Exploring for Mineral Deposits on the Seafloor with Transient Electromagnetic Systems

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ABSTRACT

Transient electromagnetic (TEM) surveys are increasingly being investigated in a marine setting as interest increases in exploring for mineral deposits on the seafloor. Similar to airborne TEM surveys conducted on land, marine TEM systems can use a concentric or coincident wire loop transmitter and receiver towed behind a ship. Such towed-loop TEM surveys could be further augmented by placing additional stationary receivers on the seafloor throughout the survey area. We examine the electric fields measured by remote receivers from an inductive source transmitter within a 1D layered earth model. At sea, it is conceivable to deploy either a horizontal transmitter (like the analogous standard airborne configuration), or a more exotic vertical transmitter. We study and compare the sensitivity of both the vertical and horizontal towed-loop systems to a buried conductive target layer. Our results show that both the horizontal and vertical loop systems are sensitive to a shallowly buried conductive target. The vertical electric field produced by the vertical loop transmitter is sensitive to greater depths than the horizontal fields, and measuring the vertical field at the receivers would therefore be advantageous. We also conducted a novel test of a towed horizontal loop system with remote dipole receivers in a marine setting. The system was tested at the Palinuro volcanic complex in the Tyrrhenian Sea, a site of known massive sulphide mineralization. Preliminary results show that sections of the seafloor are likely more conductive than the seawater, which may indicate the successful detection of massive sulphide mineralization.

MARINE ELECTROMAGNETIC METHODS

In a marine setting, electromagnetic (EM) systems have been applied successfully in exploring for electrically conductive submarine massive sulphide (SMS) deposits (Cairns et al., 1996; Kowalczyk, 2008; Lipton, 2008; Swidinsky et al., 2015; Hölz et al., 2015). SMS deposits contain valuable resources of Cu, Pb, Zn, Au and Ag (Herzig, 1999), and some of these deposits, such as the Solwara 1 deposit in the Bismarck Sea (Lipton, 2008), may have potential to be economically mined. As interest in marine mineral exploration increases, airborne-style transient electromagnetic (TEM) surveys, consisting of a wire coil or loop transmitter and a second concentric or coincident receiving coil or loop towed behind a ship have been growing in popularity. Cheesman et al. (1987) showed that such systems could theoretically detect changes in seafloor conductivity in a marine setting, and more recently Swidinsky et al. (2012) examined the layered earth response of marine TEM systems.

Towed-loop systems are most sensitive to the seafloor directly below or close to the towing path of the system, which is advantageous when attempting to pinpoint small targets. However, these towed-loop systems could potentially be augmented by placing additional stationary remote receivers on the seafloor throughout the area of interest. In this case, the data recorded by the system towed behind the ship would provide very narrowly-sensitive data along the towing path, while the remote receivers would record data which is much more broadly sensitive to the geologic structure of the entire survey region and also to greater depths.

A marine towed-loop TEM system could consist of either a horizontal loop transmitter or a vertical loop transmitter (Figure 1). If the transmitter is towed behind a ship, a large loop that is suspended horizontally by several cables can be difficult to deploy from the ship's deck, as careful management of all the suspension cables is required. However, a square horizontal coil of dimensions 4.3 m x 4.3 m was successfully deployed by Hölz et al. (2015) in the Tyrrhenian Sea, and more recently a 6.3 m x 6.3 m horizontal coil was successfully deployed at the TAG hydrothermal mound in the mid-Atlantic Ocean. Handling of the horizontal coil was found to be difficult but possible. A vertical loop suspended from a single cable may be easier to deploy, but it must be sufficiently weighted at the bottom and towed slowly enough such that it remains in a vertical orientation, and the rotation of the vertical loop about the vertical axis would also need to be recorded to later take the orientation into account when interpreting the data. Receivers should consist of at least two horizontal dipole arms ~10 m in length with electrodes on each end oriented at 90° to each other, such that both horizontal components of the electric field can be measured (Figure 1). In addition, a third vertical electrode pair could be added to measure the vertical electric field.

