A MAGNETOTELLURIC DATA EDITING AND PROCESSING PACKAGE, SUITABLE FOR EARTHQUAKE PREDICTION RESEARCH

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ABSTRACT

The study of ELF-ULF natural EM fields is particularly interesting for Earthquake Prediction Research, for they may convey information about short or long term earthquake preparation processes An EM field data editing and processing package has been developed, which may be used for both objectives above:

A. MAGNET a graphical, interactive FORTRAN program to edit and analyze natural EM field data on a computer screen, suitable for detecting transient perturbations possibly related to final stage earthquake preparation processes. It incorporates tools necessary for the classification and identification of transient events, including data conditioning (filtering, decimation etc.), spectral analysis, polarization analysis and deconvolution of the induced electric field component from the total electric field using a flexible time domain approach.

B. RESPONSE a FORTRAN program suitable for the estimation of wide band, frequency domain MagnetoTelluric Earth Response Functions (MT-ERF), which may convey information about long and/or short term changes in the electrical properties of rocks due to the accumulation of stress during the phase of earthquake preparation. It comprises a $\log_{10}$ cascaded decimation algorithm and implements enhanced frequency domain LS estimation of the MT-ERF; it is also accompanied by a graphical visualisor of time dependent changes in the MT-ERF.

In its present form, the package will handle any length of up to 7 simultaneous Cartesian components of the natural EM field (4 electric, 3 magnetic) and can easily be modified for more. It is available for DOS computer systems, but an MS Windows version is nearing completion.

I. INTRODUCTION

Monitoring and analysis of natural electromagnetic (EM) field data is important to earthquake prediction research (EPR) because it may identify :

1. Long and short term anomalous behavior of the natural electric (telluric) field that may be precede earthquakes. Transient electric field emissions from rock samples under stress have been observed before failure in laboratory experiments (Chen et al., 1984; Tang and Xu, 1988). In addition, anomalous telluric field activity in the quasi-static limit, has been observed prior to earthquakes by several authors (Sobolev, 1975; Rikitake, 1975; Wallace and Teng, 1980; Quian et al, 1990; Nomikos and Vallianatos, 1995), while an appreciable amount of work has been carried out by the VAN group (e.g. Varotsos and Alexopoulos, 1984a,b, 1987; Drakopoulos et al, 1989). The mechanism(s) that generates these telluric disturbances is not completely understood as yet and is subject to investigation as well as debate. Some (short term) such disturbances are thought to be produced by electrokinetic phenomena (fluid motion) due to stress differentials that generate streaming potentials (Mizutani et al, 1976; Dobrovolsky et al., 1989), precursory slip in the fault plane (e.g. Wang et al, 1978), propagation of charged linear dislocations, (Slifkin, 1993) and, finally, stimulated depolarization currents due to pressure variations (Varotsos and Alexopoulos, 1986). The duration and time of onset of the 'precursory' anomalous telluric field behavior varies considerably. Thus, 'signals' of a few minutes to a days of duration have been reported, while their onset ranges from a few minutes to a few days prior to the earthquake. It is possible that short duration anomalous signals occur up to a few hours prior to the earthquake, while long period signals can be detected several days prior to the same event. The amplitude of the anomalous signals varies between a few mV or even less, to several tens of mV. There exists no definite correlation between the amplitudes of the anomalous electric signals and the magnitude of the earthquake. It is, therefore, evident that this type of precursory activity requires careful and systematic investigation.

2. Time dependent changes in the MagnetoTelluric *Earth Response Functions (MT-ERF).* The accumulation (time changes) of the stress field causes both long and short term modification of the electrical properties of rocks; because of the deep penetration capability of the EM fields, such changes can potentially be detected prior to an earthquake's occurrence using Magnetotelluric (MT) analysis methods. Under steady state conditions of the subsurface rocks, the ERF are time invariant. It is well known, however, that the electrical properties of rocks depend on stress (e.g. Madden, 1980; Beamish, 1982 and references therein), water content and temperature (e.g. Keller and Rapolla, 1974). Any perturbation of the steady state electrical properties of the subsurface will be registered in the ERF and their time variation may be determinable through continuous observations of the EM field. Earthquake preparatory processes are expected to modify either one or all factors above. In theory, modification of the electrical properties will begin as soon as the preparatory processes begin inside the Earth's crust and will be sensed by the deeply penetrating EM fields. The pre-seismic and co-seismic variation of the electrical properties of rocks is a well known phenomenon, reported in accounts of field experiments (e.g. Yamazaki, 1975; Rikitake, 1976; Beamish, 1982; Quian et al, 1990) as well as laboratory measurements (e.g. Chen et al, 1984; Tang and Xu, 1988).

This paper presents and describes analysis software developed to address both EPR objectives above.

II. PROGRAM "MAGNET" - INTERACTIVE EDITING OF MT FIELD RECORDS

The program is intended for objective 1 above and therefore, it implements tools that facilitate the classification and identification of received waveforms and the discrimination of 'regular' signals (i.e. those from local and regional induction processes and repeating, near or far field sources), from 'irregular' events which may, subsequently be isolated for detailed study. The classification of signals may be based on their received characteristics, without requiring explicit knowledge of their source properties.

- The program allows the data to be examined and analyzed in any time scale desired by the user with a number of decimation/resampling and smoothing options and may also be decomposed into arbitrarily narrow band components with filtering tools, so as to facilitate the in-depth study of their frequency dependent features.
- Inasmuch as natural induction (magnetotelluric) fields constitute the most important AC component of the data, the program provides rigorous tools for the identification of local and regional induction processes and their separation from the background EM field. The time domain deconvolution method adopted in MAGNET is based on a relationship of the form

