} = 0.00368290247774$ %1 = 5.13221868392e-06
 $\Lambda- = -0.00583892975665$ $N_{i^{\wedge}R}-N_{i^{\wedge}I} = -0.00583889978983$ %1 = 5.13224502373e-06

Index 1: atan(ϕ_{12}/ϕ_0) = 4.77612839034e-07
 $\Gamma+ = 2.79085489787e-07$ $Q_{i^{\wedge}R}+Q_{i^{\wedge}I} = 2.79085489787e-07$ %1 = 3.77481906692e-14
 $\Gamma- = 4.78531152373e-07$ $Q_{i^{\wedge}R}-Q_{i^{\wedge}I} = 4.78531152373e-07$ %1 = 3.78352154458e-14

Index 2: sqrt($\phi_1^2+\phi_2^2$)/sqrt($\phi_{12}^2+\phi_0^2$) = 0.00103203952908
 $\Omega+ = 0.00103204245162$ $P_{i^{\wedge}R}+P_{i^{\wedge}I} = 0.00103204228932$ %1 = 1.57264073913e-07
 $\Omega- = 0.000660344496282$ $P_{i^{\wedge}R}-P_{i^{\wedge}I} = 0.00066034460013$ %1 = 1.57264049289e-07

Possible pair of triplets for ideal 1D :
 $(T_{1,E_1,S_1})=(1.39505982302e-07 , -8.89841666739e-07 , -0.000330708901693)$
 $(T_{2,-1/T_1,E_2,-1/E_2,S_2})=(-7168151.38316 , 1123795.43168 , -3023.80732687)$

C Matrix on Bahr Phase Sensitive Strike direction:
 $C11 = 0.999669236432$ $C12 = -1.02968800716e-06$
 $C21 = -7.50087500728e-07$ $C22 = 1.0003306542$

C Matrix on the current frame:
 $C11r = 1.00033065418$ $C12r = 7.58871105577e-07$
 $C21r = 1.03847161201e-06$ $C22r = 0.999669236456$

....

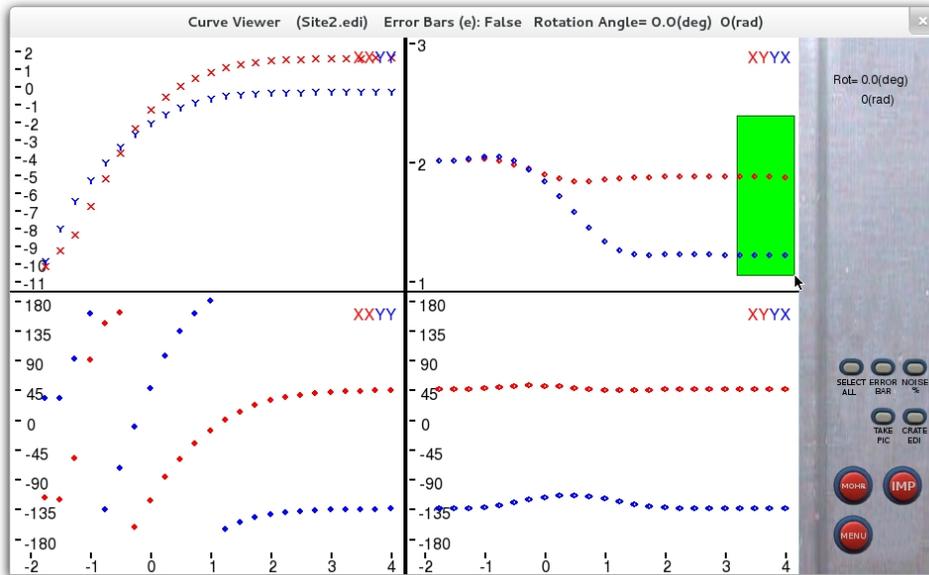
The dimensionality (1D, 2D or 3D case) refers to the values of Index1 and Index2:

$$\begin{aligned} Index1 \leq 0.1 \text{ and } Index2 \leq 0.05 &\Rightarrow 1D \\ Index1 \leq 0.1 \text{ and } Index2 > 0.05 &\Rightarrow 2D \\ Index1 > 0.1 &\Rightarrow 3D \end{aligned}$$

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.

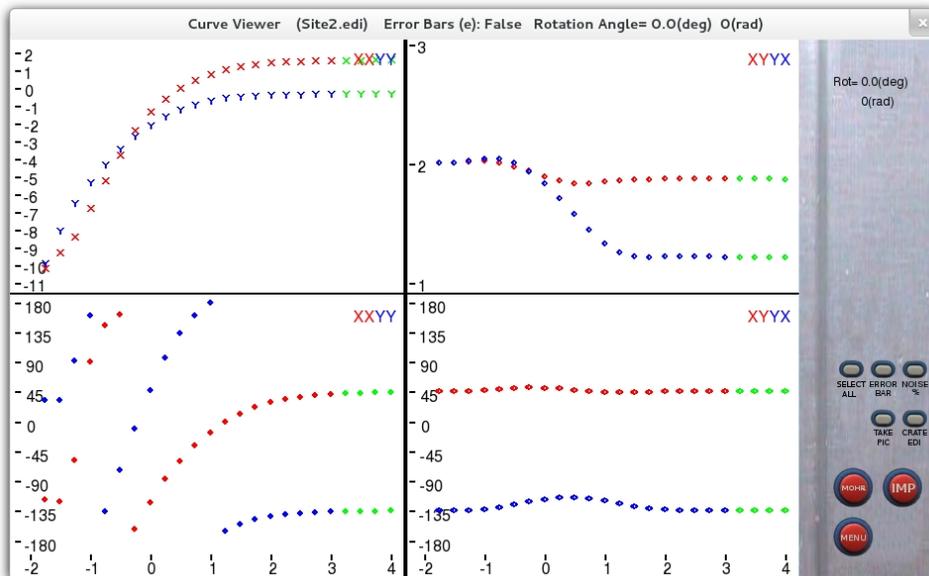
Selecting periods

In order to select a number of periods, click the right button of the mouse once 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 are selected.

