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Research stay report

Magdalena Escalas Oliver

Predoctoral Researcher at

Departament de Geodinàmica i Geofísica – Universitat de Barcelona (Spain)

Research project: Analysis of the instability of the magnetotelluric estimations using advanced statistical techniques

Hosting Institution: Istituto di metologie per l'Analisi Ambientale (IMAA), in Tito Scalo (PZ).

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1 Introduction and objectives

The magnetotelluric (MT) natural signal, i.e. the temporal fluctuations of natural electromagnetic (EM) field at the Earth's surface, is highly non-stationary (Chant and Hastie, 1992). Besides, it is expected to be non-polarized due to its wide variety of sources, i.e., interaction of solar wind with the magnetosphere, ionospheric current systems and lightning (Zonge and Hughes, 1991). Only in certain special cases does the MT natural signal show a predominant direction of polarization: if one of its sources dominates over the others (Hermance, 1973; Lezaeta et al., 2007), in the case of transients from lightning discharges (Goldak and Goldak, 2001) or if geological structures show significant electrical conductivity contrasts (Jones, 1983, 2006; Uyeshima et al., 1998; Becken and Burkhardt, 2004).

MT data acquired in the vicinity of industrialized, urban of farming areas are affected by cultural noise. Cultural noise is created by sources that produce parasitic EM fields in the Earth, including power stations and power lines, electric railways, corrosion-protection systems in metal pipelines, electric fences, electric pumps, electrical networks in mining areas, etc. (Szarka, 1988). The identification and reduction of this noise is a current challenge in the determination of reliable responses using the MT method.

The cultural noise signal is commonly highly correlated, i.e, it affects both the electric and magnetic fields of the MT signal (Fontes et al., 1988; Oettinger et al., 2001). Traditional MT processing methods include the remote reference (Gamble et. al, 1979), which is based on the use of synchronous data from an additional remote site, and robust schemes (Egbert and Booker, 1986; Chave et al., 1987), which are insensitive to the moderate presence of outliers. Although these methods are considered the most effective (Jones et al., 1989) and have been combined and improved since their initial introduction (Egbert, 1997; Ritter et al., 1998), they produce biased response function estimates in the case of correlated noise unless an uncontaminated reference site is available (Larsen et al., 1996; Oettinger et al., 2001; Chave and Thomson, 2004).

Most cultural noise sources are localised in space and create a EM signal that is linearly polarized in a certain direction (Szarka, 1988; Junge, 1996). Polarization analysis of MT data in the time-frequency domain has been proven as a complementary tool to detect and characterize its cultural noise sources. This method has been developed by the visitor and her research group at the University of Barcelona (Escalas et al., 2013). The three polarization attributes used to describe a signal are the ellipticity ratio, the polarization angle and the phase difference between its orthogonal components. This method is based on the fact that these attributes are related to the properties of the source which produces the signal. The time-frequency dependence of the method, achieved using a wavelet scheme, is due to the non-stationary character of both the natural MT signal and the cultural noise.

During the research stay, the method described in Escalas et al. (2013) has been applied to data acquired by the IMMA near Lamezia Terme (Calabria region, southern Italy). In this case, the MT time-series were contaminated by a noise source which has been identified as the DC electric railway. The detection and identification of the cultural noise source allows to select the most suitable data for the MT processing.

The quality of the MT responses depends on the presence of cultural noise, but also depends on the stability of the natural signal. The assumption of stability of the MT transfer functions is not always valid, due to fluctuations in the natural signal or in the soil electrical properties (Romano et al., 2014). In order to analyze the MT transfer function stability, the IMAA has a permanent MT monitoring station in the Agri Valley (Basilicata region, southern Italy), working since 2007 (Balasco et al., 2009). During the research stay, the method described in Escalas et al. (2013) has been applied to these data as an alternative tool to identify the sources of the recorded MT signal. In this way, the stability of the MT signal has been analyzed in the time-frequency domain by means of its polarization attributes.

2 Methodology

2.1 Wavelet analysis

The wavelet transform has been proven as one of the most powerful tools for analyzing geophysical non-stationary signals in the time-frequency domain (Foufoula-Georgiou and Kumar, 1994). This transform provides the time-frequency content of a signal with variable resolution. In the literature, the continuous wavelet transform (CWT) has been defined in many different ways using several normalization factors. Kaiser (2011) published a review of the different possibilities, explained their advantages and drawbacks and concluded that the normalization factors are completely irrelevant to the basic theory. In this work, we have chosen the following definition of the CWT of a signal $s(t)$:

$$W_{\psi}[s(\sigma,\tau)] = \sqrt{\frac{2}{\pi}} \int_{-\infty}^{+\infty} s(t) \cdot \psi^{*}(\sigma,\tau,t)\,dt, \tag{1}$$

where

$$\psi(\sigma,\tau,t) = \frac{1}{\sigma} \cdot \psi_0\left(\frac{t-\tau}{\sigma}\right) \tag{2}$$

represents the family of wavelets obtained through dilations and translations of ψ_0, a function known as the analyzing or mother wavelet, and ψ^{*} denotes the complex conjugate of ψ. The real scale parameter, $\sigma \neq 0$, fixes the dilations or compressions of the mother wavelet whereas the real parameter τ is the translation parameter that represents the sliding of ψ_0 over the signal $s(t)$. The factor $1/\sigma$ ensures that the amplitude of the wavelet spectrum is proportional to the amplitude of the signal for pure frequencies (Kaiser, 2011). The constant $\sqrt{2/\pi}$ is imposed according to Shyu and Sun (2002) to normalize the amplitude of the transform for each frequency component.

The squared modulus of the CWT defines the wavelet power spectrum (WPS), $\left|W_{\psi} s(\sigma,\tau)\right|^2$, which is displayed in a time-frequency graphic known as the scalogram.

A function $\psi_0(t)$ must satisfy two properties to be a wavelet:

(i) Compact support: The function must be well localized in the time domain: $\psi_0(t) \rightarrow 0$ when $\left|\Delta t \rightarrow \infty\right|$,

(ii) Admissibility condition: The function must be well localized in the frequency domain. Let $\hat{\psi}_0(\omega)$ be the Fourier transform of $\psi_0(t)$, where $\omega = 2\pi f$ is the angular frequency and f f is the frequency. The function must satisfy the following condition:

$$C_\psi = \int_0^{+\infty} \frac{|\hat{\psi}_0(\omega)|^2}{\omega} d\omega < \infty \, , \qquad (3)$$

where C_ψ is known as the admissibility constant. This condition implies that the wavelet has a non-zero-frequency component and a zero mean: $\hat{\psi}_0(0) = \int_{-\infty}^{+\infty} \psi_0(t) dt = 0$.

