H047

On the Removal of MT Signals from SBL Data

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SUMMARY

When performing a seabed logging (SBL) survey during a period of high magnetotelluric (MT) activity, it is not uncommon for MT signals - due to their highly variable and nonstationary nature - to significantly reduce the quality of SBL data. In the most dramatic instances, this can create the need for retowing some SBL lines at a high additional cost. We propose and describe a simple method to partially remove MT signals that may be superimposed to SBL data acquired during periods of high MT activity, and subsequently illustrate the method's performance with a real data example.

Introduction

Seabed logging (SBL) is an application of controlled source electromagnetic (CSEM) sounding which was introduced in 2002 by Eidesmo et al. and Ellingsrud et al. The SBL technique, introduced as a tool for hydrocarbon exploration, is particularly sensitive to thin resistive layers buried within the subsurface, and can also be used in shallow waters (Johnstad et al., 2005). The main idea consists in towing a horizontal electric dipole (HED) over a line or grid of electromagnetic receivers lying on the seabed in order to probe the subsurface.

When performing an SBL survey, it may be helpful to additionally collect magnetotelluric (MT) data. Indeed, MT fields – while largely insensitive to thin resistive layers – can probe very deeply into the subsurface. MT and SBL data are thus highly complementary, and can e.g. be jointly used to perform 3D inversion (Mackie et al., 2007). Furthermore, the MT method can also help image complex structures such as salt bodies (Key, 2003).

However, when the actual towing of the HED is performed during a period of high MT activity, the situation where the received SBL and MT signals have comparable powers in the same frequency band is not uncommon, especially at large source-receiver offsets, where the received SBL signal is weak. In this case, the highly variable and nonstationary nature of MT signals can significantly reduce the quality of SBL data. In the most dramatic instances, SBL lines may have to be retowed during a period of lower MT activity in order to guarantee the acquisition of SBL data of sufficient quality. This will create, needless to say, high additional costs and may take a considerable amount of time. Now, for a medium with magnetic permeability μ and conductivity σ, the skin depth – which is the distance that an electromagnetic wave must travel in order to be attenuated by a factor $1/e$ – is given by $1/\sqrt{\pi f \mu \sigma}$ [m], where f is the frequency of the propagating electromagnetic wave. We therefore see that a situation in which SBL lines may have to be retowed due to high MT activity becomes more likely as the water depth decreases, and as the frequencies at which the SBL survey is conducted (typically above 0.1 Hz) decrease. Indeed, since MT waves propagate vertically from the sea surface to the seabed, their attenuation by the time they reach the seabed decreases as the frequency and the water depth decrease. (The skin depth of seawater – for which $\mu = \mu_0 = 4\pi \times 10^{-7}$ H/m and $\sigma = 3$ S/m can be considered to be representative values – is of approximately 919 m at $f = 0.1$ Hz.)

In the remainder of this document, a simple method to partially remove the MT signals that may be superimposed to SBL data acquired during periods of high MT activity is first proposed and described, and its performance subsequently illustrated with a real data example. Somewhat related ideas were also applied to the removal of MT noise from multi-transient electromagnetic data (Wright and Ziolkowski, 2007).

Methodology

Our methodology is based on two steps; a *training* step and a *cleaning* step. Both steps are performed in the frequency domain, once for each frequency f at which MT signals are to be removed from SBL data. (For example, if an SBL survey is conducted utilising a source signal consisting of a square wave with a basic frequency of 0.25 Hz., one may be interested in cleaning the SBL data at frequencies $f \in \{0.25\,\text{Hz}, 0.75\,\text{Hz}, 1.25\,\text{Hz}\}$, i.e. the fundamental, third, and fifth harmonics.)

In order to perform the training, a time period τ of sufficiently high magnetotelluric activity during which the SBL receivers lie on the sea bottom but no CSEM source is towed is required. Such a time period may or may not be available depending on the nature of the survey. Such a time period is always available when MT data is intentionally collected as explained in the introduction. Other situations where such a time period may be available include that where due to receiver deployment and towing logistics, a sufficiently long time elapses between receiver deployment and CSEM source towing, or between CSEM source towing and receiver collection. Yet another situation where such a time period may be available is that where due to unforeseen circumstances (e.g. poor weather) prolonged time periods without any CSEM source towing are present.

