

ANALYSIS OF TIME DOMAIN MCSEM DATA IN THE PRESENCE OF RESISTIVE LAYERS

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ABSTRACT. Modeling of mCSEM data is usually done in the frequency domain, from its theoretical formulation to the analysis of the results. However, the time domain approach is, in principle, capable of providing equivalent information about the geo-electric structure of the subsurface and has the advantage of recording only the secondary fields, so the signal is not dominated by the primary field. In this work, we model frequency domain mCSEM data in 1-D environments, then we perform the discrete Fourier transform to obtain time domain results. We simulated marine geological environments with and without the resistive layer that represents the hydrocarbon reservoir. We verified that, in almost all model configurations, the time domain data are significantly different when calculated for models with and without hydrocarbons. We calculated the results considering variations in the position of the receivers and in the sea depth. We observed the influence of the airwave, even at large sea depths, and although a simple separation of this influence on data is not possible, the time domain results allowed us to do a qualitative analysis of its effects on the survey.

Keywords: time domain, mCSEM, Sea Bed Logging, discrete Fourier transform.

RESUMO. A modelagem do mCSEM é feita normalmente no domínio da frequência, desde sua formulação teórica até a análise dos resultados. No entanto, a abordagem através do domínio do tempo pode, em princípio, fornecer informação equivalente sobre a geofísica da subsuperfície aos dados no domínio da frequência, além de possuir a vantagem de registrar apenas o campo secundário, assim o sinal não é dominado pelo campo primário. Neste trabalho, modelamos o mCSEM no domínio da frequência em modelos unidimensionais, e usamos a transformada discreta de Fourier para obter os dados no domínio do tempo. Simulamos ambientes geológicos marinhos com e sem uma camada resistiva, que representa um reservatório de hidrocarbonetos. Verificamos que os dados no domínio do tempo apresentam diferenças quando calculados para os modelos com e sem hidrocarbonetos em praticamente todas as configurações de modelo. Calculamos os resultados considerando variações na posição dos receptores e na profundidade do mar. Observamos a influência da *airwave*, presente mesmo em modelos com grandes profundidades oceânicas, e apesar de não ser possível uma simples separação dessa influência nos dados, o domínio do tempo nos permitiu fazer uma análise mais qualitativa de seus efeitos sobre o levantamento.

Palavras-chave: domínio do tempo, mCSEM, *Sea Bed Logging*, transformada discreta de Fourier.

INTRODUCTION

The marine controlled-source electromagnetic (mCSEM, also known as Sea Bed Logging – SBL), has recently become a tool for exploration and mapping offshore hydrocarbon reservoirs, due to the need for risk reduction in exploration that led the oil industry to find news alternatives of prospecting. This has been made possible because of the improvement in the equipment and electronics during the almost three decades in which the marine EM methods have been developed (Christensen & Dodds, 2007).

The mCSEM is a method for detection and characterization of thin resistive structures, like hydrocarbon reservoirs, usually located in regions of deep water (Eidesmo et al., 2002). It consists of a mobile horizontal electric dipole as a source, carried close to the seafloor where an array of electromagnetic receivers are deployed. The dipole transmitter emits a low frequency signal, that spreads both in the water and in the sediments beneath it and is captured by the receivers, as shown in Figure 1. Amplitude and phase of this signal depend on the electrical resistivity of the seafloor and seawater parameters. A recent overview of the method is provided, for example, by Frenkel & Davydycheva (2012).

The mCSEM modelling consists in the computational simulation of the geological environments of which we want information. It is an important task, because it allows an a priori study, indicating the best conditions for the surveys.

Modelling of mCSEM is usually done in the frequency domain, due to simplifications that are possible when we work with low frequencies. One of them is the fact that Maxwell's equations become easier to be solved, since we do not deal with the time derivatives. However, time domain data may provide information on the geophysical characteristics of the subsurface that is equivalent to frequency domain data (Constable & Srnka, 2007).

EM time domain approaches show up very well adapted in land surveys, where the geological formations are on the conductive side of the air/earth system. In marine environments, the system is inversed, and the region of interest becomes the most resistive, i.e., the ocean subsoil, which is more resistive than the seawater. So, the information about the seafloor occurs in the early time response while the seawater response dominates later time. This separation of the responses is an appreciable feature of the time domain method and cannot be easily observed in the frequency domain. A comparative study of the two approaches is provided by Avdeeva et al. (2007). In addition, efficient applications of time domain methods can be found for example in Oldenburg et al. (2007), Börner et al. (2008) and Afanasjew et al. (2008).