$\mathbf{e}(t)=\mathbf{z}(\tau)*\mathbf{h}(t-\tau)$, from which *the tensor impedance impulse response* $\mathbf{z}(\tau)$ may be computed in the LS Wienner sense and $\mathbf{e}(t)$, $\mathbf{h}(t)$ are vectors of the horizontal Cartesian components of the electric and magnetic fields respectively. $\mathbf{e}(t)$ may be either a 2-vector of the form $\mathbf{e}(t)=[e_x(t)\ e_y(t)]^T$ or a scalar, but $\mathbf{h}(t)$ is always the 2-vector $\mathbf{h}(t)=[h_x(t)\ h_y(t)]^T$, so that both the 2-input 2-output and the 2-input 1-output cases of impedance tensor elements estimation are supported. Then, if $\check{z}(\tau)$ is the estimated tensor impulse response, the residual $\boldsymbol{\varepsilon}(t) = \mathbf{e}(t) - \check{z}(\tau)*\mathbf{h}(t-\tau)$ represents the electric field reduced by an estimate of the inductive process $\check{z}(\tau)*\mathbf{h}(t-\tau)$. The current version of MAGNET implements a multivariate (multichannel), one-step LS estimation of the impedance impulse response, enhanced with optional one-sided Hamming window damping of the trailing auto-correlation function coefficients, in order to ensure minimum delay in cases of severe contamination by noise. The time domain deconvolution approach has been adopted for its numerical robustness and capability to handle short data lengths while yielding stable results (impedance impulse responses), as opposed to the corresponding shortcomings of the frequency domain approach. Such properties of the time domain approach will normally allow better scrutiny into the details of the data. The quality of estimation is monitored by means of the usual goodness of fit statistics and, also, with rigorous verification of the physical validity (realizability) of the computed tensor impedance impulse response, by decomposing it into its minimum delay spectrum and studying the location of its root loci; these must lie outside the unit circle in the z-plane, otherwise the function does not possess the properties of minimum delay and positive realness, which are necessary and sufficient conditions for physical realizability (e.g. Claerbout, 1976, 1992). This utility is very useful in verifying the existence and effects on non-minimum delay, multiple coherent pseudo-signals, such as for instance are some transient electric field disturbances inducing secondary magnetic fields.

- The classification and identification of received waveforms may be achieved by studying their polarization and spectral characteristics. In general, local natural induction processes may have frequency dependent polarization and spectral characteristics, which, however, should remain invariant with time and therefore, easy to identify. On the other hand, signals emitted from fixed sources and propagating along a fixed path to the observation post are expected to possess similar polarization and spectral properties, which may be used to classify and identify repeating sources even if their exact nature remains unknown and, subsequently, discriminate from the waveforms of occasional transient events that may be singled out for scrutiny.
- Finally, the data (individual waveforms to long time constant variations) may be exported in a variety of ways for further analysis with external, more advanced tools.

The program is able to handle up to 7 data channels although for the more common 14" and 15" monitors this would appear to be rather impractical. It works in a graphical interactive mode, interfacing with the user through a pointer (mouse) and keyboard dialogs. The visual interfaces (tick boxes, pull down menus and check boxes) are inherent to the program; dialogs are carried out in the reserved last line of the screen (dialog area). MAGNET may be properly executed in any DOS system featuring at least 525KB of free memory, a VGA monitor and mouse (the program operates in the Microsoft™ $MAXRESMODE / $VRES16COLOR graphics mode or, equivalently, the IBM™ screen mode 18 and may also be used with monochrome or gray scale VGA adapters). The source code is written in Microsoft™ FORTRAN 77 v5.1© and uses the associated graphics libraries, as well as PLOT4PC by D. Crossley (see the IASPEI PC Shareware Library, M. Garcia-Fernandez, ed., 1994). A brief demonstration of the program's functions follows; all illustrations have been produced by capturing the screen at different stages of MAGNET's execution.

Figure 1a and 1b exhibit MAGNET's basic (home) window and menu, together with front end pull-down menus demonstrating some of the functions offered. Figure 1a shows the home window displaying a few hours of data and demonstrates the **«Tools»** menu, which offers data conditioning utilities. MAGNET allows for the interactive design of filters (e.g. Figure 1c), thus enabling optimal results. Note that filtering functions are allowed only in the home window. A second mode of presentation is shown in Figure 1b, where the home window displays a few days of data after decimating the same data set by a factor of 10 and removing a 3rd degree trend, together with the **«Data»** menu offering utilities for navigating within the data set.

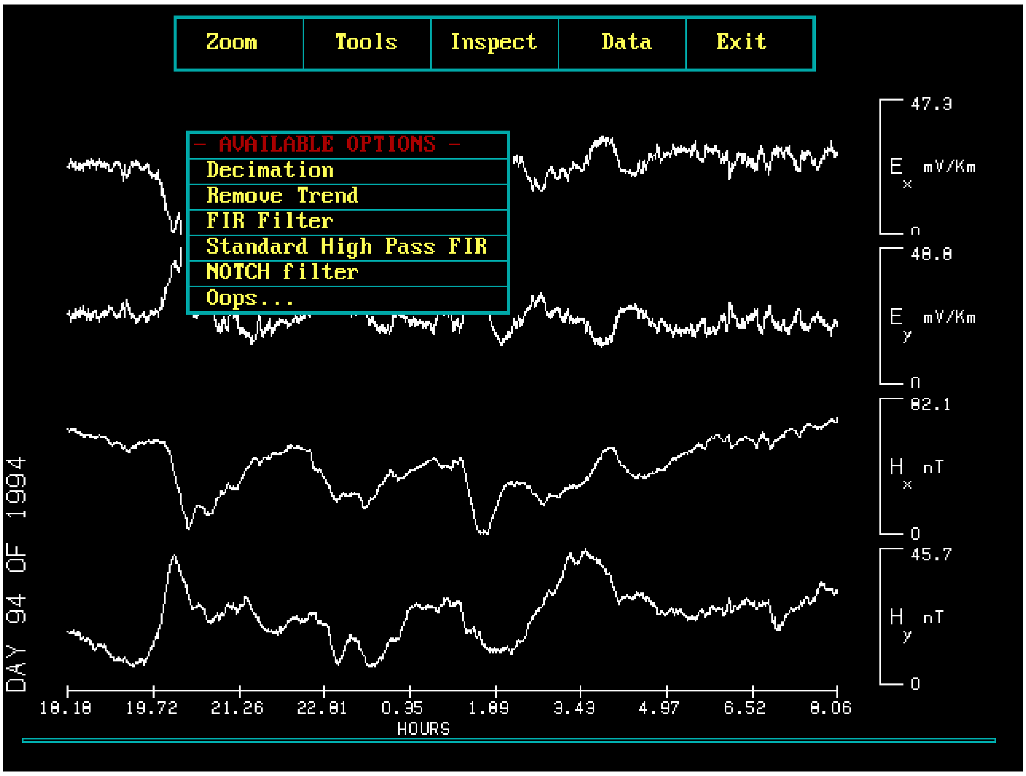
Figure 2 shows the basic zoom window and menu during a 'data inspection' session. When the **«Inspect»** box is clicked, the user may obtain amplitude and time information for each channel displayed in the zoom window. This is shown in the dialog area and in a streaming mode, continuously updated by moving the pointer (mouse) within the zoom window with all buttons released. This utility is also available in the home window. The data in the zoom window may have *any* length greater than three samples. Some polarization analysis utilities are demonstrated in Figures 3a featuring a *feather plot* presentation of polarization data and Figure 3b, featuring a *compass plot* presentation. A more conventional *hodogram* mode of presentation is also available, to allow scrutiny into the rotational properties of the data. In all cases, the user may measure any polarization angle by clicking **«Yes»** in the appropriate menu and 'rubber banding' a line from the origin to the desired point. The result is displayed at the bottom (dialog) area of the screen.