In the training step, complex Fourier coefficients at a frequency f of interest are extracted from the time series recorded by the receivers during the time period τ. This is done, following standard MT processing practice, utilising a time window of length of the order of a few times over the frequency of interest (Chave and Thomson, 2004). For each receiver channel (corresponding to the x, y, or z component of the electric or magnetic field in the receiver local coordinate system), a row vector consisting of these Fourier coefficients is then formed, and these vectors are subsequently stacked on top of each other to form a data matrix $\mathbf{X}$ of size $K \times N$. That is, $\mathbf{X}$ consists of K rows (corresponding to K receiver channels), each one of which contains N complex Fourier coefficients. Finally, the robust multiple-station MT data processing algorithm from Egbert (1997) is applied to obtain a decomposition

$$\mathbf{X} = \mathbf{W}\alpha + \epsilon, \tag{1}$$

where $\mathbf{W}$ is a matrix of size $K \times M$, α is a matrix of size $M \times N$, and ϵ is a matrix of size $K \times N$. Here, the M columns of $\mathbf{W}$ give, for each receiver, the field components associated with M independent, time-varying source polarisations given in α_i, the ith column of matrix α; and ϵ models incoherent additive noise. In the case of the MT plane-wave source field assumption (which is made throughout this paper), $M = 2$ (Egbert, 1997). When the elements of the noise matrix ϵ are independent, identically distributed with zero mean and unit variance, the columns of $\mathbf{W}$ simply are robust estimates for the eigenvectors corresponding to the $M = 2$ largest eigenvalues of the matrix $\frac{1}{N}\mathbf{X}\mathbf{X}^\dagger$ (the symbol † denotes conjugate transposition). Readers interested in further details on this step are referred to (Egbert, 1997).

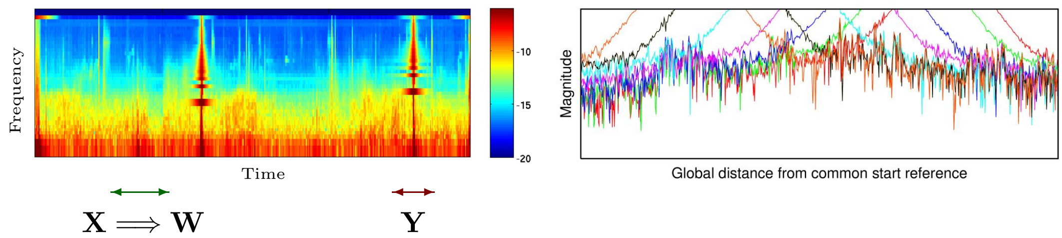
At this stage, it is important to observe that $\widehat{\mathbf{X}} \triangleq \mathbf{W}\alpha$ is an estimate for the field components in the rows of $\mathbf{X}$ that would have been recorded by the different receivers in the absence of incoherent noise. In particular, the robustness of the processing algorithm from Egbert (1997) will help remove unnatural – and unwanted – spikes from $\mathbf{X}$, which are often found not to be present in $\widehat{\mathbf{X}}$.

Another point that is worthy of attention is that the transfer tensor $\mathbf{t}$ between any two (since $M = 2$) reference rows i and j of $\mathbf{X}$ and any of its remaining rows k is simply given by

$$\mathbf{t} = \mathbf{w}_k \mathbf{W}_{\mathcal{I}}^{-1}, \tag{2}$$

where $\mathbf{w}_k$ is the kth row of $\mathbf{W}$, and $\mathbf{W}_{\mathcal{I}}$ (with $\mathcal{I} = \{i, j\}$) is a matrix consisting of rows i and j of $\mathbf{W}$. This transfer tensor only depends on the frequency f, the survey geometry, the subsurface conductivity structure, and other parameters such as the seawater conductivity; but is *independent* of the actual MT signals that are recorded at the different receivers. As long as the conductivity structure and receiver locations do not change (which is a reasonable assumption during the time span of an SBL survey), the matrix $\mathbf{W}$ and any transfer tensor $\mathbf{t}$ derived from it remain constant. This means that if the MT field components corresponding to any two rows of the data matrix $\mathbf{X}$ are known during a time period τ', estimates for the MT field components in any other row of $\mathbf{X}$ during this same time period can be simply obtained by multiplying those two rows on the left by an appropriate transfer tensor obtained as in (2).

The cleaning step is performed on the data collected by the SBL receivers during the towing of the CSEM source. In order to remove MT signals from a channel belonging to a receiver which is in range of the SBL source during a time period τ'', a pair of reference channels which are *not* in range of the SBL source during this same time period are needed. Whether or not it always is possible to find such a pair of reference



(a) (b)

Figure 1: (a) Spectrogram of the data in an electric channel from one of the SBL receivers deployed during the survey described in the text. The time periods selected for training and cleaning have respectively been marked by green and red arrows. (b) Cleaning period magnitude vs offset plots for an electric channel of seven of the SBL receivers deployed during the survey described in the text.

channels depends mostly on the survey geometry (in particular, the spacing between the receivers and the shape in which they are arranged). However, it is always possible to guarantee the availability of reference channels by deploying two or three additional receivers sufficiently far from the location where the SBL survey is conducted never to be in range of the CSEM source, but sufficiently close from this location for MT signals to remain highly correlated.