Because the time domain method is only measuring the secondary field, it offers a solution to the shallow water limitations, where the frequency-targeted techniques have great difficulty to operate due to the strong downward field that is generated at the air/sea interface (Strack et al., 2008).

In this paper, we calculate the time domain mCSEM data from 1-D frequency domain modelling using the discrete Fourier transform, with models that contain or not the resistive layer which represents the hydrocarbon reservoir.

Our research supports that the time domain mCSEM approach is feasible, although we use simplified geological models which do not correspond to all the features of real environments. The 1-D electromagnetic modelling, however, is essential to obtain initial information, like the primary EM field in a stratified medium, that can help us with more complex problems, such as those involving 2-D and 3-D modelling.

METHODOLOGY

Theoretical revision

The decay in the amplitude and the phase shift of the signal are both controlled by the geometric effect and the skindepth (Um & Alumbaugh, 2007). The geometric effect yields a field decay that is related to the kind of source that generates the signal. The skindepth is a measure of the field decay related to the signal frequency and the electrical properties of the medium. The skindepth is generally described as:

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$$

where ω is the angular frequency and μ is the magnetic permeability.

So, a distance of several skindepths between source and receiver may cause the captured signal to be dominated by the sediments response, since in the seawater the skindepth is usually smaller than in the sediments.

The mCSEM is based on the contrast of resistivity between the marine geological environments and the saturated hydrocarbon reservoirs possibly present in these locations. A reservoir filled with oil for instance, can have a resistivity up to 100 times higher than the area around it, usually dominated by shale and saline fluids. Thus, a survey using various transmitters and various receiver positions can determine a multidimensional resistive model of the ocean subsurface (Eidesmo et al., 2002).

In time domain mCSEM, we use a time variant electromagnetic field as source that induces eddy currents within the sediment layers. These eddy currents are also time variant and they

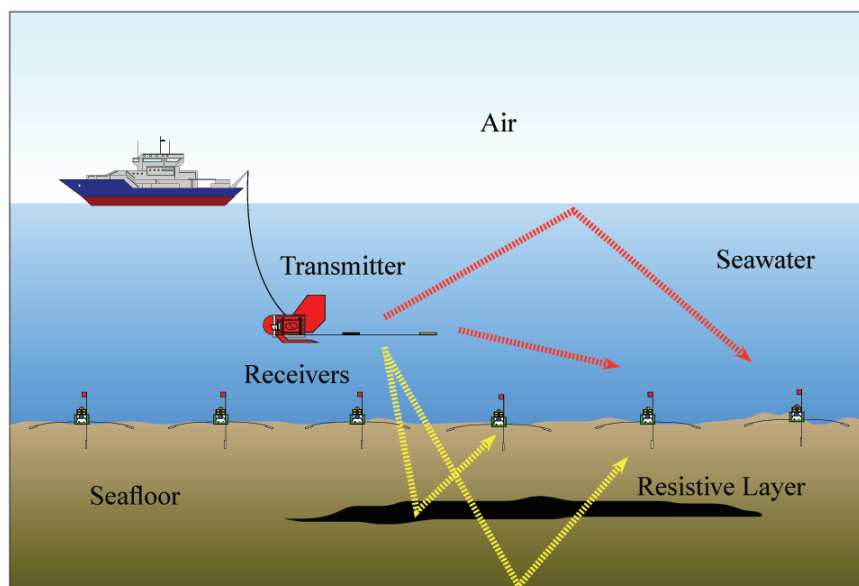


Figure 1 – Scheme of a geophysics survey using mCSEM.

produce a secondary field that can be sensed by the electromagnetic receivers. Depending on the subsurface geological structures, these fields can be more or less disturbed. In general, structures with greater resistivity are responsible for the greater disturbances and the signal transmitted by the source travels faster in them (Constable & Srnka, 2007).

But, the received signal is also composed by fields that propagated directly through the seawater and by fields that have interacted with the atmosphere (which are commonly known as airwave). Because the electrical conductivity of the seawater is usually greater than the seafloor, the response of the seawater comes later than the seafloor, and the arrival time and amplitude of the airwave will depend primarily on the seadepth (Constable & Srnka, 2007).

So, by the analysis of the time-dependent curve, we can distinctly observe the seawater and the seafloor responses. Although the same procedure cannot be done with the airwave response, in some cases, we can at least find the location in time where this influence is higher. Such a diagnostic is not easy to do in the frequency-domain although it contains the same information as the time domain data.

