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CONTINUOUS MAGNETOTELLURIC OBSERVATIONS IN WESTERN CRETE AS A TOOL FOR THE STUDY OF THE HELLENIC SUBDUCTION ZONE

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Abstract

In the frame of the "MagnetoTellurics in studying Geodynamics of the hEllenic ARc (MT-GEAR)" project, a new continuous monitoring Magnetotelluric (MT) station has been installed in Western Crete. The new permanent MT-station, designed and constructed incorporating contemporary technology, is solar powered, fully telemetric, and the data transfer can be performed alternatively through 3G network or a satellite link. The selected site for the installation resulted from an exploratory MT survey, among other prospective sites aggregating MT qualifications. The purpose of the operation of a permanent MT observatory is twofold. The primary objective is to act as remote reference station to the ongoing MT survey (at selected Islands of southern Aegean) of the geodynamics of the Hellenic Subduction Zone. In addition, possible apparent resistivity variations as well as electric and/or magnetic field transient anomalies are investigated, while it would be attempted to associate these variations with seismic activity.
***Key words:** Magnetotellurics, Remote Reference, MT Monitoring, MT-GEAR, Seismoelectromagnetism, Hellenic Subduction Zone, Crete, Southern Aegean.*

Περίληψη

Στα πλαίσια υλοποίησης του ερευνητικού έργου "MagnetoTellurics in studying Geodynamics of the hEllenic ARc (MT-GEAR)", ένας νέος μαγνητοτελλουρικός (MT) σταθμός συνεχούς παρατήρησης εγκαταστάθηκε στη Δυτική Κρήτη. Ο νέος, μόνιμος MT-σταθμός, που σχεδιάστηκε και κατασκευάστηκε ενσωματώνοντας σύγχρονη τεχνολογία, τροφοδοτείται με ανανεώσιμη, ηλιακή ενέργεια, είναι πλήρως τηλεμετρικός και η μεταγωγή των δεδομένων πραγματοποιείται εναλλακτικά είτε μέσω δικτύου κινητής τηλεφωνίας (3G) είτε μέσω δορυφορικής ζεύξης. Η θέση εγκατάστασης, που προέκυψε από διερευνητικές MT διασκοπήσεις, επιλέχθηκε ανάμεσα σε άλλες υποψήφιες θέσεις που συγκέντρωναν τις προδιαγραφές για MT. Ο σκοπός της λειτουργίας του μόνιμου MT-σταθμού είναι διττός. Ο κύριος αντικειμενικός στόχος είναι να αποτελεί σταθμό αναφοράς για τις εξελισσόμενες MT-διασκοπήσεις (σε επιλεγμένα νησιά του Νοτίου Αιγαίου) που ερευνούν τη γεωδυναμική της Ελληνικής Ζώνης Υποβύθισης. Επιπροσθέτως, διερευνώνται πιθανές μεταβολές της φαινόμενης αντίστασης της γεωηλεκτρικής δομής, όπως επίσης και ηλεκτρικές και/ή μαγνητικές μεταβατικές ανωμαλίες με σκοπό να επιχειρηθεί η συσχέτισή τους με τη σεισμική δραστηριότητα.

Λέξεις κλειδιά: *Μαγνητοτελλουρική μέθοδος, Τεχνική Απομακρυσμένου Σταθμού, Συνεχής παρακολούθηση ΜΤ δεδομένων, MT-GEAR, Σεισμοηλεκτρομαγνητικά, Ελληνική Ζώνη Υποβύθισης, Κρήτη, Νότιο Αιγαίο.*

