Geophysical Journal International

Geophys. J. Int. (2014) **198,** 484–494 doi: 10.1093/gji/ggu147
Advance Access publication 2014 May 23
GJI Geomagnetism, rock magnetism and palaeomagnetism

A new methodology to estimate magnetotelluric (MT) tensor relationships: Estimation of Local transfer-functIons by Combining Interstation Transfer-functions (ELICIT)

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Accepted 2014 April 17. Received 2014 April 17; in original form 2013 August 14

SUMMARY

A new methodology to estimate magnetotelluric (MT) tensor relationships, called Estimation of Local transfer-functIons by Combining Interstation Transfer-functions (ELICIT), is proposed whereby the MT tensor relationships of the local site are derived using only interstation transfer functions. The MT impedance tensor and the geomagnetic transfer function at the local site are characterised by combining interstation tensor relationships between electric and magnetic fields at the local site with the horizontal magnetic fields acquired at a neighbouring site. The main property of the proposed method is that the employed interstation transfer functions are independently constrained, without the need to acquire the electric and the magnetic fields at the local site simultaneously to recover the local MT tensor relationships. Due to this property, the ELICIT method offers new possibilities for MT data acquisition and processing, providing significant improvements when the magnetic time-series at the local site are affected by local noise or are truncated. Error analysis shows that, even when magnetic fields are truncated, the quality of the results obtained following the ELICIT method are similar to those we would obtain if the magnetic fields had not been truncated. Another important property is that different neighbouring sites can be used to recover the tensor relationships at the local site. Averaging of results obtained using different neighbouring sites can be performed to improve the statistics. For our example data, when the ELICIT method is used to improve the statistics, errors of the estimates for periods between 1000 and 20 000 s periodicities are clearly reduced. All interstation transfer functions are calculated doing remote reference and the bootstrap method is used to compute the errors, when necessary. Long period magnetotelluric data acquired in the Pyrenees and in the Atlas Mountains in Morocco, and magnetic data provided by Fürstenfeldbruck magnetic observatory have been used to test the proposed ELICIT method, with positive results. Due to the lack of requirement that the electric and the magnetic fields of the local site be acquired simultaneously, the proposed method also offers new possibilities for MT data acquisition, optimizing the available instrumentation.

Key words: Electromagnetic theory; Magnetotellurics; Magnetic and electrical properties.

1 INTRODUCTION

The most commonly used magnetotelluric (MT) responses of a local site, the MT impedance tensor (Neves 1957; Cantwell 1960; Rokityanski 1961) and the geomagnetic transfer functions (Parkinson 1962; Weise 1962), are obtained from frequency-domain tensor relationships between collocated orthogonal horizontal electric and magnetic time-varying fields recorded simultaneously at the surface of the study area. Due to this time simultaneity, the presence of noise in any of the acquired components will degrade the characterization of the tensor relationships through auto-power noise contributions by either downward or upward bias (see e.g. Sims *et al.* 1971; Jones *et al.* 1983).

One way to improve the processing of MT data when time-series are affected by local noise is to use correlated time-series acquired at a neighbouring location to characterize and or remove the effect of the local noise. Use of such removed series was first proposed in economic theory in the early-1940s by Reiersøl (1941), and independently by Geary (1943) (see Reiersøl 1950; Akaike 1967), where they are termed ‘instrumental variables’. In MT, examples are remote reference (RR) (Gamble *et al.* 1979a), multi-RR (e.g. Jones *et al.* 2001; Varentsov *et al.* 2003a; Chave & Thomson 2004) and robust multivariate errors-in-variables estimation (Egbert 1997). Smirnov & Egbert (2012) improve the method suggested by Egbert (1997) recovering gaps of missing data (up to 20 per cent). The horizontal magnetic tensor (HMT; Berdichevsky 1968; Schmucker 1970; Egbert & Booker 1989) has also been used to detect and remove the segments of the time-series affected by non-stationary events (e.g. Varentsov *et al.* 2003b; Sokolova & Varentsov 2007; Varentsov 2007) as has the geomagnetic transfer functions (Jones & Spratt 2002). Larsen *et al.* (1996) also used the HMT to improve the signal-to-noise ratio level by separating MT signals and correlated noise and Oettinger *et al.* (2001) suggested the signal-noise separation remote reference (SNS-RR) method, where an extra RR site is introduced to improve the signal-to-noise ratio level. However, all of these methods require the simultaneous recording of electric and magnetic time-varying fields at the local site and in general do not provide improvements when the quality of the horizontal magnetic fields of the local site is poor (Ritter *et al.* 1998) or some of the time-series are truncated.

Another way to improve the estimations is to process the MT data using interstation transfer functions, which relates electric or magnetic fields at one site with electric or magnetic fields at another site. In audiomagnetotellurics (AMT), where the distance between sites is typically around 200 m (e.g. Asch & Sweetkind 2011; Falgàs *et al.* 2011; La Terra & Mezenes 2012), the horizontal magnetic fields acquired at a neighbouring site have been used to process the data of the local site, obtaining quasi-MT transfer functions. This technique is already used by Mount Isa Mines' MIMDAS (Sheard 2001) and Quantec's TITAN-24 (White & Gordon 2003) systems. The derived quasi-MT transfer function can substitute for the MT transfer function of the local site when there are no main differences between the horizontal magnetic fields of the two sites. However, Jones & McNeice (2002) and Muñoz & Ritter (2013) show that, especially for sub-horizontal conductors where most of the anomalous response is in the magnetic field not the electric field, the horizontal magnetic fields can vary significantly even over short distances between sites, so care has to be taken when using this limited methodology.

The advantages of processing the MT data replacing the horizontal magnetic fields of the local site with those from a neighbouring site are outlined in Ritter *et al.* (1998). Garcia & Jones (2005) also used the data recorded at a neighbouring site to process the data of a local site, helping to solve the problem of the daytime low signal in the AMT dead-band. They suggested a method for processing AMT data combining two tensor relationships constrained from time-series recorded at different times. The method consists of determining the quasi-MT transfer function at a local site from the multiplication of two tensor relationships: (1) The transfer function between the daytime telluric channels of the local site and a base site and (2) the transfer function of the night-time conventional MT impedance tensor at the base site. The obtained transfer function represents the ratio of the local-telluric to base-magnetic fields obtaining the telluric-magnetotelluric (T-MT; Hermance & Thayer 1975) AMT transfer function of the local site. Garcia & Jones (2005) also note that the quasi-MT transfer function can be a reasonable approximation of the real AMT impedance tensor of the local site if there are no major differences between the horizontal magnetic fields acquired at the two sites.

For broad-band magnetotelluric (BBMT) data and long period magnetotelluric (LMT) data, where the distance between sites is far larger than 200 m, MT sites can be easily located above different geoelectrical structures resulting in large differences between the horizontal magnetic fields acquired at the two sites (Egbert 2002; Varentsov *et al.* 2003a,b; Habibian *et al.* 2010). In this case the quasi-MT transfer function should not be interpreted as the MT transfer function of the local site, or the bias errors introduced will be important and will lead to significant misinterpretation of the data.

Therefore, from the previous studies, the use of the magnetic time-series from a neighbouring site instead of the magnetic time-series of the local site can improve the processing of the MT data. However, the resulting quasi-MT transfer function should not be interpreted as the local MT transfer function, except when it is possible to demonstrate that the time-varying magnetic fields are the same at the local and neighbouring sites, that is, that there is no anomalous magnetic field present at the local site that is not present at the remote site. One solution for this problem could be to modify the inversion programs to allow using quasi-MT transfer functions. However, in this case the magnetic fields of the analysed sites will be ignored, reducing the resolution to constrain the conductivity structures of the subsurface (Stodt *et al.* 1981; Jones & McNeice 2002).