The spectral analysis functions of MAGNET are demonstrated in Figures 4a,b. The user decides which of the zoom window's data channels will be FFT'ed and their power spectra are displayed in the spectral window of Figure 4a. The colour coding of individual data channels is presented in the lower left corner of the screen. The user is then asked to smooth and/or inspect the spectra. Individual channels may be selected by clicking in the relevant check-box menu. An arbitrary wide frequency band may then be selected for close-up inspection and is displayed in the spectral zoom window as per Figure 4b. Spectral similarities or dissimilarities may be assessed visually and amplitude / frequency information is displayed in the dialog area in a streaming mode continuously updated by moving the pointer (mouse) within the spectral zoom window with all buttons released. In a forthcoming update of MAGNET, two-channel transfer functions and coherences will also be available.

Figures 5a,b outline a deconvolution session, after **«Deconvolv»** has been clicked in the zoom window. The user is prompted to define the output channel(s) and then to enter their experimental choice of the deconvolution operator length. Electric data channels may be processed individually (2-input 1-output systems), or in orthogonal vector pairs (2-input 2-output systems). A option for the analysis of vertical magnetic field data is also available (a 2-input 1-output system). The results will be superimposed on the original traces of the electric field channels. The predicted (model) electric field is shown in red and the residual (deconvolved traces) in green (Figure 5a). Goodness of fit statistics are displayed in the dialog area. The user may now inspect and verify the impedance tensor polynomial (impulse response) for physical validity and realizability by choosing to study its root loci (Figure 5b). Finally, the user may replace the total electric field channels with their cleaned traces (residuals), representing the non-inductive part of the observed electric field.

MAGNET may export the zoom window data (original or deconvolved) as ASCII files for additional analysis and also as HPGL graphics metafiles. The polarization analysis results may also be exported as HPGL graphics metafiles (HPGL is a Trade Mark and copyright of the Hewlet-Packard Corporation). Finally, **«Return»** will simply yield control to MAGNET's home window.

(a)



(b)

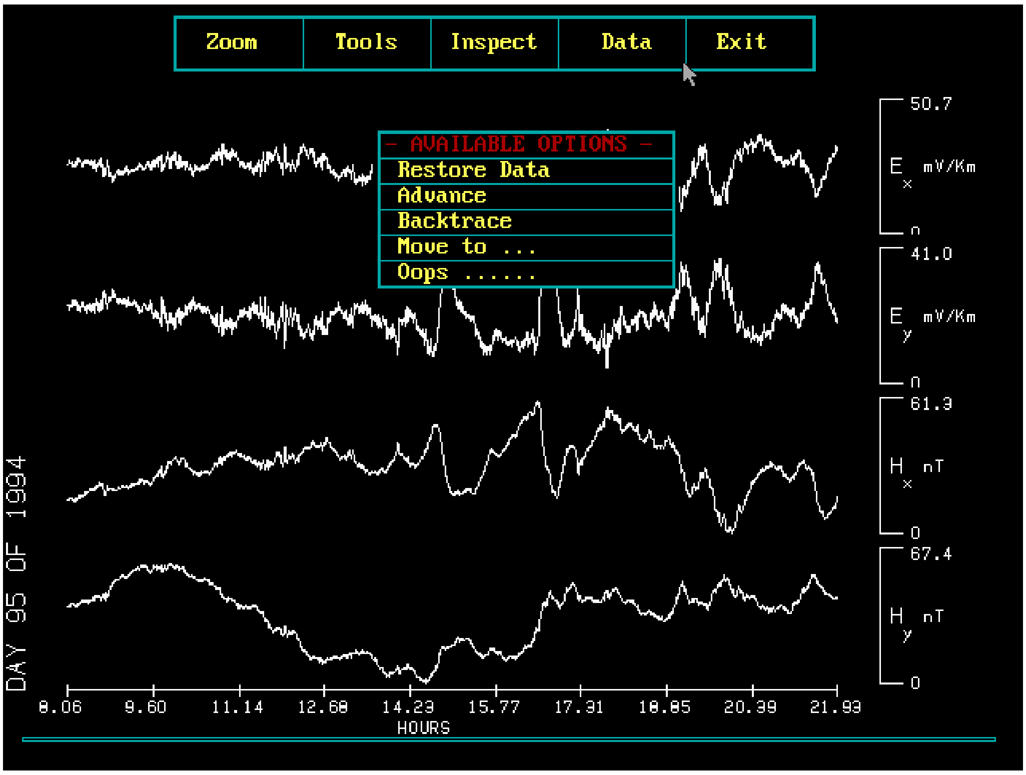


FIGURE 1. Two modes of MT data presentation in the home window of MAGNET: **(a)** Afew hours of data are displayed, enabling scrutiny into the fine details of the natural EM field -Nyquist frequency is 0.025 Hz. **(b)** Several days of data are displayed, after decimation of the same data

