

- 1 Contents
- 2 About
- 3 Editorial Board – Technical Support
- 4 Information for Peers – Guiding Principles
- # Telecommunications Engineering – Métrologie
- 7 Measurement Uncertainty in Network Analyzers:  
Differential Error DE Analysis of Error Models  
Part 6: FLOSS – Software Tools  
N.I. Yannopoulou, P.E. Zimourtopoulos



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# Measurement Uncertainty in Network Analyzers: Differential Error DE Analysis of Error Models Part 6: FLOSS - Software Tools

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## Abstract

Two software tools were developed to compute and illustrate the uncertainty estimation of one-port VNA measurements using Complex Differential Error Regions, DERs, and their corresponding Differential Error Intervals, DEIs, in polar and rectangular form. The first tool, [REGION], was written in Open Watcom FORTRAN F77 Compiler as a Command Line Interface for calculations and is the programming realization of the graphical DER construction presented by the authors in the previous part of this series. The second tool, [DERDEI], was written in Maxima and is used as a Graphical User Interface for illustrations. Both of them were written with these Open, Free and under continuous support software development systems, in order to be publicly available, since the corresponding previously written and used by the authors programs demand the proprietary Mathematica application. The presented tools were tested with our VNA system measurement data but they can be easily used with any other VNA data ensuring that the text files have the same, specifically defined, format, valid under SLO calibration for one-port measurements. In order to demonstrate our method a number of selected experimental results along with some extreme cases of DERs and their DEIs, under particular circumstances, are also presented. The developed software tools are available on the Internet as FLOSS Free Libre Open Source Software.

## Keywords

microwave measurements, network analyzer, differential error region, differential error interval, calibration

## Introduction

The graphical construction of the Differential Error Regions DERs and their corresponding polar and rectangu-

lar Differential Error Intervals DEIs was already presented by the authors' [1]. This graphical construction was carried out step-by-step as a sequence of figures which illustrate a more or less complicated procedure of building a complex DER with its real DEIs around a VNA measurement. For this purpose the authors developed two software applications which are presented here.

Initially, the used program for these works was written in Mathematica, an enhanced language that combines evaluation and illustration, but close to those who do not own one of its versions. This program in Mathematica's package form is limited by successive Mathematica's upgrades and unavoidable variations in the used built-in functions. Thus, we decided to replace it with two separate open software tools: the [REGION] CLI-Tool and the [DERDEI] GUI-Tool. The Open and free distribution of Watcom FORTRAN Compiler version 1.8 -a programming language that includes as built in the complex number type- was used for the needed computations of [REGION]. The Open Source MAXIMA 5.17.1 language with GNUplot version 4.6 patch-level 5 -binary distribution for Windows, was used for [DERDEI], in order to draw

the DERs and DEIs in the complex and real plane respectively, resulting from [REGION].

These tools are appropriate for one-port measurements by assuming SLO calibration. They were tested with our Vector Network Analyzer VNA system, already described in detail [2], using an introduced by us data format which is fully explained in the following. Notably, it is easy to use the tools, with any other VNA data for one-port measurements either by keeping the same format for the input files or by direct modification of the open source [REGION] program. The source code has been released as FLOSS Free Libre Open Source Software and thus it may be freely used, copied, modified or redistributed, individually or cooperatively, by the interested user to suit her/his personal needs under the MIT license [3].

The two tools were presented for first time on 2 April 2009 by the authors through distance connection to the attendees, both local and distant, of the 31st ANAMET Club meeting of National Physical Laboratory NPL held in Winnersh, Berkshire at Agilent Technologies UK and an updated version of the presentation is available online [4].

### Working Formulas

The well-known one-port Error Model is shown in Fig. 1. To simplify notation, just one symbol was used for each one of the complex valued so called system errors: (a) D, M, R and (b) m for DUT measurements.

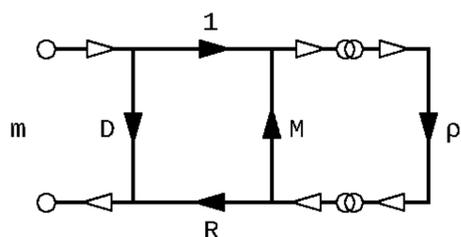


Fig. 1: Full one-port Error Model

Since the tools concern one-port measurements it is appropriate to summarize here the relations we used in programming. Thus, from [2], [5]

$$\rho = (Z - Z_0)/(Z + Z_0) \quad (1)$$

$$\rho = (m - D)/[M(m - D) + R] \quad (2)$$

$$d\rho = [-RdD - (m - D)^2dM - (m - D)dR + Rdm]/[M(m - D) + R]^2 \quad (3)$$

$$dZ = 2Z_0d\rho/(1 - \rho)^2 \quad (4)$$

where, the complex differential  $d\rho$  represents the uncertainty of reflection coefficient of any one-port DUT and  $dZ$  its corresponding impedance uncertainty with  $Z_0$  the

characteristic impedance of the system. The differentials are dependent on seven (7) complex variables, four (4) measurements and three (3) standard loads, that is on fourteen (14) real variables and their corresponding differential as we already thoroughly explained [2].

It is assumed that the user who is interested to use these tools is able to collect the measurement data of the three standard loads and the unknown DUT.

### [REGION]

In order to compute the Uncertainties, the [REGION] tool needs as its input four (4) text-files containing the measurement data of the SLO standards and the DUT with fixed names: [SH.SC], [OP.OC], [LD.LD] and [ME.ME] correspondingly, and an additional text file named [INPUT.TXT] with contents explained below.

The exact structure of the measured data with a two line example for each file is shown in Fig. 2. It must be emphasized that the text-files must have exactly these names and the format as it is detailed in Tab. 1. The empty line after each data line is required even for the last and final line of data.