This localization in both the time and frequency domains enables the wavelet transform to perform a local analysis of any signal.

The mother wavelet can be chosen depending on the features of the analyzed signal (Zhang and Paulson, 1997). In this work, we use the complex Morlet wavelet (Goupillaud et al., 1984; Kronland-Martinet et al. 1987) consisting of a plane wave modulated by a Gaussian function:

$$\psi_0^M(t) = e^{i\beta t} e^{-t^2/2}, \qquad (4)$$

where $\beta = 2\pi f_0$, f_0 is the central frequency of the wavelet, and β is the non-dimensional frequency, which must be greater than five to satisfy the admissibility condition (Goupillaud et al., 1984). The non-dimensional frequency governs the time-frequency resolution of the CWT; its value depends on the characteristic range of frequencies of the signal to be analyzed.

The Morlet wavelet was previously used for MT data processing (Zhang and Paulson, 1997; Arango, 2005; Garcia and Jones, 2008; Arango et al., 2009). The MT natural signal has a spectrum that varies smoothly with the frequency. Therefore, the use of a smooth and undulating wavelet such as the Morlet wavelet is a good choice. Moreover, the use of a complex wavelet as the mother wavelet allows derivation of the modulus and the phase of its CWT, and both of these parameters provide useful information on the analyzed signal (Farge, 1992; Sailhac et al., 2000, Kulesh et al., 2007).

The scale parameter, σ, which governs the dilations or compressions of the wavelet, is inversely proportional to the physical frequency f of the signal to be analyzed. The specific relationship depends on the mother wavelet function, which can be obtained from the scale of maximum correlation, i.e., the scale at which the wavelet power spectrum reaches its maximum (Meyers et al., 1993):

$$\frac{\partial\left|W_{\psi}s(\sigma,\tau)\right|^{2}}{\partial\sigma}=0\,. \tag{5}$$

For the Morlet wavelet, using the factor $1/\sigma$ to obtain the family of wavelets (2), this relationship is $\sigma = f_0/f$.

The Fourier transform of the Morlet wavelet at a scale σ is:

$$\hat{\psi}_{o}^{M}(\sigma\omega)=\sqrt{2\pi}e^{-(\sigma\omega-\beta)^{2}/2} \tag{6}$$

Figure 1 shows the real and imaginary parts of the complex Morlet wavelet as well as its Fourier spectrum for different values of the parameters β and σ.

In the frequency domain, the CWT is obtained through the Fourier transforms of the signal and the mother wavelet using the convolution theorem:

$$W_{\psi}\left[s(\sigma,\tau)\right]=\frac{1}{2\pi}\int_{-\infty}^{+\infty}\hat{s}(\omega)\cdot\hat{\psi}_{0}(\sigma\omega)e^{i\omega\tau}d\omega, \tag{7}$$

i.e., it is the inverse Fourier transform of the product $\hat{s}(\omega)\cdot\hat{\psi}_0(\sigma\omega)$. Consequently, if $\hat{\psi}_0(\sigma\omega)$ is known, the CWT can be calculated computationally using fast Fourier transform (FFT) algorithms.

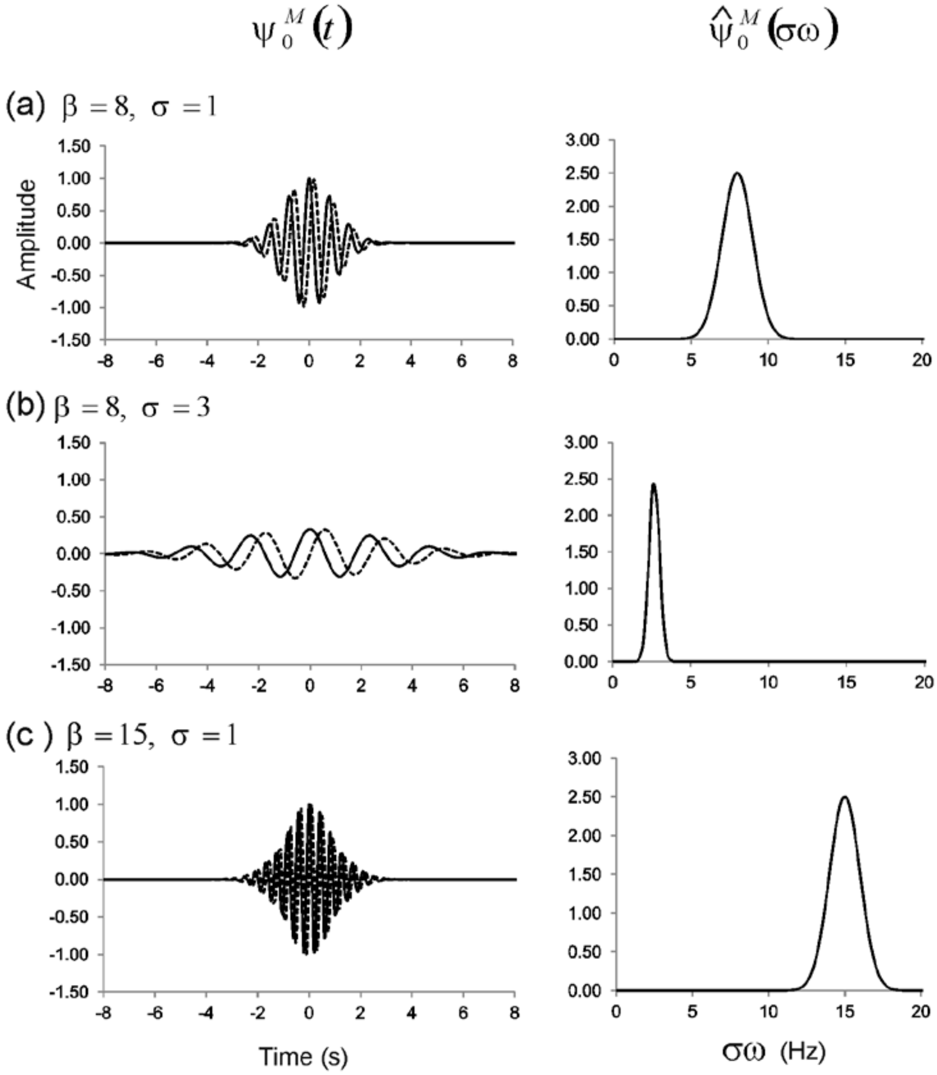

Figure 1. (Left) The real (solid line) and imaginary (dashed line) components of the complex Morlet wavelet for different values of the parameters β and σ, (Right): their corresponding Fourier transforms.