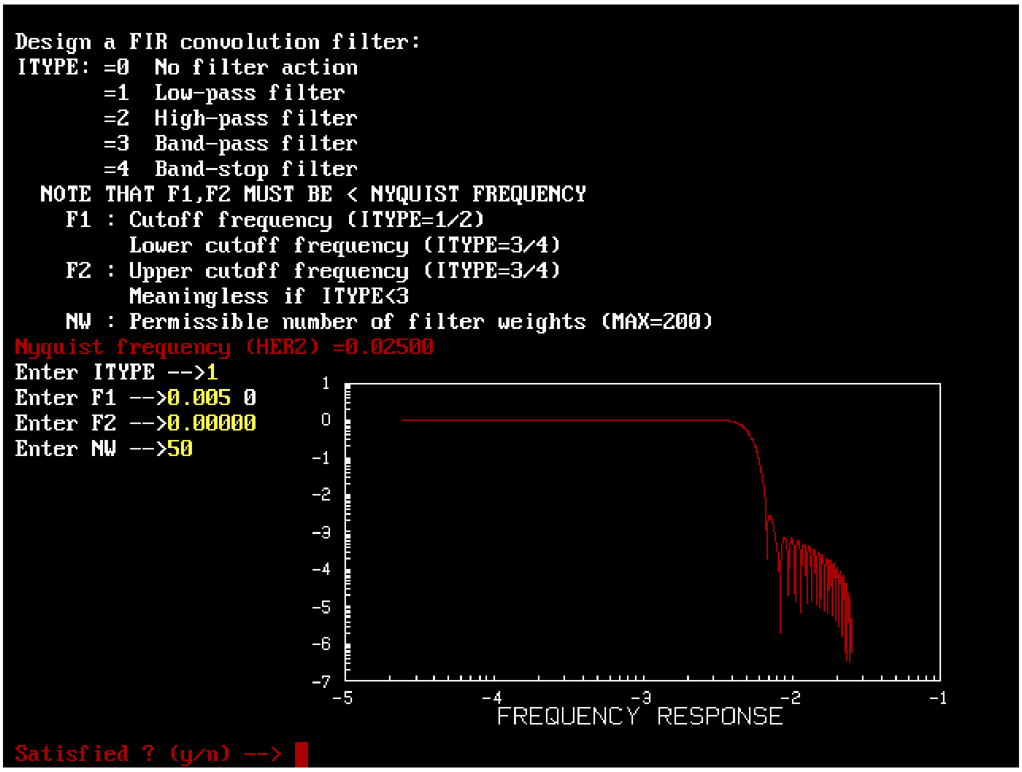


FIGURE 1c. A demonstration of the on-line filter design facility in MAGNET.

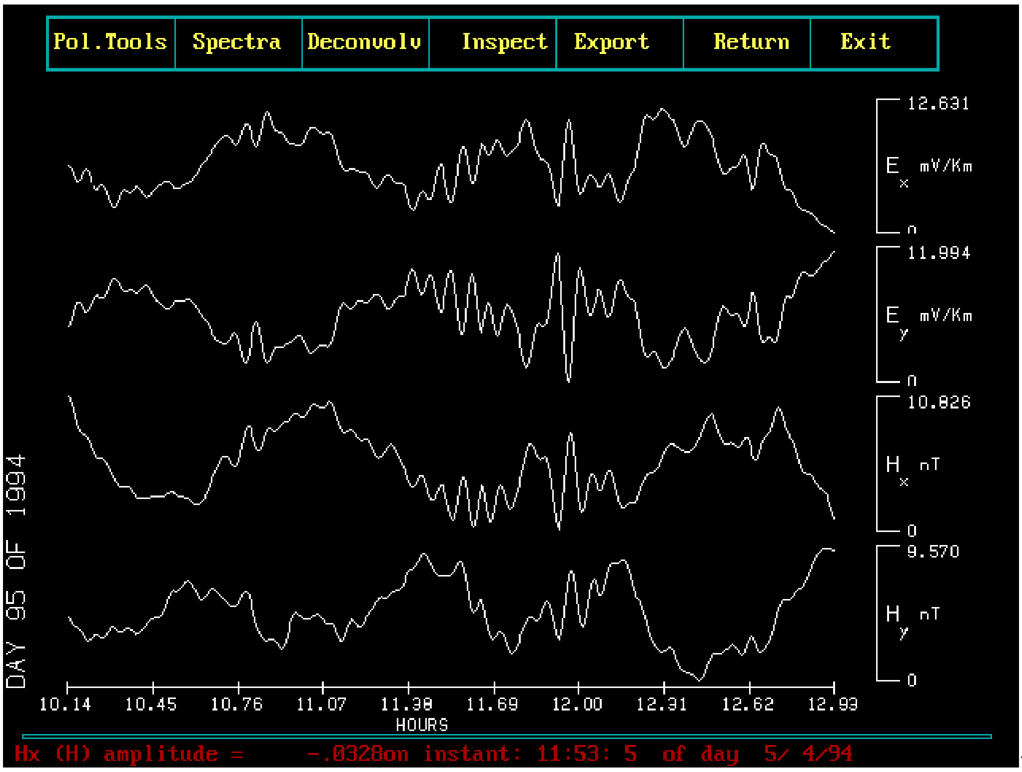


FIGURE 2. The MAGNET zoom window with available options. The screen has been captured during a data inspection session.

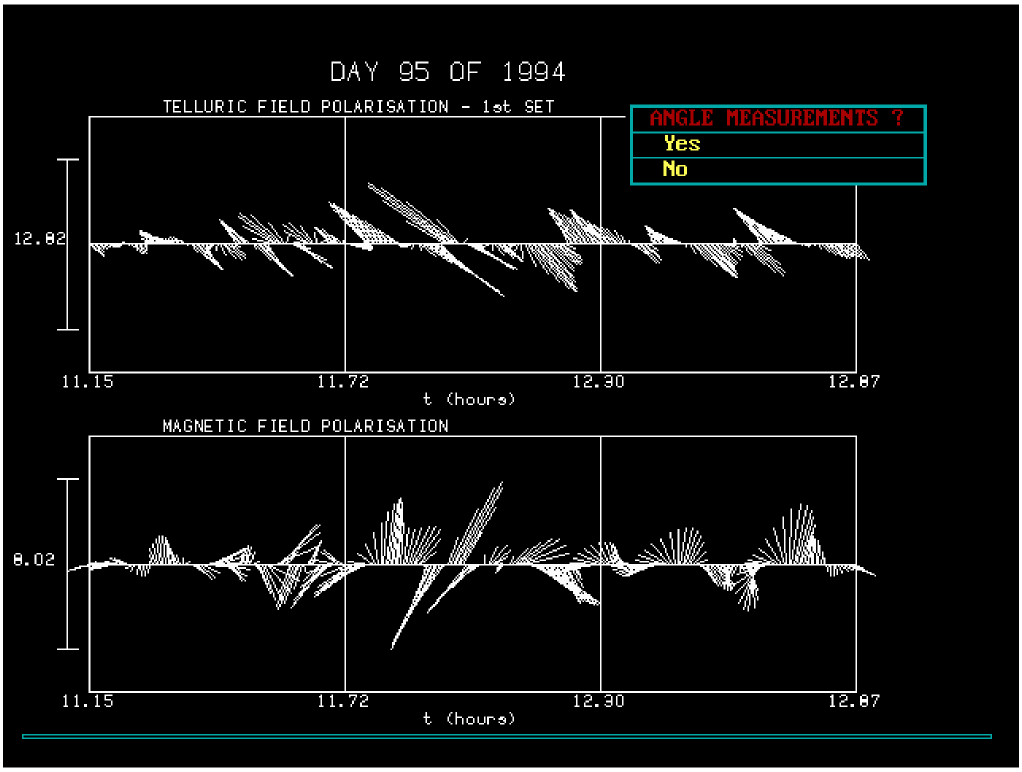


FIGURE 3a. The *"feather plot"* mode of polarization data. Polarization analysis tools are provided only in the zoom window