Let $\mathbf{Y}$ have the same row structure as $\mathbf{X}$ but contain the complex Fourier coefficients for frequency f (obtained exactly as outlined above for the training step) corresponding to the data acquired during time period τ''. Moreover, let $\mathbf{y}_k$ denote a row of $\mathbf{Y}$ from which MT signals are to be removed, and let $\mathbf{Y}_\mathcal{I}$ denote a matrix consisting of the two rows of $\mathbf{Y}$ which are to be used as a reference to remove MT signals from $\mathbf{y}_k$. The cleaning step then consists in computing

$$\mathbf{y}'_k = \mathbf{y}_k - \mathbf{w}_k \mathbf{W}_\mathcal{I}^{-1} \mathbf{Y}_\mathcal{I}, \tag{3}$$

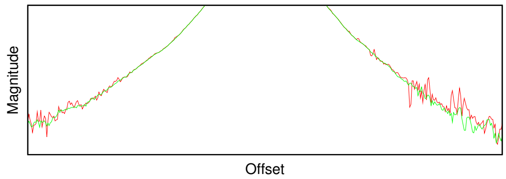
where $\mathbf{y}'_k$ is the cleaned version of $\mathbf{y}_k$, $\mathbf{w}_k$ and $\mathbf{W}_\mathcal{I}$ are obtained from the matrix $\mathbf{W}$ calculated during the training step, and the product $\mathbf{w}_k \mathbf{W}_\mathcal{I}^{-1} \mathbf{Y}_\mathcal{I}$ is an estimate for the MT signals in $\mathbf{y}_k$. This step should be repeated as many times as necessary for the entire survey to be cleaned (doing so in an automatic fashion poses no major difficulties).

One possible improvement, if sufficient data is available for this aim, is to use a subset $\mathcal{J} \supset \mathcal{I}$ of the rows of $\mathbf{Y}$, none of which are in range of the SBL source, to find an estimate $\widehat{\mathbf{Y}}_\mathcal{I}$ for the field components in the rows of $\mathbf{Y}_\mathcal{I}$ that would have been recorded in the absence of incoherent noise during time period τ'' (this is done in a manner akin to that described above for the training step). Eq. (3), with $\mathbf{Y}_\mathcal{I}$ replaced by $\widehat{\mathbf{Y}}_\mathcal{I}$, is then used to find $\mathbf{y}'_k$.

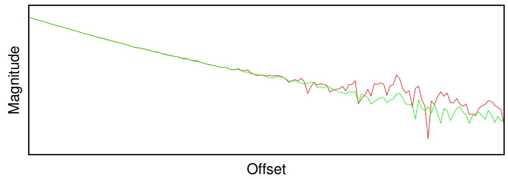
Real Data Example

The MT signal removal method described in the previous section was tested on an SBL survey. Fig. 1(a) shows the spectrogram of the data recorded in an electric channel of one of the SBL receivers deployed for this survey, from the instant when this receiver was released until the instant when it was recovered. The time periods selected for training and cleaning have respectively been marked by green and red arrows. Fig. 1(b) shows magnitude vs offset plots for an electric channel of seven of the SBL receivers deployed for this survey at a frequency f of interest. The magnitude vs offset plots were obtained utilising data acquired during the cleaning period. The presence of strong MT signals is clearly apparent both in Figs. 1(a) and 1(b). In particular, note the strong correlation between the MT signals on the different electric channels in Fig. 1(b).

Magnitude vs offset plots for an electric channel of two different SBL receivers deployed for this survey before and after MT signal removal are depicted in Fig. 2. Although there are obvious improvements in data quality, it also is apparent from the figure that



(a)



(b)

Figure 2: Magnitude vs offset plots for an electric channel of two different SBL receivers deployed during the survey described in the text before (red) and after (green) MT signal removal.

some reminiscent MT signals still are present in the cleaned data, and that retowing the appropriate SBL line would have produced data of even better quality.

Similar tests on different data sets tend to indicate that our method always succeeds in partially removing MT signals from SBL data, and that the amount of reminiscent MT signals varies from data set to data set.

Conclusion

A simple method to partially remove the MT signals that may be superimposed to SBL data acquired during periods of high MT activity was first proposed and described, and subsequently illustrated with a real data example. Tests of the method on different data sets tend to indicate that it always succeeds in partially removing MT signals from SBL data, with the amount of reminiscent MT signals varying from data set to data set. We believe that this can, at least in some cases, eliminate the need for retowing SBL lines acquired during periods of heavy MT activity.

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