On electric fields produced by inductive sources on the seafloor

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Abstract

The transient electromagnetic (TEM) method has recently been proposed as a tool for mineral exploration 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. Therefore we study and compare the sensitivity of both the vertical and horizontal towed-loop systems to a variety of seafloor conductivity structures. Our results show that the horizontal loop system is more sensitive to the thickness of a buried conductive layer and would be advantageous over the vertical loop system in characterizing the size of a shallowly buried mineralized zone. The vertical loop system is more sensitive to a resistive layer than the horizontal loop system. 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 sulfide mineralization. Preliminary results are consistent with shallowly buried material in the seafloor of conductivities > 1 S/m.

Introduction

In a marine setting, electromagnetic systems have been applied successfully in exploring for oil and gas reserves (see Constable 2010 for a review), gas hydrates (Yuan and Edwards, 2000; Weitemeyer et al., 2006; Schwalenberg et al., 2010a,b; Constable et al., 2016), and submarine massive sulfide (SMS) deposits (Cairns et al., 1996; Kowalczyk, 2008;

Lipton, 2008; Kowalczyk et al., 2015; Swidinsky et al., 2015; Hölz et al., 2015; Mueller et al., 2016). 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 Bismark Sea (Lipton, 2008), may have potential to be economically mined. As interest in marine mineral exploration increases, airborne-style 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. More recently, Swidinsky et al. (2012) examined the layered earth response of a system with a horizontal loop transmitter and either a coincident or concentric receiver loop, and Jang and Kim (2015) examined the layered earth responses of systems with either a horizontal or vertical loop transmitter and an in-loop magnetometer receiver.

Marine TEM systems have been successfully tested over SMS mineral deposits. Tao et al. (2013) tested a system consisting of coincident horizontal transmitter and receiver loops towed behind a ship at an altitude of 80–100 m above the seafloor and claim to have detected a known vent site at the South Atlantic Ridge. Hölz et al. (2015) also conducted an experiment with coincident horizontal transmitter and receiver loops towed behind a ship at the Palinuro volcanic complex in the Tyrrhenian Sea. The loops were towed very close to the seafloor, with the altitude of the loop maintained between 5–10 m. This low towing altitude allows for better sensitivity to the conductivity of the seafloor, and the system detected high conductivities in the vicinity of previously drilled massive sulfides. Nakayama and Saito (2016) and Asakawa et al. (2016) both used an ROV-mounted system to detect high conductivities at known SMS deposits in the Okinawa hydrothermal area. Their system consisted of a horizontal loop transmitter and both a coincident-loop and magnetometer receiver towed between 4–20 m below an ROV, such that EM noise from the ROV was minimized; in addition, the system could be set down directly on the seafloor to obtain very sensitive measurements. The use of an ROV allows for more precise navigation than towing behind a ship, but also greatly increases the cost of a survey.

In addition to the exploration and characterization of SMS mineral deposits, towed-loop TEM surveys could potentially have applications in the characterization of shallow marine gas hydrates. Controlled source electromagnetic (CSEM) methods have already been applied in investigating marine gas hydrates, both for hazard mitigation purposes and as a potentially economic resource of natural gas (Yuan and Edwards, 2000; Weitemeyer et al., 2006; Schwalenberg et al., 2010a,b; Constable et al., 2016).

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. In a marine setting it is quite simple to deploy remote receivers on the seafloor: the receivers can be attached to a buoyant device, such as a block of foam, and then sunk to the seafloor with an anchor which is released after the experiment is complete (eg. Swidinsky et al. 2015; Hölz et al. 2015). The data from the remote receivers could be used to detect additional targets which are either too deep or not close enough to the towing path to be detected by the towed receiver. Target areas detected by the array of remote receivers could then be further investigated with a second towing operation which would provide a detailed characterization.

The concept of combining a self-contained towed system with remote stationary receivers has been used in other marine electromagnetic applications. Wolfgram et al. (1986) tested a system consisting of a vertical long wire bipole transmitter and remote ocean-bottom magnetometer receivers at a massive sulfide deposit on the northern Juan de

Fuca Ridge. More recently, Constable et al. (2016) have developed and tested a system known as the "Vulcan". The Vulcan system consists of a dipole transmitter and an array of self-contained 3-component dipole receivers which are towed behind a ship. Stationary dipole receivers are also placed on the seafloor as is typical in a conventional marine CSEM survey. By collecting data from both the towed receivers and the stationary receivers the Vulcan system gives a more complete picture of the survey area.

We believe that a self-contained towed TEM system could likewise be augmented by placing receivers on the seafloor. 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 TEM system consisting of a loop transmitter and dipole receivers has been tested on land (Macnae and Irvine, 1988; Macnea et al., 1989). Macnae et al. used a large ungrounded wire loop transmitter located several hundred meters away from an array of dipole receivers. Macnae found that dipole receivers, which directly measure the electric field, were more sensitive to buried resistive targets than the loop or magnetometer receivers more traditionally used in land-based EM surveys. However, loop or magnetometer receivers remain the popular choices for land-based EM surveys for two reasons: in many geologic settings the electrodes of dipole receivers experience high contact resistance with the ground resulting in noisy measurements, and on land it often takes a lot of time and effort to deploy dipole receivers throughout a survey area, especially if the terrain is rugged or not easily accessible by vehicle. Neither of these issues are significant in a marine setting: electrodes couple well with conductive seawater and seafloor sediment, and receivers with a dipole length of up to $\sim$10 m can quickly and efficiently be deployed from a ship.