In "Proceedings of Exploration 17: Sixth Decennial International Conference on Mineral Exploration" edited by V. Tschirhart and M.D. Thomas, 2017, p. 813–816

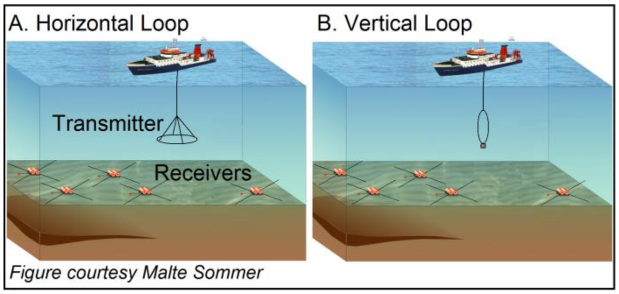

Figure 1: Illustration of a marine TEM system with a towed loop transmitter and dipole receivers deployed on the seafloor. A) Horizontal loop suspended by multiple cables. B) Vertical loop weighted at the bottom.

In this study we examine in detail the potential of electric field measurements on the seafloor related to a towed loop source in detecting and characterizing buried conductive targets such as SMS deposits. A TEM system consisting of a loop transmitter and dipole receivers has been tested on land (Macnae and Irvine, 1988), but to our knowledge a towed TEM system augmented with remote dipole receivers has not been tested in a marine setting prior to this study.

A FORWARD MODELLING STUDY

We developed a code for numerical 1D forward modelling of the electric fields from either a horizontal or vertical loop transmitter. The code was verified against analytical solutions for a whole-space derived by Ward and Hohmann (1988). Next we chose a simple layered model of the seafloor. Our model (Figure 2) consists of seawater with a conductivity of 3 S/m (σ_0), a seafloor background conductivity of 0.1 S/m (σ_1), and a buried mineralized target layer with a conductivity of 10 S/m (σ_2). The transmitter is a loop with a radius of 2 m and a current of 50 A. The receiver is located at a distance of 100 m from the transmitter and 37° from inline to the vertical loop axis (at x = 80 m, y = 60 m), such that both E_x and E_y fields will be present for the vertical loop.

In practice, when electric field measurements are made on the seafloor, the horizontal electrode arms of the receivers do not have a consistent orientation. One simple way to examine the data is to calculate a rotationally invariant quantity which we shall refer to as the horizontal field magnitude, E_h, defined as

$$\sqrt{E_x + E_y}.$$

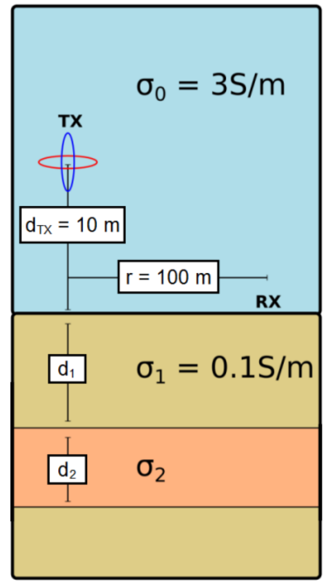

Figure 2: The 1D layered model used in this study.

We examine the E_h response produced by a target layer buried at various depths within the seafloor (Figure 2). Since the radius of the transmitter loop is small compared to the transmitter-receiver separation distance, the depth of investigation of the system will be primarily controlled by the separation distance rather than the loop radius. For the transmitter-receiver separation of 100 m used in this study, the horizontal loop system (Figure 3a) is sensitive to the target burial depth up to ~50 m, beyond which increases in burial depth produce very small changes in the signal amplitude, which would make it difficult to estimate the burial depth from the data. E_h for the vertical loop system (Figure 3b) has poorer sensitivity to burial depth than the horizontal loop system, and by 50 m burial depth the response is already almost indistinguishable from the homogeneous seafloor case. E_z for the vertical loop system (Figure 3c) has a similar sensitivity to burial depth as the horizontal loop system and is significantly more sensitive than E_h for the vertical loop system.

HORIZONTAL LOOP EXPERIMENT AT THE PALINURO VOLCANIC COMPLEX

We carried out an experiment with a loop transmitter and dipole receiver at the Palinuro volcanic complex in the southern Tyrrhenian Sea, a volcanic seamount located at the northern end of the Aeolian Volcanic Arc. Shallow drilling at Palinuro has recovered massive sulphides buried under several metres of mud (Petersen et al., 2014); thus this is an ideal site for testing the exploration of a shallowly buried deposit.