In this paper, we propose a new method to estimate MT tensor relationships: Estimation of Local transfer-functIons by Combining Interstation Transfer-functions (ELICIT). Following the ELICIT method, the MT impedance tensor and the geomagnetic transfer function of the local site can be characterized by combining interstation transfer functions, which do not need to be acquired simultaneously or during the same period of time, between the electric and magnetic fields at the local site and the horizontal magnetic fields at a neighbouring site. The proposed ELICIT method is demonstrated theoretically and applied to real LMT data acquired in the Atlas Mountains in Morocco and in the Pyrenees. The results obtained from the ELICIT method are compared with conventional MT results obtained from RR processing. Finally, advantages of the ELICIT method are shown with improvement of results when the time-series are truncated, improvement of the statistics when determining the local tensor relationships and modification of MT surveys to better optimise the available instrumentation.

2 THEORY

Using the ELICIT method, three interstation tensor relationships have to be computed to constrain the MT impedance tensor and the geomagnetic transfer functions of the local site. These interstation tensor relationships relate the local horizontal telluric components at site l with the neighbouring horizontal magnetic components at site n (eq. 1), the local vertical magnetic component at site l with the neighbouring horizontal magnetic components at site n (eq. 2), and the neighbouring horizontal magnetic components at site n with the local horizontal magnetic components at site l (eq. 3). The nomenclature of the tensor relationships is based on Berdichevsky & Dmitriev (2008)

$$\boldsymbol{e}_l = \boldsymbol{Z}_{ln}\boldsymbol{h}_n \tag{1}$$

$$\boldsymbol{h}_z^l = \boldsymbol{S}_{ln}\boldsymbol{h}_n \tag{2}$$

$$\boldsymbol{h}_n = \boldsymbol{M}_{nl}\boldsymbol{h}_l\,, \tag{3}$$

where $\boldsymbol{h}_l$ and $\boldsymbol{h}_n$ are vectors with two components comprising the horizontal magnetic components of the local site l $[h_x^l, h_y^l]$ and the neighbouring site n $[h_x^n, h_y^n]$, respectively. $\boldsymbol{e}_l$ is a vector with two components comprising the horizontal electric components of the site l $[e_x^l, e_y^l]$ and h_z^l is the vertical component of the magnetic field recorded on site l. $\boldsymbol{Z}_{ln}$ and $\boldsymbol{M}_{nl}$ are 2 × 2 complex matrix and $\boldsymbol{S}_{ln}$

is a 1 × 2 complex vector. In all cases dependence on frequency is assumed.

With the aim of avoiding the effects of local noise, the RR method (Gamble *et al.* 1979a,b) with a magnetic site r, $\boldsymbol{h}_r$, is applied when calculating $\boldsymbol{Z}_{ln}$, $\boldsymbol{S}_{ln}$ and $\boldsymbol{M}_{nl}$:

$$\boldsymbol{Z}_{ln}^{RR} = [\boldsymbol{e}_l \boldsymbol{h}_r]\,[\boldsymbol{h}_n \boldsymbol{h}_r]^{-1} \tag{4}$$

$$\boldsymbol{S}_{ln}^{RR} = \left[\boldsymbol{h}_z^l \boldsymbol{h}_r\right][\boldsymbol{h}_n \boldsymbol{h}_r]^{-1} \tag{5}$$

$$\boldsymbol{M}_{nl}^{RR} = [\boldsymbol{h}_n \boldsymbol{h}_r]\,[\boldsymbol{h}_l \boldsymbol{h}_r]^{-1}, \tag{6}$$

where the value $[\boldsymbol{pq}]$ is the spectral density matrix for fields p and q, defined by Gamble *et al.* (1979b), viz. p and q can be associated with electric or magnetic fields ($\mathbf{e}_l$, $\mathbf{h}_l$, $\mathbf{h}_n$, h_z^l, $\mathbf{h}_r$) depending of the tensor relationship and in case of RR, q will be associated with $\mathbf{h}_r$.

$$[\boldsymbol{pq}] = \begin{bmatrix} \langle p_x q_x^* \rangle & \langle p_x q_y^* \rangle \\ \langle p_y q_x^* \rangle & \langle p_y q_y^* \rangle \end{bmatrix}. \tag{7}$$

The asterisk denotes the complex conjugate and ⟨⟩ denotes ensemble averaging either by summation over neighbouring frequencies or by averaging different estimates at the same frequency, or both.

In case of $\left[h_z^l \boldsymbol{h}_r\right]$

$$[\boldsymbol{pq}] = \left[\langle p_x q_x^* \rangle \quad \langle p_x q_y^* \rangle\right]. \tag{8}$$

In case of RR processing of site l using site r as a remote site, the MT impedance tensor is obtained by (equivalent equation for $\boldsymbol{W}_l^{RR}$):

$$\boldsymbol{Z}_l^{RR} = [\boldsymbol{e}_l \boldsymbol{h}_r]\,[\boldsymbol{h}_l \boldsymbol{h}_r]^{-1}. \tag{9}$$

Combining eqs (4) and (6) the MT impedance tensor of site l, $\boldsymbol{Z}_l^{RR}$ (eq. 9), can be recovered, namely:

$$\begin{aligned}\boldsymbol{Z}_{ln}^{RR}\boldsymbol{M}_{nl}^{RR} &= [\boldsymbol{e}_l \boldsymbol{h}_r]\,[\boldsymbol{h}_n \boldsymbol{h}_r]^{-1}\,[\boldsymbol{h}_n \boldsymbol{h}_r]\,[\boldsymbol{h}_l \boldsymbol{h}_r]^{-1} \\ &= [\boldsymbol{e}_l \boldsymbol{h}_r]\,\boldsymbol{I}\,[\boldsymbol{h}_l \boldsymbol{h}_r]^{-1} = \boldsymbol{Z}_l^{RR},\end{aligned} \tag{10}$$

where $\boldsymbol{I}$ is the identity matrix. Equivalent steps can be followed to obtain the geomagnetic transfer function, $\boldsymbol{W}_l^{RR}$, combining eqs (5) and (6). If the horizontal magnetic fields of the local site are used as a RR ($\boldsymbol{h}_r = \boldsymbol{h}_l$), results will be equivalent to single site processing.

In the particular case where the neighbouring site is the remote site ($\boldsymbol{h}_n = \boldsymbol{h}_r$), we obtain the approach suggested by Schmucker (1984) and Neska (2006) used to define the RR method using interstation transfer functions. However, following the ELICIT method different sites can be used as neighbouring sites to obtain, from each neighbouring site, equivalent results to those obtained undertaking conventional RR processing.

One of the advantages of the ELICIT method is that the time-series do not need to be acquired simultaneously nor during the same period of time. In that case, if we assume that the interstation transfer functions are constant with time (equivalent equation for $\boldsymbol{S}_{ln}^{RR}$ and $\boldsymbol{M}_{nl}^{RR}$)

$$\begin{aligned}\left[\boldsymbol{Z}_{ln}^{RR}\right]_{t1} &= \left[[\boldsymbol{e}_l \boldsymbol{h}_r]\,[\boldsymbol{h}_n \boldsymbol{h}_r]^{-1}\right]_{t1} \approx \left[[\boldsymbol{e}_l \boldsymbol{h}_r]\,[\boldsymbol{h}_n \boldsymbol{h}_r]^{-1}\right]_{t2} \approx \dots \\ &\approx \left[[\boldsymbol{e}_l \boldsymbol{h}_r]\,[\boldsymbol{h}_n \boldsymbol{h}_r]^{-1}\right]_{tn},\end{aligned} \tag{11}$$

where t_i are different time-series acquired at a different times and with different lengths, the obtained interstation transfer function can always be related to an hypothetical time where all of the interstation transfer functions are acquired simultaneously. Then we will be in the same situation than eq. (10), demonstrating that the method works even when the interstation transfer functions are not acquired simultaneously. This approximation cannot be applied in areas where the geoelectrical structures of the subsurface change with time [i.e. when monitoring geothermal or carbon capture and sequestration (CCS) areas].