1-D modelling

For the 1-D problem, we use the formulation based on the decomposition of the primary signal in flat waves and the Schelkunof Potentials to obtain the electric field in the receivers (Ward & Hohmann, 1988). We start from Maxwell's Equations in the

frequency domain, obtaining values that represent the radial electric field. To calibrate our program, we approximated the mCSEM geoelectrical model for a homogeneous formation and compared the results with the exact solution of this problem, which can be found in, for instance, Ward & Hohmann (1988). Figure 2 shows the exact and numerical frequency domain solutions for the E_x normalized by the dipole moment of the source, measured by a single receiver in a homogeneous formation with resistivity of $\rho = 1\Omega\text{m}$ and distance of 900 m from the transmitter.

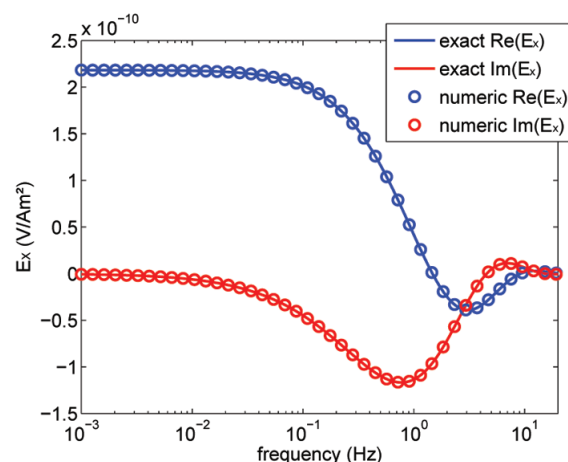


Figure 2 – Real (blue) and imaginary (red) part of E_x for various frequencies in a homogeneous medium.

To obtain the time domain solution, we need to perform the discrete Fourier transform and this implies in calculating the responses for a large number of frequencies. The details of the

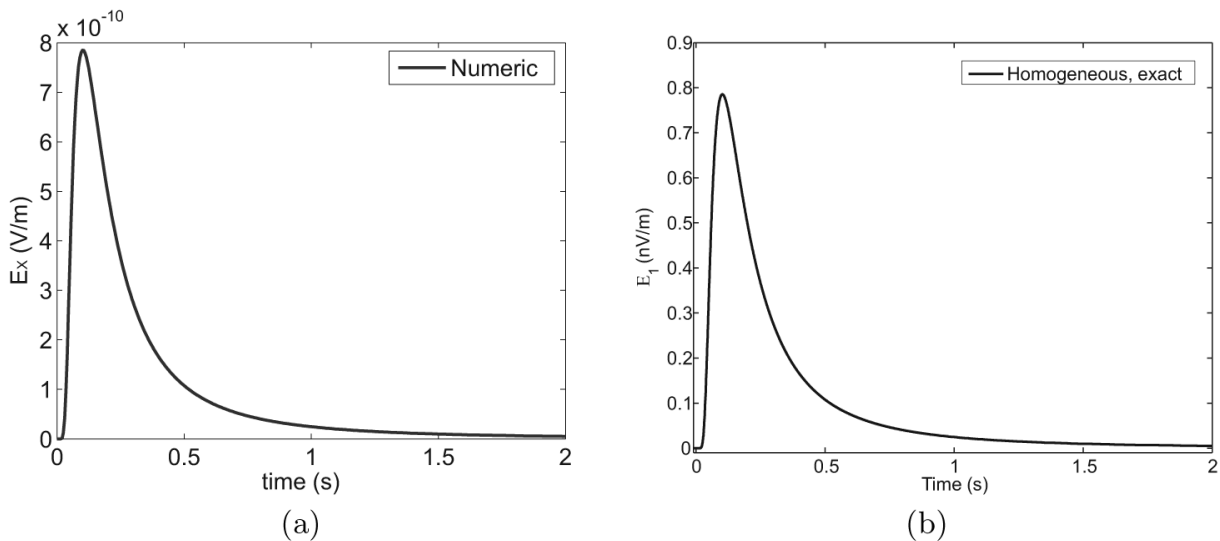


Figure 3 – Program validation. Comparison of our result (a) with the result presented by Mulder et al. (2008) (b) both using a homogeneous medium.

discrete Fourier transform applied in our frequency data can be found in Miranda (2007). Naturally, the use of such a number of frequencies increases the computational time of the task. For a 1-D model this is not necessarily an issue, but for 2-D and 3-D models, it can be a very demanding problem. To address this problem, we also adapted our code to run in parallel machines. We have used the parallel environment provided by the Netuno cluster, located at the Universidade Federal do Rio de Janeiro (UFRJ). Thus, the task could be divided (we distributed the calculations for various frequencies among the Netuno's execution nodes), decreasing the total execution time. Working with parallel computing will be our best choice when we apply our code to 2-D models in our next research phase.