A sample of the file [INPUT.TXT] is shown in Fig. 3 and has the structure speci-

fied in Tab. 2. At the first line a "0" means that [REGION] will compute  $\rho$ -DERS while an "1" means Z-DERS. Line 2 specifies the number of frequencies. Line 3 contains five (5) real numbers with the uncertainty in magnitude of the three (3) SLO standards and the two (2) phase uncertainties for the short and open standards. In this example we decided to accept as common inaccuracy for all measurements one (1) digit of the LSD (Least Significant Digit) and this is indicated at the fourth line. Notably, it is possible to

describe the inaccuracy more precisely using the related data given by the manufacturer of Network Analyzer, but a different approach is needed which is not provided in this version of [REGION].

The above described in details five (5) files must be in the same folder with the executable REGION.EXE in order the program to accomplish correctly the evaluation of the uncertainty in  $\rho$  or Z according the user's choice. Then the program produces a number of output files, also in the same folder.

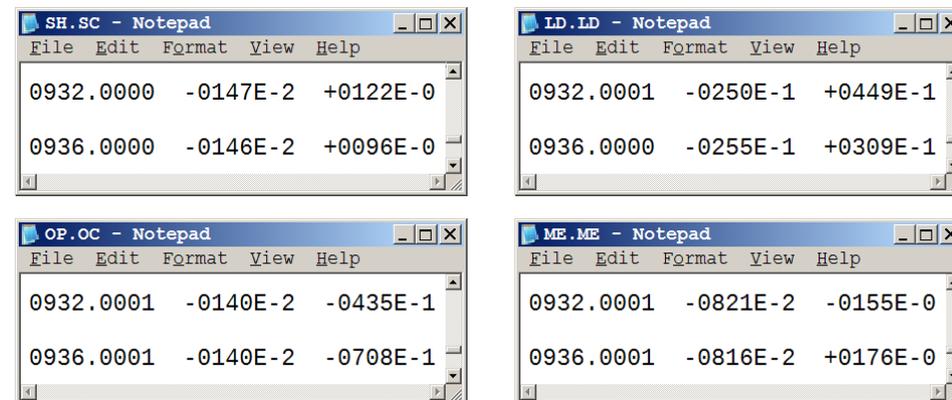


Fig. 2: Samples of the four measurement files

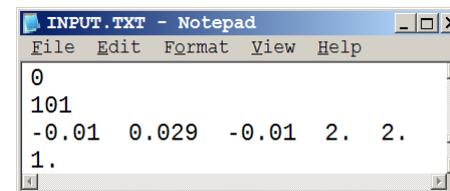


Fig. 3: Sample of INPUT.TXT file

Tab.1: Measurement Data Format

A. For each Data Line,  
 N = Mantissa digit, M = Exponent digit and s = Sign

| # | Field            | Length | Characters | Aligned | Format    |
|---|------------------|--------|------------|---------|-----------|
| 1 | Frequency in MHz | 9      | 01 - 09    | Right   | NNNN.NNNN |
| 2 | 2 spaces         | 2      | 10 - 11    |         |           |
| 3 | Magnitude in dB  | 8      | 12 - 19    | Right   | sNNNNEsM  |
| 4 | 2 spaces         | 2      | 20 - 21    |         |           |
| 5 | Phase in Degrees | 8      | 22 - 29    | Right   | sNNNNEsM  |

B. Add one Empty Line after each Data Line

Tab.2: INPUT.TXT Structure

| # | Data Type | Sample | Meaning                           |
|---|-----------|--------|-----------------------------------|
| 1 | INTEGER   | 0      | $\rho$ -DER computations          |
|   |           | 1      | Z-DER computations                |
| 2 | INTEGER   | 101    | Number of frequencies             |
| 3 | REAL      | -0.01  | Short magnitude uncertainty       |
|   |           | 0.029  | Load magnitude uncertainty        |
|   |           | -0.01  | Open magnitude uncertainty        |
|   |           | 2.     | Short argument uncertainty in [°] |
|   |           | 2.     | Open argument uncertainty in [°]  |
| 4 | REAL      | 1.     | Measurement inaccuracy in LSDs    |

Initially, the files with the specific name **NNNNR.TXT**, one for each frequency, are produced. As already clearly shown in Tab. 1 the four "N"s are the frequency in [MHz], and the letter "R" indicates that the data represent Rectangular coordinates, i.e. points and line segments of the DER. A sample file is shown in Fig. 4 for the frequency of 932 MHz. All specific numbers of points, seg-

ments and arcs are thoroughly mentioned in [1], [2]. The first line with 0 [or 1] corresponds to  $\rho$  [or Z] coordinates, as its real and imaginary parts, in this figure is 0 for reflection coefficient  $\rho$ . The next forty eight (48) lines give the coordinates of the forty eight (48) vertices of DER. Next, the description of the twenty four (24) line segments is given, for example, segment 2 is between points 3 and 4. The last 4 lines contain the minimum and maximum values of rectangular (1: Real and 2: Imaginary part) and polar coordinates (3: magnitude and 4: argument). Tab. 3 shows the information needed to illustrate the DER and its DEIs.

Then, the files with the specific name **NNNNA.TXT**, one for each frequency again, are produced, with the letter "A" to indicate the circular Arcs. 24 arcs are described with 7 numbers. The starting and ending point of each one, its center (X, Y), its radius R and the corresponding starting and ending arguments in radians. These data lines complete the DER description. A sample file for 932 [MHz] is shown in Fig. 5

The next produced output text files, **RDEIS.TXT** and **PDEIS.TXT**, contain the Rectangular and Polar DEIS respectively, for all frequen-

cies with the specified format as it is shown in Fig. 6. Thus the rectangular and polar differential error intervals against frequency can be drawn using the [DERDEI] tool.