In all examples below the time-series data were processed using the Birrp.5 robust processing program (Chave & Thomson 2004). The same parameters were adopted for all processing runs, avoiding effects unrelated with the purpose of the study. Where necessary, error estimation were carried out following the bootstrap method (Efron 1979), computing a sample of 5000 bootstrapped standard deviation of 1000 samples from the analysed parameter. The 1000 samples of the analysed parameter were derived using 1000 random samples within the margin of error of each variable.

3 EXPERIMENTS AND RESULTS

The ELICIT method was tested using real data acquired in the Atlas Mountains of Morocco (sites j, k and m), in the Pyrenees (sites b and c), and using the magnetic time-series provided by Fürstenfeldbruck (FUR) magnetic observatory (Fig. 1). The MT data of sites j, k and b were processed following the ELICIT method ($\boldsymbol{Z}_l^{RR} = \boldsymbol{Z}_{ln}^{RR}\boldsymbol{M}_{nl}^{RR}$ and $\boldsymbol{W}_l^{RR} = \boldsymbol{S}_{ln}^{RR}\boldsymbol{M}_{nl}^{RR}$) and substituting the magnetic fields of the local site with the ones acquired at a neighbouring site (the quasi-MT transfer functions, $\boldsymbol{Z}_{ln}^{RR}$ and $\boldsymbol{W}_{ln}^{RR}$). In all cases, results are compared with RR processing with the respective sites ($\boldsymbol{Z}_l^{RR}$ and $\boldsymbol{W}_l^{RR}$). Table 1 shows the sites used for processing the data of sites b, j and k. Estimates obtained are shown in Figs 2–4,

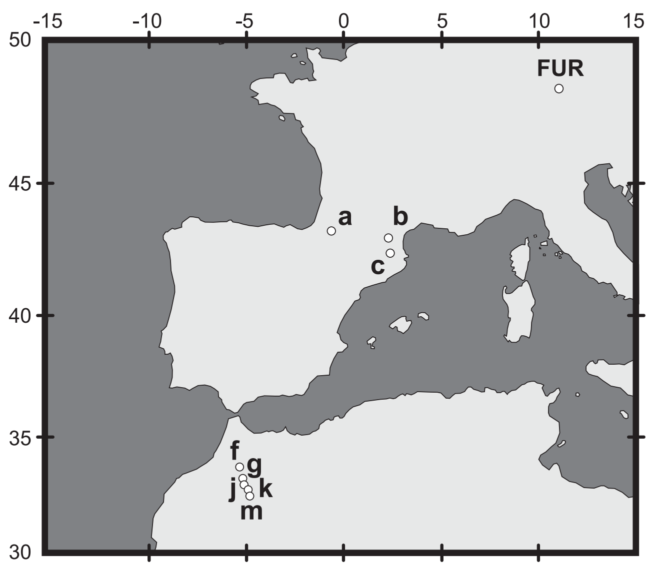

Figure 1. Map with the location of the LMT sites. a, b and c are LMT sites acquired in the Pyrenees, FUR is the Fürstenfeldbruck Magnetic Observatory (INTERMAGNET) and f, g, j, k, m are LMT sites acquired in the Atlas Mountains in Morocco.

Table 1. Roles of the used sites when process the data of the local sites following different methods (ELICIT, quasi-magnetotelluric transfer function and remote reference processing). There is also the period of time when data have been acquired and the figures where the results are shown.

Local site (l)	Neighbouring site (n)	Remote reference site (RR)	Period data acquisition	Figure
b	*c*	*FUR*	26/10/2010–09/11/2010	2
j	*k*	*m*	29/11/2009–21/12/2009	3
k	*m*	*j*	29/11/2009–21/12/2009	4

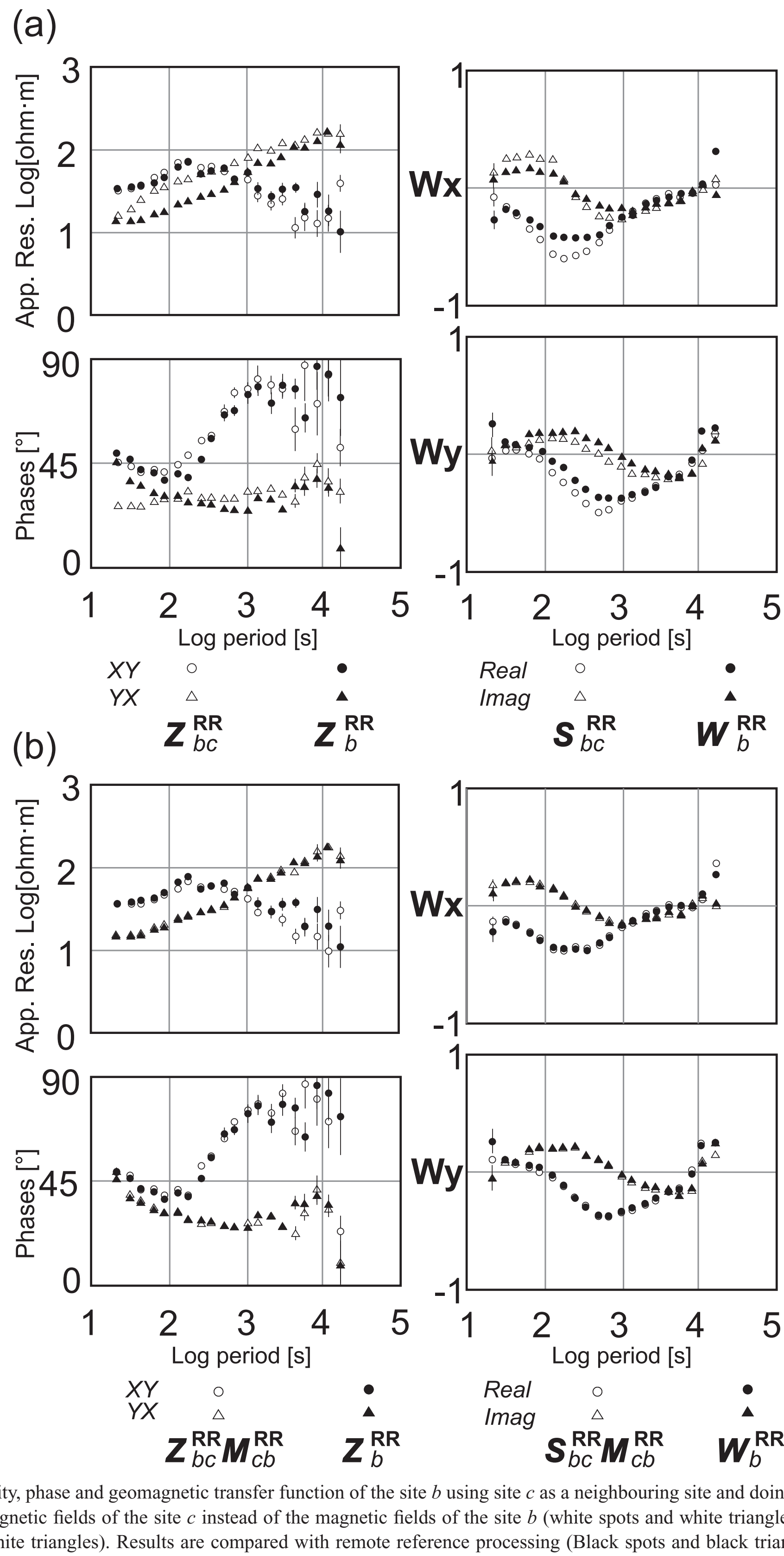

Figure 2. Apparent resistivity, phase and geomagnetic transfer function of the site *b* using site *c* as a neighbouring site and doing remote reference with FUR. (a) Using the horizontal magnetic fields of the site *c* instead of the magnetic fields of the site *b* (white spots and white triangles). (b) Following the ELICIT method (white spots and white triangles). Results are compared with remote reference processing (Black spots and black triangles). In all three cases FUR magnetic observatory has been used for remote reference.