We study two different functions representing the current in the source: an impulse function, representing a sudden increase and decrease in the current in a very short time and a step function, representing a current that is turned suddenly on and remains steady for a long time. The second one, where the input function of the source is a Heaviside function, provides information about the time evolution of the system in such a way that allows us to make a normalization of the responses, by dividing the result of a particular model by another, so we can get a curve of the anomaly due to the differences between the geologic models.

To check our time domain result, we compared the impulse response of the horizontal electric dipole in a homogeneous formation obtained by numerical modelling with the exact time solution of this problem presented by Mulder et al. (2008), at a distance of 900 m from the transmitter, as shown in Figure 3.

RESULTS

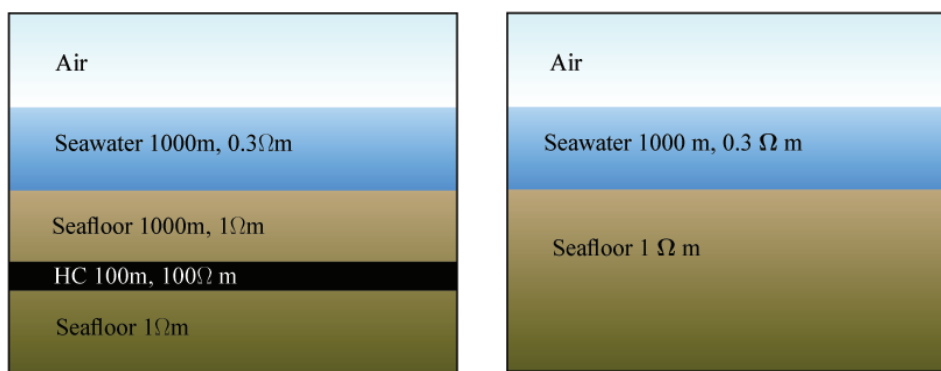
We use the models presented by Constable & Weiss (2006) showed in Figure 4. The model called HC has a hydrocarbon reservoir with a resistivity of $100\Omega\text{m}$ and thickness of 100 m, buried at a depth of 1000 m between sediments of resistivity of $1\Omega\text{m}$. The sea has resistivity of $0.3\Omega\text{m}$ and depth of 1000 m. The model called noHC is similar to the previous, but it has no resistive layer.

The results below are the time domain solution obtained by discrete Fourier transform of the frequency domain data.

Figures 5, 6 and 7 show the time domain amplitudes of E_x viewed as colormaps relating time \times offset for seadepths of 500 m, 1000 m and infinite, considering an impulse function as source waveform.

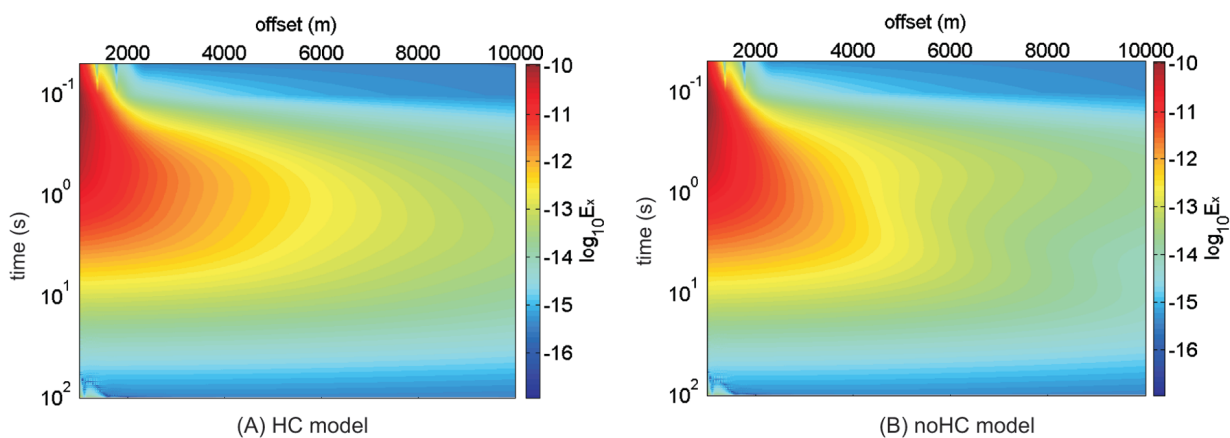
Figure 8 shows the relative difference (rd) ($rd = 100 \times |1 - HC/noHC|$) between HC and noHC curves for seadepths of 500 m and 1000 m respectively.