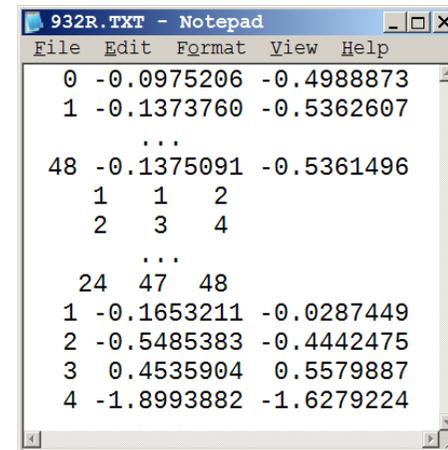


Fig. 4: Sample NNNNR.TXT file

The [REGION] tool structure is shown in Fig. 7. The main program is relied on seven (7) basic subroutines with four (4) support subroutines. The blue color and the capital letters indicate the subroutine's name, while the full name explains the usage of its one. The most important subroutine is the **FindDZDY** which finds the inaccuracy of the measurements. It depends absolutely on the specifically defined format of measured data, so any violation of it will produce unpredictable results.

Tab.3: **NNNNR.TXT** Output File Structure

```

0 : ρ coordinates (ρ', ρ'')  1 : Z coordinates
1
...: 1 to 48 ρ-DER vertices (ρ', ρ'')
48
1
2
...: 1 to 24 segment vertices (N, M)
24
1 : Min-Max of ρ'   Real part
2 : Min-Max of ρ'' Imaginary part
3 : Min-Max of ρ   Magnitude
4 : Min-Max of ρ   Argument
    
```

| #   | S  | E  | X          | Y          | R         | Start      | End        |
|-----|----|----|------------|------------|-----------|------------|------------|
| 1   | 48 | 1  | -0.1143378 | -0.5085294 | 0.0360526 | -2.2688255 | -2.2640164 |
| 2   | 2  | 3  | -0.1136405 | -0.5091087 | 0.0360526 | -2.2640162 | -1.7956039 |
| ... |    |    |            |            |           |            |            |
| 23  | 44 | 45 | -0.1290650 | -0.4937884 | 0.0360526 | -2.9138367 | -2.9079981 |
| 24  | 46 | 47 | -0.1283557 | -0.4967694 | 0.0360526 | -2.9079981 | -2.2688258 |

Fig. 5: Sample NNNNA.TXT file

|        |            |            |            |             |             |             |
|--------|------------|------------|------------|-------------|-------------|-------------|
| 932.00 | 25.5119305 | 21.7462788 | 29.5803146 | -34.3245926 | -38.6615753 | -29.8124733 |
|--------|------------|------------|------------|-------------|-------------|-------------|

| f | Value     | Min | Max | Value               | Min | Max |
|---|-----------|-----|-----|---------------------|-----|-----|
|   | Real Part |     |     | Imaginary Part      |     |     |
|   | Magnitude |     |     | Argument in radians |     |     |

|        |           |           |           |            |            |            |
|--------|-----------|-----------|-----------|------------|------------|------------|
| 932.00 | 0.5083295 | 0.4535904 | 0.5579887 | -1.7638383 | -1.8993882 | -1.6279224 |
|--------|-----------|-----------|-----------|------------|------------|------------|

Fig. 6: Sample files for Rectangular and Polar DEIs

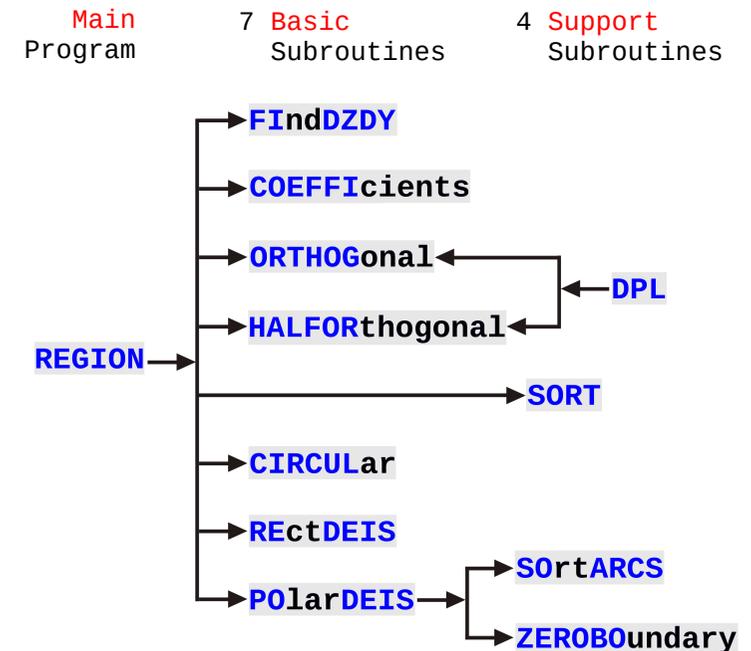


Fig. 7: REGION tool structure

**COEFF**icient subroutine computes the corresponding coefficients in relation (6) of [1]. The three types of involved basic DERs, that is, the orthogonal, half orthogonal and circular, are fully explained in [1] and they are formed in the corresponding subroutines **ORTHOG**onal, **HALFOR**thogonal and **CIRCULAR**. The support subroutine **DPL** evaluates the distance between a point and a straight line and **SORT** orders the points so that it will be possible to draw the DER as a convex polygon. **REctDEIS** and **PolarDEIS** computes the corresponding DEIs.

The **SORTARCS** orders the arguments of polar DEIs and the final **ZEROBO**oundary subroutine treats some special cases of the polar DEIs.