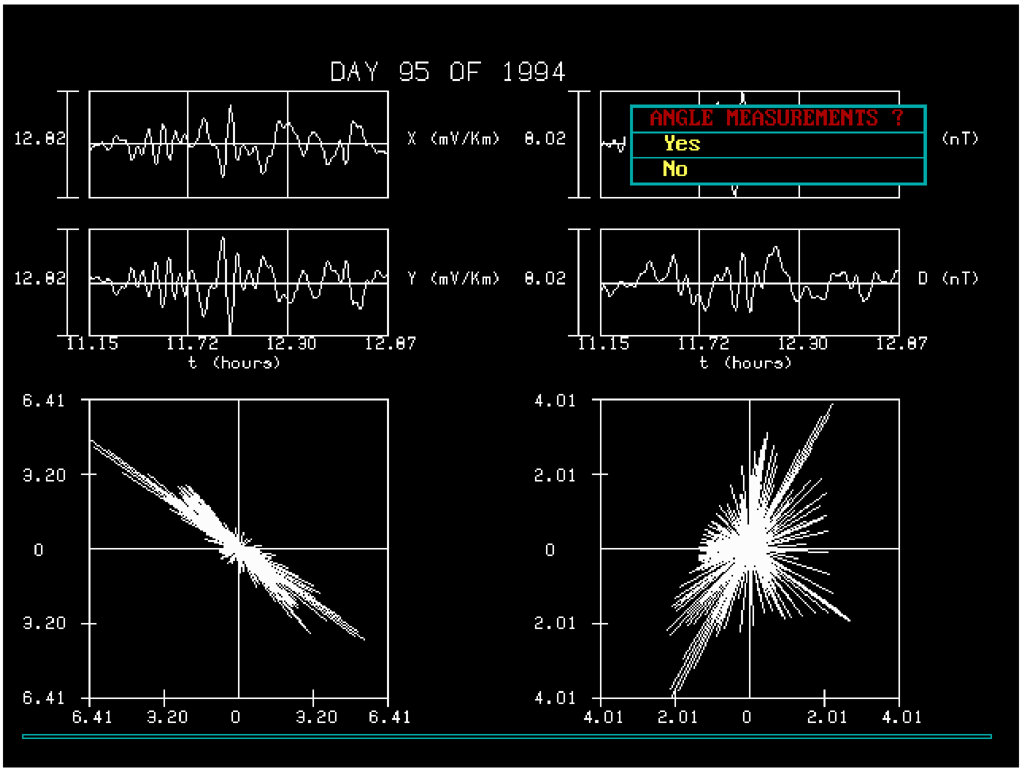


FIGURE 3b. The 'compass plot' mode of polarization data.

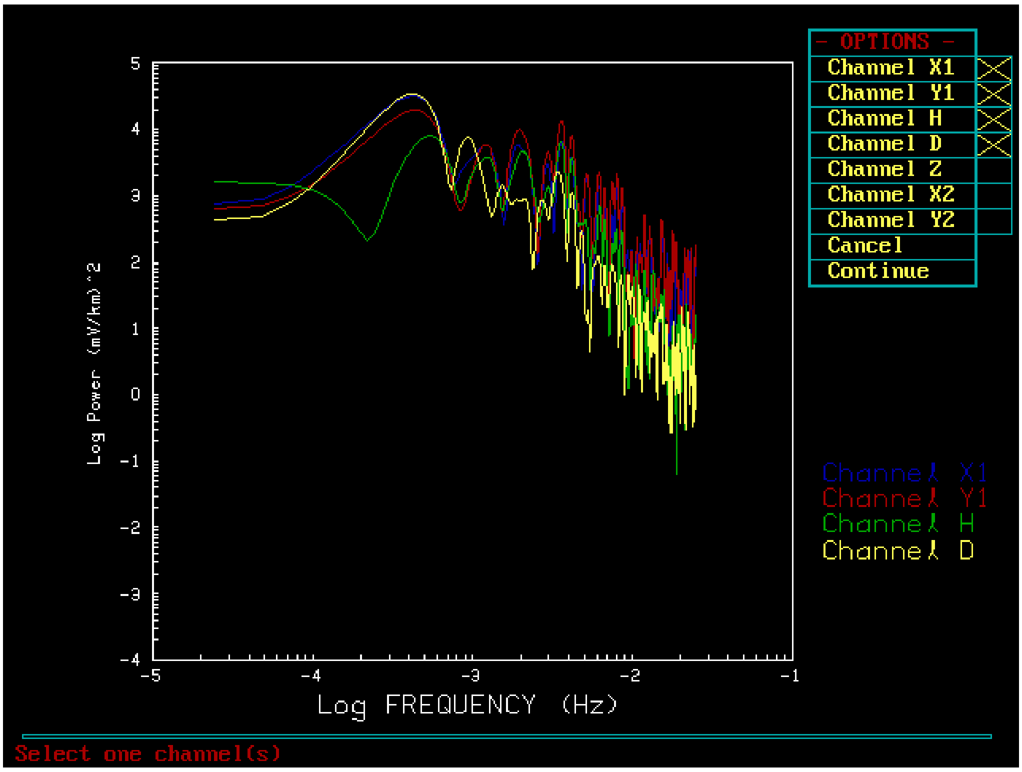


FIGURE 4a. FFT spectral power density functions of the selected data channels, after smoothing and prior to second stage selection for close up scrutiny. Spectral analysis tools are provided only in the zoom window