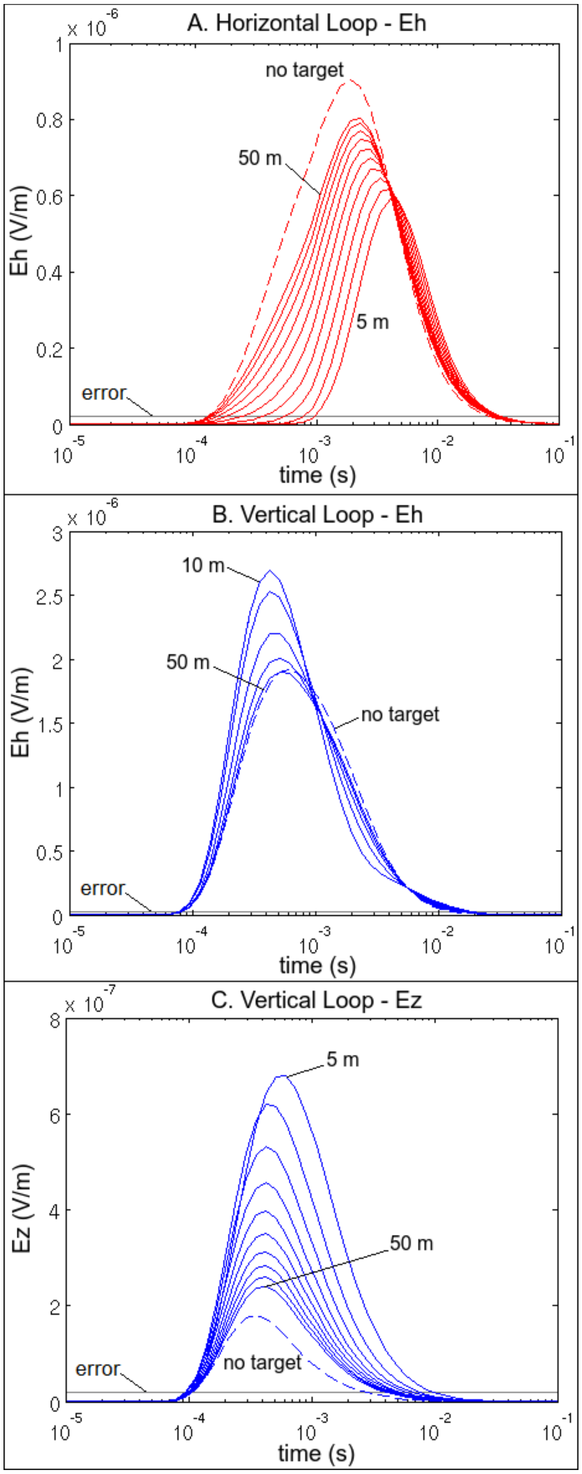

Figure 3: Plots of electric field magnitude modeled using the basic geometry depicted in Figure 2, with fixed target layer thickness (d_2 = 10 m) and conductivity (σ_2 = 10 S/m). Electric field transients are plotted for various target layer burial depths, $d1$, as well as the case with no target layer present (dashed line). The typical maximum measurement error of a seafloor receiver (2×10^{-8} V/m) is indicated by the grey line.

The experiment consisted of two dipole receivers placed on the seafloor and a horizontal loop transmitter towed behind a ship. The receivers consisted of two perpendicular arms 10 m in length with Ag-AgCl electrodes on the ends. The transmitter loop was a square with sides of 4.3 m length containing two windings of wire with a current of 38 A. The transmitter was suspended in a horizontal orientation and maintained at a height of ~5 m above the seafloor at all times, as verified by a proximity sensor. The same frame that carried the transmitter loop wire also carried a receiver loop, such that coincident-loop TEM data was simultaneously collected during the experiment (Hölz et al., 2015). A 50% duty-cycle square wave with a frequency of 4 Hz was transmitted by the loop for 30 seconds at each transmission site. The electric field transients at the transmitter current off-time were stacked to obtain a single transient decay curve for each transmission.

