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Robust and Fast Data-Driven MT processing

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SUMMARY

We present marine magnetotelluric (MT) results from data extracted from multiple controlled source electromagnetic (CSEM) surveys using a new multi-station processing code with a highly automated workflow. The quality of the MT response estimates processed with multi-station processing are dependent on the subset of receivers (i.e. stations) that is processed together, and the subset of available receiver-data recording time intervals selected for processing. Historically these steps have been manual and very time consuming. The MT workflow described in this paper replaces these manual steps with automated receiver grouping and data-driven algorithms for locating the expected best subset of time intervals for processing.

This code has produced high-quality MT data over a wide range of geological settings. Two case studies are cited, an example of MT processing results from Espirito Santo, a deep water basin offshore Brazil and 2D MT inversion of lines set together from multiple CSEM surveys, acquired over several years in the Hoop area in Barents Sea, Norway.

Introduction

Marine magnetotelluric (MT) data can be the primary focus of a marine EM survey, but often it can also be an additional signal acquired alongside controlled source electromagnetic (CSEM) data. This is because the CSEM source is inactive during receiver deployment, retrieval and while the source makes turns between towlines. During this source inactivity, the receivers are unaffected by CSEM signal and record only the MT signal. If CSEM towing starts immediately after all receivers have been deployed and receiver recovery begins as soon as source towing is finished, each receiver will typically record two to three days of MT signal depending on water depth.

MT may add complementary and valuable geological information when used in combination with CSEM data, for example information on deep basement boundaries and large resistive structures (Constable, 2009). By using MT alone or in simultaneous joint inversion with CSEM data, we can improve seismic imaging of the subsurface (Panzner, 2014). Although MT may potentially add geological value to a CSEM survey, the available MT recordings have seldom been processed, mainly because of the amount of manual work required to extract good estimates of MT responses. Typically, an experienced geophysicist would spend several weeks in full-time work processing MT responses from a typical 3D EM survey with 100–150 receivers.

We have developed an almost fully-automated MT processing code, which enables a geophysical operator to extract reliable MT impedances for all receivers in a 3D CSEM survey within a few days' work. The main MT estimation algorithm is based on the robust multivariate errors in variables (RMEV) algorithm (Egbert, 1997), where MT data is processed in a group of simultaneous recordings from several receivers. The RMEV algorithm is considered a very reliable MT processing technique, as it removes non-planar wave effects and allows for noise on all electric and magnetic channels on all receivers. It also provides an assessment of the coherent dimension of the data.

Historically there are two manual and time-consuming steps needed to extract good MT responses during RMEV processing. The first step is to choose which receivers are to be processed together in each group. The second step is to choose sections of the time domain data with (assumed) clean and strong MT signal from all available simultaneous recordings in each receiver group. Both of these choices can greatly influence the quality of the estimated MT response. Data from a receiver can produce a better MT response estimate simply by being processed together with data from an altered set of receivers. Similarly, data from a group of receivers can give a better estimate merely by choosing different time recording intervals for the RMEV processing. Previously, the operator needed to run these steps multiple times for each receiver to achieve satisfactory results. In the next section we will explain how these steps have been automated. We will then show results from a fully automated MT processing of a deep water multi-client survey offshore Brazil. Finally, we will show multiple 2D MT inversion results from several multi-client surveys in the Hoop area, Barents Sea, Norway.

Automated MT processing workflow

An overview of the different processing stages, from raw time domain recorded data to MT impedances, is shown in Figure 1. Preparatory work of the workflow is described in Markhus (2013). Initially, data from all receivers is run through a fully automatic processing flow (marked with red arrows), from calibration, demodulation (transformation from time to frequency domain), auto grouping, pre-screening; to multi-station processing. The operator will then make a quality assessment (QA) of the responses and mark receivers that have a poorer response quality than what is the average. Each of these will be regrouped together with receivers with good MT responses in a second multi-station processing run. Usually most of the receivers will get good responses within only a few processing runs. There may be receivers that have a worse MT response estimate than others, and the operator may need to look more closely at these receivers and take steps to manually improve the results by for example masking out noisy time intervals. Once the operator is satisfied with the MT response estimates, this data can be used further in inversion and interpretation. We will now explain the three processing steps (marked with light green in Figure 1) demodulation, auto grouping and pre-screening, in more detail.