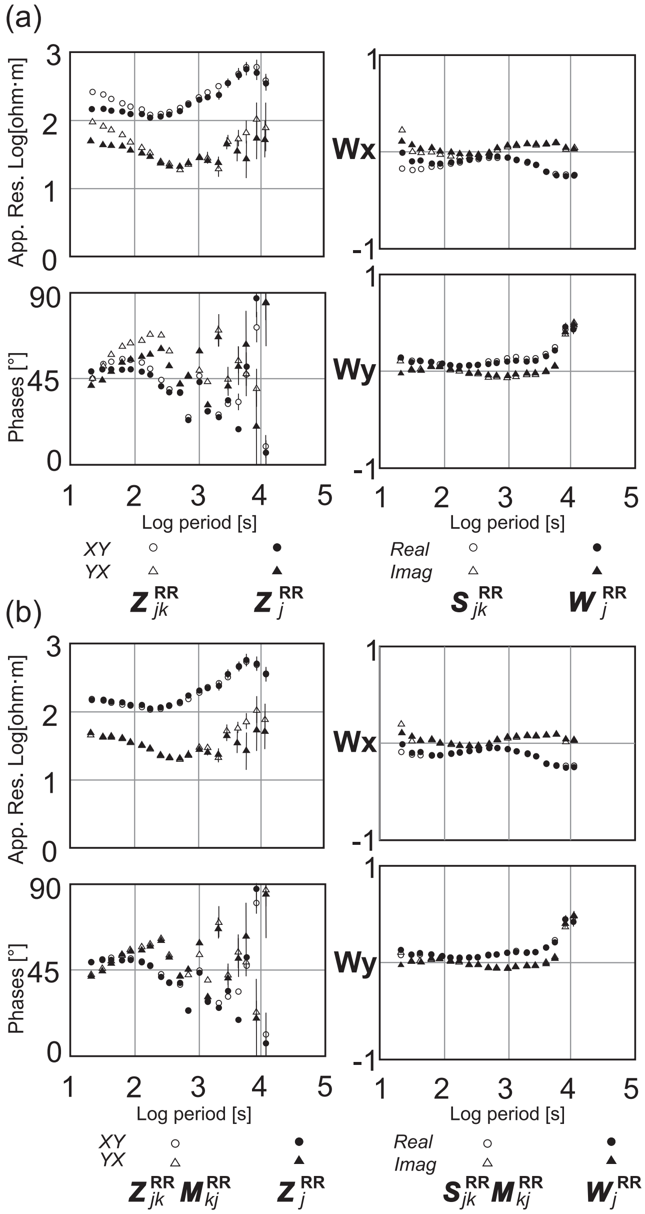

Figure 3. Apparent resistivity, phase and geomagnetic transfer function of the site j using site k as a neighbouring site and doing remote reference with m. (a) Using magnetic fields of the site k instead of the magnetic fields of the site j (white spots and white triangles). (b) Following the ELICIT method (white spots and white triangles). Results are compared with remote reference processing (black spots and black triangles). In all three cases site m has been used for remote reference.

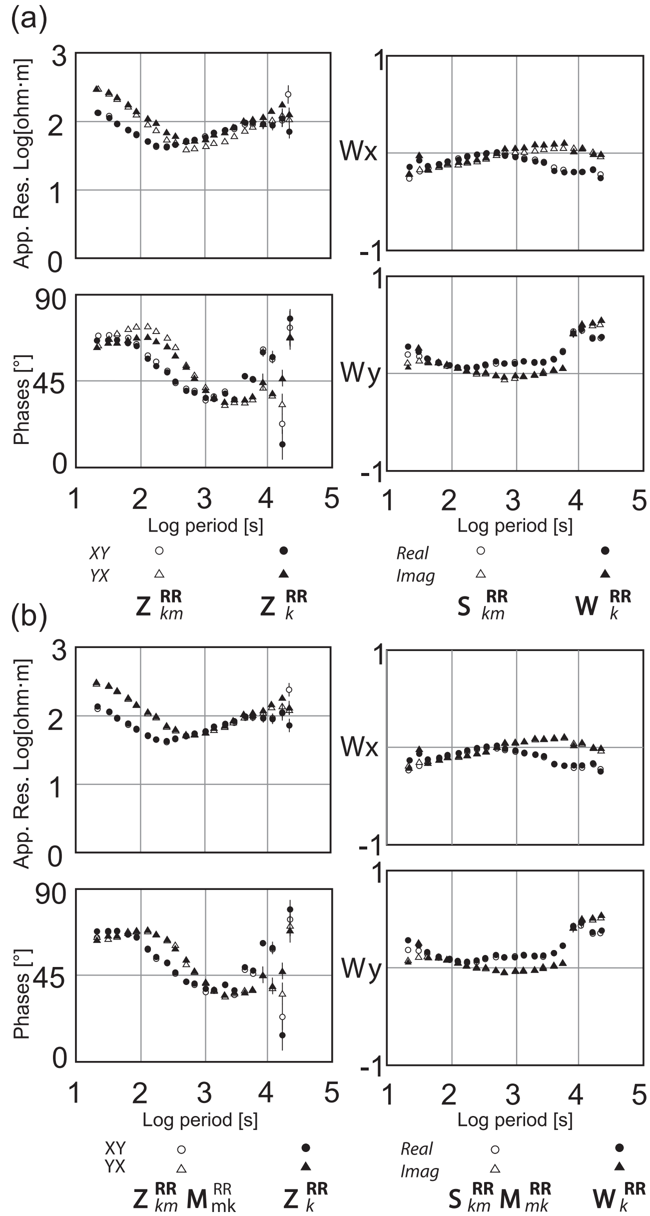

Figure 4. Apparent resistivity, phase and geomagnetic transfer function of the site k using site m as a neighbouring site and doing remote reference with j. (a) Using magnetic fields of the site m instead of the magnetic fields of the site k (white spots and white triangles). (b) Following the ELICIT method (white spots and white triangles). Results are compared with remote reference processing (black spots and black triangles). In all three cases site j has been used for remote reference.

respectively. Fig. 5 compares the errors, for the MT impedance tensor and the geomagnetic transfer function, obtained using the ELICIT method and from conventional RR processing.

These results corroborate the validity of the ELICIT method, properly recovering the MT transfer functions of the local sites, and also show three cases where the quasi-MT transfer functions differs from the local MT transfer functions. The *xx* and *yy* components of the MT impedance tensor (Figs S1, S2 and S3) are not used to analyse the validity of the ELICIT method and evaluate its possibilities due to their lower quality and do not involve differences in the final conclusions.