In order to cover more cases concerning the polar DEIs in [REGION], which maybe met in practice, Fig. 8 (a), (b) shows two special, artificially constructed cases. In Fig. 8 (a) the origin of coordinate system 0 lies within a DER. In this case it is impossible to define an annular sector circumscribed about the complex DER that will give the Polar DEIs, so, we have to consider the circumscribed

whole circle. In Fig. 8 (b) the origin 0 coincides with a contour point of DER. The annular sector is a semicircle in this case. For both cases the circumscribed orthogonal about the complex DER, that results the rectangular DEIs, can be easily determined.

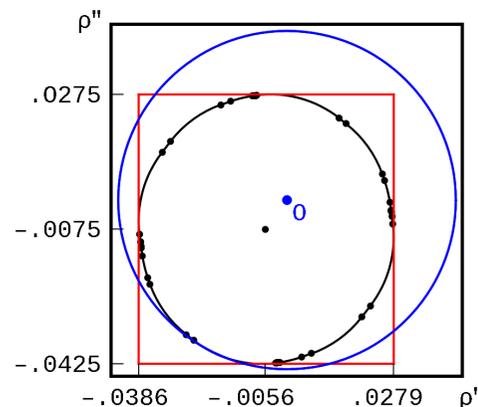
The authors are aware of the fact that additional work is needed in order to treat the special case of the non-empty intersection of  $\rho$ -DER and unit- $\rho$  circle.

**[DERDEI]**

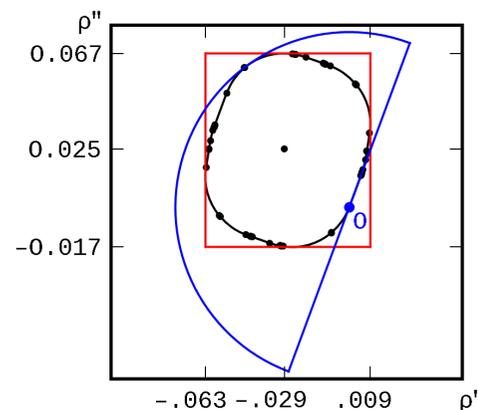
The [DERDEI] tool is the package DERDEI.MC developed for Maxima in order to plot the complex DER at each frequency, that is, a combination of line segments and circular arcs. This is not such an easy task, as it may seem, that can be carried out using simple applications that permit plotting data-lists of 2d functions, e.g. such as Excel. In addition [DERDEI] plots the rectangular and polar differential error intervals against frequency.

Fig. 9 shows the four needed steps in order to use this package: (a) run Maxima, (b) select from the file menu [Batch file Silently], (c) open the package [DERDEI.MC] and (d) the package is loaded in Maxima and contains four (4) functions. The der func-

tion reads the two files, (NNNRR.TXT, NNNNA.TXT) with the information for vertices, lines and arcs and plots the complex DER for each frequency.



(a) 0: internal point



(b) 0: contour point

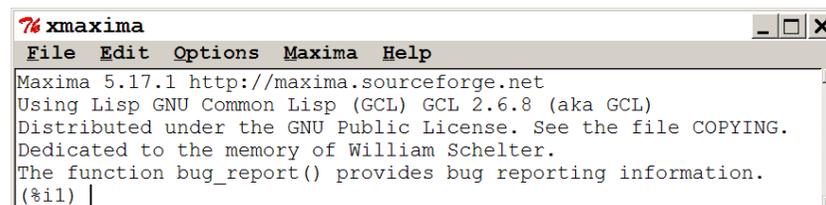
Fig. 8: Special polar  $\rho$ -DEIs

The deisRM function reads from the text file RDEIS.TXT

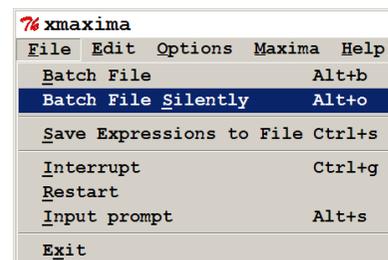
or PDEIS.TXT, n lines, and plots the DEIs of Real Part or Magnitude respectively, in terms of frequency. The labels of the graph are specified as labelx and labely.

The deisIA function plots the DEIs of Imaginary Part or Argument respectively, using the same input data as the

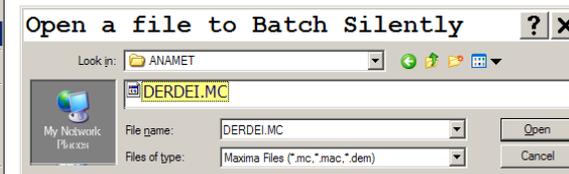
previous function. The deis function plots the DEIs of Real and Imaginary Part together at the same graph or the DEIs of Magnitude and Argument. The exact syntax of these four functions is shown directly in Maxima's main window as it is shown in Fig. 9 (d).



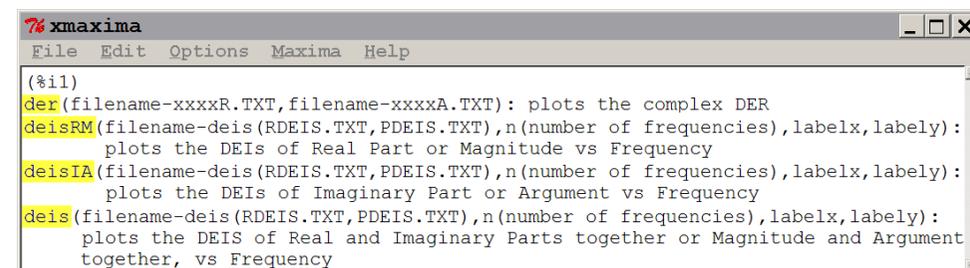
(a)



(b)



(c)



(d)

Fig. 9: Using [DERDEI] in 4 steps

**Application**

As we mentioned in Introduction the user must prepare the required four (4) files of measurements and the INPUT.TXT file. This can be done either manually, for a small number of measurements, e.g. 10 or 20 or whatever, or automatically, e.g. using a data acquisition system.