A marine towed-loop TEM system could consist of either a horizontal loop transmitter or a vertical loop transmitter (**Fig. 1**). The strength of the induced electric fields is proportional to the area of the loop, and thus a larger loop is generally favorable. However 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. Alternatively, increasing the strength of the transmitter by using many windings of wire coiled around the loop will increase the ramp time when the current is shut off; thus for TEM systems it is recommended to use a transmitter coil with only a few windings of wire. A square horizontal coil of dimensions 4.3 x 4.3 m was successfully deployed by Hölz et al. (2015) in the Tyrrhenian Sea, and more recently a 6.3 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 possible with careful management of the suspension cables. 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. Transmitter loops that are fixed to an ROV independent of the ship may be easier to maneuver in the water, but the use of an ROV greatly increases the cost of the survey. Receivers should consist of at least two horizontal dipole arms of at least 10 m length with electrodes on each end oriented at 90 degrees to each other such that both horizontal components of the electric field can be measured (**Fig. 1**). In addition, a third vertical electrode pair could be added to measure the vertical electric field. The inclusion of a 10 m tall vertical electrode arm might make the receiver difficult to deploy from the ship, thus it might be favorable to use a shorter dipole for the vertical field measurements, although this would result in a larger measurement error.

In this study we examine in detail the potential of electric field measurements on the seafloor from a towed inductive source in detecting and characterizing buried conductive and resistive targets. We also examine the advantages and disadvantages of deploying a vertical loop transmitter in contrast to a more standard horizontal loop transmitter. While 3D modeling of this problem is computationally expensive, we can gain great insight about the theoretical capabilities of these systems by examining their responses to a simple 1D layered-Earth model. We therefore derived a numerical method to forward model the 1D response of both systems.

Forward Modeling Theory

Consider a horizontal loop sitting on the surface of the Earth, with resistive air above it and horizontal layers of various thicknesses and conductivities below it. A DC current is transmitted through the loop for some period of time and then abruptly shut off. This will cause a transient electric field tangential to the loop to diffuse downward from the loop, as described in the "smoke rings" theory by Nabighian (1979). If the same loop is immersed in seawater, with layers of conductive seawater above the loop, then these smoke rings will diffuse both upwards and downwards into the seawater and seafloor (Swidinsky and Nabighian, 2015). Swidinsky et al. (2012) derived a method to calculate the transient voltage within the loop, which can be used with the in-loop or coincident loop systems. For our study, we modified their numerical method to instead calculate the transient electric field at some distance away from the loop, since our remote receivers are offset from the loop. In addition, we have developed a numerical method for a vertical loop transmitter (derived in **Appendix A**).

For the case of the horizontal loop transmitter, the tangential electric field, E_ϕ, at some radial distance r from the transmitter and at some layer interface K below the transmitter is the inverse Laplace transform of the expression modified from Swidinsky et al. (2012) equation A-13:

$$E_\phi(r) = \mu_0 I a \int_0^\infty \frac{F_K G_1}{F_1 + G_1} \prod_{i=1}^{K} L_i^F \lambda J_1(\lambda a) J_1(\lambda r) d\lambda \tag{1}$$

where a is the radius of the loop transmitter, I is the current in the transmitter, and J_1 is a Bessel function of the first kind. The parameters F_1 and G_1 are calculated by upward and downward recursion relations as such:

$$F_i = \frac{1}{\theta_i}\left[\frac{\theta_i F_{i+1} + \tanh(\theta_i d_i)}{\theta_i F_{i+1}\tanh(\theta_i d_i) + 1}\right] \tag{2}$$

and

$$G_j = \frac{1}{\theta_j}\left[\frac{\theta_j G_{j+1} + \tanh(\theta_j d_j)}{\theta_j G_{j+1}\tanh(\theta_j d_j) + 1}\right] \tag{3}$$

where θ_i is defined as $\sqrt{\lambda^2 + s\mu_0\sigma_i}$ for the ith seafloor layer, θ_j is defined as $\sqrt{\lambda^2 + s\mu_0\sigma_j}$ for the jth seawater layer, d_i and d_j denote the thickness of each layer, σ_i and σ_j denote the conductivity of each layer, μ_0 is the magnetic permeability of free space, and s is the Laplace variable. The recursions are started with the values $F_N = 1/\theta_N$ for the lower halfspace and $G_M = 1/\theta_M$ for the upper halfspace. For a full derivation of these recursion relations, see Swidinsky et al. (2012). The parameter L^F is the "ladder operator" which must be repeatedly applied as a product:

$$L_i^F = \frac{\theta_{i-1}F_{i-1}\operatorname{sech}(\theta_{i-1}d_{i-1})}{\theta_{i-1}F_i + \mu_0\tanh(\theta_{i-1}d_{i-1})} \tag{4}$$

where i represents each successive layer interface below the transmitter until the desired interface K (where the receiver is located) is reached. If the fields are to be calculated in the horizontal plane of the transmitter, $K = 1$ and by definition the ladder operator $L_1^F \equiv 1$.