4 ADVANTAGES OF THE ELICIT METHOD

4.1 Improved results when the horizontal magnetic time-series are truncated

Taking advantage of the properties of the ELICIT method, we test new possibilities for processing MT data with the aim of improving the results when the horizontal magnetic time-series are strongly affected by noise and only a small window of the total time-series has good quality data. The ELICIT method was tested in three hypothetical cases where the magnetic time-series of site k were truncated (Fig. 6a). Site m was used as a neighbouring site and site j for the

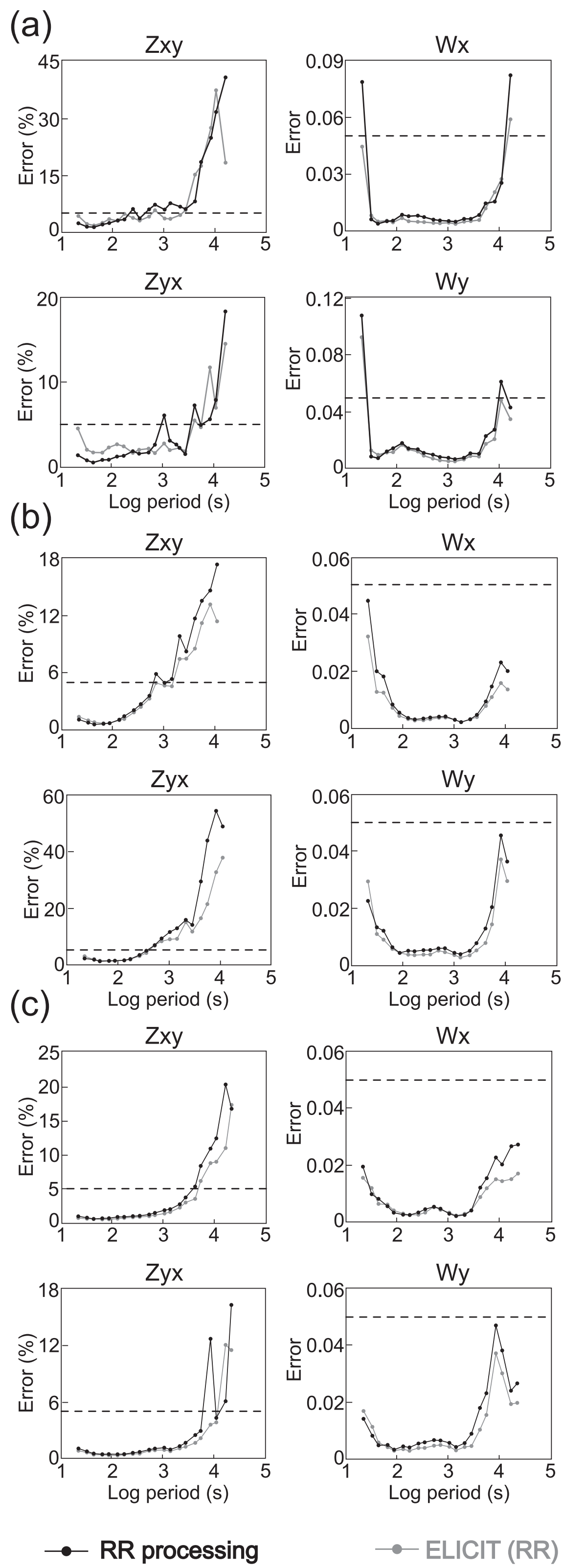

Figure 5. Comparison between errors obtained doing remote reference processing (Black) and using the ELICIT method (grey). Black dashed line is the 5 per cent of error for the MT impedance tensors and the 0.05 of errors for the geomagnetic transfer functions. (a) Processing site *b* (errors from Fig. 2b). (b) Processing site *j* (errors from Fig. 3b). (c) Processing site *k* (errors from Fig. 4b).

RR. In the first case (b.1) we only have 2 d of horizontal magnetic time-series acquired at the beginning of the electric time-series. In the second case (b.2) we only have 2 d of horizontal magnetic time-series acquired at the end of the electric time-series. Finally, we recreate another hypothetical situation where the magnetic fields had not been recorded during the acquisition of the electric fields, and we use 2 d of horizontal magnetic time-series acquired 20 d after recording the electric time-series (b.3). Results are compared with the RR processing of the site *k* using 20 d of electric and magnetic time-series as if magnetic time-series were not truncated (Fig. 6b, left), and are also compared with RR processing only using the 2 corresponding days of electric and magnetic time-series (Fig. 6b, right). The associated errors are shown in Fig. 7.

Following the ELICIT method, the MT impedance tensor of the local site can be recovered with similar errors as if the magnetic time-series were not truncated, even when the electric and the magnetic time-series of the local site are acquired at different times. In addition, results obtained using the ELICIT method are superior to those obtained doing RR processing with the 2 d of data where the electric and magnetic time-series were acquired simultaneously.

Using MT data acquired in the Pyrenees, the ELICIT method was used to improve the processing of an LMT site, site *a* in Fig. 1, at which the magnetic fields were truncated after 36 hr of acquisition. Using site *b* as a neighbour site and *FUR* for RR, we applied the ELICIT method using 10 d of the electric time-series of the local site and the 36 hr of magnetic time-series of the local site (Fig. 8a). Results show that the ELICIT method provides good results until 10 000 s, improving the results obtained doing RR processing with FUR with the 36 hr where electric and magnetic time-series of the local site were acquired simultaneously. Errors were also significantly reduced when applying the ELICIT method (Fig. 8b).

Although for onshore MT surveys this is not a common situation, for offshore MT surveys small movements of the instruments distort the electric and magnetic time-series, more intensely affecting the magnetic time-series than the electric time-series (Neska *et al.* 2013). In this case, using onshore neighbouring and remote sites, which can be the same site, the ELICIT method could be used to improve the results independently using the segments of the electric and magnetic time-series of the local site where data is less distorted.

4.2 Improving the statistics using the ELICIT method

Another advantage of the ELICIT method is that it can be used to improve the statistics if two or more neighbouring sites are acquiring data simultaneously with the local site, in a equivalent manner to that suggested by Varentsov *et al.* (2003a) with multi-RR: Tensor relationships of the local site can be constrained following the ELICIT method for each one of the neighbouring sites and then average the results obtained. An example of this advantage is shown in Fig. 9 where results of site *j* are improved by applying the ELICIT method, always using site *k* as the RR, using five different sites as a neighbouring site (*j*, *f*, *g*, *k*, *m*) and averaging the obtained results. Comparing with the results obtained from conventional RR processing with site *k*, the apparent resistivities and phases are remarkably improved between 1000 and 20 000 s. As shown in Fig. 9(c), the errors are also significantly reduced for periods between 1000 and 20 000 s. In this example, induction arrows are slightly improved following the ELICIT method but without notable differences to the results obtained from RR processing. The ELICIT method could be also applied in combination with multi-RR processing (Varentsov