For this purpose we developed the [ANALYZE] GUI software tool using Visual Basic 3, to control our Automated Network Analyzer System [2], via HP-IB. The application takes as input the current physical state, recorded by the operator for a future statistical use, the frequency range and the file name for each measurement, as shown in Fig. 10 and gives as GUI output a draft plot of measured magnitude in [dB] and phase in degrees [°] against frequency as shown in Fig. 11. [ANALYZE] also produces the output text file with corresponding measurement, three for the three (3) calibration standards SLO and one (1) for the unknown device, for further data processing. This program is instrument dependent and it will be available some time in the future as FLOSS.

It must be emphasized that [ANALYZE] is simply a measurement data collector, thus

it is not involved at all into the application of the presented tools.

A practical application of the developed software tools is given for a UHF ground plane antenna measured from 600 to 1000 MHz with 4 MHz step. Therefore, as it is explained above, the "number of frequencies" in the second line of "INPUT.TXT" is  $101 = (1000 - 600)/4 + 1$ .

Fig. 12 shows how the three tools (in blue color) transfer data between them (red color). Data are given as input to [ANALYZE] that it is responsible to collect the measurements from our VNA system and to provide the four (4) files for the four (4) measured loads. These 4 files together with the input file are then passed to [REGION] which will output two files (2) for each frequency, total two hundred two ( $101 \times 2 = 202$ ) files for the current example, that fully describe the DERs. It also produces a file with the rectangular DEIs for all frequencies and a corresponding one for Polar DEIs. All that files can be used with the [DERDEI.MC] package in Maxima to illustrate the results. Fig. 13 shows Maxima's window with all the built function's and the corresponding input files for the plots.

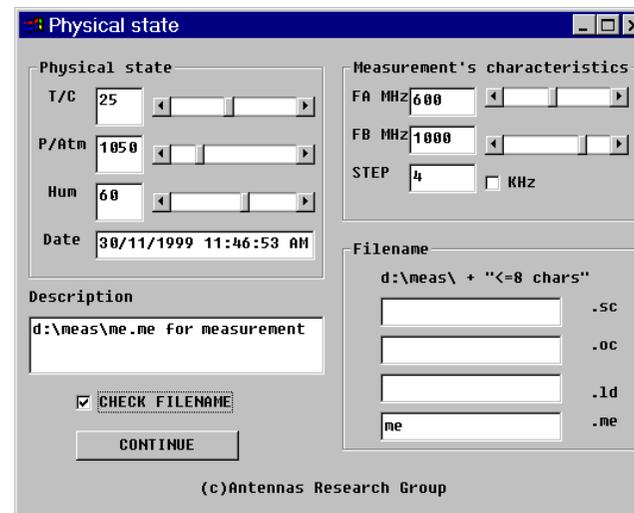


Fig.10: [ANALYZE]-Input

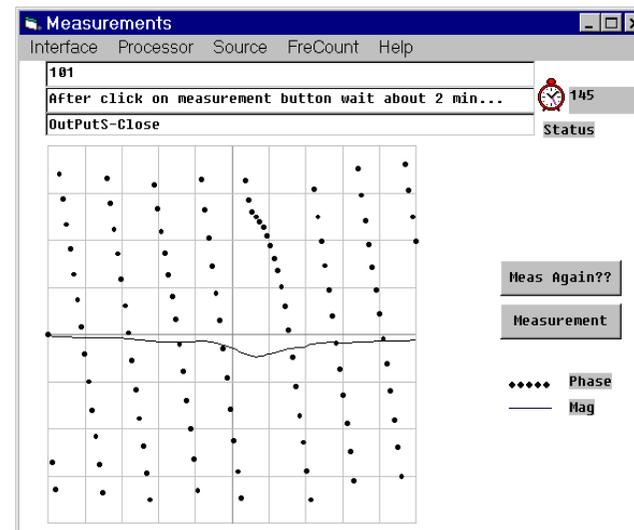


Fig. 11: [ANALYZE]-Output

Fig. 14 shows (a) the already published by the authors input impedance [2], and (b) the output graph of deis function from Maxima with the rectangular DEIs for both Real and Imaginary Part together at the same plot. Fig. 15 shows the result DERS for reflection coefficient (left column) and input impedance (right column) for the ground plane antenna, at the selected frequency. At the first line, the graphs are from Mathematica (a, d), at the middle are the published graphs with data from Mathematica package that we used (b, e), and at the last line are the Maxima graphs exactly as they are outputted (c, f). Finally, Fig. 16 shows the result graphs from Maxima and the functions deisRM and deisIA for Magni-

tude and Argument of reflection coefficient and Fig. 17 for Real and Imaginary Part of the input impedance exactly as they are produced.

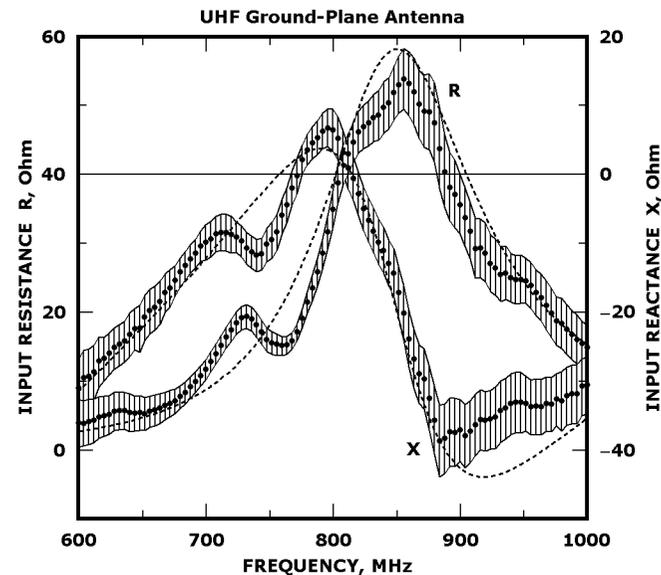
GUI-Input  
 ANALYZE  
 SH.SC  
 LD.LD  
 OP.OC  
 ME.ME  
 INPUT.TXT  
 REGION  
 NNNNA.TXT(101)  
 NNNNR.TXT(101)  
 RDEIS.TXT  
 PDEIS.TXT  
 DERDEI  
 GUI-Output