Now consider a vertical loop immersed in the seawater. In this case the smoke rings of electric fields produced by the transmitter are perpendicular to the layers of the model, and the radial symmetry of the problem is broken (Swidinsky and Nabighian, 2016). The problem can be separated into the transverse electric (TE) and transverse magnetic (TM) parts, which can then be solved independently and added together. We derive equations for the components of the electric field produced by a vertical loop in a 1D layered model

(**Appendix A**). At a radial distance r offset from the axis of the loop by an angle ϕ, the x and y components of the electric field, E_x and E_y, and the vertical current density, J_z, are the inverse Laplace transform of the expressions:

$$\begin{aligned} E_x(r,\phi) =& \frac{-\mu_0 I a^2}{2}\cos(\phi)\sin(\phi)\Bigg[\int_0^\infty \left(\frac{F_K}{F_1+G_1}\right)\prod_{i=1}^{K} L_i^F \lambda J_1'(\lambda r)d\lambda \\ & - \frac{1}{r}\int_0^\infty \left(\frac{F_K}{F_1+G_1}\right)\prod_{i=1}^{K} L_i^F J_1(\lambda r)d\lambda \\ & + \int_0^\infty \left(\frac{U_K}{U_1+V_1}\right)\prod_{i=1}^{K} L_i^U \lambda J_1'(\lambda r)d\lambda \\ & - \frac{1}{r}\int_0^\infty \left(\frac{U_K}{U_1+V_1}\right)\prod_{i=1}^{K} L_i^U J_1(\lambda r)d\lambda\Bigg] \end{aligned} \tag{5}$$

$$\begin{aligned} E_y(r,\phi) =& \frac{\mu_0 I a^2}{2}\Bigg[\cos^2(\phi)\int_0^\infty \left(\frac{F_K}{F_1+G_1}\right)\prod_{i=1}^{K} L_i^F \lambda J_1'(\lambda r)d\lambda \\ & + \frac{\sin^2(\phi)}{r}\int_0^\infty \left(\frac{F_K}{F_1+G_1}\right)\prod_{i=1}^{K} L_i^F J_1(\lambda r)d\lambda \\ & + \sin^2(\phi)\int_0^\infty \left(\frac{U_K}{U_1+V_1}\right)\prod_{i=1}^{K} L_i^U \lambda J_1'(\lambda r)d\lambda \\ & + \frac{\cos^2(\phi)}{r}\int_0^\infty \left(\frac{U_K}{U_1+V_1}\right)\prod_{i=1}^{K} L_i^U J_1(\lambda r)d\lambda\Bigg] \end{aligned} \tag{6}$$

$$J_z(r,\phi) = \frac{-\mu_0 I a^2}{2}\sin(\phi)\int_0^\infty \left(\frac{1}{U_1+V_1}\right)\prod_{i=1}^{K} L_i^U \lambda^2 J_1(\lambda r)d\lambda \tag{7}$$

Similarly to F and G in the TE mode, U and V are calculated by upward and downward recursion relations in the TM mode (see **Appendix A** for full derivation):

$$U_i = \frac{\theta_i}{\sigma_i}\left[\frac{\sigma_i U_{i+1} + \theta_i \tanh(\theta_i d_i)}{\theta_i + \sigma_i U_{i+1}\tanh(\theta_i d_i)}\right] \tag{8}$$

$$V_j = \frac{\theta_j}{\sigma_j}\left[\frac{\sigma_j V_{j+1} + \theta_j \tanh(\theta_j d_j)}{\theta_j + \sigma_j V_{j+1}\tanh(\theta_j d_j)}\right] \tag{9}$$

These recursion relations are started with the values $U_N = \theta_N/\sigma_N$ for the lower halfspace and $V_M = \theta_M/\sigma_M$ for the upper halfspace. The parameter L^U is the "ladder operator" which must be repeatedly applied as a product:

$$L_i^U = \frac{\theta_{i-1}\,\mathrm{sech}(\theta_{i-1}d_{i-1})}{\theta_{i-1} + \sigma_{i-1}U_i\tanh(\theta_{i-1}d_{i-1})} \tag{10}$$

where i represents each successive layer interface below the transmitter until the desired interface K (where the receiver is located) is reached. If the fields are to be calculated in the horizontal plane of the transmitter, $K = 1$ and by definition the ladder operator $L_1^U \equiv 1$ (see **Appendix A** for a full derivation of the ladder operators).