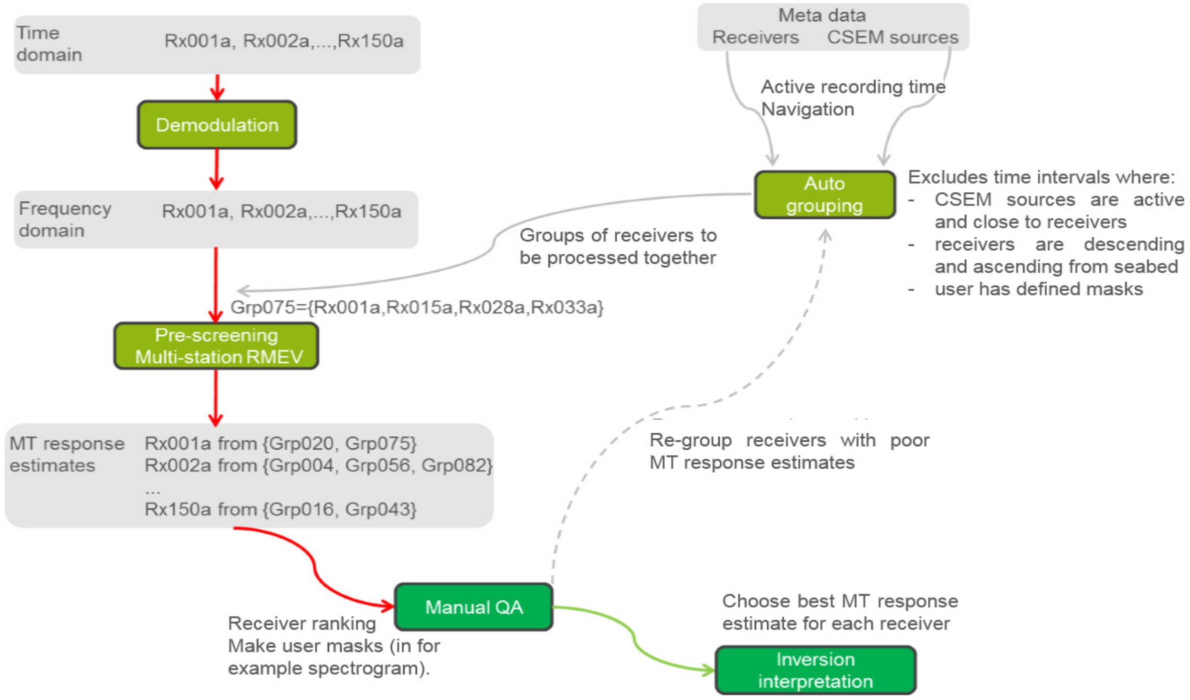

Figure 1: *Sketch of the automated MT processing workflow.150 receivers (Rx) are processed simultaneously in this example. Three receivers, numbered 001, 002 and 150, are indicated to have been processed in two or three different groups (Grp).*

All electric (E) and magnetic (H) channels are demodulated, one frequency at a time, from the start to the end of each receiver recording. Prior to demodulation of each desired MT period (=1/frequency) the time series is cascade-decimated and run through a very narrow band filter in time domain [Cave 2004]. The taper window selection of each segment is chosen such that the corresponding frequency observation (one per taper window) for different receivers is aligned in time, making it possible to select data segments later or multi-station process directly in the frequency domain (FD). Each MT period is demodulated using a window length which is three times the length of the MT period itself, resulting in different numbers of segments for each MT period.