2.2 Polarization attributes of the magnetotelluric time-series in the time-frequency domain

An elliptically polarized rotating signal $S(t)$ with orthogonal components in the North-South (NS) and East-West (EW) directions (S_{NS}, S_{EW}) is described by the following polarization attributes (Fig.2):

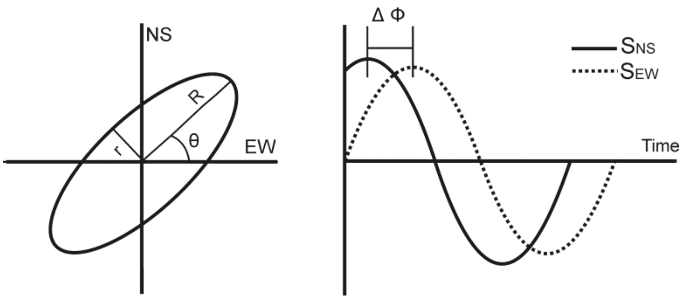

Figure 2. (a) Polarization ellipse associated with the complex signal *C(t)* and its geometric parameters, (b) Orthogonal components of the signal and their phase difference.

- $\varepsilon = a/b$: The ellipticity ratio obtained from the semi-major ($b \geq 0$) and the semi minor-axis ($a \geq 0$) of the ellipse; $\varepsilon \in [-1,1]$
- θ : The polarization angle, which is the angle of the semi-major axis with the EW direction; $\theta \in [0°, 180°]$
- $\Delta\phi = \phi_{NS} - \phi_{EW}$: The phase difference between the orthogonal components of the signal; $\Delta\phi \in [-180°, 180°]$

In the context of seismic data analysis, these polarization attributes were defined in the time-frequency domain in terms of a CWT by Diallo et al. (2006). The method is based on construction of a new complex signal, $C(t)$, from the orthogonal components of $S(t)$ such that $C(t) = S_{EW} + i \cdot S_{NS}$. The polarization attributes of the signal are computed in the time-frequency domain from the progressive and regressive components of its continuous wavelet transform.

In order to adapt the method proposed by Diallo et al. (2006) to the analysis of the MT signal, several modifications have been done. We have used the definition (1) for the CWT of a signal and the definition (2) for the family of wavelets, to normalize the amplitude of the CWT at each scale. A value of $\beta = 8$ for the Morlet wavelet (4) has been used, taking into account the range of frequencies analyzed in this work. The ellipticity is computed in the range $\varepsilon \in [-1,1]$ to analyze the sense of rotation of the signals. The polarization angle is obtained in the range $\theta \in [0°, 180°]$, whereas the phase difference is computed with respect to the NS component, and in the range $\Delta\phi \in [-180°, 180°]$. The non-significative region of the time-frequency domain is defined as the region where the modulus of the CWT is close to zero. In this region, the polarization attributes do not contain significant information for the signal properties. Thus, the polarization attributes are not computed in this region, which has been displayed in white color in all the figures of this work. Taking into account that a signal can be recovered from its inverse wavelet transform using only the significant region of the time-frequency domain, in this work we have obtained this region from the calculus of the inverse CWT of each analyzed signal.

Man-made electromagnetic signals generated by cultural noise sources are usually linearly polarized in a certain direction due to their fixed location in space (Szarka, 1998; Junge, 1996). In contrast, the MT natural signal is expected to be non-polarized in any preferred direction because of its wide variety of sources (Zonge and Hughes, 1991). Thus, the polarization analysis in the time-frequency domain allows the MT natural signal and the signal contaminated by cultural noise sources to be differentiated. The time-frequency dependence of the method, achieved using a wavelet scheme, is due to the non-stationary character of the signals.

3 Results

3.1 Cultural noise created by DC electric railways

DC electric railways are one of the most common cultural noise sources in MT surveying. Since the rails are not perfectly insulated, significant leakage occurs between the rails and the earth. This current system is time-varying due to the movement of the trains and generates noise in the MT measurements (Szarka, 1988, Pádua et al., 2002).

During the research stay, MT data from several sites acquired in the vicinity of a DC electric railway have been analyzed. Data were recorded near Lamezia Terme (Calabria region, southern Italy) by the IMMA. Figure 3 shows the location of sites N6 and S4, and the trace of the railway lines. S4 is the closest to the railways (3km distant) while N6 is the furthest. In this work, the results obtained at these two sites are shown.

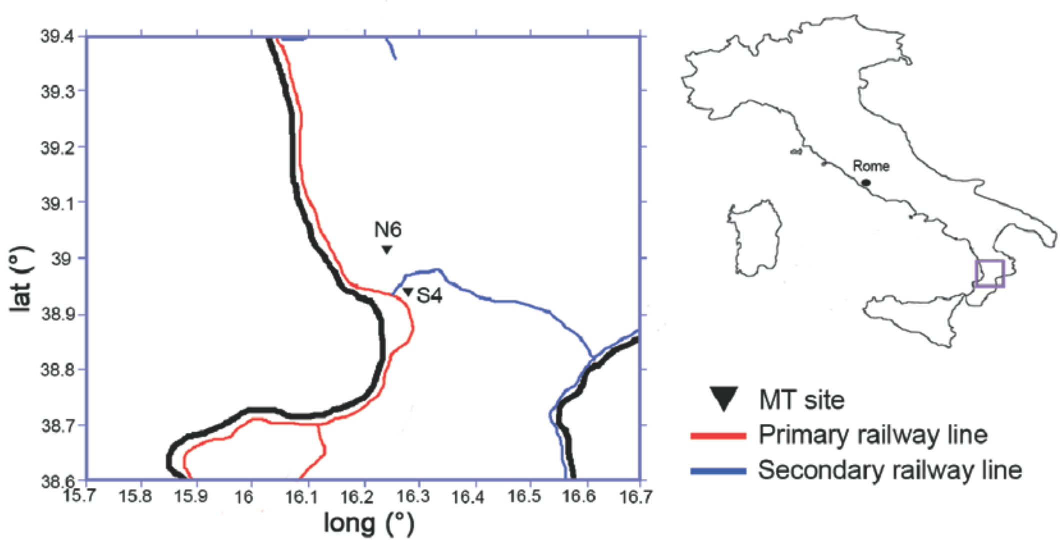

Figure 3. Location of the MT sites acquired near Lamezia Terme, and the railway lines in their vicinity.

A 24h-segment of electric and magnetic time-series recorded at each site (sampling frequency=6.25 Hz) has been analyzed using the method proposed in Escalas et al., 2013.