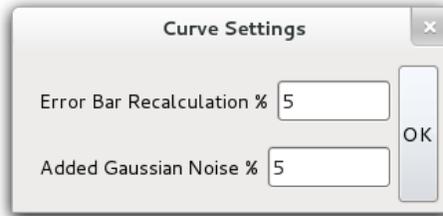
Then click one more time to select the periods included. The selection can be done both in upper panels or lower panels.



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.

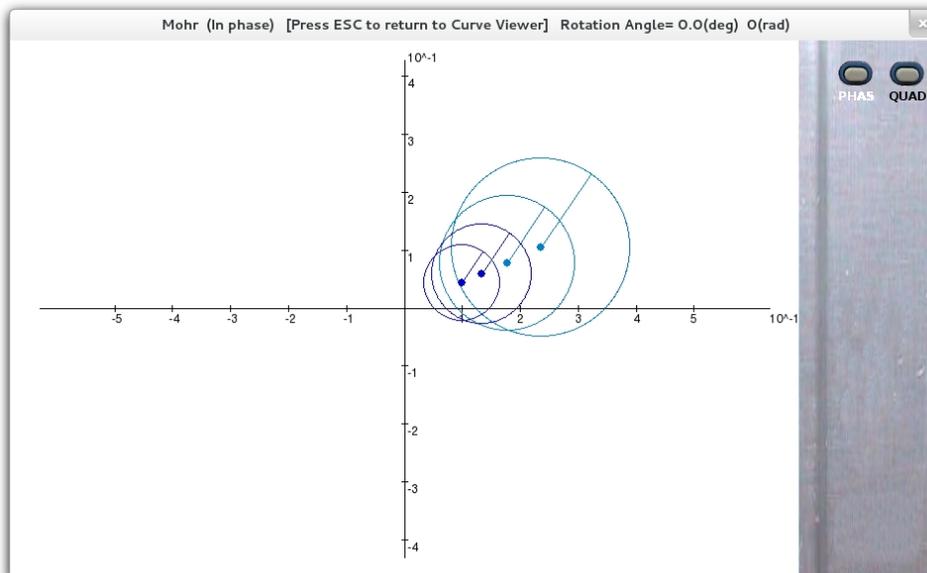


Once a selection of periods has been made, press key “w” to assign error bar to the selected periods and then key “q” (or button **NOISE %**) to add the Gaussian noise to the selected periods. **ERROR BAR** button shows the error bars. By clicking the button **MENU**, a list of the commands used by **Curve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

Curve Viewer sub-menu allows 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 file called filename_1.edi is created in /EDIS folder. When creating a new edi file, all the selected periods are eliminated and in a new plotting the 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.

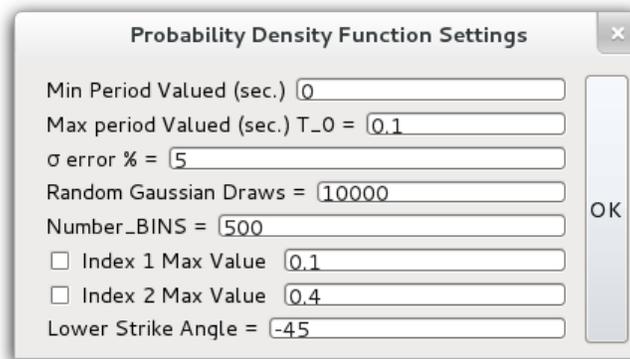
By creating an edi file, all selected periods are removed in the new edi file.

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.

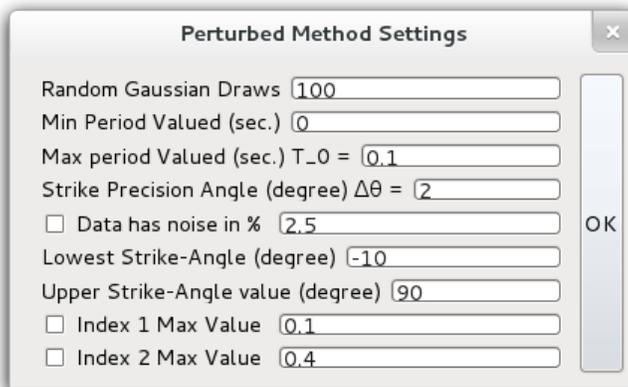
By clicking sub-menu **Calculate**, the program asks for an edi file and the probability density functions are depicted. Information about statistics being carried out are shown in the terminal.

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 (*Pseudoimpedance 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.

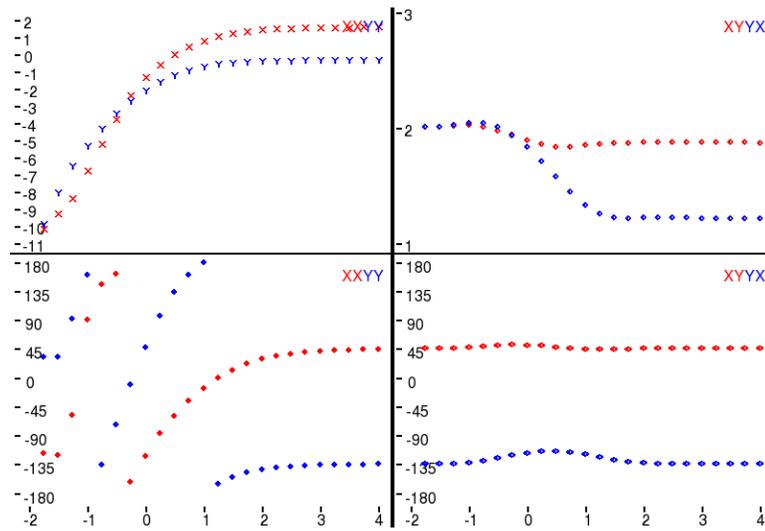


By selecting **Regional Phase Sensitive Strike** sub-menu, if the checking box *Data noise %* is activated in **Perturbed Method Settings**, the program will apply the perturbed method, otherwise the program will plot the rose diagram of the desired edi file. *Index 1* and *Index 2* are constraints defined in Romero-Ruiz and Pous (2015), 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.