1. Introduction

Crete is located in a prominent position in the fore-arc of the Hellenic Subduction Zone (HSZ), i.e. on top of the shallow portion of the presently active region of convergence (Spakman et al., 1988; Papazachos et al., 1995). It lies in the southern Aegean Sea (34° N-37° N, 21° E-29° E) among the islands of Kithira, Kassos, Karpathos and Rhodes, which those five islands consist the Hellenic Arc (Angelier, 1976). This arcuate feature, extending from the Peloponnese in the northwest to the island of Crete in the south, is the seismically most active region in western Eurasia due to subduction of the oceanic African lithosphere beneath the Eurasian plate (Vallianatos & Makris, 2000; Snopek et al., 2007). Due to the fact that the African plate moves to the north, compression between the Arabian and Eurasian plate is caused (Molnar & Tapponier, 1975). The rate of convergence consists of a 3-4 cm/year SSW-ward movement of Crete relative to stable Eurasia (Jackson, 1994; Noomen et al., 1999; Bohnhoff et al., 2001) and an 1 cm/year northward movement of Africa towards Eurasia (McKenzie, 1970; Bohnhoff et al., 2001), resulting in a net convergence rate of 4 to 5 cm/year at the plate boundary. The Benioff zone seismicity reaches down to ca. 180 km (Makris & Röwer, 1986), being situated at a depth of ca. 140 km underneath the magmatic arc, with volcanic activity on the islands of Santorini, Nisyros etc in the Aegean Sea. This procedure results in the movement of the Aegean and Anatolia lithospheric plates to the west, and then the gravitational spreading of the Aegean to the east Mediterranean (McKenzie, 1978; Le Pichon & Angelier, 1979; Angelier et al; 1981). This gravitational spreading of the Aegean is proved by the large amount of normal faults (Upper Miocene) (Aubouin & Dercourt, 1965; Aubouin, 1971; McKenzie, 1978; Le Pichon & Angelier, 1979; Angelier et al., 1981; Peters, 1985; Mascle & Martin, 1990). For this reason, Crete and Aegean Islands provide excellent onshore access to the internal structure of the fore-arc at various levels (Seidel, 2003).

The aforementioned area is very interesting both for its structural geological setting and, of course, for its historical (Pirazzoli, 1996; Stiros, 2001) and recent seismicity (Nikolintaga et al., 2008). Therefore, apart from the obvious study of seismotectonics, it is considered to be an excellent area to attempt to associate variations in electric (Huang and Liu, 2006) and magnetic fields and/or changes in the geoelectrical structure of subsoil (Nagao et al., 2002) with seismic activity (Merzer and Klemplerer, 1997). Literature is replete with reports of pre-earthquake phenomena, mainly of electric, magnetic or electromagnetic nature. Comprehensive reviews can be found in Johnston (1997), Tzanis & Vallianatos (2002), while much additional information exists in the collections edited by Hayakawa & Fujinawa (1994).

The magnetotellurics is a passive geophysical exploration technique that utilizes a broad spectrum of naturally occurring geomagnetic variations as a power source for electromagnetic source induction in the earth. As such, MT is distinct from active geoelectric techniques (Kaufman & Keller, 1981; Simpson & Bahr, 2005). In the 1950s, Tikhonov (1950) and Cagniard (1953) realized that if electric, E, and magnetic, B, field variations are measured simultaneously then complex ratios (impedances) can be derived that describe the penetration of electromagnetic fields into the earth. The penetration depths of electromagnetic fields within the earth depend on the electromagnetic sounding period, and on the earth's conductivity structure. By inverting the impendance tensor, which linearly relates the two horizontal electric components to the horizontal magnetic ones, the electrical resistivity distribution of the Earth's interior can be defined.

Continuous MT observations can be used both for applying the Remote-Reference-Technique (Gamble et al, 1979) and of course in order to provide information on seismoelectromagnetic