Site S4

Figure 4 shows the results obtained with the magnetic field at site S4. The magnetic field modulus scalogram shows an intermittent enhancement of the signal at all frequencies in the range 0.004 Hz – 1.2 Hz; it is more intense at the lowest frequencies. This enhancement matches with the general train schedule during daytime, superposed in black onto the scalogram. Thus, this strong signal could be the EM noise caused by the DC electric railway. During night-time, the noisy signal is less frequent and it could be due to circulation of few commercial trains (schedule not available). On the other hand, the magnetic field time-series are very disturbed, and the wave packets also match with the train schedule.

The polarization attributes of the noisy signal are constant in time and frequency, suggesting that the noise source is artificial, not natural (Escalas et al., 2013). Besides, when there are no trains circulating the polarization attributes achieve random values: they correspond to the natural MT signal. Therefore, from both the scalogram and the polarization attributes, it is clearly seen that the noisy signal is originated by the DC electric railway.

Since the artificial signal dominates over the natural signal in the analyzed segment, the peaks observed in the histograms of the polarization attributes are related to the noisy signal. In particular, the phase difference of the artificial signal is $\pm 180°$, and therefore its ellipticity tends to 0: the signal is linearly polarized. The angle of polarization of the artificial signal, at site S4, is $160°$.

Site N6

The results obtained with the magnetic field recorded at site N6 are shown in Figure 5. The scalogram of the magnetic field shows that the signal recorded at this site has less amplitude than the signal recorded at site S4. Besides, in contrast with site S4, at site N6 the scalogram does not show an intermittent enhancement of the amplitude of the signal for all the frequencies. The magnetic field time-series are spiky, but they do not show wave packets as in site S4.

The polarization attributes of the magnetic field at site N6 are not time-frequency independent as they were at site S4. In this case, they are nearly random for all frequencies during all the time. The peaks in the histograms are not comparable to those obtained at site S4. Therefore, the signal recorded at site N6 is mainly natural signal.

Comparison of sites S4 and N6

The obtained results at site S4 suggest that it is strongly affected by the noise created by the DC electric railway. In contrast, results at site N6 do not show the contamination of the MT signal. Taking into account the location of both sites with respect to the railway (S4 is the closest, N6 the furthest) the obtained results show successfully the degree of EM noise in each site.

Analogous results are obtained at each site with the electric field time-series.

Site S4

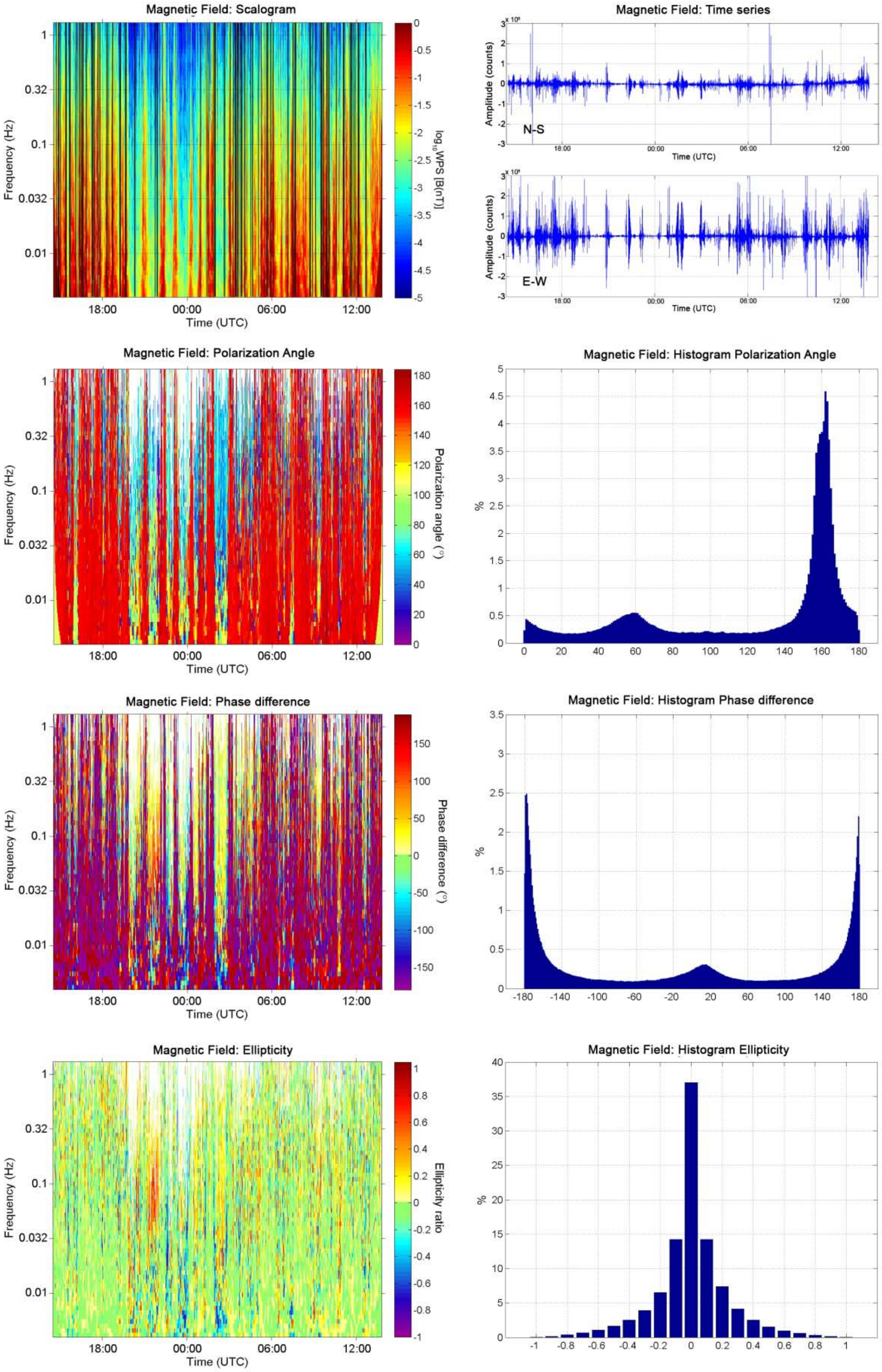

Figure 4. Site S4. Magnetic field scalograms, time series, polarization attributes in the time-frequency domain and their corresponding normalized histograms. The general train schedule is superposed in black onto the scalogram.