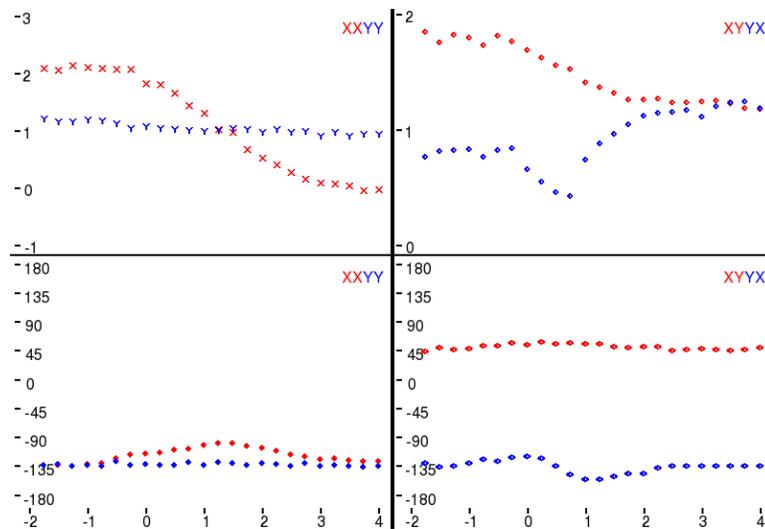
Block 4: Galvanic Distortion

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 )
  Λ+ = 5.4533621445   N_i^R+N_i^I = -2.40562094529   %1 = 1.44112620463
  Λ- = 0.0614570345849   N_i^R-N_i^I = 0.150024377584   %1 = 0.590353010794

Index 1: atan(φ12/φ0) = 0.00888539237385
  Γ+ = 2.88111833885   Q_i^R+Q_i^I = -2.81223481011   %1 = 1.97609139208
  Γ- = 0.0220313156849   Q_i^R-Q_i^I = 0.065567208966   %1 = 0.663988813428

Index 2: sqrt(φ12+φ22)/sqrt(φ122+φ02) = 0.052674016489
  Ω+ = 1.33618145087   P_i^R+P_i^I = 1.00151480147   %1 = 0.250464971795
  Ω- = 0.0273775258291   P_i^R-P_i^I = 0.0342346370637   %1 = 0.200297471296

Possible pair of triplets for ideal 1D :
(T1,E1,S1)=( 0.542163039391 , 3.3060819716 , -2.48100485856 )
(T2,-1/T1,E2,-1/E2,S2)=( -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 )
  Λ+ = 3.1311755513   N_i^R+N_i^I = -2.75726063515   %1 = 1.88058321546
  Λ- = -0.0982834535858   N_i^R-N_i^I = -0.283113666757   %1 = 0.652848077906

Index 1: atan(φ12/φ0) = 0.0131196123365
  Γ+ = 2.79292473424   Q_i^R+Q_i^I = -2.84076624416   %1 = 1.98315894171
  Γ- = -0.0125541406025   Q_i^R-Q_i^I = -0.037877468434   %1 = 0.668559142901

Index 2: sqrt(φ12+φ22)/sqrt(φ122+φ02) = 0.0630501642085
  Ω+ = 1.25285621407   P_i^R+P_i^I = 0.962750340727   %1 = 0.231555600781
  Ω- = -0.0209518757262   P_i^R-P_i^I = -0.0258033998975   %1 = 0.188018795606

Possible pair of triplets for ideal 1D :
(T1,E1,S1)=( 0.572194734293 , -2.32030814397 , 4.65568817446 )
(T2,-1/T1,E2,-1/E2,S2)=( -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 **
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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)

Λ+ = 2.69494778894 N_i^R+N_i^I = -2.88253898824 %1 = 1.93492153963
Λ- = -0.0569845796942 N_i^R-N_i^I = -0.174920348636 %1 = 0.674225553868

Index 1: atan(φ₁₂/φ₀) = 0.00974779237236

Γ+ = 2.64278767084 Q_i^R+Q_i^I = -2.89628874495 %1 = 1.91247382549
Γ- = -0.022381062386 Q_i^R-Q_i^I = -0.0692900199957 %1 = 0.67699443026

Index 2: sqrt(φ₁²+φ₂²)/ sqrt(φ₁₂²+φ₀²) = 0.025859272354

Ω+ = 1.41359225631 P_i^R+P_i^I = 1.03502151045 %1 = 0.26780759739
Ω- = -0.00493450308241 P_i^R-P_i^I = -0.00625600049723 %1 = 0.211236782254

Possible pair of triplets for ideal 1D :

(T₁,E₁,S₁)=(0.593769055171 , -1.99953414216 , 7.34897425266)
(T₂,-1/T₁,E₂,-1/E₂,S₂)=(-1.68415647682 , 0.500116491594 , 0.136073411829)

C Matrix on Bahr Phase Sensitive Strike direction:

C11 = 0.946979487751 C12 = 0.853814652019
C21 = -0.608628965017 C22 = 0.0616536513106

C Matrix on the current frame:

C11r = 0.765757198981 C12r = 1.10888337887
C21r = -0.35356023817 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)

Λ+ = 3.10796409538 N_i^R+N_i^I = -2.74661575353 %1 = 1.88373471161
Λ- = 0.0328231720242 N_i^R-N_i^I = 0.0946533205114 %1 = 0.653227463687

Index 1: atan(φ₁₂/φ₀) = 0.0145445894111

Γ+ = 2.64655634126 Q_i^R+Q_i^I = -2.8937300405 %1 = 1.91458301369
Γ- = -0.00316257671261 Q_i^R-Q_i^I = -0.00978309728079 %1 = 0.676730525943

Index 2: sqrt(φ₁²+φ₂²)/ sqrt(φ₁₂²+φ₀²) = 0.0236993952802

Ω+ = 1.29112047336 P_i^R+P_i^I = 0.980689996634 %1 = 0.240434942465
Ω- = -0.00291780091977 P_i^R-P_i^I = -0.00361934221604 %1 = 0.193831158922

Possible pair of triplets for ideal 1D :

(T₁,E₁,S₁)=(0.750277267686 , 2.0656874802 , 12.4671012266)
(T₂,-1/T₁,E₂,-1/E₂,S₂)=(-1.33284059516 , -0.484100334434 , 0.0802111077647)