The vertical electric field, E_z, is discontinuous across layer boundaries. However, using Ohm's Law, E_z can be calculated at a small distance above a layer boundary from J_z at the boundary and the conductivity of the layer.

It is important to note that while equation 1 for the horizontal loop is derived from a finite horizontal loop current source, equations 5 – 7 for the vertical loop are derived from a horizontal magnetic dipole source. We have carried out sensitivity analysis which shows that when the separation between the source and the receiver is approximately an order of magnitude greater than the radius of the loop source, the approximation of the source as a magnetic dipole results in an error of $<$5%. For the loop radius of 2 m and transmitter-receiver separation of 100 m used in this study, the error is $<$1%. We also note that in using μ_0 in our equations we have approximated the magnetic susceptibility of the model as 0. This assumption is reasonable when the magnetic susceptibility of the model layers is small.

A Forward Modeling Study

Using equations 5 – 7, we developed a code for numerical 1D forward modeling of the electric fields from either a horizontal or vertical loop transmitter. The code was verified against analytical solutions for a wholespace derived by Ward and Hohmann (1987). Next we chose a simple layered model of the seafloor. Our model (**Fig. 2**) consists of an upper halfspace of seawater above the transmitter and an additional 10 m of seawater below the transmitter (because the transmitter loop will be slightly above the seafloor as it is towed by the ship). The seafloor consists of various layers of different conductivities with a final lower halfspace at the bottom. Since the receivers will be located directly on the seafloor, and not at the same height as the transmitter, we must calculate our electric fields at the interface between the seawater and seafloor, which is the first layer interface below the horizontal plane of the transmitter. Thus we will make use of the ladder operators from equations 4 and 10 with $K = 2$.

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 $|E_\phi|$ for the horizontal loop system and $\sqrt{E_x^2 + E_y^2}$ for the vertical loop system.

When E_h is modeled at the surface of a simple homogeneous seafloor, the horizontal loop transmitter produces the classical "smoke ring" pattern (Nabighian, 1979), with the field attenuating as it spreads outward and downward from the transmitter site (**Fig. 3a**). With the vertical loop transmitter, the radial symmetry is broken and the E_h field is strongest at locations in line with the loop axis (**Fig. 3b**), while the vertical field, E_z, is strongest at locations perpendicular to the loop axis (**Fig. 3c**).

When E_h is modeled in a cross-sectional view, the smoke ring pattern is once again apparent for the horizontal loop transmitter, with the rings traveling faster in the resistive seafloor than in the conductive seawater (**Fig. 4a**). For the vertical loop transmitter, E_h does not have a ring pattern but rather spreads out and away from the transmitter as two hemispheres, with the fields again traveling faster in the resistive seafloor than in the conductive seawater (**Fig. 4b**). E_z for the vertical loop has a similar ring-like spreading pattern to E_h for the horizontal loop, but unlike E_h, E_z is discontinuous across the seawater-seafloor boundary (**Fig. 4c**).

We choose a model consisting of seawater conductivity of 3 S/m, a seafloor background conductivity of 0.1 S/m, and a buried target layer with a conductivity different than the background seafloor. The transmitter is a loop with a radius of 2 m, a single winding of wire, 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.

First we examine a 10 m thick target layer with various conductivities buried 5 m below the surface of the seafloor:

- The horizontal loop system (**Fig. 5a**) has very poor sensitivity to a resistive target layer; even when the target layer is two orders of magnitude less conductive (0.001 S/m) than the background seafloor, it can barely be distinguished from the homogeneous seafloor case. This is a consequence of the horizontal loop only producing a TE mode in the seafloor. In contrast, a conductive target layer can be distinguished by the horizontal loop system as the signal is more attenuated and the arrival time is delayed.

- E_h for the vertical loop system (**Fig. 5b**) is sensitive to a resistive target, as a consequence of this configuration producing both a TE and a TM mode; a resistive target produces increased signal amplitude and an earlier arrival time.

- E_h for the vertical loop system is also sensitive to a conductive target and shows interesting behavior: at lower conductivity contrasts between background seafloor and target layer, the signal is attenuated and delayed, as seen with the 1 S/m curve in **Fig. 5b**, but at higher conductivity contrasts the signal moves back to an earlier arrival time and a higher amplitude, as seen with the 10 S/m curve in **Fig. 5b**. This occurs because the resistive overburden layer, sandwiched between a conductive target layer and conductive seawater, behaves like a waveguide; E_h preferentially travels through and is guided by the thin resistive layer, arriving at a slightly earlier time than in the homogeneous seafloor case.

- E_z for the vertical loop system (**Fig. 5c**) is highly sensitive to the presence of a conductive target layer, much more so than E_h for either the vertical or horizontal loop systems. The presence of a conductive target produces an increased amplitude in E_z, and a resistive target produces a decreased amplitude in E_z. The amplitudes for E_z are nearly an order of magnitude smaller than E_h for the vertical loop system, but are still well above the typical maximum measurement error for a seafloor receiver, which our experimentation in the Tyrrhenian Sea has shown to be $\sim 2 \times 10^{-8}$ V/m.