Site N6

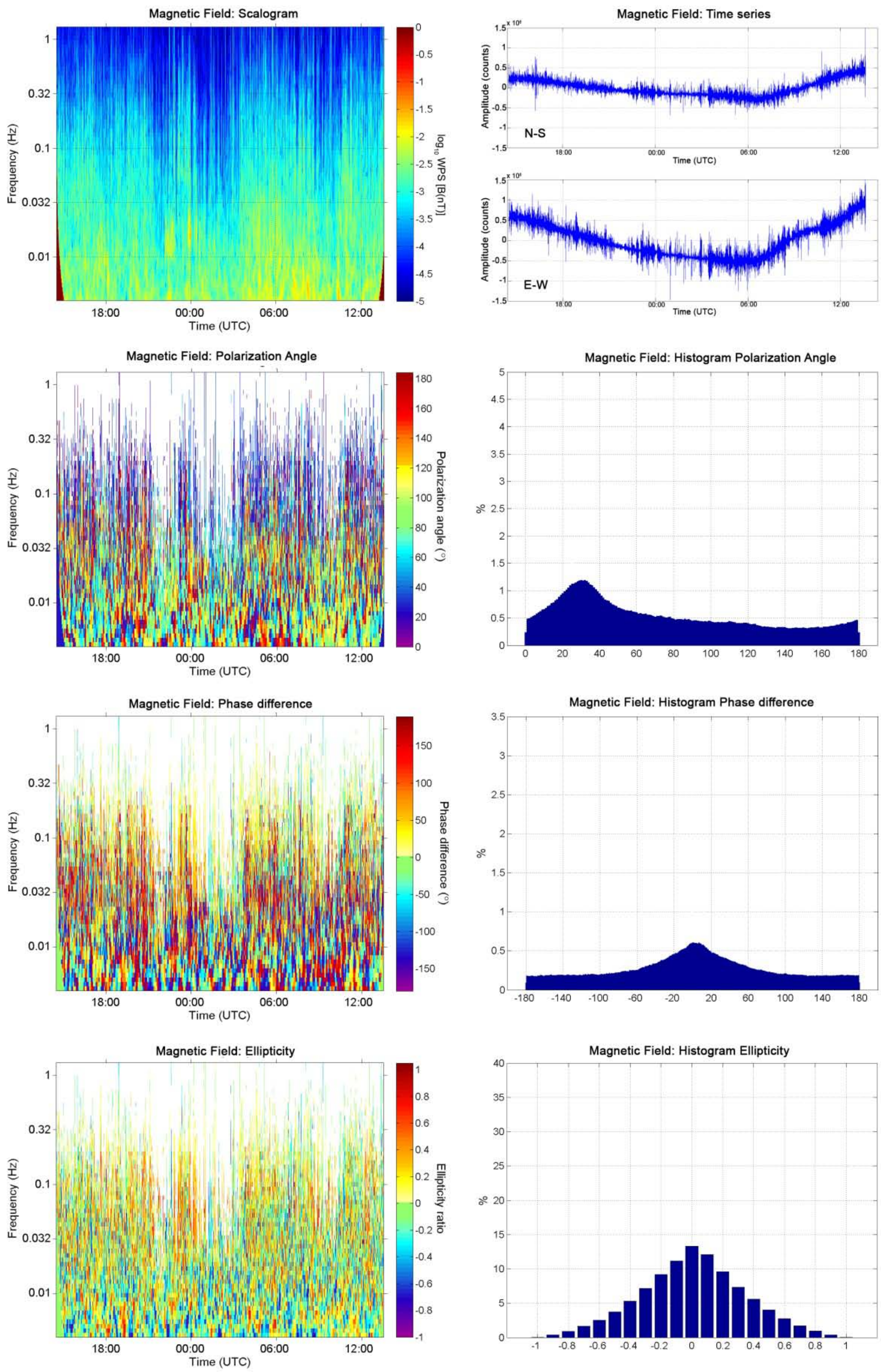

Figure 5. Site N6. Magnetic field scalograms, time series, polarization attributes in the time-frequency domain and their corresponding normalized histograms.

Figure 6 shows the MT responses at both sites. At site S4, the logarithm of apparent resistivity rises with a slope of approximately 45° with the logarithmic period, and the phases decay to zero for periods higher than 1 second. This behavior is characteristic of the MT responses in the near field of a grounded horizontal electric dipole source (Zonge and Hughes, 1991). Therefore, the DC electric railway acts as an electric dipole (Egbert, 1997; Egbert et al., 2000). At site N6 the MT responses are smoother; only the XY polarization shows a small presence of noise.

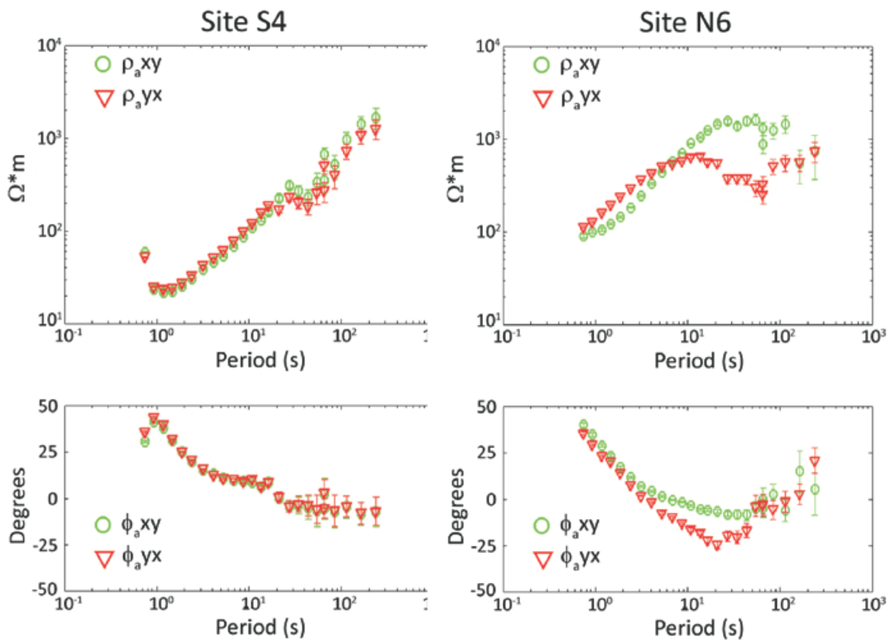

Figure 6. MT responses (apparent resistivity and phase) at sites S4 and N6

The analysis of the MT time-series in the time-frequency domain has successfully identified the cultural noise source. The intermittent behavior of the source has been detected in the scalograms, whereas its fixed location has been inferred from the time-frequency independent polarization attributes. The linear polarization of the artificial signal, typical of the cultural noise, has also been detected.