C Matrix on Bahr Phase Sensitive Strike direction:

C11 = -0.206347359917 C12 = -0.4203437684
C21 = 1.05679584249 C22 = -0.814809444417

C Matrix on the current frame:

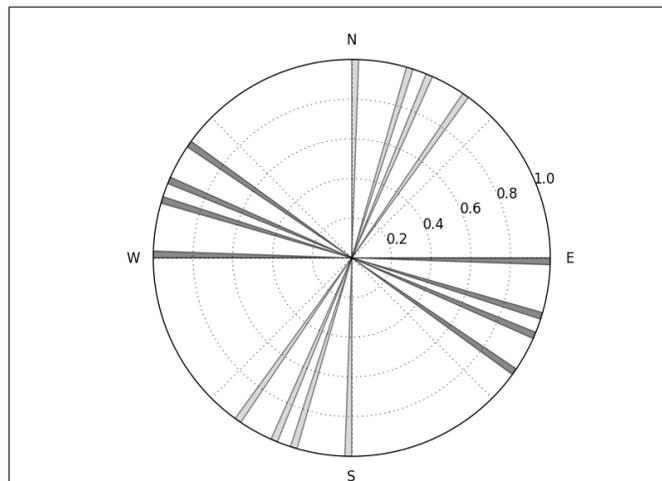
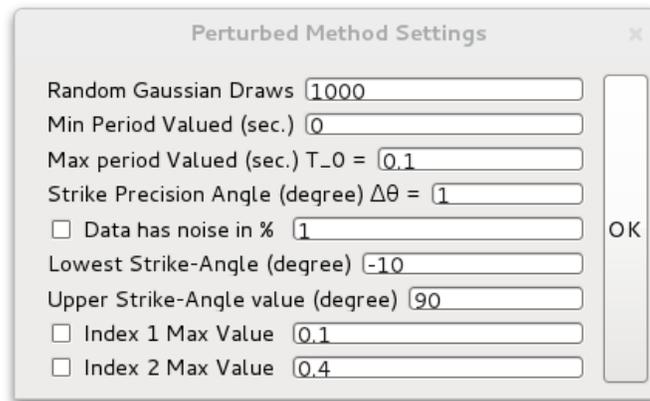
C11r = -0.769593100351 C12r = -1.09456941759
C21r = 0.382570193302 C22r = -0.251563703982

....
....
....

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.

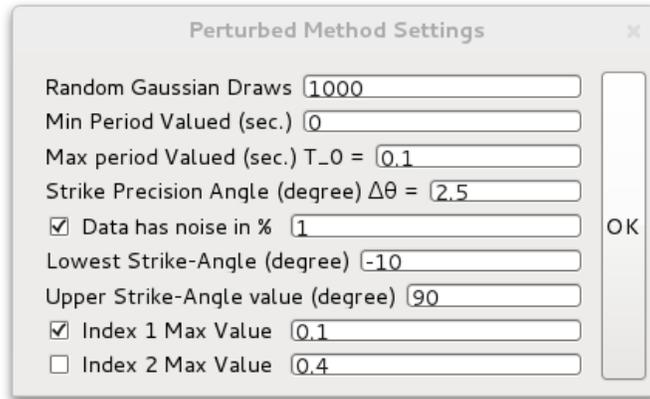
Perturbed Method

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



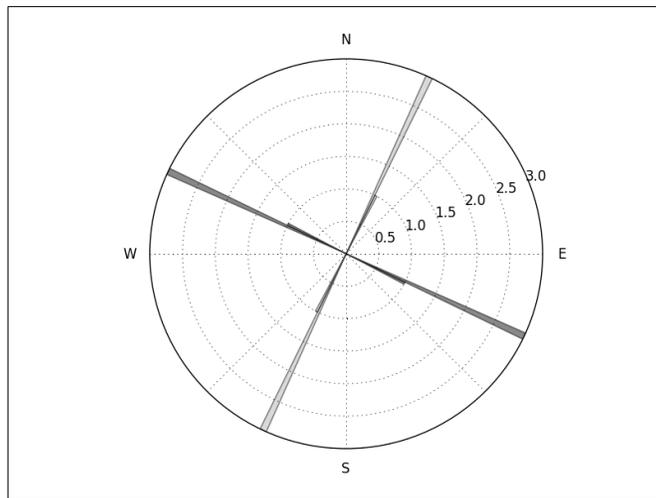
Rose Diagram for the Site 2 distorted, rotated, and with noise. The four periods considered have different Phase Sensitive strike angle due to noise.

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



The results are shown in the terminal. The Phase Sensitive Strike angle obtained is $27.67^\circ \pm 2.9^\circ$ and a new file in the /EDIS folder appears (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 of 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 -61.36° (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 0.017782794897  ** 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*[ -175.897395184 -178.869923131e123 -18.3335267286e1 -8.7913655836e23 -110.479295888e2 -105.864788848e31
+128.673850168e12 -123.86449744e3]

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

Index 1: atan( $\Phi_{12}/\Phi_0$ ) = 0.00728181494971
     $\Gamma^+ = 2.88595084285$      $Q_i^R+Q_i^I = -2.81107929461$  %1 = 1.9740565407
     $\Gamma^- = 0.0259159609247$      $Q_i^R-Q_i^I = 0.0770755330966$  %1 = 0.66375891436

Index 2: sqrt( $\Phi_1^2+\Phi_2^2$ )/sqrt( $\Phi_{12}^2+\Phi_0^2$ ) = 0.0505101189784
     $\Omega^+ = 1.33774948756$      $P_i^R+P_i^I = 1.00211518772$  %1 = 0.250894732505
     $\Omega^- = 0.02047408425$      $P_i^R-P_i^I = 0.0256109241412$  %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_1,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 )
     $\Lambda^+ = 0.120220963134$      $N_i^R+N_i^I = 0.120046741878$  %1 = 0.0014491753483
     $\Lambda^- = -0.0926801225469$      $N_i^R-N_i^I = -0.0928144322958$  %1 = 0.00144707827813