Next we examine a 10 m thick target with a conductivity of 10 S/m buried at various depths within the seafloor. 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 (**Fig. 6a**) 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 (**Fig. 6b**) 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 (**Fig. 6c**) 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.

- When the conductive layer is at the seafloor surface ($d_1 = 0$ m), the signal amplitude is attenuated and the signal arrives at a later time, as it is traveling entirely through conductive media with no resistive layer to act as a "waveguide". While the fields from the horizontal loop consist of only a TE mode, the fields from the vertical loop consist of both a TE and TM mode; the effect of a resistive overburden is thus much more pronounced for the vertical loop system than the horizontal loop system since the resistive layer impedes vertical current.

Finally, we examine a target with a conductivity of 10 S/m, the top of which is buried at 5 m below the seafloor and with varying layer thickness. This model is a proxy for detecting the base (or depth extent) of a mineralized zone:

- The horizontal loop system (**Fig. 7a**) is sensitive to the target layer thickness up to ∼30 m, while both E_h and E_z for the vertical loop system (**Figs. 7b and 7c**) are only sensitive up to ∼10 m thickness.

- With E_h for the vertical loop system we see similar behavior as in **Fig. 5b**: when the conductive target layer is thin (1 m), the signal is attenuated and delayed, but a thicker conductive target layer (5 m) produces a waveguide effect in which the horizontal field is guided by the resistive overburden layer between the conductive layers and arrives at an earlier time.

Horizontal Loop Test 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. Massive sulfide samples were first discovered at Palinuro in 1984 (Minniti and Bonavia) at a depth of ∼650 m. Shallow drilling carried out by Petersen et al. (2014) indicate that the massive sulfides are buried under several meters of mud; thus this is an ideal site for testing the exploration of a shallowly buried deposit. While gravity, magnetic, sonar backscatter reflectivity, and detailed bathymetry data had previously been collected over the deposit (Caratori Tontini et al., 2014; Ligi et al., 2014), electromagnetic methods had not previously been attempted.

The experiment consisted of two dipole receivers placed on the seafloor and a horizontal loop transmitter towed behind a ship (**Fig. 8a**). The receivers consisted of two perpendicular arms 10 m in length with Ag-AgCl electrodes on the ends (**Fig. 8b**). The use of two perpendicular dipoles allows the total horizontal electric field to be measured. 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 $\sim$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 (**Fig. 9**). 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 R is the 3D separation distance between the TX and RX, 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 affect on the amplitude due to the greater attenuation of a signal that has traveled a farther distance. Due to bathymetry most of the TX-RX combinations have some vertical offset, but the vertical offset is small compared to the horizontal separation; out of all the TX-RX combinations the greatest angle is $\sim 7°$ from horizontal. In addition, the height difference between the TX and RX will be partially normalized out since the data are plotted with amplitudes normalized by 3D TX-RX separation distance.

We briefly examine the transients recorded by receiver 11 (**Fig. 10**). On the same plot we show transients calculated with a horizontal loop transmitter of the same area, current, and windings as used in the experiment for a model following the basic geometry depicted in **Figure 2** with seawater conductivity of 4.6 S/m (consistent with the seawater conductivity measured during the experiment). Since we are dealing here with the horizontal field magnitude, E_h, which is always positive, we need not convert our modeled response curves from a transmitter on-time response to an off-time response, as the only difference between the two would be a change of sign. When the conductivity of the target layer is varied (**Fig. 10a**), we find that at early times most of the data plot below the curve for a 1 S/m target layer and above the curve for a 100 S/m layer, while at late times the data plot below the curve for a 100 S/m layer. Difficulty in matching the data to the 1D model curves at late times likely results because the late time part of the signal is sensitive to greater distances from the transmitter and thus is detecting more 3D structural variability in the seafloor than the early time part of the signal. When the burial depth of the target layer is varied (**Fig. 10b**), we find that at early times most of the data plot between the curves for 0 m burial depth and 30 m burial depth. When the thickness of the target layer is varied (**Fig. 10c**), we find that at early times most of the data plot between the curves for 3 m thickness and 50 m thickness. While this 1D modeling exercise can give us some sense of the conductivity structure of the seafloor, the real seafloor structure is three-dimensional and thus the data cannot be perfectly matched by a 1D model, particularly at late times. In general, the early time part of the data appear to be consistent with material being present in the seafloor with conductivity > 1 S/m, burial depth of a few meters to 10s of meters, and thickness of a few meters to 10s of meters. 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 modeling in a future publication.

Conclusions

The electric field components of both a vertical loop and horizontal loop TEM system are studied using layered earth theory. Results of modeling the sensitivity of remote dipole E-field receivers to a buried target layer have implications for which system will give better results in different exploration settings. The modeling results show that both the vertical loop and horizontal loop systems are sensitive to a shallowly buried conductive target. Since massive sulfides are typically several orders of magnitude more conductive than 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 sulfide resources.