In consequence, the proposed method has been proven as a useful tool to detect and identify the presence of the DC electric railway from the analysis of the MT time-series. In this way, it is not necessary the computation of the MT responses to detect the noise.

3.2 Pc3 pulsation observed in MT time-series

Tramutola (TRAM) site is a permanent MT monitoring station located at Val d'Agri (Basilicata region, southern Italy). It has been working since July 2007 to study the stability of the MT transfer function estimates (Balasco et al, 2009). Figure 7 shows its location.

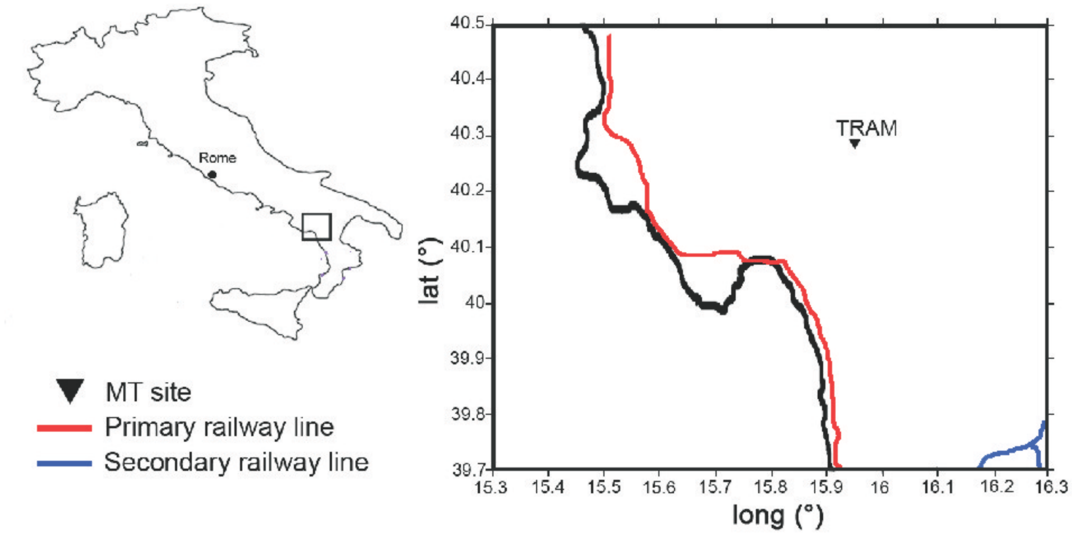

Figure 7. Location of the Tramutola site, and the DC railway lines in the region (the closest is 50km distant from the site)

The analysis of about 4 year of MT data acquired in Tramutola show that MT monitoring estimates are affected by two time dynamics (Romano et al., 2014). On the one hand, there is a quasi-annual oscillation related to seasonal changes: modification of the subsoil electrical properties due to the drying and wetting in the shallowest layers. On the other hand, there is an oscillation in the [20-100s] period range, which seems to be related to the geomagnetic activity.

Several segments of MT time-series (sampling frequency= 6.25 Hz) have been analyzed during the research stay using the method proposed in Escalas et al., 2013. In this report, the results of a 24-h segment (30/10/2007) analyzed in the frequency range 0.004Hz- 1.2Hz are shown.

Figure 8 shows the results obtained for the magnetic field time-series. In the scalogram of the magnetic field modulus, an enhancement of the signal is detected from 5h to 8h UTC and in the frequency range 0.02 Hz - 0.36 Hz (period 28 s – 48 s). In the time-series, this oscillation is not easily visible.

In general, the polarization attributes in the time-frequency domain (blue histograms) achieve nearly random values, typical behavior of the MT natural signal (Escalas et al., 2013). However, in the region from 5h to 8h UTC, and from 0.02 Hz to 0.36 Hz the polarization attributes exhibit nearly constant values (red histograms). The ellipticity is around 0.2, and the phase difference between the orthogonal components of the signal is around $140°$: the signal is elliptically polarized. The polarization angle (angle of the semi-major axis of the ellipse with the EW axis) is around $150°$. The obtained results with the electric field data, not shown here, reproduce the same features.

From the analysis of the results, the signal detected in the region [5h-8h UTC, 0.02Hz - 0.36 Hz] seems to have a natural origin. This kind of “anomalous signal” is detected in many other segments of Tramutola data. Its dominant frequency is not constant in time and its duration is always longer than 30 min, but shorter than 4 hours. It is a day-side phenomena, and the polarization attributes change during the day. The occurrence of this signal seems to be related with the geomagnetic activity. From all these results and according to the literature (Saito, 1969; Villante et al., 1999; Kleimenova et al., 2013; Sutcliffe et al., 2013; Zelinskiy et al., 2014) this signal can be a Pc3 pulsation.

The Pc3 pulsations constitute a natural source of the MT signal, in the range 20mHz-100mHz. If they dominate over the other natural sources, the MT signal can show a predominant direction of polarization.

Figure 9 shows the MT responses at Tramutola site during two different time intervals. From 04:00 to 08:00 AM, simultaneously to the enhancement of the signal amplitude shown in the scalogram (Figure 8), the apparent resistivity decreases and the phases increase in comparison to the MT responses obtained in the interval 04:00 to 08:00 PM. This variation in the MT estimates is the same observed in Romano et al. (2014) for the long period range. Therefore, the Pc3 pulsations could be one of the sources of variability of the MT estimates in their characteristic frequency range (20mHz-100mHz).

From the analysis of three month data (09-11/2007) they have been computed the lombperiodograms (Lomb, 1976) of the magnetic field amplitude. In Figure 10, they are compared to the lombperiodograms of the solar wind velocity for the same dates. It is clearly seen the correlation between these two parameters in the frequency range $8.8 \cdot 10^{-4}$ Hz - 0.05 Hz. They show the same frequency of recurrence, 27 days, which is related to the solar activity.