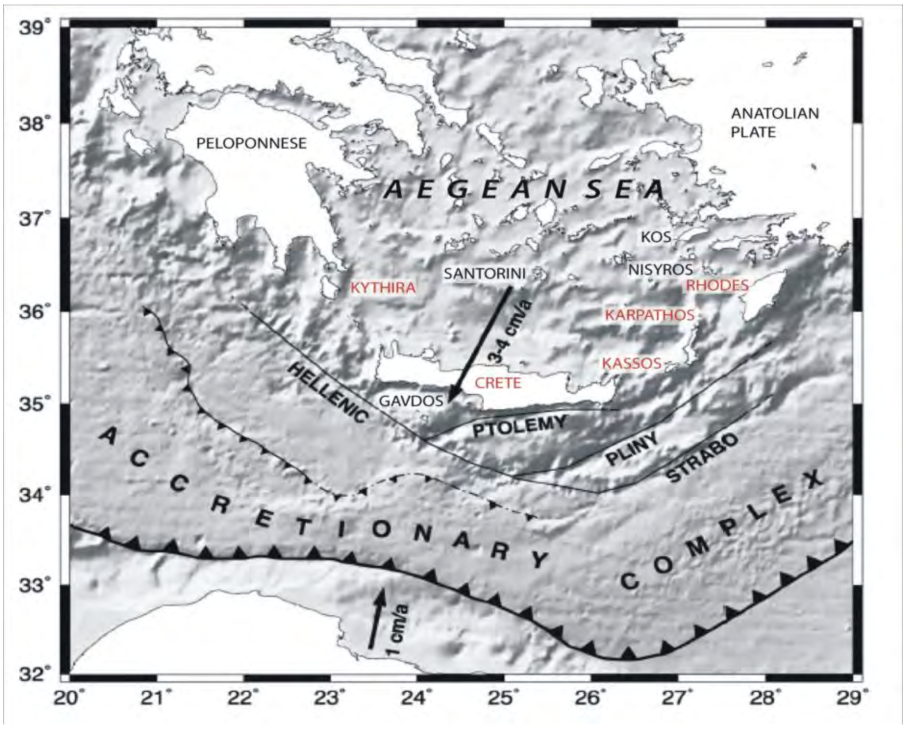

Figure 1 - Generalized map of the main tectonic elements of the South Aegean region (after Le Pichon & Angelier, 1979; Jackson, 1994) depicting the geodynamic framework of the south Hellenic Arc, which is consisted by five islands, highlighted with red color. See text for more explanation.

phenomena, such as: a change in resistivity or a generation of EM fields of internal (geodynamic) origin (Svetov et al, 1997). Globally there are many monitoring MT stations in Japan (Wakuya station and Esashi station), in Taiwan (located on Penghu Island), in Greece (Zlotnicki et al, 2006) in Italy (Balasco et al, 2008; Balasco et al, 2004), in Russia (Svetov et al, 1997), in Germany (Eydam & Munoz, 2011), etc operating either as remote reference stations or for earthquake prediction research.

Since early 2013 a new magnetotelluric (MT) monitoring station has been installed by Laboratory of Applied Geophysics and Seismology of Technological Educational Institute of Crete (LGS-TEICR) at Omalos Plateau (35.33N, 23.89E), Western Crete, Greece, in the frame of MT-GEAR project. Simultaneously during 2013, Electromagnetic Measurements (Magnetotellurics and Transient Electromagnetics - TEM) in selected sites in Southern Aegean -on Crete and on Aegean Islands across the Hellenic Arc (Kithira, Karpathos and Rhodes) but also at Santorini, Mylos, Folegandros, Gavdos, Nisyros, Kos, Tilos, Astipalaia, Southern Peloponnese, etc.- are being acquired. Several MT-TEM field campaigns have been organized at the aforementioned selected islands during this year for the study of the geoelectric structure of the Hellenic Subduction Zone and of course data from the Omalos' MT reference station will be used for the application of the remote reference technique.

The overall aim of this research is actually to produce important results concerning the geoelectrical structure of the fore-arc of the HSZ, using the permanent MT station as a remote station and to attempt to associate variations in electric and magnetic fields and changes in the geoelectrical structure with seismic activity.