The following algorithm is applied to find a suitable group of receivers. Let $\theta(i,j)$ be the total "score" for grouping receiver i with receiver j, defined by the formula

$$\theta(i,j) = a_1\theta_T(i,j)^{b_1} + a_2\theta_W(i,j)^{b_2} + a_3\theta_D(i,j)^{b_3}$$

Where $\theta_T(i,j)$ represents the relative time overlap, $\theta_W(i,j)$ represents the relative water depth, and $\theta_D(i,j)$ represents the relative distance, all with a value range between 0 and 1 from lowest to best score, respectively. Examples of usage: If receivers i and j have 80% common time recordings with no active CSEM sources $\theta_T(i,j) = 0.8$ and if they are at the same water depth $\theta_W(i,j) = 1$. $\theta_D(i,j)$ may be set as the relative distance between the receivers normalized against the relative distance for those two receivers which are farthest from each other in the survey area. a_i and b_i are freely chosen parameters used to tune the contribution of the different weights. Note that by choosing b_3 to be negative we can put more weight on receivers that are closer to each other.

A receiver group is expanded by first calculating $\theta(i,j)$ from all receivers already in the group towards the pool of receivers available for grouping. The receiver j with the highest score will be the best candidate for grouping. A good strategy is not to always pick the best score, but instead to randomly pick receivers from the best 20% scores. This approach guarantees random, but nonetheless good grouping, each time the MT processing is run.

We will now explain the new pre-screening approach for automatic data selection for the RMEV algorithm. It exploits the fact that it is usually easy to produce good MT response estimates for longer MT periods (especially around 100 seconds), while the quality of the estimate for shorter MT periods (especially around 1-20 seconds depending on water depth) is highly dependent on the time sections used for RMEV processing. Natural MT activity varies strongly with time. When MT activity is high, it is usually stronger on all frequencies. The RMEV algorithm processes MT periods independently (Egbert, 1997). Therefore, by first processing the longer MT periods using RMEV, we get a good estimate of the planar wave MT field at each FD segment. Since each FD segment corresponds to a time interval, FD segments with the highest estimated MT energy are used to select a subset of FD segments for shorter MT periods. The RMEV algorithm also detects FD segments that have large outliers (spikes), hence we omit FD segments from corresponding time intervals for shorter MT periods.

Example from deep water - Espirito Santo region outside Brazil

Figure 2 shows an encircled receiver line with 55 receivers in the Espirito Santo region outside Brazil, together with MT pseudo sections where Ex is rotated along the line towards south-east. MT mode Ex/Hy and Ey/Hx are defined as inline electric (ILE) and crossline electric (CLE), respectively. We obtained good MT responses, from between 8 to 2000 seconds, on 53 receivers by only using the data-driven MT processing approach (i.e. the red arrows in Figure 1). The water depth along the line varied from 2000 to 2290 m. The receivers had a planned MT only listening time of approximately two weeks. Regions “A” and “B” in the pseudo-section plots are indications of salt, with increased apparent resistivity and a smaller impedance phase relative to the rest of the line. Placements of these regions agree with the position of salt bodies previously analyzed in a broadband CSEM inversion study by Zerilli et al. (2014).