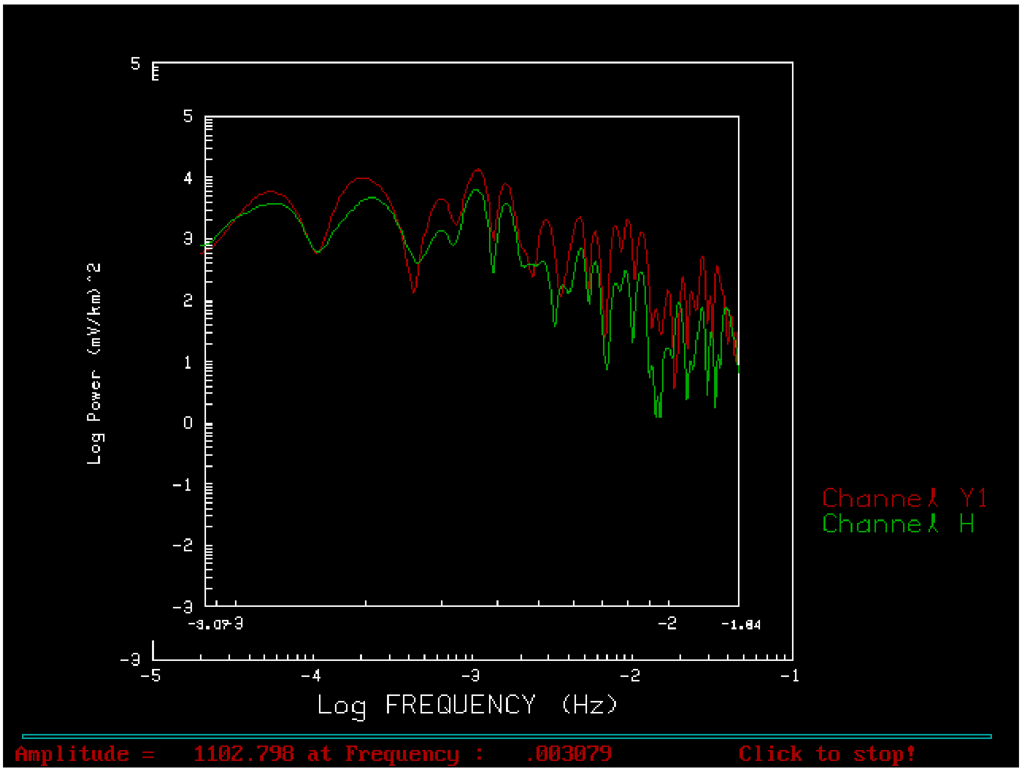


FIGURE 4b. A window of two of the power density functions shown in figure 4a (channels Y1 and H), selected for close up inspection (with the pointer).

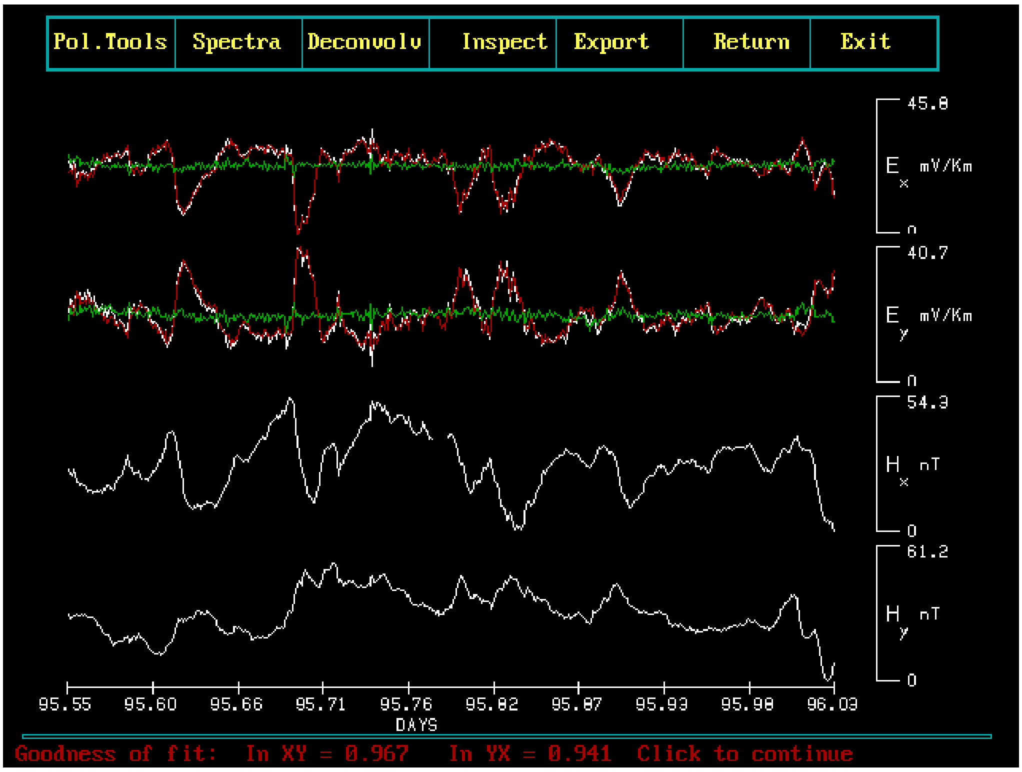


FIGURE 5a. The outcome of a deconvolution operation. The 2-input (H_x, H_y) 2-output (E_x, E_y) option has been exercised. The deconvolved (cleaned) E_x and E_y traces are indicated with the gray line. Goodness of fit statistics are shown in the dialog area (bottom line of the screen).