Tramutola site

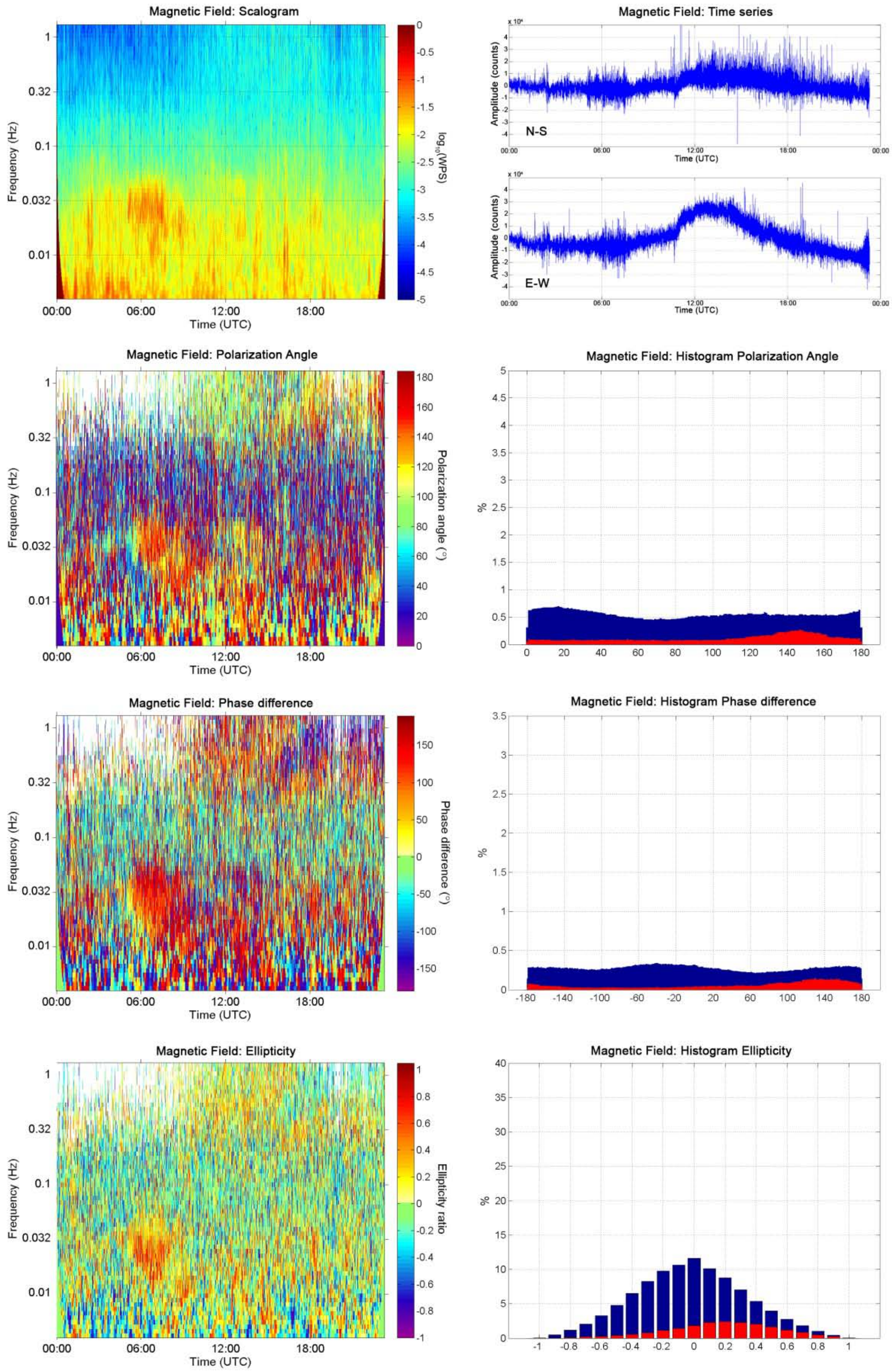

Figure 8. Tramutola site. Magnetic field scalograms, time series, polarization attributes in the time-frequency domain and their corresponding normalized histograms (blue). In red, the histograms of the Pc3 time-frequency range [5h-8h UTC, 0.02Hz - 0.36 Hz].

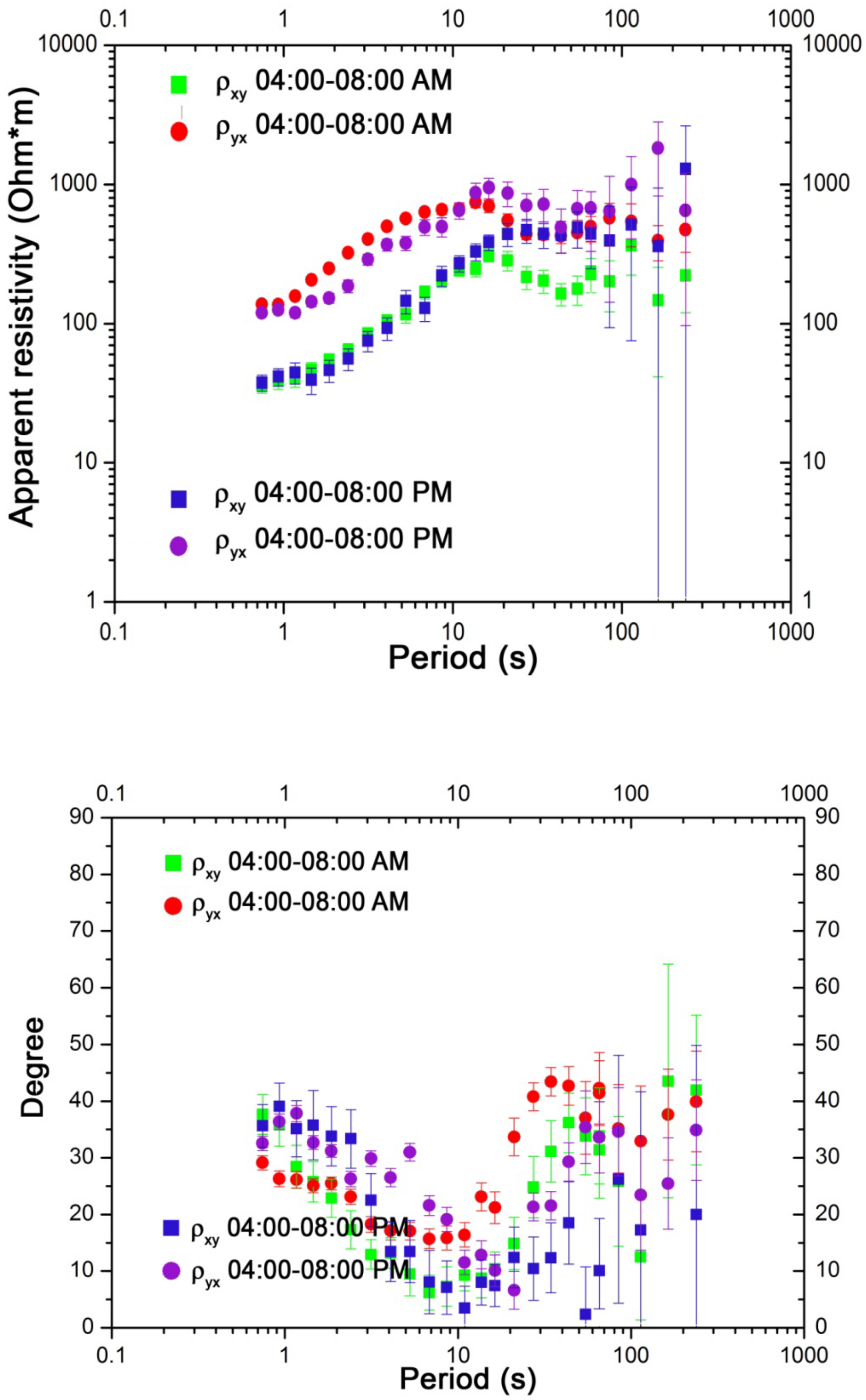

Figure 9. MT responses at Tramutola site for two time intervals: 04:00-08:00 AM, and 04:00-08:00 PM.