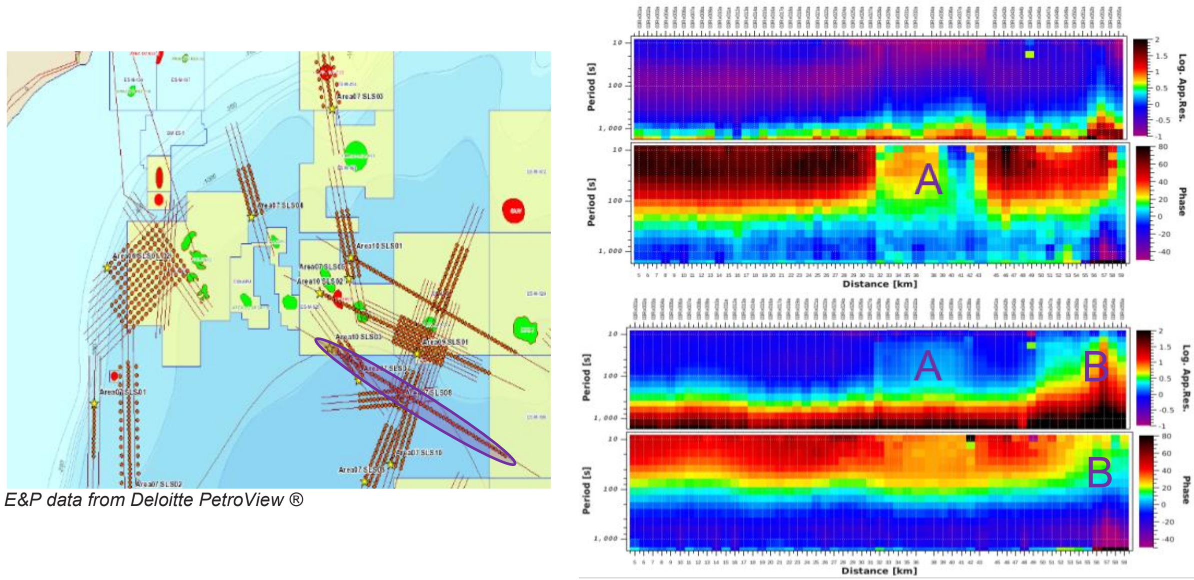

Figure 2. *Left: EMGS multi-client data in the Espirito Santo region. Right: Pseudo-sections of apparent resistivity and impedance phase for ILE (top) and CLE mode (bottom) from the encircled receiver line. Log10 apparent resistivity cuts below 0.1 and over 100 [ohm*m].*

Example from multiple surveys - Hoop area in the Barents Sea.

Figure 3 shows EMGS data coverage of the Hoop area in the Barents Sea that originally were planned for only CSEM data acquisition. We tested our new MT code in order to process MT data for most of the blocks in this area (about 10, 000 km^2 with about 1700 receivers). This process was achieved within just one month’s time. Figure 3 also shows 2D inversion results from receiver lines that pass through several blocks. Consistent regional structures, deep and shallow, can be seen between and along receiver lines from surveys acquired in different years. Resistivity contrasts can be observed when crossing the main structures in the Barents Sea, e.g. the Loppa High and Hoop Main fault. The inversions were carried out using MARE2DEM (deGroot-Hedlin and Constable, 1990) and a half-space start model.

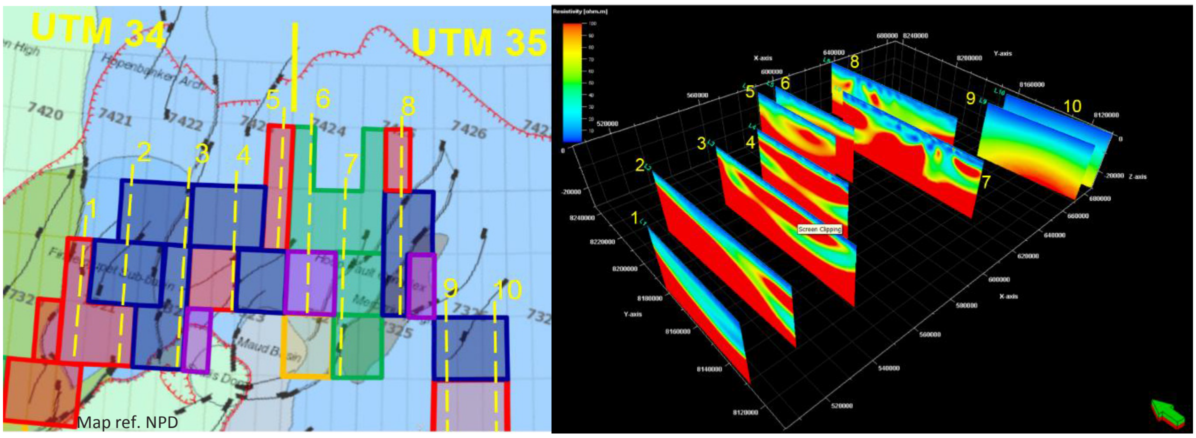

Figure 3. *Left: EMGS EM multi-client data in the Hoop area in the Barents Sea, Norway. Different colors on the blocks represent different year of acquisition. Right: Petrel visualization of 2D MT inversion results along the yellow dotted lines of the left figure*.

Conclusions

Extracting MT response estimates has been a manual, time-consuming process. By automating previously manual steps in MT processing, we have been able to extract high-quality MT responses from several CSEM surveys where MT processing previously had not been carried out. The results are very consistent, and we conclude that the new automated MT processing is robust enough to extract MT responses from most CSEM surveys.

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