We can observe that, for distances closer to the transmitter, the signal looks similar in all sections. This is because, for a very short offset the response from sediments arrives before the direct response (signal that travels through the water) gets decayed. As we consider larger offsets, like 4 km or more, we noticed greater differences between the HC and noHC results. Distances, like 10 km, presents very weak signals, whose amplitudes are in the range of the geological noise. So, we can assume that a distance of 5 km is well suited for the time domain measurements for this model and it was the offset used in the next results.



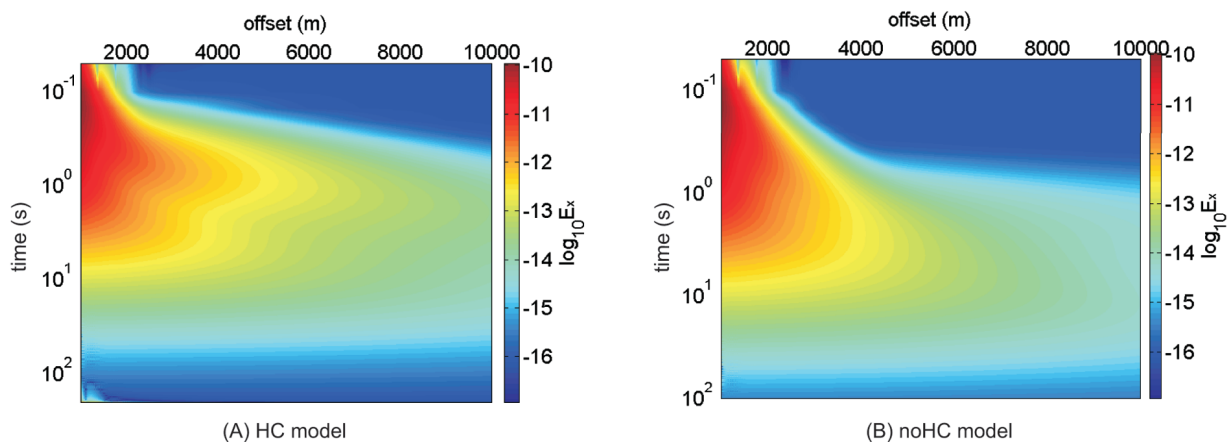
(a)HC (b)noHC

Figure 4 – 1-D geolectrical models.



seadepth = 500m

Figure 5 – E_x amplitude relating time \times offset for 500 m of seadepth.



seadepth = 1000m

Figure 6 – E_x amplitude relating time \times offset for 1000 m of seadepth.

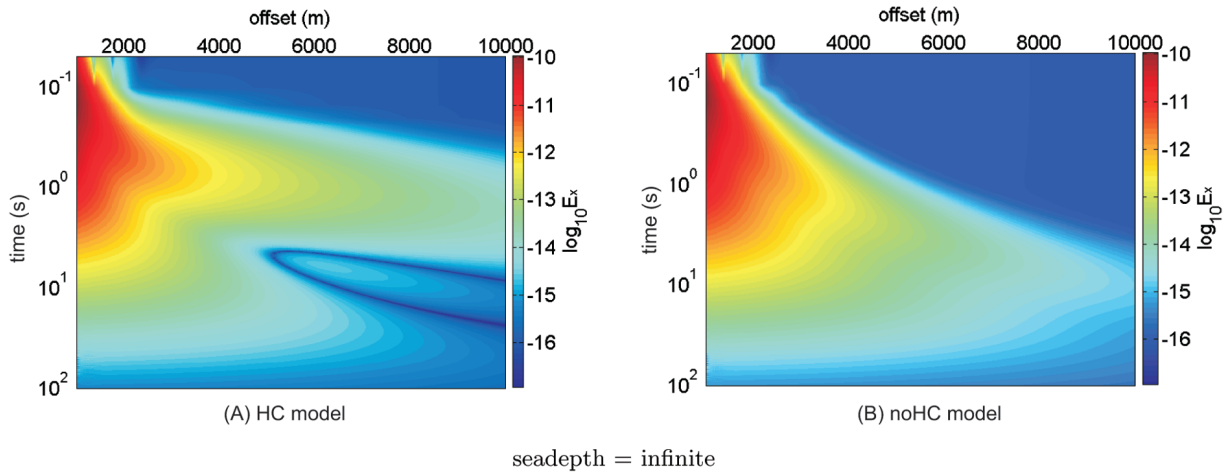


Figure 7 – E_x amplitude relating time \times offset for an infinite seadepth.