When attempting to characterize the size of a mineralized zone in the seafloor, it is important to be able to estimate the thickness (depth extent) of the mineralization. Drilling in a marine setting is much more expensive and difficult than on land, so it is desirable to estimate the thickness of the mineralization from geophysical data prior to investing in a drilling program. For this application, the horizontal loop system is advantageous to the vertical loop system as it is sensitive to greater thicknesses of a conductive target layer.

When a conductive target layer is located at the seafloor surface with a burial depth of 0 m, the vertical loop system experiences significant attenuation of the signal in the conductive layer. The horizontal loop system experiences much less attenuation and would therefore be advantageous when exploring for conductive targets that are not buried.

When attempting characterization of resistive targets, as would be the case in gas hydrate exploration, the vertical loop system is advantageous to the horizontal loop system in that it has much greater sensitivity to resistive targets.

Whenever a vertical loop system is used, the vertical field should be measured along with the horizontal field components. The vertical field has higher sensitivity to shallow conductive targets and is sensitive to greater target burial depths than the horizontal field. The inclusion of vertical electrode pairs on the receivers would be well worth the additional information gained.

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 E-field receivers is possible in a marine setting. A total of 168 transients were successfully recorded by two dipole receivers placed on the seafloor which measured the tangential electric field. 1D forward modeling suggests that the Palinuro data are consistent with shallowly buried material in the seafloor of conductivities > 1 S/m. 3D interpretation of these data will be published in a future manuscript. While our system is at this time capable of measuring only E-fields at the receivers, the potential exists to further augment this system by measuring both E-field and B-field data at the remote receivers, a configuration which to our knowledge has not been previously tested in a marine setting with an inductive source. To our knowledge a TEM experiment with a vertical loop transmitter, with or without remote receivers, has also not yet been attempted in a marine setting.

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Appendix A: Derivation of Electric Fields Produced by a Vertical Current Loop in a 1D Layered Earth

Throughout this derivation, we use a coordinate system in which z is positive downwards (**Fig. A1**).

A vertical loop of current can be represented by a horizontal magnetic dipole which produces both an electric and magnetic field (**Fig. A2**). We will approach this problem by breaking it up into the Transverse Electric (TE) and Transverse Magnetic (TM) modes. In the TE mode no vertical electric field is present and in the TM mode no vertical magnetic field is present. Throughout this derivation, we will employ some useful mathematical relations which are summarized in Appendix B.

TE Mode

The vertical magnetic field, b_z, is unique to the TE mode. Working in the Fourier domain, where $\frac{\partial}{\partial x} = -ip$ and $\frac{\partial}{\partial y} = -iq$, we begin with the Helmholtz equation for b_z:

$$\frac{\partial^2 b_z}{\partial z^2} - \theta^2 b_z = 0 \tag{A-1}$$

$$\theta^2 = p^2 + q^2 + i\omega\mu_0\sigma$$

A solution to this differential equation has the form:

$$b_z = Ce^{(-\theta|z|)} + De^{(\theta|z|)}$$

As $z \to \infty$, $b_z \to 0$, so $D = 0$ and the equation simplifies to:

$$b_z = Ce^{(-\theta|z|)} \tag{A-2}$$

From Ward and Hohmann (1987) equation 4.104 we have the solution for the primary vertical magnetic field produced by a horizontal magnetic dipole at a depth z:

$$b_z^{primary} = \mu_0 h_z^{primary} = \pm \frac{\mu_0 ipm}{2} e^{-\theta z} \tag{A-3}$$

where m is the magnetic moment of the dipole and μ_0 is the permeability of free space. By substituting (A-3) into (A-2) we find that $C = \pm\frac{\mu_0 ipm}{2}$. b_z is discontinuous across the plane of the dipole source, and we solve for the change in b_z across the source:

$$\delta b_z = b_z^+ - b_z^- = 2C = \mu_0 ipm \tag{A-4}$$

For a layered earth model, a solution to (A-1) within a layer i has the form:

$$b_{z,i} = C\cosh(\theta_i z) + D\sinh(\theta_i z) \tag{A-5}$$

Making use of relation (B-7) derived from Gauss' Law and Ampere's Law we solve for b_y:

$$\begin{aligned} b_{y,i} &= \frac{-iq}{p^2+q^2}\frac{\partial b_z}{\partial z} \\ &= \frac{-iq}{p^2+q^2}\theta_i\left[C\sinh(\theta_i z) + D\cosh(\theta_i z)\right] \end{aligned} \tag{A-6}$$

We define a variable F as:

$$F = \frac{iq}{p^2+q^2}\frac{b_z}{b_y} \tag{A-7}$$

For the ith layer, from (A-5) and (A-6) we have:

$$\begin{aligned} F_i &= \frac{-1}{\theta_i}\left[\frac{C\cosh(\theta_i z) + D\sinh(\theta_i z)}{C\sinh(\theta_i z) + D\cosh(\theta_i z)}\right] \\ &= \frac{-1}{\theta_i}\left[\frac{1+\frac{D}{C}\tanh(\theta_i z)}{\tanh(\theta_i z)+\frac{D}{C}}\right] \end{aligned} \tag{A-8}$$