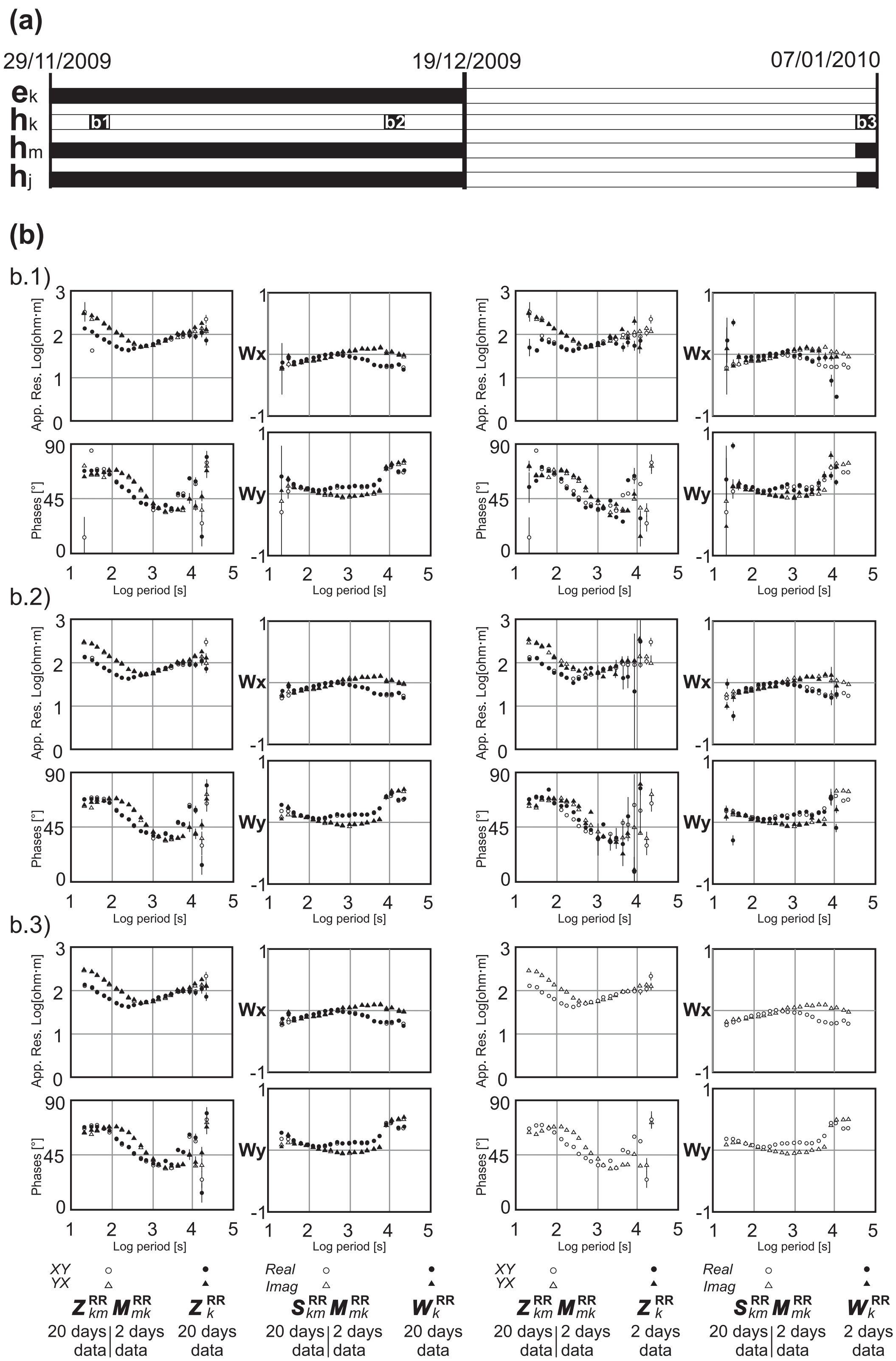

Figure 6. (a) Days of acquired electric and magnetic time-series of sites *k* (local site), *m* (neighbouring site) and *j* (remote reference site) used to process the data of site *k* using ELICIT method. (b) Apparent resistivity, phases and geomagnetic transfer functions of site *k*. White spots/triangles: results obtained processing with ELICIT method, using 2 d segment of magnetic time-series: b1, b2 and b3, respectively. Left block: results are compared with black spots/triangles obtained processing LMT data of site *k* doing remote reference processing with site *j*. In all cases (b1, b2 and b3) using electric and magnetic time-series of site *k* acquired between 2009 November 20 and 2009 December 19. Right block: results are compared with black spots/triangles obtained processing LMT data of site *k* using electric and magnetic time-series of segments b1, b2, respectively. No black spots/triangles for b3 because no electric time-series were acquired during this period.

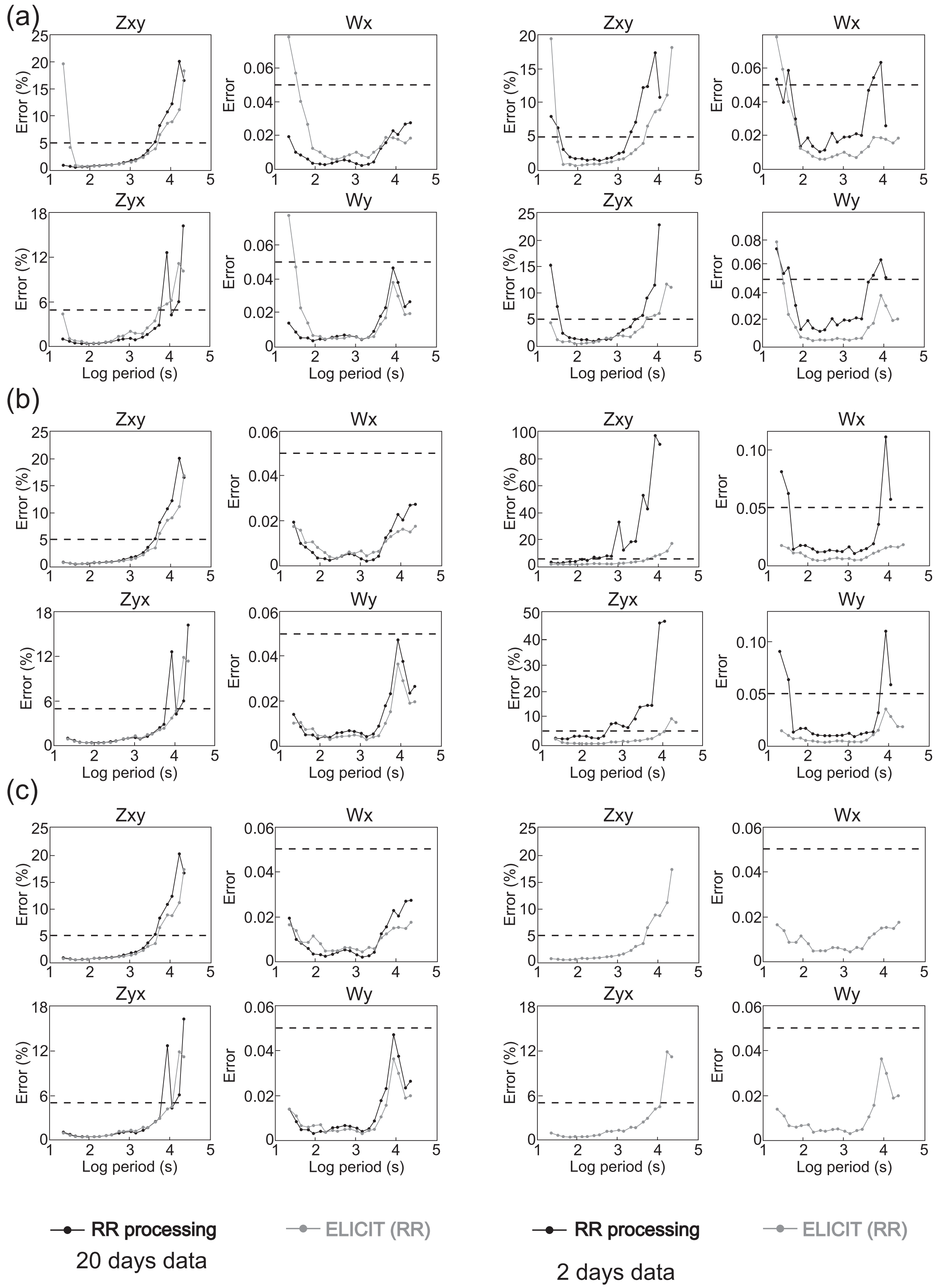

Figure 7. Comparison between errors obtained doing remote reference processing (black) and using the ELICIT method (grey). Black dashed line is the 5 per cent error for the MT impedance tensors and the 0.05 error for the geomagnetic transfer functions. (a) Errors from Fig. 6(b1). (b) Errors from Fig. 6(b2). (c) Errors from Fig. 6(b3).