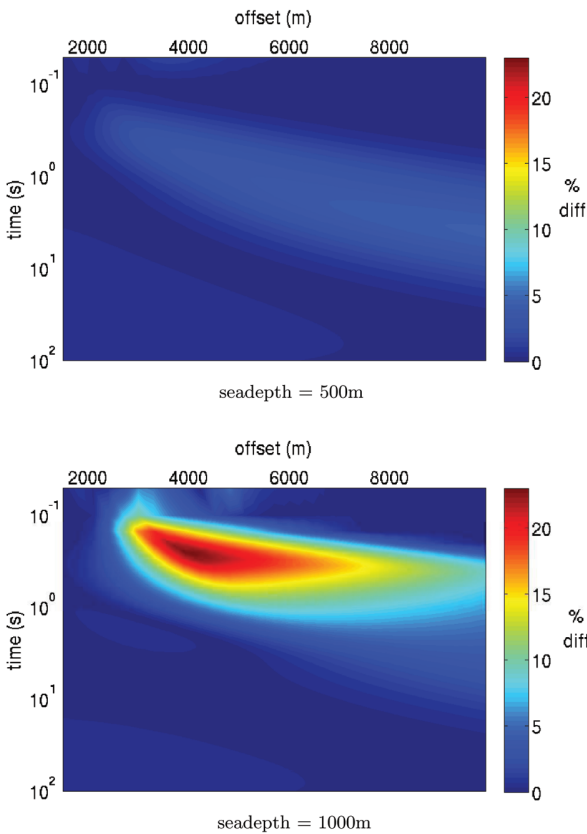


Figure 8 – Relative difference between HC and noHC curves for seadepths of 500 m and 1000 m.

Figure 9 shows the amplitude of the E_x component for seadepths of 100 m, 250 m, 500 m, 1000 m, 2000 m and an infinite seadepth, at an offset of 5 km using the same source as the previous example, where we can observe the effects due to the changes of seadepth. The seadepth controls the rate of in-

fluence of the fields that interacted with the atmosphere in the results. The shallower the sea, the smaller the attenuation of these fields, also called airwave.

Although it is not possible a simple separation of the airwave in the results, the curves showed in Figure 9 provide information about its interaction with the geological environments. Figure 9(a) shows the electrical response of the sediments without any airwave influence, since we have an infinite seadepth which completely attenuates this response. In the HC curve of the same Figure, we can see two peaks, the first with amplitude of $2,5 \times 10^{-13}$ V/m² and the second with amplitude of $0,125 \times 10^{-13}$ V/m² approximately. Since the signal going through the sediments have been spread in a more resistive medium than the seawater, its arrives first, making us conclude that the peak of greater amplitude is the sediments response. So, the lower peak would be the seawater response, that is, the signal that propagates only through the seawater.

Looking at Figure 9(b), with the results for the model with 2000 m of seadepth, we noticed a slight increase in amplitude for both HC and noHC results, around the time of 5 seconds, indicating the region of influence of the airwave.

Figure 9(c) shows the result for 1000 m of seadepth and we can observe striking changes not only in the shapes of the curves but also in their amplitudes when compared with the previous examples. For this model, the airwave effect occurs earlier than in the model with greater seadepths, coinciding with the time response of the sediment without the resistive layer.

A similar analysis can be done in Figure 9(d) corresponding to the model with 500 m of seadepth. In this example we observed a strong influence of the airwave. Comparing the red