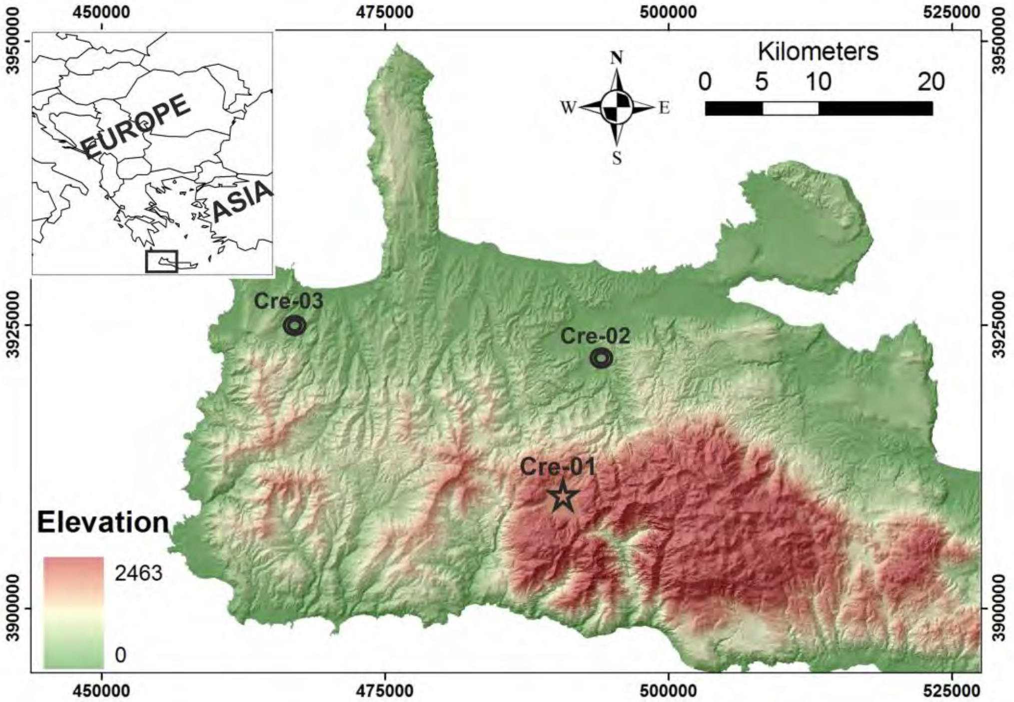

Figure 2 - Star indicates the Magnetotelluric (MT) monitoring station in Omalos (Cre-01). Circles indicate two MT surveys which took place in Fournes (Cre-02) and Kastelli (Cre-03). The Remote Reference (RR) technique was applied in order to improve MT data quality of Cre-02 and Cre-03 by using Cre-01 as RR.

2. The Permanent MT Station at Omalos

Laboratory of Geophysics and Seismology of TEI of Crete owns two complete systems to conduct magnetotelluric surveys. Each MT system comprises a MT24LF Magnetotelluric 24-bit Low Frequency receiver (developed by EMI Technology Centre owned now by Schlumberger SpA) that uses a power-efficient CPU and dual high- and low-speed 24-bit A/D acquisition, external GPS combined with a high-accuracy internal oscillator for time synchronization, three high sensitivity, very low noise Magnetic Field Induction Sensors in the range 10,000s – 1kHz and Pb-PbCl2 non-polarized electrodes with 100m cables. The MT system uses a CompactFlash memory card for data storage.

MT24LF is portable MT equipment that records orthogonal electric and magnetic fields which are processed to provide tensor impedance measurements for interpreting complex 2D and 3D subsurface geoelectric structures. Once sensor and hardware setup and installation in the field is completed, the MT acquisition phase is set up, controlled and stopped by software running on a PC that is connected to MT24LF receiver.

The location of the appropriate reference site was a complicated task, as the landscape of Western Crete has bold relief. Finally, data quality of 11 sites across western Crete was tested. Every MT system was left recording at every site for about 3 nights with sampling rate 6.25Hz in continuous mode and bursts of 500Hz every 12 hours for 30 minutes. Omalos site was selected as the best area, far away from current sources, pipelines or metallic fences. High quality data were found and the new permanent monitoring MT station was installed there. However, in the future annually snowfalls maybe disqualify the site during winter period.

Here, we present the transformation of the above portable, in-situ configured and controlled MT system, to a permanent MT-station featuring continuous unmanned operation with long-time autonomy, full remote control and telemetry.