Index 1: atan( $\Phi_{12}/\Phi_0$ ) = 0.0131770472694
     $\Gamma^+ = 2.79524383155$      $Q_i^R+Q_i^I = -2.83990363302$  %1 = 1.98427418418
```

$$\Gamma = -0.0112164532156 \quad Q_i^R - Q_i^I = -0.0338285656854 \quad \%1 = 0.668432492234$$

$$\text{Index 2: } \sqrt{\phi_1^2 + \phi_2^2} / \sqrt{\phi_{12}^2 + \phi_0^2} = 0.0627519878205$$

$$\begin{aligned} \Omega + &= 1.25234874733 & P_i^R + P_i^I &= 0.962534647975 \quad \%1 = 0.231416448469 \\ \Omega - &= -0.0230713726496 & P_i^R - P_i^I &= -0.0284104677695 \quad \%1 = 0.187927040244 \end{aligned}$$

Possible pair of triplets for ideal 1D :

$$\begin{aligned} (T_1, E_1, S_1) &= (0.562145568671, -2.3963064463, 4.15921801396) \\ (T_2, E_2, S_2) &= (-1.77889866207, 0.417308897009, 0.240429810759) \end{aligned}$$

C Matrix on Bahr Phase Sensitive Strike direction:

$$\begin{aligned} C11 &= 0.950304841915 & C12 &= 0.733494027053 \\ C21 &= -0.742632174522 & C22 &= 0.0860504100835 \end{aligned}$$

C Matrix on the current frame:

$$\begin{aligned} C11r &= 0.0866953919595 & C12r &= 0.762102420203 \\ C21r &= -0.714023781373 & C22r &= 0.949659860039 \end{aligned}$$

PERIOD 0.0562341454856 ** 1D Case **

Cl3 Clifford Algebra Decomposition:

$$\begin{aligned} &1/2 * [S1R + S1I e123 + D1R e1 + D1I e23 + S2R e2 + S2I e31 + D2R e12 - D2I e3] = \\ &= 1/2 * [-104.413811244 \quad -100.532784989e123 \quad -0.6926742584e1 \quad -4.0035464995e23 \quad -64.5372790293e2 \quad -64.248455269e31 \\ &+ 70.5344952347e12 \quad -71.0143048114e3] \end{aligned}$$

Bahr Phase Sensitive Strike = -1.24182958898 (88.758170411)

$$\begin{aligned} \Lambda + &= 0.0730953250689 & N_i^R + N_i^I &= 0.0730464384293 \quad \%1 = 0.000668806652054 \\ \Lambda - &= -0.0515460990911 & N_i^R - N_i^I &= -0.051580573465 \quad \%1 = 0.000668359648675 \end{aligned}$$

$$\text{Index 1: } \text{atan}(\phi_{12}/\phi_0) = 0.00968292353391$$

$$\begin{aligned} \Gamma + &= 2.64317841329 & Q_i^R + Q_i^I &= -2.89599214926 \quad \%1 = 1.91270220258 \\ \Gamma - &= -0.0208851808307 & Q_i^R - Q_i^I &= -0.0646531604228 \quad \%1 = 0.676965817384 \end{aligned}$$

$$\text{Index 2: } \sqrt{\phi_1^2 + \phi_2^2} / \sqrt{\phi_{12}^2 + \phi_0^2} = 0.0261796840829$$

$$\begin{aligned} \Omega + &= 1.41399100137 & P_i^R + P_i^I &= 1.03520586821 \quad \%1 = 0.267883694303 \\ \Omega - &= -0.008509815672 & P_i^R - P_i^I &= -0.0107894565321 \quad \%1 = 0.21128412291 \end{aligned}$$

Possible pair of triplets for ideal 1D :

$$\begin{aligned} (T_1, E_1, S_1) &= (0.537048259371, -2.17179325468, 4.15587593916) \\ (T_2, E_2, S_2) &= (-1.86203005512, 0.460448985116, 0.240623159748) \end{aligned}$$

C Matrix on Bahr Phase Sensitive Strike direction:

$$\begin{aligned} C11 &= 0.96282381913 & C12 &= 0.736915516505 \\ C21 &= -0.726551924633 & C22 &= 0.0452561118837 \end{aligned}$$

C Matrix on the current frame:

$$\begin{aligned} C11r &= 0.0454625333792 & C12r &= 0.746437940972 \\ C21r &= -0.717029500165 & C22r &= 0.962617397634 \end{aligned}$$

PERIOD 0.1 ** 1D Case **

Cl3 Clifford Algebra Decomposition:

$$\begin{aligned} &1/2 * [S1R + S1I e123 + D1R e1 + D1I e23 + S2R e2 + S2I e31 + D2R e12 - D2I e3] = \\ &= 1/2 * [-73.7741160823 \quad -76.8581650436e123 \quad -2.9604179299e1 \quad -2.310501931e23 \quad -44.1509436125e2 \quad -45.5178619109e31 \\ &+ 50.6661929479e12 \quad -53.5407649617e3] \end{aligned}$$

Bahr Phase Sensitive Strike = 88.4738100096 (-1.52618999041)

$$\begin{aligned} \Lambda + &= 0.11821489119 & N_i^R + N_i^I &= 0.11781253591 \quad \%1 = 0.00340359218493 \\ \Lambda - &= 0.0162366026122 & N_i^R - N_i^I &= 0.016291865386 \quad \%1 = 0.00339204704014 \end{aligned}$$

$$\text{Index 1: } \text{atan}(\phi_{12}/\phi_0) = 0.0139086426947$$

$\Gamma^+ = 2.65230828483$ $Q_i^R + Q_i^I = -2.89158910833$ %1 = 1.91724936893
 $\Gamma^- = -0.00665787772067$ $Q_i^R - Q_i^I = -0.0205742807085$ %1 = 0.676398032329

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

Possible pair of triplets for ideal 1D :

$(T_1, E_1, S_1) = (0.549438651913, 2.32157727043, -4.17257399992)$
 $(T_2 = -1/T_1, E_2 = -1/E_1, S_2) = (-1.82003941026, -0.430741639632, -0.239660219332)$

C Matrix on Bahr Phase Sensitive Strike direction:

$C_{11} = 0.0706441964795$ $C_{12} = 0.740706576654$
 $C_{21} = -0.736019228107$ $C_{22} = 0.95112504996$

C Matrix on the current frame:

$C_{11r} = 0.071393576048$ $C_{12r} = 0.764145563248$
 $C_{21r} = -0.712580241513$ $C_{22r} = 0.950375670392$

....

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 (2015).

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 $\varepsilon=0.08$ (even $\gamma=0.05$ and $\varepsilon=0.05$).

The screenshot shows the 'Galvanic Distortion Search Settings' dialog box. The parameters are as follows:

- 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 $\varepsilon = 0.08$
- Some other Consider:
 - ρ_{xy} and ρ_{yx} max values < 1000
 - No phases greater than 90 degrees
 - Curve slope condition (-45,45) degrees

Buttons: OK, STOP

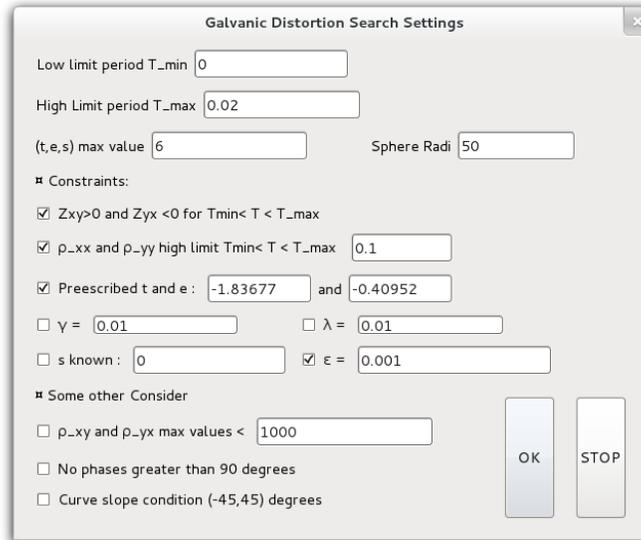
Once a prescribed values for t and e are obtained, we can apply all the constraints of the first set.

The screenshot shows the 'Galvanic Distortion Search Settings' dialog box with refined parameters:

- 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: -1.3299916 and 0.4442669
 - $\gamma = 0.001$ $\lambda = 0.01$
 - s known: 0 $\varepsilon = 0.008$
- Some other Consider:
 - ρ_{xy} and ρ_{yx} max values < 1000
 - No phases greater than 90 degrees
 - Curve slope condition (-45,45) degrees

Buttons: 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:

- $Z_{xy} > 0$ and $Z_{yx} < 0$ for $T_{min} < T < T_{max}$
- ρ_{xx} and ρ_{yy} high limit $T_{min} < T < T_{max}$: 0.1
- Prescribed t and e: -1.83677 and -0.40952
- $\gamma =$ 0.01 $\lambda =$ 0.01
- s known: 0 $\epsilon =$ 0.001

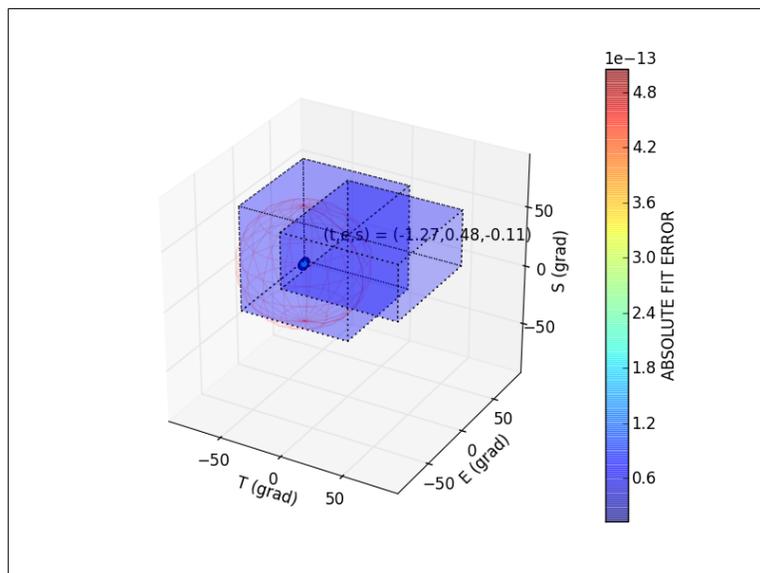
Some other Consider

- 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.

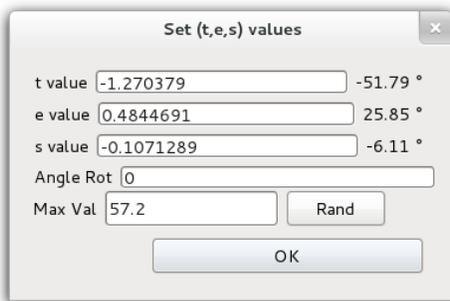
By using the first set of constraints above, once the process ends, click **Galvanic Distortion/Search/Plotting Results** sub-menu and select Site2(-1.1+0.4-0.3)_rot13,006_p5.edi (instead Site2(-1.1+0.4-0.3)_rot13,006_p5_ZP-1.0p_A5.0_I1-0.1_rot-61,36.edi) file to obtain the figure:



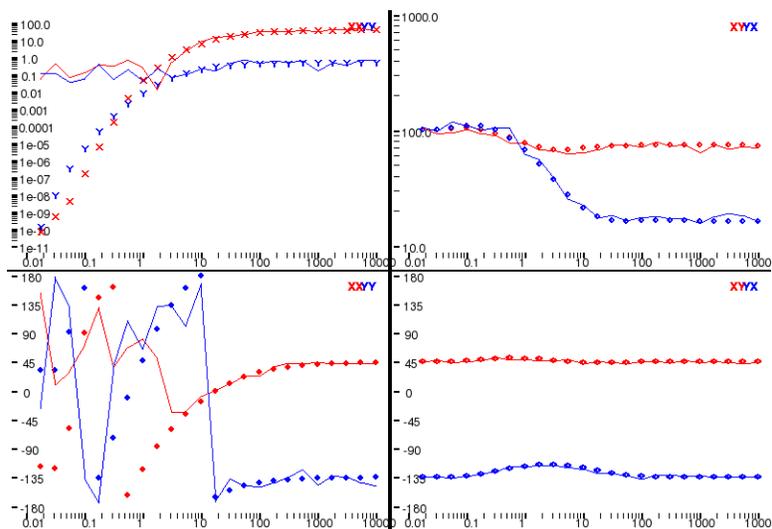
In the terminal, the obtained distortion parameter values appear:

```
_____  
_/_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 )
```

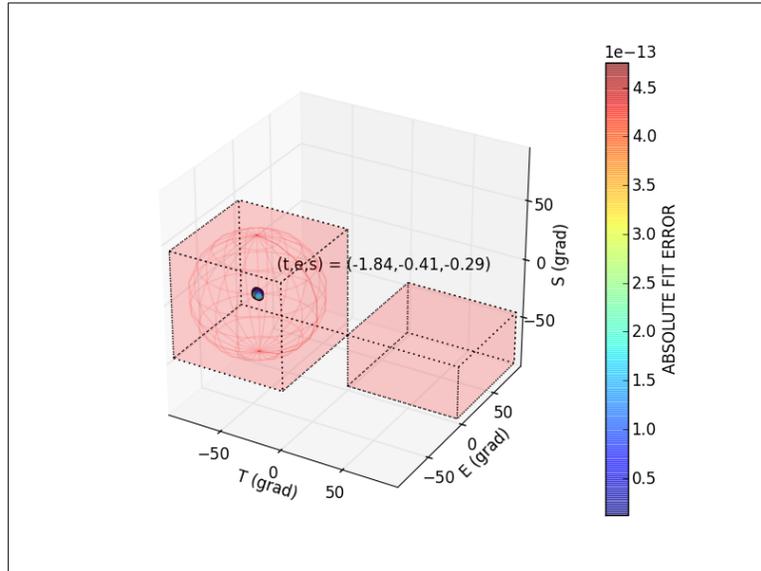
In order to correct the galvanic distortion and obtain the regional impedance tensor, click the sub-menu **Galvanic Distortion/Add or Remove GD/Settings (t,e,s) values**



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 (13°). In order to compare with the original synthetic Site2 (not rotated), the current edi must be rotated to -13° resulting:



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:



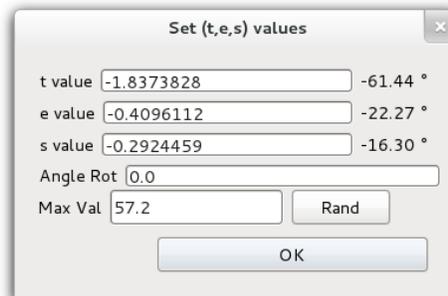
The obtained values are shown in the terminal:

```

_____/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 )

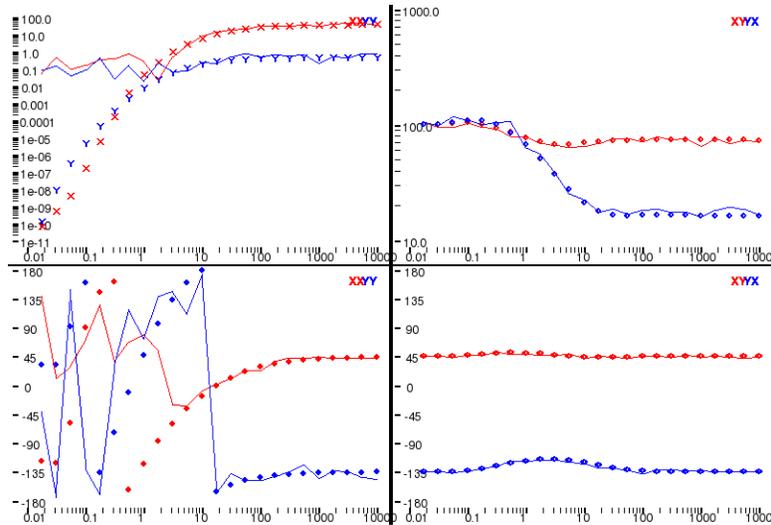
```

In order to correct the galvanic distortion and obtain the regional impedance tensor in the Phase Sensitive Strike direction (-61.36°), 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 (-61.36°). In order to compare with the

original synthetic Site2 (not rotated), the current edi must be rotated to $48.36^\circ (= 61.36^\circ - 13^\circ)$ resulting:



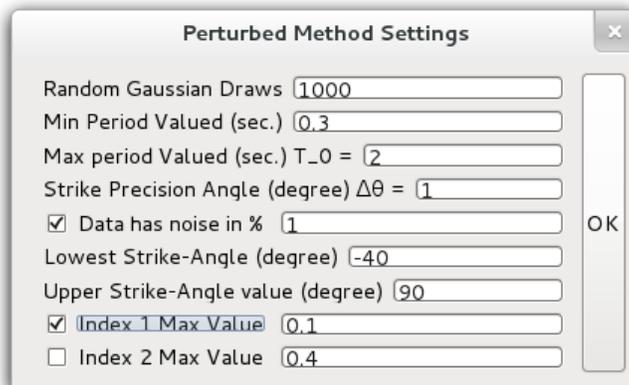
Solid line: corrected of distortion. Dots: original site2.

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 no rotation is required. In case 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.

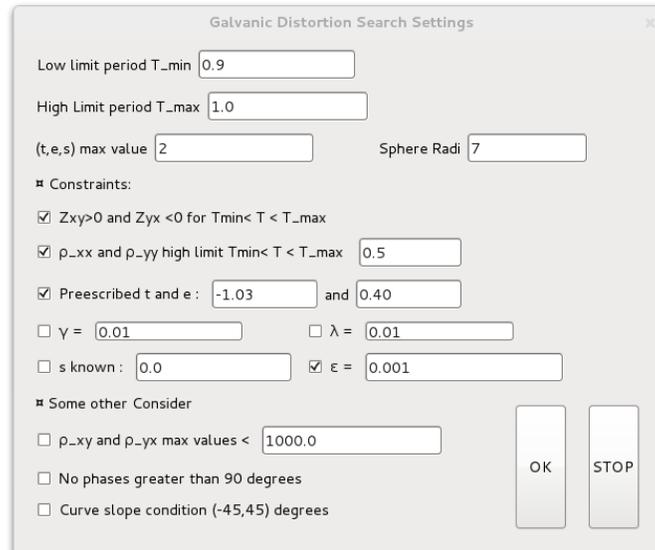
In the sub-menu **Galvanic Distortion/Add or Remove GD/Settings (t,e,s) values** by specifying *Angle Rot*, the terminal shows the distortion matrix in the current frame (C Matrix), and the distortion matrix rotated to the specified *Angle Rot* (C Matrix rotated).

Repetition with a new selection of the short periods

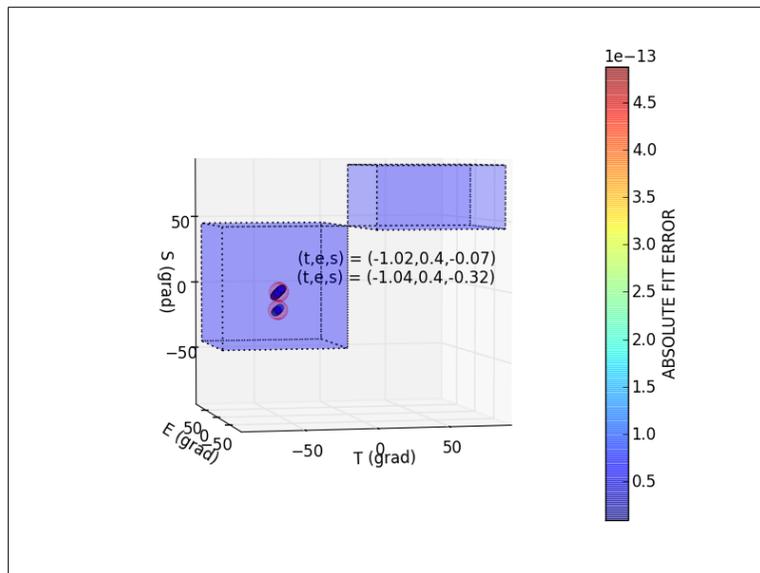
By taking as short periods, the interval $T_{min}=0.3s$ and $T_{max}=2s$, which are really 2D, the Perturbation Method with the settings:



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 to illustrate it we proceed rotating by, -15.68° . Starting the Galvanic Distortion Search with settings:



The Plotting Results are:



And the terminal shows:

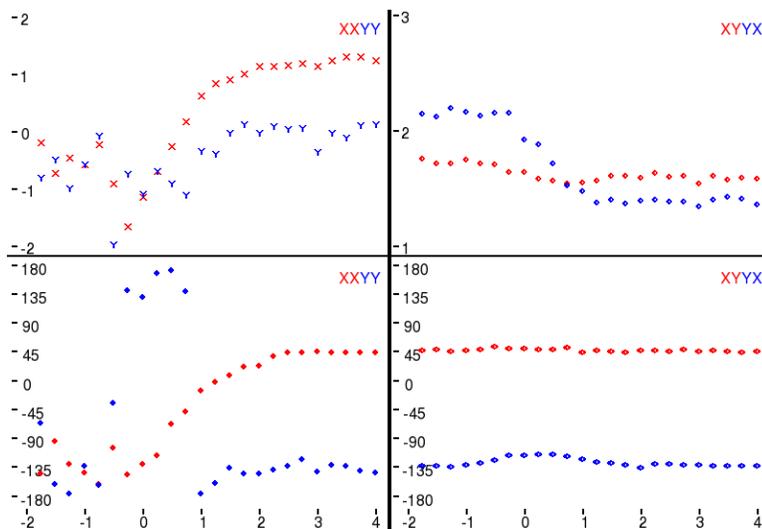
```

_/SOLUTIONS\
(t,e,s) = ( -1.0159245 , 0.3985394 , -0.072834 )
(theta,thetae,thetas) = ( -45.4525904 , 21.7292317 , -4.1657234 ) +-( 1.1801291 , 0.2082965 , 1.1074383 )
(t,e,s) = ( -1.0434373 , 0.3965492 , -0.3161543 )
(theta,thetae,thetas) = ( -46.2177518 , 21.6307627 , -17.5445762 ) +-( 0.9038443 , 0.5272168 , 0.7013945 )

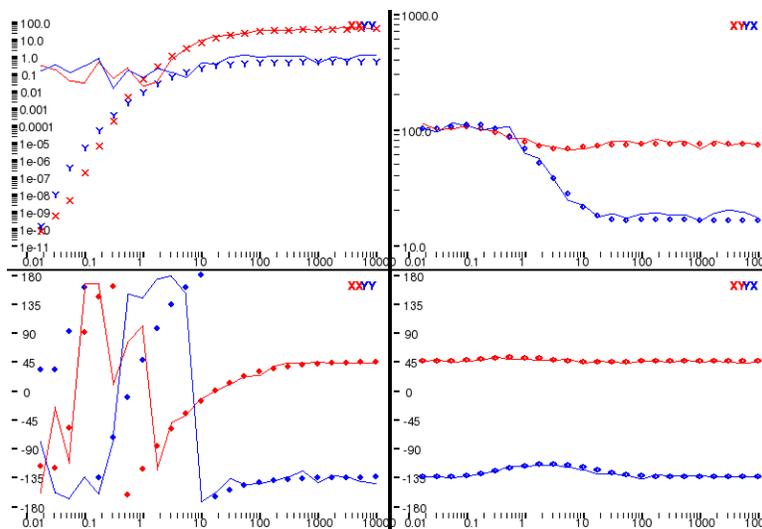
```

The terminal gives two possible solutions because of the 2D case of this period (Romero-Ruiz and Pous 2015). 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 (15.68°-13°) 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 (15.68°-13°) 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. (2015). Galvanic distortion in a 3D case: a constrained stochastic heuristic method for recovering the magnetotelluric regional impedance tensor. *Geophysical Prospecting*, submitted.