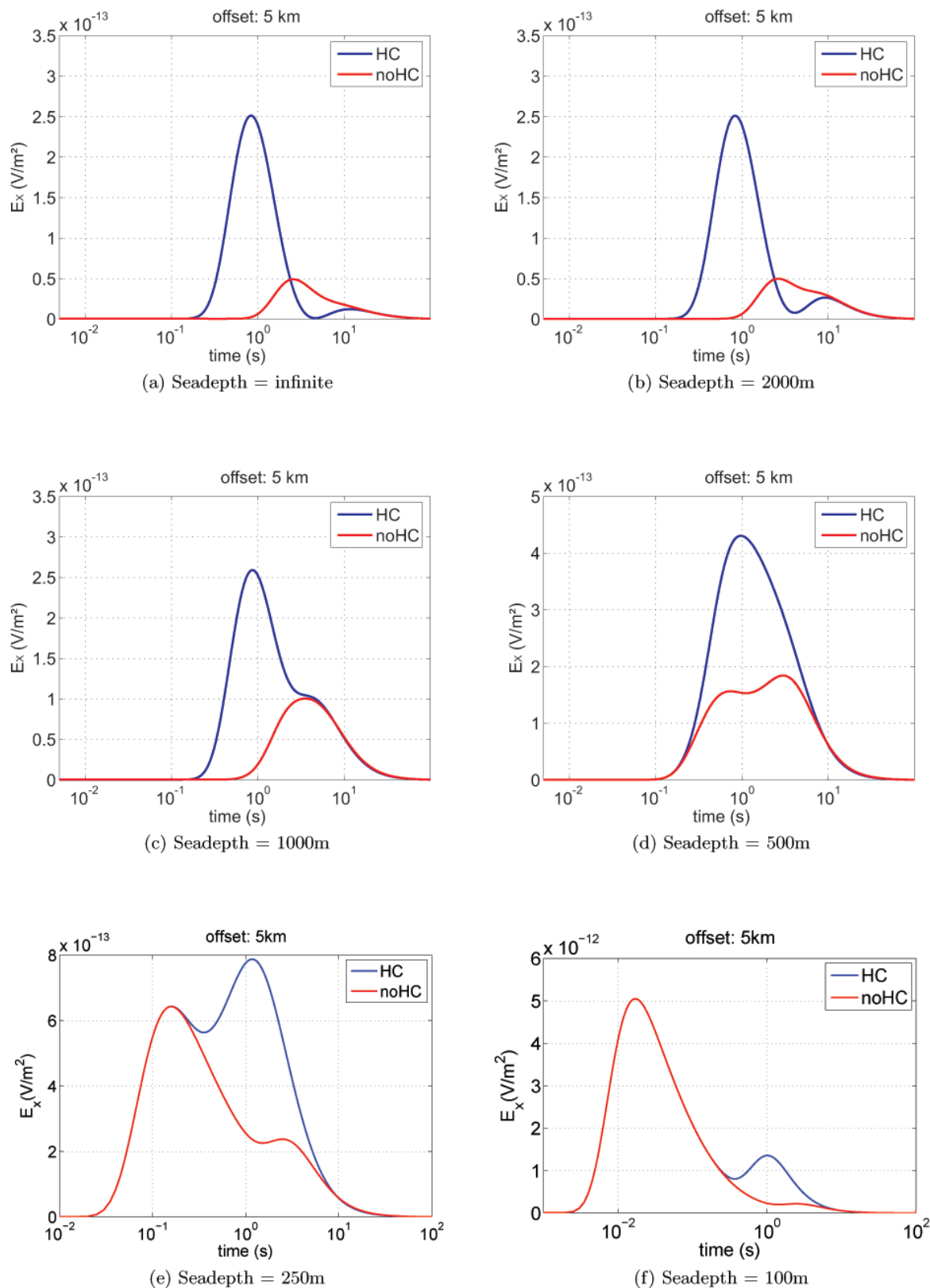


Figure 9 – Time domain amplitude of E_x for various seadepths: (a) infinite, (b) 2000 m, (c) 1000 m, (d) 500 m, (e) 250 m and (f) 100 m.

curve of this graph, related to the noHC model, with the noHC curves of the other models, we can infer that the first of the two peaks in Figure 9(d) is due to the direct response of the airwave, and the second peak is due to the seafloor response, which is also affected by the airwave. This is because the time response of the sediment without the resistive layer is almost the same in all graphs. In the blue curve of Figure 9(d), it is not possible to distinguish these peaks, because there is an overlap between the responses of the airwave and the sediments.

Figures 9(e) and 9(f) show the results for the models with 250 m and 100 m of seadepth respectively, which correspond to what is usually called shallow water (seadepths less than 500 m) by the geophysicists. In these Figures, we can notice a stronger influence of the airwave than in the previous examples, characterized by the large amplitude of the earlier peaks that appears in each of the curves of both Figures. Because these peaks occur in a quite different time than that of the sediment response, the signatures of resistive structures are not masked, indicating that the method can be used even in shallow water environments.

Figures 10 and 12 display the step response for receivers located at 2000 m and 5000 m from the source, respectively, considering seadepths of 500 m, 1000 m and 2000 m. Figures 11 and 13 display the same HC data normalized by the corresponding noHC response.

In the normalized curves we have a measure of the relative influence of the resistive layer on the data. The lower peak in the 2 km offset shows a strong influence of the field directly from the source, which is greater than the influence of the resistive layer as well as of the air-water interface. When the offset is 5 km the peaks are higher than before, which shows that the resistive layer is felt more strongly, while the direct field from the source is relatively weaker. Also, note that the influence of the air-water interface is increased, since now the curves for the depths of 1000 m and 2000 m are clearly separated, which was not the case in the 2 km offset.