If we define the z-axis to coincide with the bottom of the ith layer, and considering that F is continuous across the layer:

$$
\begin{aligned}
F_i = F_{i+1} &= \frac{-1}{\theta_i}\frac{C}{D} \\
\frac{C}{D} &= -\theta_i F_{i+1}
\end{aligned}
\tag{A-9}
$$

Now we substitute (A-9) into (A-8) to define an upward recursion relation, where $z = d_i$ is the thickness of the ith layer:

$$F_i = \frac{1}{\theta_i}\left[\frac{\theta_i F_{i+1} + \tanh(\theta_i d_i)}{\theta_i F_{i+1}\tanh(\theta_i d_i) + 1}\right] \tag{A-10}$$

At the top of the lower halfspace, the halfspace thickness $d_N = \infty$, so the recursion can be started with the value $F_N = 1/\theta_N$.

If we define $z = 0$ as the bottom of the ith layer, and considering b_z is continuous across the layer boundaries, we have from (A-2):

$$b_{z,i}\big|_{z=0} = b_{z,i+1} = C \tag{A-11}$$

Substituting (A-11) into (A-9) we have:

$$D = \frac{b_{z,i+1}}{-\theta_i F_{i+1}} \tag{A-12}$$

Now we set $z = -d_i$ for the bottom of the $(i+1)$th layer. By substituting (A-11) and (A-12) into (A-5) we derive a downward recursion relation to define b_z at any layer interface below the source:

$$b_{z,i} = b_{z,i+1}\cosh(\theta_i d_i) + b_{z,i+1}\frac{1}{\theta_i F_{i+1}}\sinh(\theta_i d_i)$$

$$b_{z,i+1} = b_{z,i}\left[\frac{\theta_i F_{i+1}\operatorname{sech}(\theta_i d_i)}{\theta_i F_{i+1} + \tanh(\theta_i d_i)}\right] \tag{A-13}$$

Substituting the relationship between b_y and b_z defined in (A-7) we get:

$$\left(\frac{p^2+q^2}{iq}\right) F_{i+1} b_{y,i+1} = \left(\frac{p^2+q^2}{iq}\right) F_i b_{y,i}\left[\frac{\theta_i F_{i+1}\operatorname{sech}(\theta_i d_i)}{\theta_i F_{i+1} + \tanh(\theta_i d_i)}\right]$$

$$\begin{aligned} b_{y,i+1} &= b_{y,i}\left[\frac{\theta_i F_i\operatorname{sech}(\theta_i d_i)}{\theta_i F_{i+1} + \tanh(\theta_i d_i)}\right] \\ &= b_{y,i} L^F_{i+1} \end{aligned} \tag{A-14}$$

where L^F is the "ladder operator" defined by the recursion relation:

$$L^F_i = \frac{\theta_{i-1} F_{i-1}\operatorname{sech}(\theta_{i-1} d_{i-1})}{\theta_{i-1} F_i + \tanh(\theta_{i-1} d_{i-1})} \tag{A-15}$$

If b_y is to be calculated in the plane of the dipole source, $i = 1$ and by definition $L^F_1 \equiv 1$. The electric field components, e_x and e_y, can be derived from b_y at any layer interface i using relations (B-8) and (B-9) derived from Ampere's Law and Faraday's Law:

$$e_{x,i} = i\omega b_{z,i}\left(\frac{iq}{p^2+q^2}\right) = F_i i\omega b_{y,i} \tag{A-16}$$

$$e_{y,i} = i\omega b_{z,i}\left(\frac{-ip}{p^2+q^2}\right) = \left(\frac{-p}{q}\right) F_i i\omega b_{y,i} \tag{A-17}$$

Similar to F, we can define a recursion relation G to represent the layers above the magnetic dipole source. We calculate the change in b_z across the plane of the dipole source from (A-7) as:

$$\delta b_z = b_z^+ - b_z^- = (F_1 + G_1)\left(\frac{p^2+q^2}{iq}\right) b_{y,1} \tag{A-18}$$

By equating (A-18) to (A-4), we find that:

$$b_{y,1} = \left(\frac{1}{F_1 + G_1}\right)\left(\frac{-\mu_0 pqm}{p^2 + q^2}\right) \tag{A-19}$$

We find the electric field components using the relations in (A-16) and (A-17):

$$e_{x,1} = F_1 i\omega \left(\frac{1}{F_1 + G_1}\right)\left(\frac{-\mu_0 pqm}{p^2 + q^2}\right) \tag{A-20}$$

$$e_{y,1} = F_1 i\omega \left(\frac{1}{F_1 + G_1}\right)\left(\frac{\mu_0 p^2 m}{p^2 + q^2}\right) \tag{A-21}$$