The developed permanent MT-station comprises of the following basic units (Figure 3):

- Solar Panel 12V/95W combined with a battery of 60AH for energy storage.
- 3G Router for wireless internet access through mobile network
- Low Power Field Computer (netbook type)
- MT24LF receiver with sensors
- System Controller based on MSP430F5438A Microcontroller

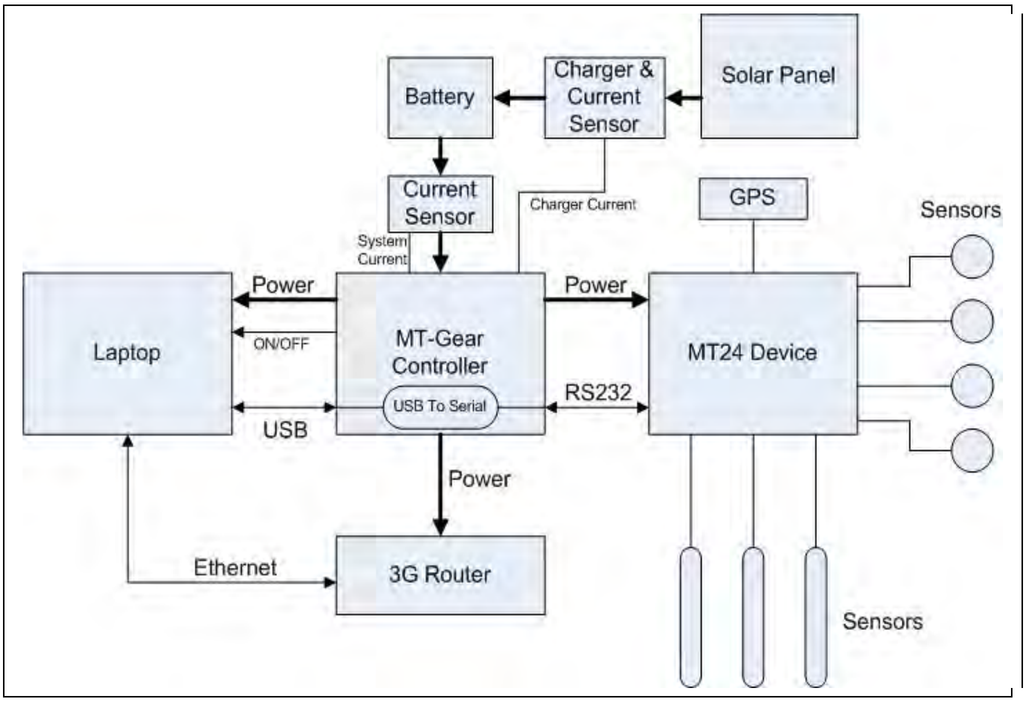

Figure 3 – Block diagram depicting the basic units and modules of the developed permanent MT-station, incorporating advanced remote control technology and telemetry.

A fundamental as well as crucial point to deal with, in the direction to develop a permanent station in the field, is uninterruptible power. As Crete is characterized by a great average of daily sunny hours (8.67) and more than 300 days of sunshine per year, renewable energy, namely solar energy, was the straightforward selection for providing station with energy autonomy. The solar panel is suitably selected in the sense that in a sunny day close to the aforementioned average is capable to fully charge the battery which in turn is able to power the whole MT-station for about 10 days without any sunshine.

The System Controller stands for the "remote master control" of the MT-station. It checks all the units of the station and provides the variety of the necessary constant and stable power voltages: +12 Volts for the 3G Router, +19 Volts for the Field Computer, ±12 Volts and +6 Volts (with low noise and galvanic isolation) for the MT24LF receiver. Furthermore, the System Controller is equipped with a GSM module in order to accept remote commands from a distant user. In addition, it incorporates a converter USB to Serial (galvanically isolated) enabling transparent serial communication and data transfer between the Field Computer and the MT24LF receiver.