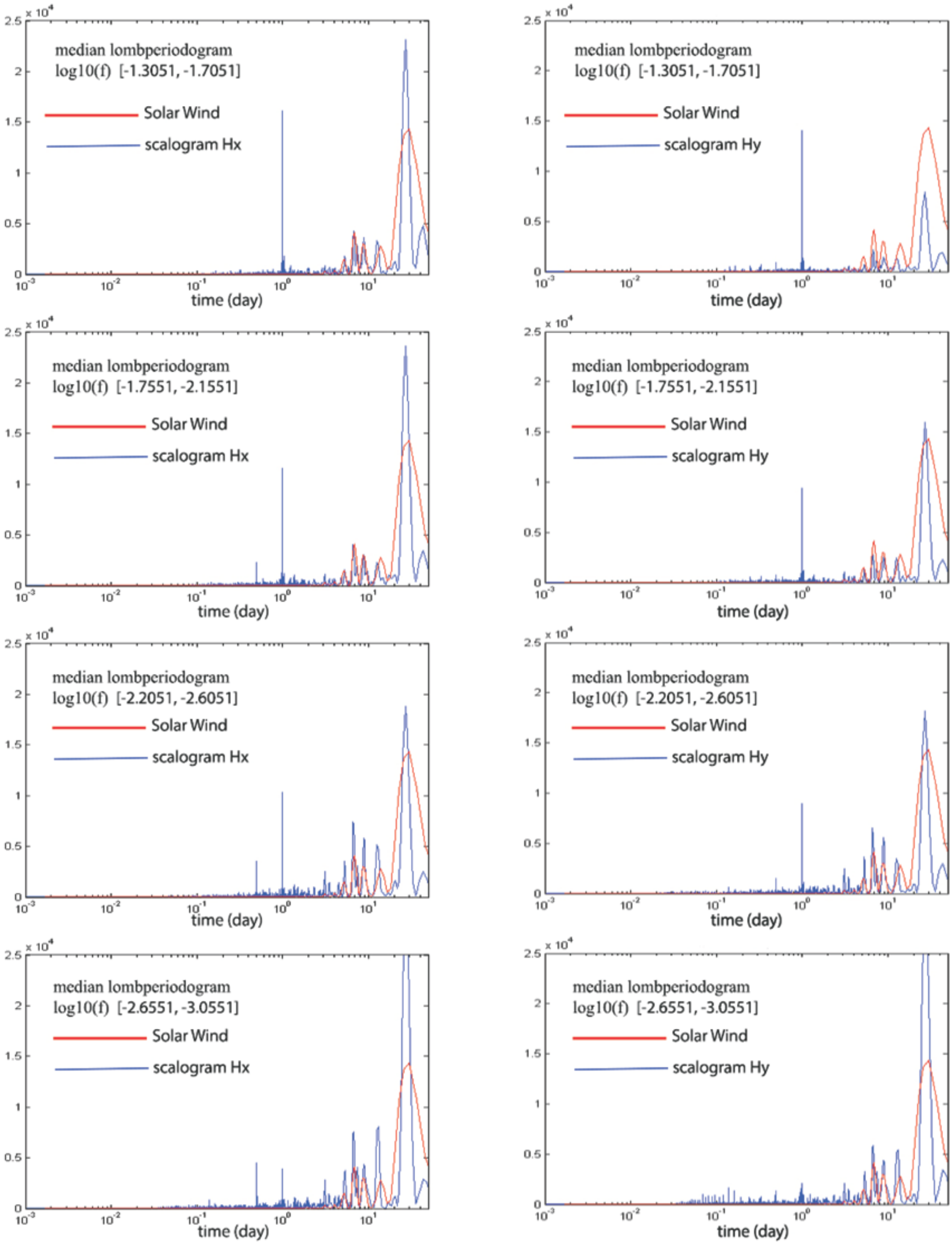

Figure 10.Tramutola site. Lombperiodograms of the magnetic field components and the solar wind.

4 Conclusions

During the research stay several MT data sets acquired by the IMAA have been analyzed using the method proposed by Escalas et al. (2013). In this way, both the energy and the polarization attributes of the MT time-series have been fully characterized in the time-frequency domain, using a wavelet scheme.

On the one hand, this analysis has permitted detecting the presence of EM noise in the Lameiza Terme data. Besides, in this case the noise source has been identified: the DC electric railways in the vicinity of the acquired sites. The analysis of the scalograms has allowed us to identify the intermittent artificial signal created by the DC trains. The polarization attributes of this signal are time-frequency independent. The phase difference oscillates between $\pm 180°$, and the ellipticity tends to 0: the signal is linearly polarized. The polarization angle is constant for each site, as it was expected from a fixed artificial noise source; it depends on the relative location source-site. The analysis of several sites at different locations has shown the effect of the DC railways as a function of the distance.

On the other hand, the analysis of Tramutola site data has suggested the presence of Pc3 pulsations in the frequency range 20 mHz-80 mHz (12.5 s – 50 s). Several events have been detected in daytime segments whose frequency, duration and polarization attributes are characteristics of the Pc3 pulsations, according to the literature. Besides, a variation in the MT estimates has been detected related to these events. Thus, these events need to be analyzed in detail to quantify the violation of the MT assumptions.

The method proposed by Escalas et al. (2013) has been proven as a powerful technique to analyze non-stationary signals, such as the cultural noise created by DC trains and the Pc3 pulsations, due to its wavelet scheme. Besides, the analysis of the polarization attributes in the time-frequency domain has allowed identifying the noise source due to its specific patterns. The obtained results also show how the MT signal can be polarized if one of its sources dominates over the others, as it occurs in the case of the observed Pc3 pulsations.

The research done during the stay has reinforced the collaboration between the CNR and the University of Barcelona. The obtained results are planned to be published in two articles in international journals, with CNR citation.

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