The loop was towed past the site of previously drilled mineralization, and 84 transmissions were made along the towing path, which were recorded by the two receivers, resulting in a total of 168 transients recorded. The separation between transmission sites and receivers, denoted as r, ranged from 80 m to 300 m. The recorded transients are plotted with their timescales normalized by the time constant, $\tau = \mu_0 \sigma r^2$ where σ is the conductivity of the seawater and μ_0 is the permeability of free space, so that variations in arrival time due to varying transmitter-receiver separation distance are removed. Transient amplitudes are multiplied by r^2 such that variations in amplitude related to geometric spreading of the fields are removed, although the separation distance will still have some effect on the amplitude due to the greater attenuation of a signal that has traveled a farther distance.

We briefly examine the transients recorded by receiver 11 (Figure 4). On the same plot we show three transients calculated for a simple homogeneous seafloor model with seawater conductivity of 4.6 S/m (consistent with the seawater conductivity measured during the experiment) and seafloor conductivities of 0.1 S/m, 4.6 S/m, and 100 S/m. From the plot we can see that the transients measured at Palinuro mostly fall between the modeled transients for a 0.1 S/m seafloor and a 100 S/m seafloor, and many of the transients have both smaller amplitudes and later arrival times than would be expected for a seafloor with the same conductivity as the seawater (4.6 S/m). This suggests that there are portions of the seafloor which are more conductive than seawater and may be indicative of the highly conductive massive sulphides present there. While this 1D modelling exercise can give us some sense of the upper and lower bounds of seafloor conductivity, the real seafloor structure is three-dimensional and the data cannot be perfectly matched by a 1D model. A thorough interpretation of these data will require considering the 3D structure of the seafloor, and we intend to pursue further analysis of the Palinuro data using 3D forward modelling in a future publication.

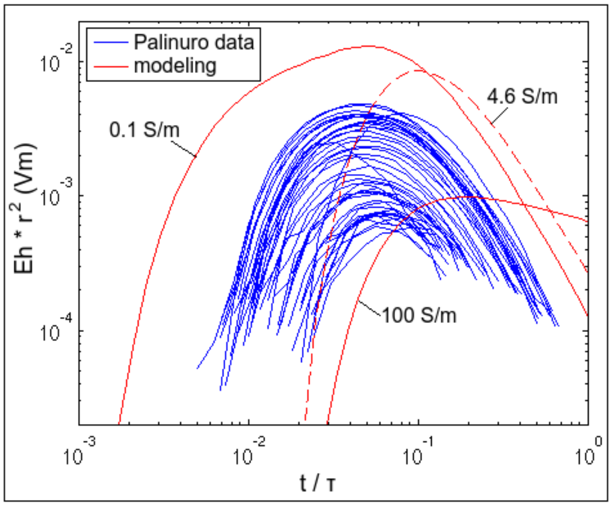

Figure 4: Horizontal electric field transients from the experiment at the Palinuro volcanic complex, plotted with their timescales normalized by the time constant, τ, and their amplitudes multiplied by the square of the transmitter-receiver separation distance, *r*. Solid red lines indicate forward modelling of the horizontal electric field for seawater with conductivity of 4.6 S/m and a homogeneous seafloor with conductivity of 0.1 S/m and 100 S/m. Dashed red line indicates forward modelling of the horizontal electric field for a homogeneous seafloor with conductivity equal to the seawater conductivity at 4.6 S/m.

CONCLUSIONS

The electric field components of both vertical and horizontal loop TEM systems were studied using 1D forward modelling. The modelling results show that both the vertical and horizontal loop systems are sensitive to a shallowly buried conductive target. Since massive sulphides are typically highly conductive compared to unmineralized rock and marine mineral exploration tends to focus on deposits which are at or near the surface, both the horizontal and vertical loop systems could have applications in exploring for and characterizing marine massive sulphide resources. Whenever a vertical loop system is used, the vertical field should be measured along with the horizontal field components, as the vertical field is sensitive to greater target burial depths than the horizontal field.

Our experiment at the Palinuro volcanic complex in the Tyrrhenian Sea has demonstrated that the acquisition of TEM data with a horizontal loop transmitter and remote dipole receivers is possible in a marine setting. A total of 168 transients were successfully recorded by two dipole receivers placed on the seafloor. Further interpretation of these data will be published in a future manuscript. To our knowledge a TEM experiment with a vertical loop transmitter, with or without remote receivers, has not yet been attempted in a marine setting.

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