Finally, the System Controller checks and records all the vital parameters and status of the permanent MT-station, i.e., charge current, system current, battery voltage, laptop status, MT24LF Status, 3G router status and all this information is available to distant user through GSM.

The Field Computer hosts the software for the setup MT24LF system, the start and stop of the acquisition and the retrieval of the collected MT-data. Of course it is remotely controlled by means of the 3G Router using either remote desktop or Teamviewer applications. The Field Computer is normally in shutdown state and it is activated, when remote access to it, is requested. The operation of the developed permanent MT-station has two distinct modes:

- The mode where only the MT24LF system is working as a regular standalone magnetotelluric measuring equipment. The MT-data are continuously recorded to its internal memory (Compact Flash). In this mode the power consumption is to the minimum and all communication is idle.
- The mode where all system units are on. In this mode, there is availability for the distinct user to access remotely the Field Computer. In this mode, with software we developed it is possible to directly and remotely give commands to MT24LF and download the collected MT-data to the base (the premises of TEI of Crete at Chania).

In order for the permanent MT-station to exchange mode of operation, it needs to be called (through the GSM module in the System Controller) by the distinct user and then the appropriate instruction (DTMF code) has to be keyed. The distinct user is able to use either fixed or mobile phone.

3. Results

3.1. MT Data Analysis and Processing

In this study three data sets of apparent resistivity were analyzed, from Cre-01, Cre-02 and Cre-03 sites. The frequency of data recording was set to 6.25Hz in continuous mode. The apparent resistivity curves ρxy and ρyx, related respectively to the off-diagonal components of impedance tensor Zxy and Zyx, were estimated using the procedure and the Robust Transfer Function Estimation Program for data reduction described in Egbert, 1997.

Two different MT processing methods were applied to the MT data: the robust Single Site processing method (*zss*) and the Remote Reference (*zrr*, Gamble *et al.*, 1979; Egbert and Booker 1986) processing method. Figure 4 shows the apparent resistivity curves estimate for the Cre-01, Cre-02 and Cre-03 sites with the two above-mentioned methods. In *zrr* estimates, we use the magnetic field recorded at Cre-01, i.e. Omalos site, as a reference field. Single Station processing seems to generally give better results than the RR one. As expected, RR method works well for long period where, especially for *xy* component, the two methodologies provide quite similar results (past 10s the three curves in fig. 6a are fairly coincident). For Cre-02, a visual inspection of the time series, highlighted a strong presence of noise affecting mainly the electric field. The noise presence can be a possible explanation for the low quality of the results both with the SS and RR processing especially in period range 1-10s, the «dead band», where signal to noise ratio is generally low.

3.2. Magnetotelluric Monitoring of Geodynamic Processes at Omalos Area

MT data from Omalos monitoring MT station (Cre-01) have not used yet for the investigation of the existence of temporal anomalous patterns in the geoelectrical structure and in that case, their correlation with the simultaneously observed seismic activity. In the frame of MT-GEAR project it will be attempted the correlation of any apparent resistivity fluctuations with local seismicity and regional strong events that may occur.