CONCLUSION

The results show that meaningful information about the geoelectrical structure under the sea can be inferred from time domain mCSEM data. Because the measurements are done with the dipole source turned off, the method has the potential to detect weak reservoir responses or, as in the case of shallow water, it provides that the signal can be separated from the airwave response. In regions of greater seadepths, the air interaction response takes a longer time to reach the receiver and can over-

ride the seafloor response or even intensify it, since this downward signal can spread in the sediments also. Furthermore, we observed relevant differences between the resistive and conductive curves corresponding to the HC and noHC models respectively in all seadepths that we have tested, for the two kinds of source waveforms used. In the sequence of this research, we will investigate the information that can be gathered from 2-D and 3-D models, by formulating the problem in the time domain from first principles.

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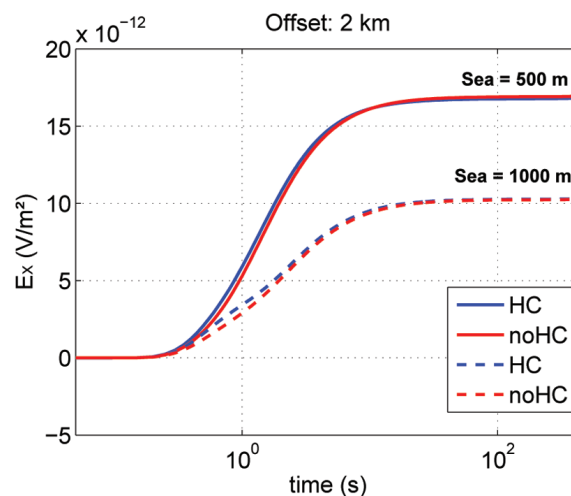


Figure 10 – Time-domain solution for the step response at a source-receiver distance of 2000 m.

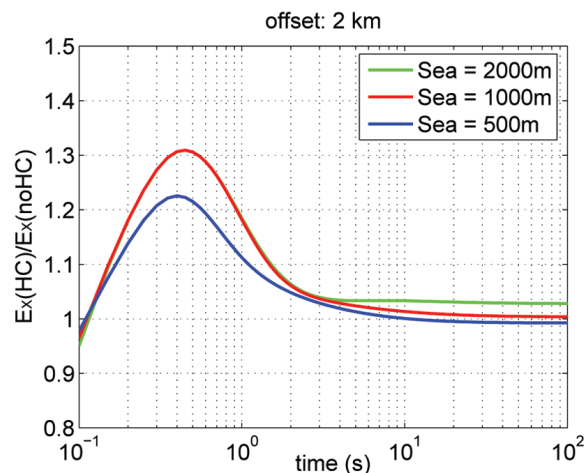


Figure 11 – Normalized solution for the step response at a source-receiver distance of 2000 m.

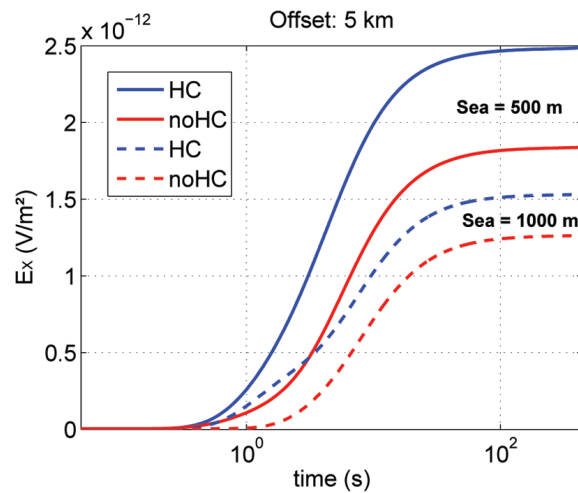


Figure 12 – Time-domain solution for the step response at a source-receiver distance of 5000 m.

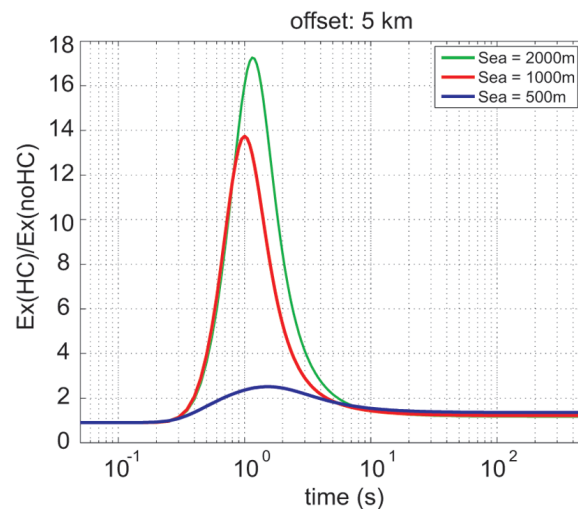


Figure 13 – Normalized solution for the step response at a source-receiver distance of 5000 m.

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