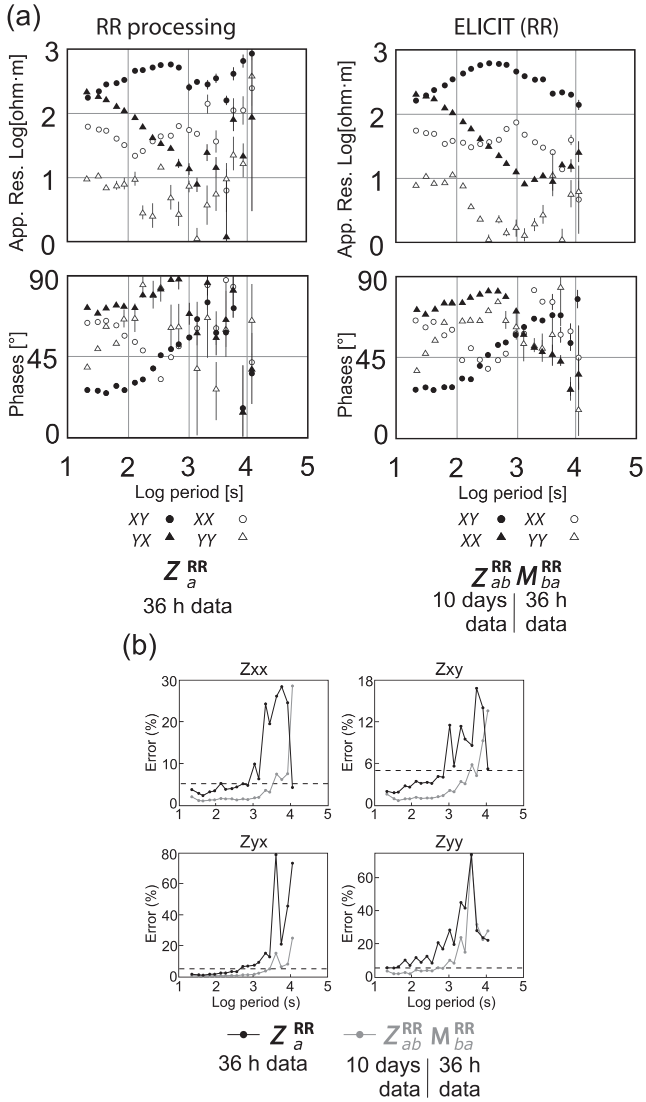

Figure 8. (a) Apparent resistivity and phase of site *a*. Left-hand side: doing remote reference processing with FUR. Right-hand side: using the ELICIT method: processing site *a* using the horizontal magnetic fields acquired on the site *b* and doing remote reference with *FUR*. (b) Comparison between errors obtained doing remote reference processing (black) and using the ELICIT method (grey). Black dashed line is the 5 per cent error for the MT impedance tensors.

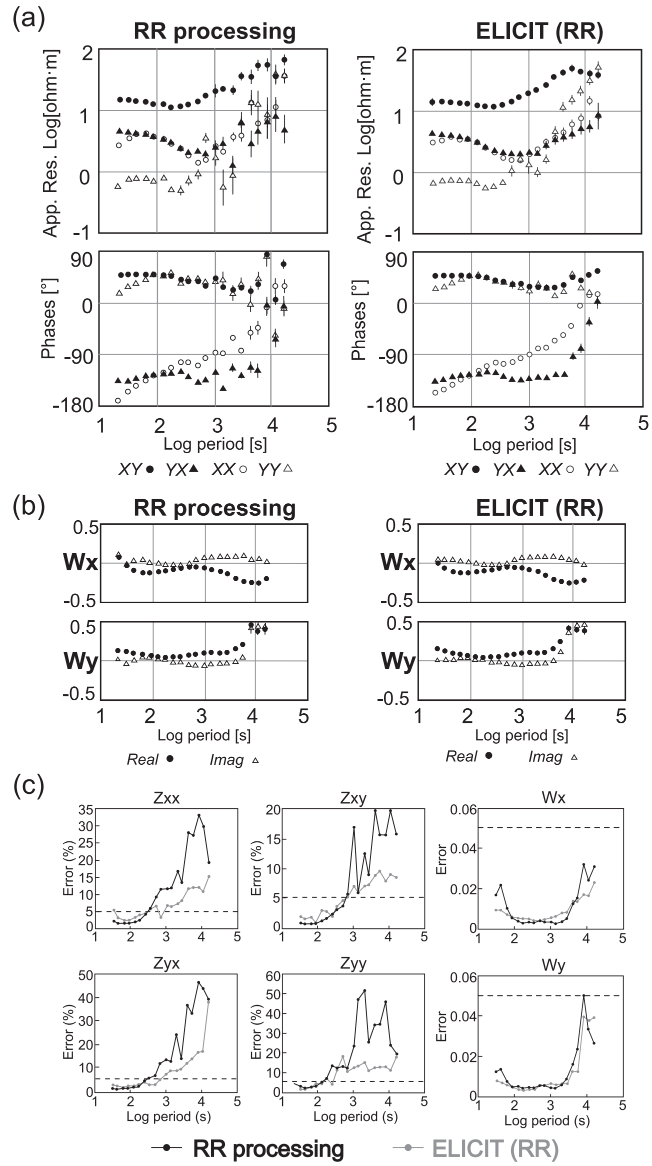

Figure 9. (a) Apparent resistivity and phase of site *j*. Left-hand side: doing remote reference processing with site *k*. Right-hand side: using the ELICIT method: processing site *j* using the horizontal magnetic fields acquired at sites *j*, *f*, *g*, *k*, *m* and doing remote reference with *k*. (b) Geomagnetic transfer function of site *j*. Left-hand side: doing remote reference processing with site *k*. Right-hand side: using the ELICIT method: processing site *j* using the horizontal magnetic fields acquired at sites *j*, *f*, *g*, *k*, *m* as a neighbouring sites and doing remote reference with *k*. (c) Comparison between errors obtained doing remote reference processing (black) and using the ELICIT method (grey). Black dashed line is the 5 per cent error for the MT impedance tensors and the 0.05 error for the geomagnetic transfer functions. All the time-series used in this figure have been acquired simultaneously.

et al. 2003a), increasing the statistics by the number of employed neighbouring sites for each used RR site. In the example shown in Fig. 9, for the result obtained processing site *j* performing RR processing, the statistics can be increased by five using the ELICIT method with the same RR site, by four doing multi-RR with sites *f*, *g*, *k*, *m* and by 20 (five neighbouring sites for each used remote site) using ELICIT method in combination with multi-RR processing.