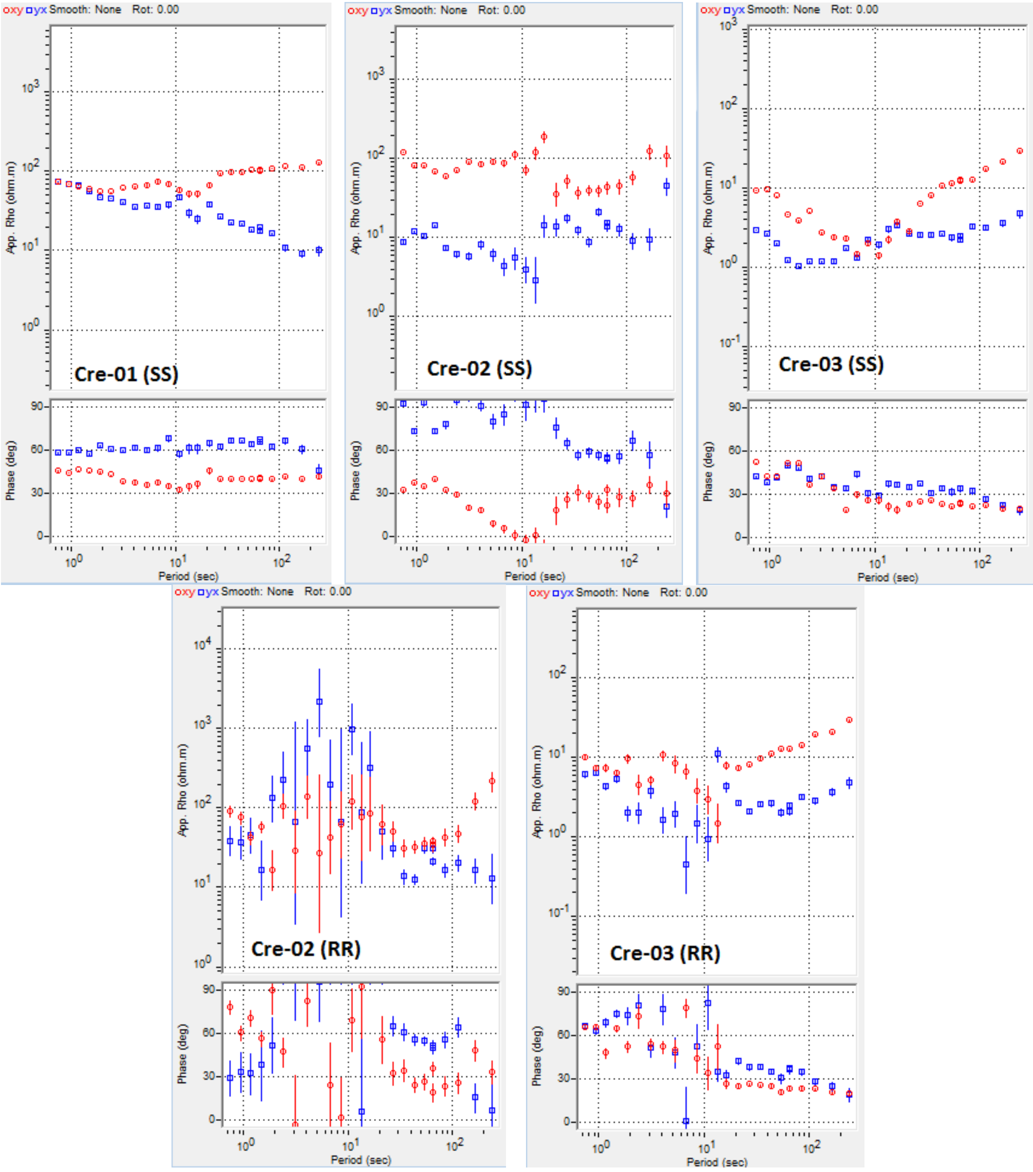

Figure 4 - Above they are shown the resistivity curves ρxy and ρyx and phases of Cre-01, Cre-02 and Cre-03 sites after using the robust Single Site processing method (*zss*). Below they are shown the results of referencing data from Cre-02 and Cre-03 to the permanent referencing site Cre-01.

4. Conclusions

Since early 2013 a new, continuous MT-monitoring station (Cre-01) has been installed by Laboratory of Applied Geophysics and Seismology of TEI of Crete at Omalos Plateau, Western Crete, Greece, in the frame of MT-GEAR project. New technology was developed for the remote control and the telemetry and the data transfer can be efficiently performed through a 3G Router using remote desktop applications. Cre-01 site was used as reference for MT measurements in western Crete (Cre-02 and Cre-03 sites). However, robust Single Site processing method (*zss*) furnished better results. RR processing seems to suffer much more than the SS when the local data are noisy (as the case of Cre-02). Future analysis will take this into account in order to increase estimates reliability. High quality reference data are being continuously recorded since early 2013, improving MT data quality from campaigns across southern Aegean. Future task is the correlation of any apparent resistivity fluctuations with local seismicity.

5. Acknowledgments

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