Fig. 12: Software Tools Interoperability

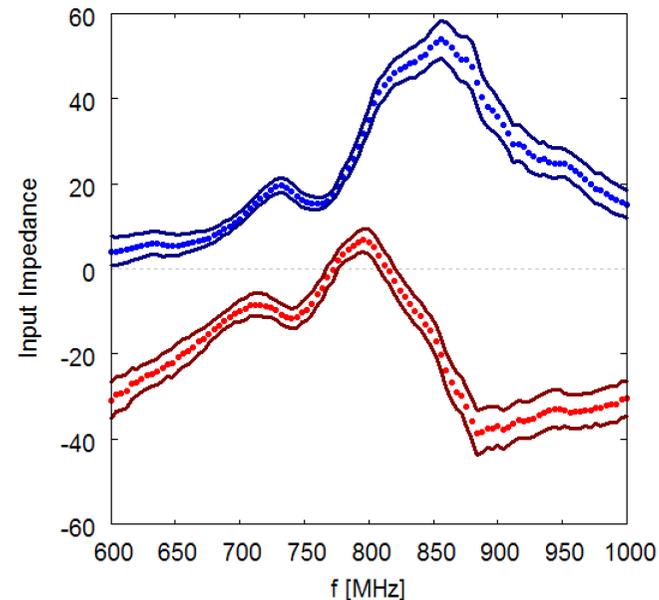
```

% xmaxima
File Edit Options Maxima Help
(%i2) der("D:\\ANAMET\\932R.TXT","D:\\ANAMET\\932A.TXT");
(%o2)
(%i3) deisRM("D:\\ANAMET\\RDEIS.TXT",101,"f [MHz]","Input Resistance");
(%o3)
(%i4) deisIA("D:\\ANAMET\\RDEIS.TXT",101,"f [MHz]","Input Reactance");
(%o4)
(%i5) deis("D:\\ANAMET\\RDEIS.TXT",101,"f [MHz]","Input Impedance");
(%o5)
(%i6) deisRM("D:\\ANAMET\\PDEIS.TXT",101,"f [MHz]","Magnitude of RHO");
(%o6)
(%i7) deisIA("D:\\ANAMET\\PDEIS.TXT",101,"f [MHz]","Argument or RHO [rad]");
    
```

Fig. 13: A sample application of [DERDEI.MC] package



(a) Published [2]