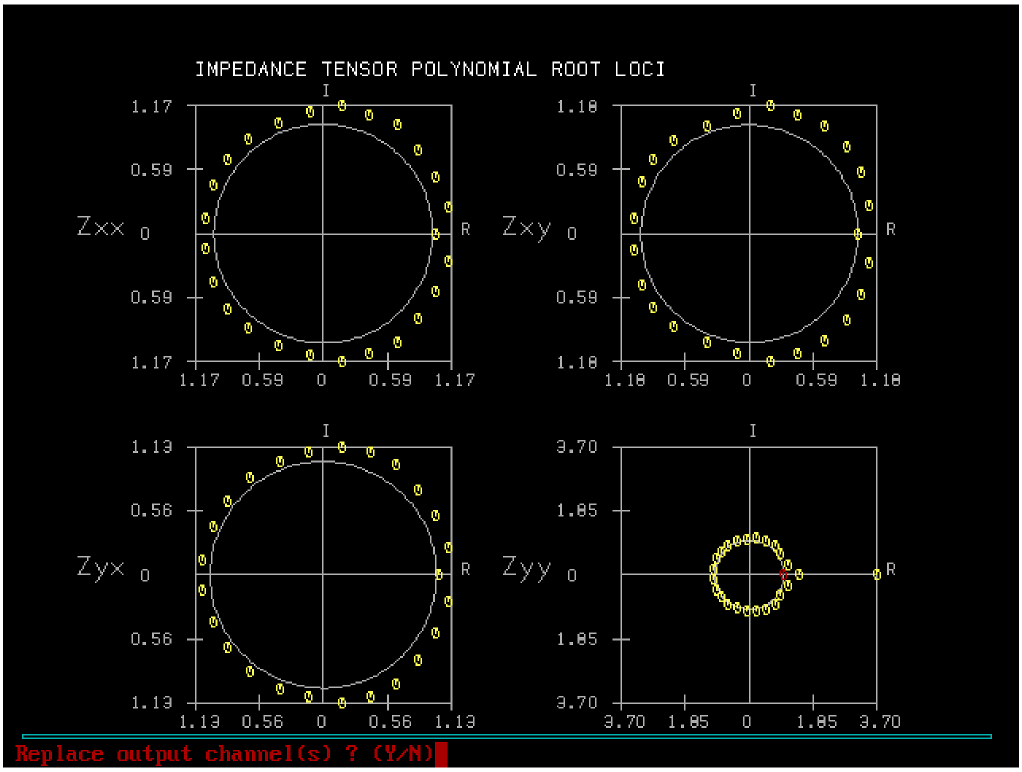


FIGURE 5b. The polynomial tensor impedance root loci, corresponding to the solution of the data in Figure 5a. All roots lie outside the unit circle and therefore, the EM field of Figure 5a is generated by a physical (realizable) induction process.

III. PROGRAM "RESPONSE" - SOFTWARE FOR MT-ERF ESTIMATION

This program computes the frequency domain MT-ERF using a *cascaded decimation* algorithm, which facilitates the very wide band analysis. The input format is the same as per MAGNET. The data is decimated in the time domain through 6 levels of $\log_{10}$ frequency bands and, given a sufficiently long data series, would allow the simultaneous estimation of the MT-ERF over 6 frequency decades (it may easily be modified to allow estimation over a wider band). The data registers at each decimation level comprise finite realizations *(windows)* of 125, 250 or 500 data samples per channel (user selectable). Once the registers are full, they are FFT'ed into the frequency domain and then reset to accept new data. The approach towards frequency domain ERF estimation is based on the theory of stochastic (Gaussian) time processes and frequency domain LS procedures (Sims et al, 1971). Some information about these enhancements to the standard procedures incorporated in RESPONSE, are provided below.

The standard LS method of impedance tensor estimation implements least squares solution of the 2-input 1-output linear system,

$$E_i = Z_{ix} \cdot H_x + Z_{iy} \cdot H_y, \quad i = x,y, \qquad (1)$$

for the elements Z_{ij}, $i,j = x,y$, by minimizing noise on the output data channel. The quality of the solution can be monitored by means of the output or predicted coherence function defined as $\gamma^2_{i.23} = \hat{E}_i / E_i$, $0 \le \gamma^2_{i.23} \le 1$, where $\hat{E}_i = \breve{Z}_{ix} \cdot H_x + \breve{Z}_{iy} \cdot H_y$, $ij=x,y$ represents the output electric field component predicted from the estimated impedance elements $\breve{Z}_{ij}$. A large number of finite data realizations will yield eight independent populations $\{\breve{Z}_{ij}\}$ of the impedance tensor elements. These are, then, combined to produce the final estimators $\breve{Z}_{ij}$ of the impedance tensor elements. The impedance tensor elements resulting from (1) are biased by noise in the auto-spectra of the electric and the magnetic field. Without a priori information about the distribution of noise across the data channels, it is necessary to provide two limiting cases of noise content. The first gives stable, downwards biased estimates of the impedance tensor $\breve{\mathbf{Z}}$ as

$$\mathbf{E} = \breve{\mathbf{Z}} \cdot \mathbf{H} \Rightarrow \mathbf{E} \cdot \mathbf{H}^{\dagger} = \breve{\mathbf{Z}} \cdot \mathbf{H} \cdot \mathbf{H}^{\dagger} \Rightarrow \breve{\mathbf{Z}} = [\mathbf{E} \cdot \mathbf{H}^{\dagger}] \cdot [\mathbf{H} \cdot \mathbf{H}^{\dagger}]^{-1}$$

in which the bias derives from noise in **H** only. The second case gives stable, upwards biased estimates of the impedance tensor $\breve{\mathbf{Y}}^{-1}$, derived from downwards biased estimates of the admittance tensor **Y** as

$$\mathbf{H} = \breve{\mathbf{Y}} \cdot \mathbf{E} \Rightarrow \mathbf{H} \cdot \mathbf{E}^{\dagger} = \breve{\mathbf{Y}} \cdot \mathbf{E} \cdot \mathbf{E}^{\dagger} \Rightarrow \breve{\mathbf{Y}} = [\mathbf{H} \cdot \mathbf{E}^{\dagger}] \cdot [\mathbf{E} \cdot \mathbf{E}^{\dagger}]^{-1}$$

in which the source of bias derives from noise in **E** only. Although derived from the same set of auto- and cross-spectra, individual populations $\{\breve{\mathbf{Z}}\}$ and $\{\breve{\mathbf{Y}}^{-1}\}$ are formed and treated independently, because they constitute biased estimates of the true expectation values. Bias reduction takes place by selecting high signal/noise (S/N) data windows. Typically, if the data set provides an adequate distribution of high S/N portions, (high predicted coherences), the bias errors can reduce to the magnitude of random errors. Subsequently, $\{\breve{\mathbf{Z}}\}$ and $\{\breve{\mathbf{Y}}^{-1}\}$ are used in a weighted least squares regression to form weighted averages $\langle\breve{\mathbf{Z}}\rangle$ and $\langle\breve{\mathbf{Y}}^{-1}\rangle$ and weighted variances $\Delta\breve{\mathbf{Z}}$ and $\Delta\breve{\mathbf{Y}}^{-1}$ of all eight estimators. The reciprocal variances (random errors) of Pedersen (1982) associated with each individual estimate in a population can be used as weights (e.g. Tzanis, 1988). An additional quality constraint is the requirement of minimum phase in $\{\breve{\mathbf{Z}}\}$ and $\{\breve{\mathbf{Y}}^{-1}\}$, to ensure physical validity. The 'true' values of the impedance tensor elements can, then, be estimated from the lower and upper bounds, ($\langle\breve{\mathbf{Z}}\rangle$ and $\langle\breve{\mathbf{Y}}^{-1}\rangle$ respectively), with errors taken into account. One successful combination is the weighted average

$$\breve{Z}_{ij} = \frac{\langle \breve{Z}_{ij} \rangle \cdot [\Delta \breve{Z}_{ij}]^{-2} + \langle (\breve{Y}^{-1})_{ij} \rangle \cdot [\Delta (\breve{Y}^{-1})_{ij}]^{-2}}{[\Delta \breve{Z}_{ij}]^{-2} + [\Delta (\breve{Y}^{-1})_{ij}]^{-2}} \quad \text{with } i, j = x,y.$$