4.3 Optimizing acquisition of MT data

The ELICIT method could be also used to modify MT surveying as the electric and magnetic fields of the local site do not need to be acquired simultaneously, offering new possibilities for the flexible acquisition of the MT data. Here we suggest an example for LMT data, based on better quality of magnetic time-series than telluric time-series (e.g. Jiang & Xu 2013) and supported by the results shown in Figs 6 and 7, where 3 d of the horizontal magnetic time-series is sufficient to constrain the HMT tensor. Note that the applicability of this example to other regions would be conditioned on the MT signals in the study area. Performing RR with an INTERMAGNET observatory, 12 LMT sites could be acquired using only three magnetic sensors and obtain equivalent MT impedance tensors as if 12 complete LMT sites were acquiring data simultaneously. Following the ELICIT method, we can install 12 LMT sites that would be acquiring electric fields simultaneously for 30 d. In two of them also magnetic sensors would be installed acquiring magnetic

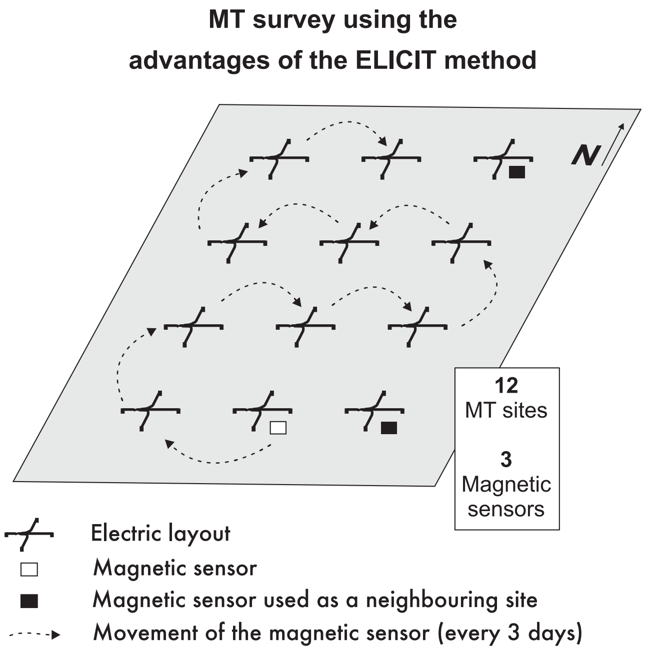

Figure 10. Configuration of a MT survey where thanks to the ELICIT method the number of needed magnetic sensors is reduced.

data for the 30 d; these two sites would be the neighbouring sites. Finally, one magnetic sensor would be moved every 3 d from site to site until the whole LMT array is covered (Fig. 10), reducing the number of required magnetic sensors from 12 to 3. (Note: this deployment scenario assumes that there are separate recorders for the electric and magnetic fields). Although only one neighbouring site is required to apply the ELICIT method, using two of them will ensure the applicability of the method if there are any problems with one of the neighbouring sites. Where there are no problems with the neighbouring sites, then as each site could be processed using both neighbouring sites, the statistics will be improved.

5 CONCLUSIONS

As demonstrated, the RR processing of site l using site r as a remote site $[\boldsymbol{Z}_l^{RR}(\boldsymbol{e}_l, \boldsymbol{h}_l, \boldsymbol{h}_r)$ and $\boldsymbol{W}_l^{RR}(\boldsymbol{h}_z^l, \boldsymbol{h}_l, \boldsymbol{h}_r)]$ can be recovered using interstation tensor relationships with a neighbouring site n $[\boldsymbol{Z}_{ln}^{RR}(\boldsymbol{e}_l, \boldsymbol{h}_n, \boldsymbol{h}_r)$, $\boldsymbol{S}_{ln}^{RR}(\boldsymbol{h}_z^l, \boldsymbol{h}_n, \boldsymbol{h}_r)$ and $\boldsymbol{M}_{nl}^{RR}(\boldsymbol{h}_n, \boldsymbol{h}_l, \boldsymbol{h}_r)]$ following the proposed ELICIT method $[\boldsymbol{Z}_l^{RR} = \boldsymbol{Z}_{ln}^{RR}\boldsymbol{M}_{nl}^{RR}$ and $\boldsymbol{W}_l^{RR} = \boldsymbol{S}_{ln}^{RR}\boldsymbol{M}_{nl}^{RR}]$. If local site is used as a RR site, $\boldsymbol{h}_r = \boldsymbol{h}_l$, results would be equivalent to single site processing. Two main advantages are associated with the ELICIT method. First, the electric and magnetic fields of the local site do not need to be acquired simultaneously. Second, different neighbouring sites can be used to process the MT data of the local site obtaining equivalent results to conventional RR processing. The first advantage introduce new possibilities for processing of MT time-series data, obtaining significant improvements when the magnetic time-series of the local site are affected by noise or truncated, and offers new ways of acquiring MT data getting more out of the measuring instruments. The second advantage facilitates improving the statistics when determining the MT tensor relationships if one or more neighbouring sites are acquiring data simultaneously with the analysed MT site. Equivalent steps to those shown in this manuscript could be done applying the ELICIT method using the horizontal electric fields, instead of the horizontal magnetic fields, acquired at a neighbouring site.

ACKNOWLEDGEMENTS

We sincerely thank the reviewers Dr Iv. Varentsov, Dr J.C. Larsen, the anonymous reviewer and the Editor Dr Gary Egbert for their useful comments on the previous versions of the manuscript. This research was funded by MAGBET (CGL2006-101660), PIERCO2 (CGL2009-07604), TopoMed (CGL2008-03474-E/BTE), projects, Grup de Recerca de Geodinàmica i Anàlisi de Conques (2009SRG1198) and the Departament d'Universitats, Investigació i Societat de la informació de la Generalitat de Catalunya. The results presented in this paper relied on the data collected at FUR magnetic observatory. We thank the Ludwig-Maximilians Universität München for supporting its operation and INTERMAGNET for promoting high standards of magnetic observatory practice (www.intermagnet.org). We are also grateful to the land owners and to l'Agence de l'Office National des Forêts (ONF), who allowed us to install the LMT sites in their fields. The Moroccan data were acquired as part of the MT component of the PICASSO and TopoMed projects, and funding to AGJ from Science Foundation Ireland for PICASSO (grant 06/RFP/GEO001) and the Irish Research Council for Science, Engineering and Technology (now the Irish Research Council) for Ireland's contribution to the EUROCORES project TOPO-EUROPE is gratefully acknowledged.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Figure S1. XX and YY components of the apparent resistivity and phase of the site *b* using site *c* as a neighbouring site and doing remote reference with FUR. (a) Using the horizontal magnetic fields of the site *c* instead of the magnetic fields of the site *a* (white spots and white triangles). (b) Following the ELICIT method (white spots and white triangles). Results are compared with remote reference processing with FUR (black spots and black triangles).

Figure S2. XX and YY components of the apparent resistivity and phase of the site *j* using site *k* as a neighbouring site and doing remote reference with *m*. (a) Using magnetic fields of the site *k* instead of the magnetic fields of the site *j* (white spots and white triangles). (b) Following the ELICIT method (white spots and white triangles). Results are compared with remote reference processing with site *m* (black spots and black triangles).

Figure S3. XX and YY components of the apparent resistivity and phase of the site *k* using site *m* as a neighbouring site and doing remote reference with *j*. (a) Using magnetic fields of the site *m* instead of the magnetic fields of the site *k* (white spots and white triangles). (b) Following the ELICIT method (white spots and white triangles). Results are compared with remote reference processing with site *j* (black spots and black triangles) (http://gji.oxfordjournals.org/lookup/suppl/doi:10.1093/gji/ggu147/-/DC1)

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