(b) deis function exact output

Fig. 14: Input Impedance versus frequency

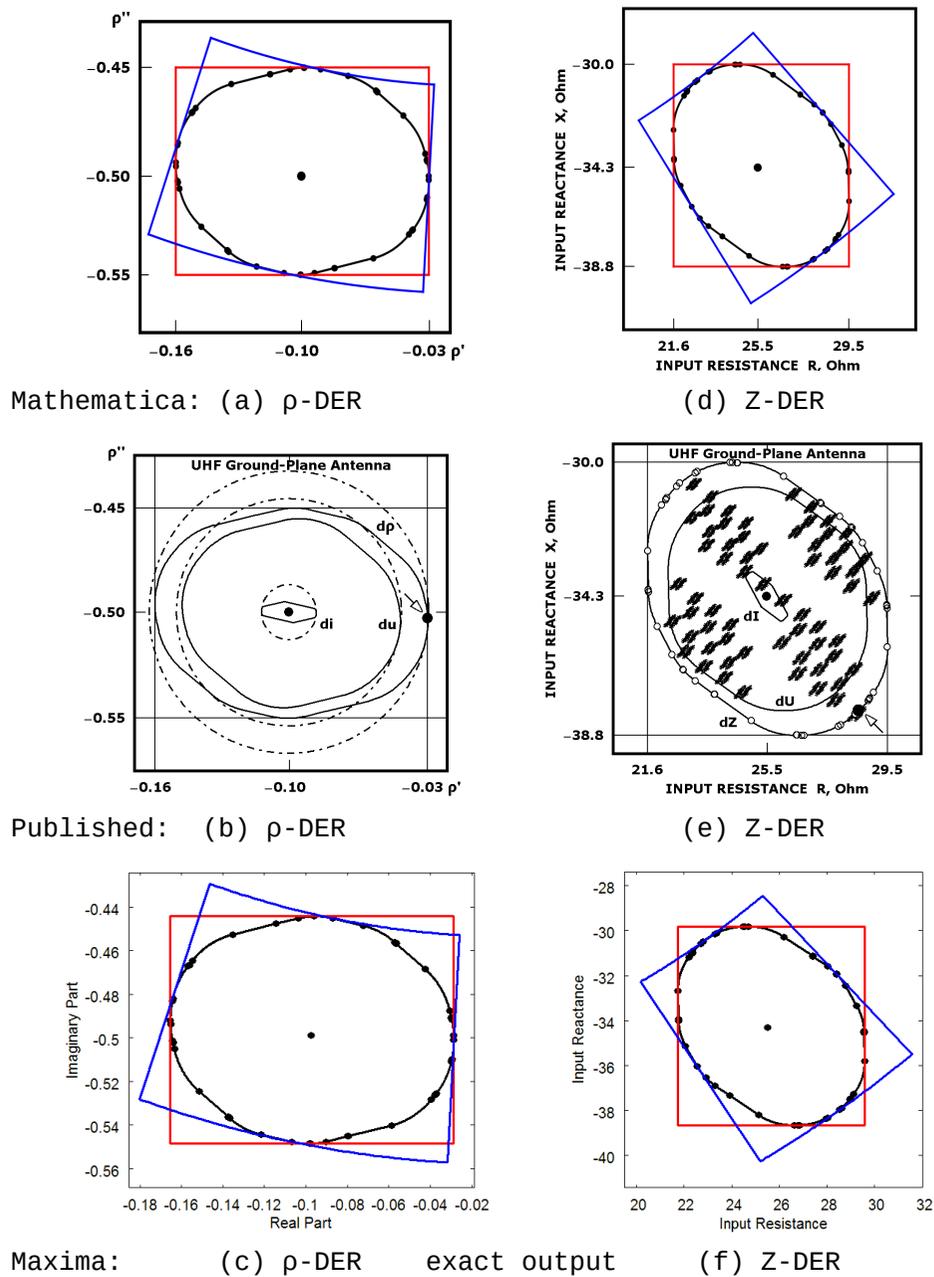


Fig. 15: Antenna DER uncertainty estimation comparison

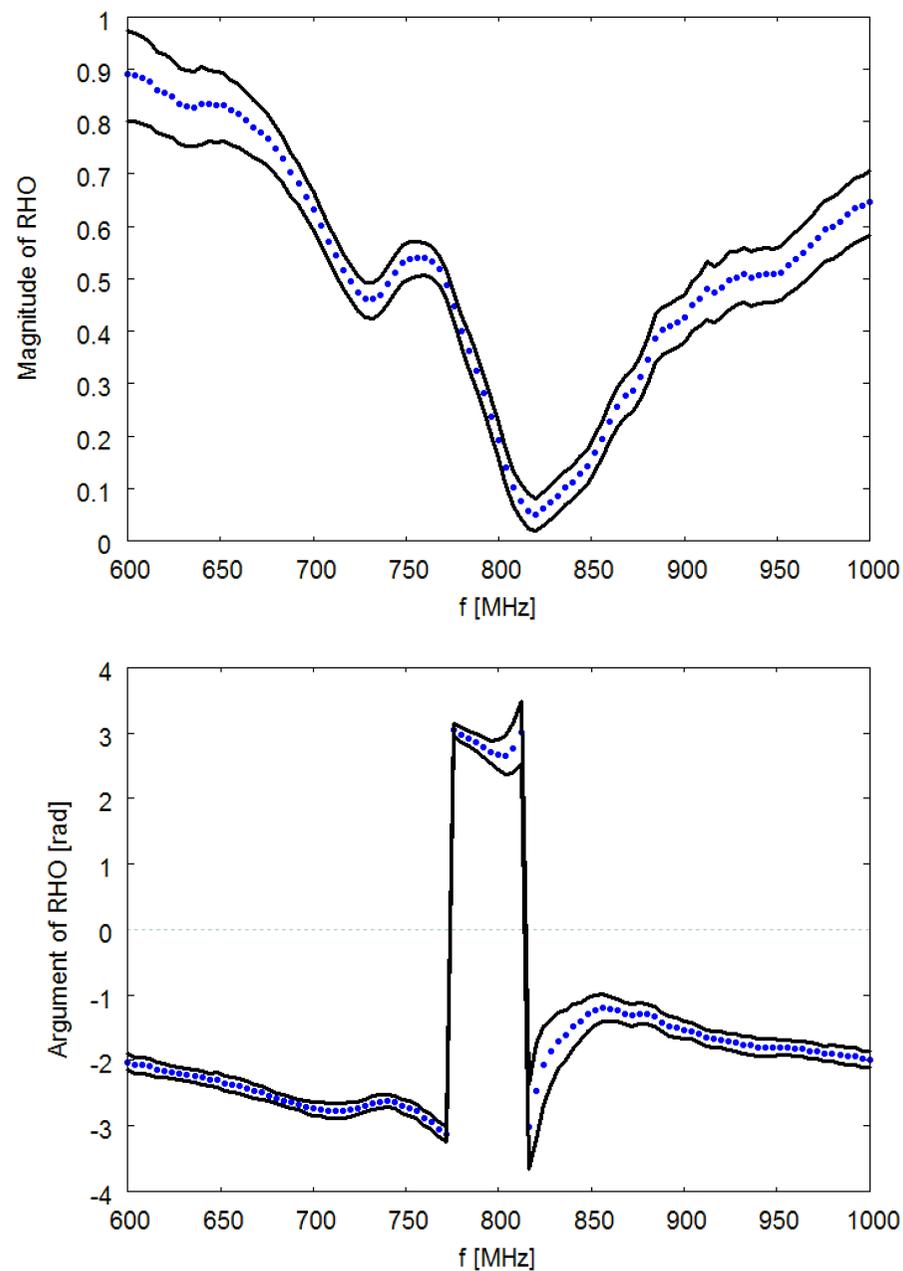


Fig. 16: Reflection coefficient  $\rho$  versus frequency

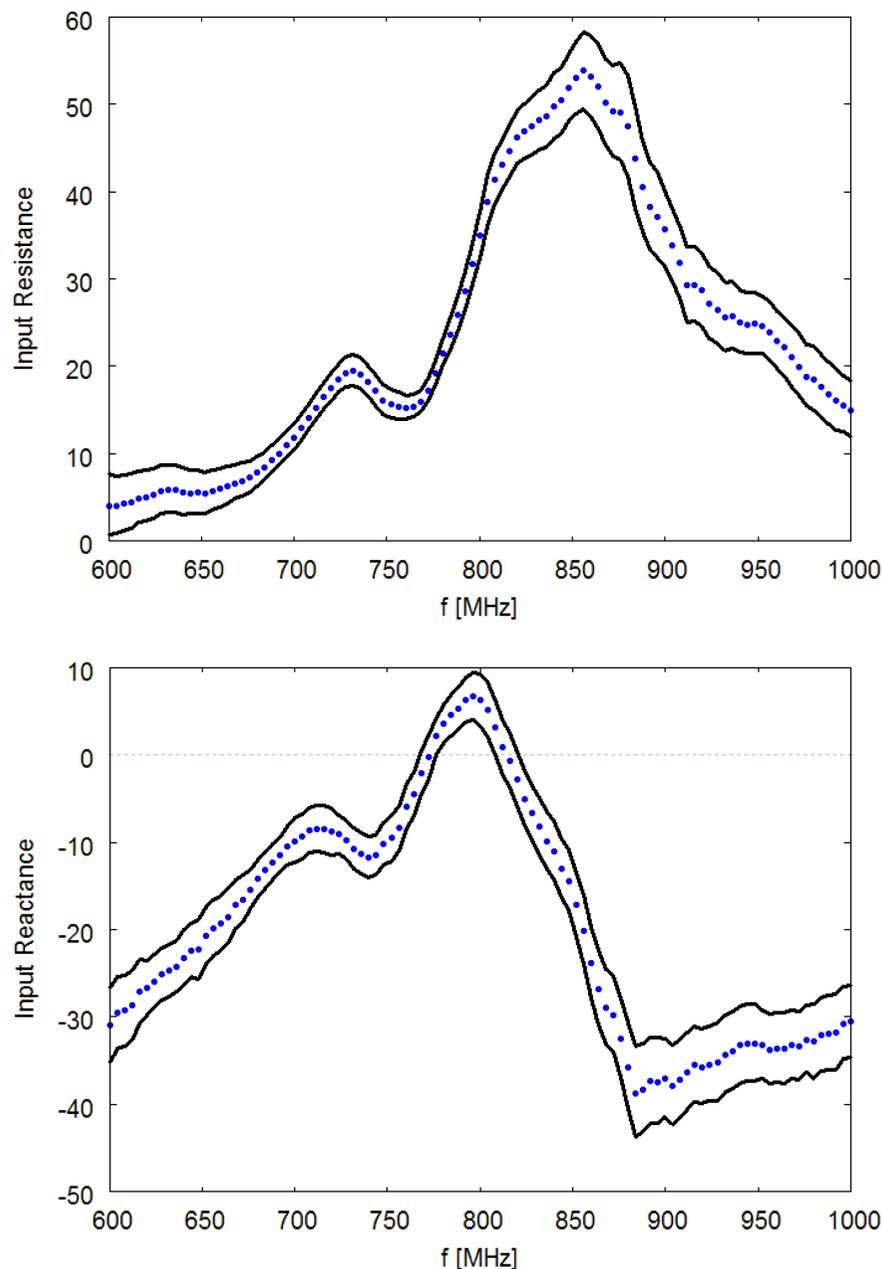


Fig. 17: Input impedance versus frequency

### Conclusion

Two developed FLOSS tools were presented. Both of them implement the technique we invented for the error estimation in VNA measurements. These tools produce and cross-check the results needed to construct DERs and DEIs. The [REGION] tool was developed using Open Watcom FORTRAN in fixed format [6]. The [DERDEI] tool, was developed using Maxima [7] as a package of it.

The also presented application example covers the case of the least uniform inaccuracy at discrete, uniformly stepped, multiple frequencies - e.g. in the commonly known "CW mode".

Notably, the presented results are exactly the same as they are produced by the corresponding developed by us Mathematica package. The illustrations from GNUplot [8], which is called by Maxima, are purposely presented exactly as they are produced, that is without any additional processing of them - a work which we left on user's choice - e.g. we use Paint Shop Pro 5.03 [9].

Since [REGION] tool concerns only one port measurements with full one port SLO calibration, it is obvious that further development of it is needed in order to include the full two port measurements as they are presented in [10] and [11], either for zero-length or for non-zero-length through standard, or even for the simplest short calibration case [12]. Similarly, further development of the corresponding