The MT-ERF estimation technique described above is very rigorous because it combines weighted populations of MT-ERF element estimators with a random error weighting scheme which is quite effective in attenuating the effects of some grossly erroneous estimators (outliers), in particular those produced by transient, multiple coherent noise which has been shown to possess quite bizarre, non-linear properties (e.g. Tzanis, 1988). The technique is certainly superior to the older practices of stacking (combining) populations of auto- and cross-spectral estimators from which the MT-ERF is computed (e.g. Tzanis, 1988). The technique is not robust in the formal sense of the term (as per Huber, 1981 and Hampell et al, 1986). However, RESPONSE may export the reduced auto- and cross-spectral estimators (1 file per decimation level) for further manipulation with robust statistical processing software, such as has been developed in the Geophysics - Geothermy Department, University of Athens (1995).

Finally, RESPONSE is accompanied by the special program EVOLVE, which will import its results and produce a graphical representation of the evolution of the MT-ERF with time, as per Figure 6. EVOLVE may also display the time history of the MT-ERF rotated to their principal coordinate systems.

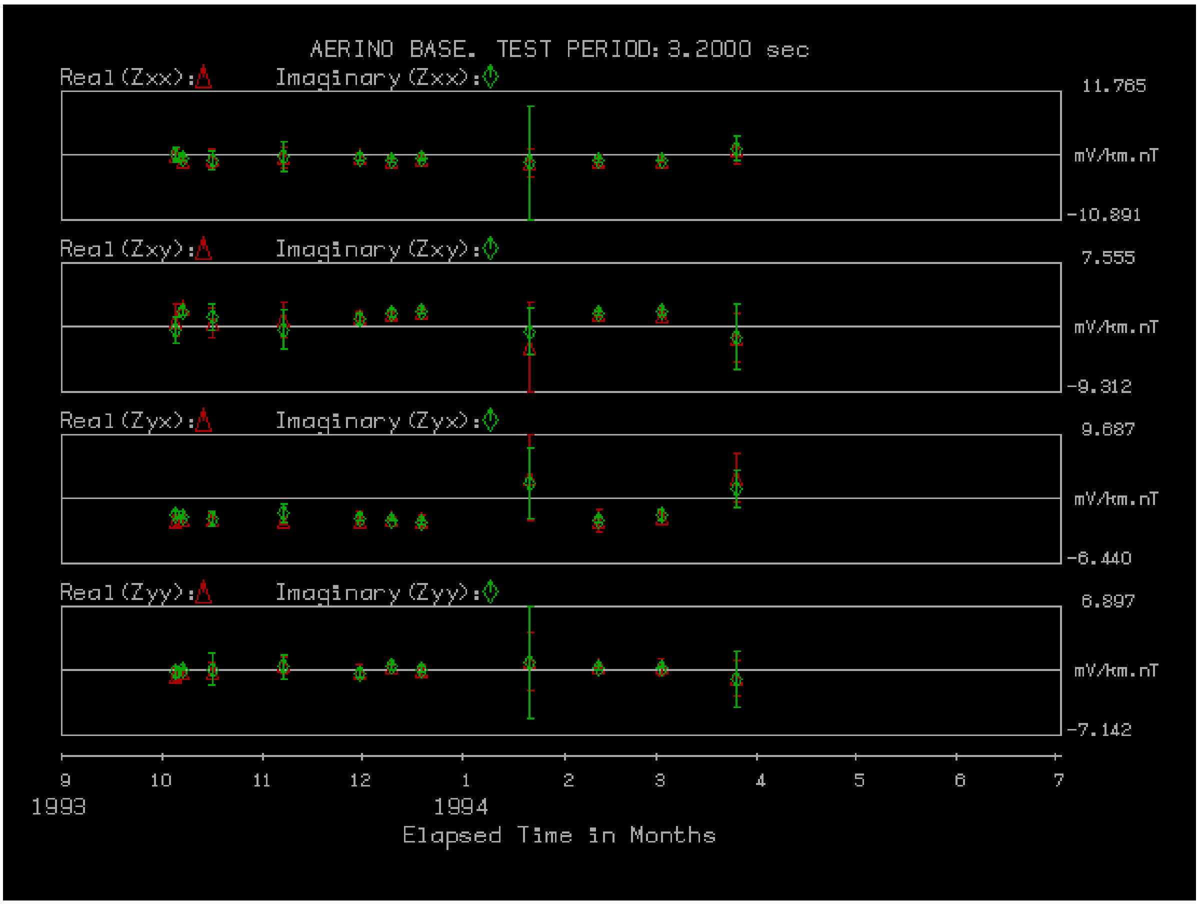


Figure 6 An example of MT-ERF time history at 3.2s, observed by Aerino base, SE Thessaly, Greece. The impedance tensor has been computed with RESPONSE and its evolution is displayed with EVOLVE.

IV. EPILOGUE

This paper presents a Magnetotelluric data analysis package, which has been adapted to the requirements of Earthquake Prediction Research. The package comprises two main units, MAGNET to facilitate the interactive editing and analysis of wide-band natural EM field records and RESPONSE to compute the wide-band MT-ERF. To the best of the author's knowledge, MAGNET is the only program of its kind and function in existence. On the other hand the estimation of MT-ERF is a subject extensively (although not exhaustively) investigated in international MT literature, and several other packages exist to perform the same tasks. Note however that RESPONSE is adapted to the processing of very long and very wide-band data sets with rigorous means of data selection and noise suppression. It may prove to be a very efficient analysis tool, especially when is supported by robust statistical MT-ERF estimation software.

The programs presented herein are available from the author in executable form, together with a test data set. More information may be obtained by normal or electronic mail in the Internet address atzanis@atlas.uoa.ariadne-t.gr.

All programs in the system are currently being upgraded to operate in a Microsoft Windows™ environment and progress towards this effect may be reported in the near future.

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