Maxima package [DERDEI]. This work is in the author's future plans, together with the development of a GUI application which will integrate in one application both the data evaluation and the graphical representation, as well as the possibility of using another form of input data for the case of non-uniform inaccuracy available from more detailed manufacturer's data [13]

However, the immediate authors' plans include the presentation of their work with a substantially different method of data collection in the case of NanoVNA measurements [14].

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## FRONT COVER VIGNETTE

A faded synthesis of an anthemion rooted in a meandros

The thirteen-leaf is a symbol for a life tree leaf.  
"Herakles and Kerberos", ca. 530–500 BC,  
by Paseas, the Kerberos Painter,  
Museum of Fine Arts, Boston.

[www.mfa.org/collections/object/plate-153852](http://www.mfa.org/collections/object/plate-153852)

The simple meandros is a symbol for eternal immortality.  
"Warrior with a phiale", ca. 480–460 BC,  
by Berliner Maler,  
Museo Archeologico Regionale "Antonio Salinas" di Palermo.

[commons.wikimedia.org/wiki/File:Warrior\\_MAR\\_Palermo\\_NI2134.jpg](https://commons.wikimedia.org/wiki/File:Warrior_MAR_Palermo_NI2134.jpg)

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\* The Constitution of Greece, Article 12(3) – 2008:

[www.hellenicparliament.gr/en/Vouli-ton-Ellinon/To-Politevma](http://www.hellenicparliament.gr/en/Vouli-ton-Ellinon/To-Politevma)

\* The Hellenic Supreme Court of Civil and Penal Law:

[www.areiospagos.gr/en](http://www.areiospagos.gr/en) – [Court Rulings:Civil|A1|511|2008](http://www.areiospagos.gr/en/Court-Rulings:Civil|A1|511|2008)