We transform (A-20) and (A-21) to the Hankel domain, where $\lambda^2 = p^2 + q^2$ and J_1 is a Bessel function of the first kind. We make use of relations (B-14) and (B-17):

$$E_{x,1}(r,\phi) = \frac{-\mu_0 m i\omega}{2\pi}\cos(\phi)\sin(\phi)\left[\int_0^\infty \left(\frac{F_1}{F_1 + G_1}\right)\lambda J_1'(\lambda r)d\lambda - \frac{1}{r}\int_0^\infty \left(\frac{F_1}{F_1 + G_1}\right)J_1(\lambda r)d\lambda\right] \tag{A-22}$$

$$E_{y,1}(r,\phi) = \frac{\mu_0 m i\omega}{2\pi}\left[\cos^2(\phi)\int_0^\infty \left(\frac{F_1}{F_1 + G_1}\right)\lambda J_1'(\lambda r)d\lambda + \frac{\sin^2(\phi)}{r}\int_0^\infty \left(\frac{F_1}{F_1 + G_1}\right)J_1(\lambda r)d\lambda\right] \tag{A-23}$$

If we wish to calculate the fields at a layer interface K below the transmitter, we must include the ladder operator which must be repeatedly applied as a product for each layer interface i until the desired interface K is reached. Also note that as per (A-16) and (A-17) we must use F_K in place of F_1 in the numerator of the integral kernel:

$$\begin{aligned} E_{x,K}(r,\phi) = &\frac{-\mu_0 m i\omega}{2\pi}\cos(\phi)\sin(\phi)\Bigg[\int_0^\infty \left(\frac{F_K}{F_1 + G_1}\right)\prod_{i=1}^{K} L_i^F \lambda J_1'(\lambda r)d\lambda \\ &- \frac{1}{r}\int_0^\infty \left(\frac{F_K}{F_1 + G_1}\right)\prod_{i=1}^{K} L_i^F J_1(\lambda r)d\lambda\Bigg] \end{aligned} \tag{A-24}$$

$$E_{y,K}(r,\phi) = \frac{\mu_0 m i\omega}{2\pi}\left[\cos^2(\phi)\int_0^\infty \left(\frac{F_K}{F_1+G_1}\right)\prod_{i=1}^{K} L_i^F \lambda J_1'(\lambda r)d\lambda \right.$$
$$\left. + \frac{\sin^2(\phi)}{r}\int_0^\infty \left(\frac{F_K}{F_1+G_1}\right)\prod_{i=1}^{K} L_i^F J_1(\lambda r)d\lambda\right] \tag{A-25}$$

TM Mode

The vertical electric field, e_z, is unique to the TM mode. Working in the Fourier domain, we begin with the Helmholtz equation for e_z:

$$\frac{\partial^2 e_z}{\partial z^2} - \theta^2 e_z = 0 \tag{A-26}$$

Similar to (A-1), a solution to this equation has the form:

$$e_z = Ce^{(-\theta|z|)} \tag{A-27}$$

We have the vertical electric field e_z at a depth z from a horizontal magnetic dipole source from Ward and Hohmann's equation 4.103 (1987):

$$e_z^{primary} = \pm\left(\frac{iq(i\omega\mu_0)m}{2\theta}\right)e^{-\theta z} \tag{A-28}$$

where m is the magnetic moment of the dipole source and μ_0 is the permeability of free space. From relations (B-11) and (B-12) derived from Gauss' Law and Faraday's Law, we have expressions for e_x and e_y:

$$e_x = \left(\frac{-ip}{p^2+q^2}\right)\frac{\partial e_z}{\partial z} \tag{A-29}$$
$$e_y = \left(\frac{-iq}{p^2+q^2}\right)\frac{\partial e_z}{\partial z} \tag{A-30}$$

From (A-28) we find $\frac{\partial e_z}{\partial z}$:

$$\frac{\partial e_z}{\partial z} = \pm \left(\frac{iq(i\omega\mu_0)m}{2} \right) e^{-\theta z} \tag{A-31}$$

By substituting (A-31) into (A-30) we get:

$$e_y = \pm \left(\frac{q^2 i\omega\mu_0 m}{2(p^2+q^2)} \right) e^{-\theta z} \tag{A-32}$$

e_y is discontinuous across the plane of the dipole source. We solve for the change in e_y across the source by subtracting e_y just above the source from e_y just below the source:

$$\delta e_y = e_y^+ - e_y^- = \frac{q^2 i\omega\mu_0 m}{p^2+q^2} \tag{A-33}$$

Now we consider the layered earth model. A solution to (A-26) within each layer i has the form:

$$e_{z,i} = C\cosh(\theta_i z) + D\sinh(\theta_i z) \tag{A-34}$$

Substituting (A-34) into (A-30) we get:

$$e_y = \left(\frac{-iq}{p^2+q^2} \right) \theta \left[C\sinh(\theta z) + D\cosh(\theta z) \right] \tag{A-35}$$

With σ being the electrical conductivity, we define a variable U as:

$$U = \left(\frac{p^2+q^2}{iq} \right) \left(\frac{e_y}{\sigma e_z} \right) \tag{A-36}$$

Similar to the derivation of F in (A-10), we derive an upward recursion relation for U, where $z = d_i$ is the thickness of the ith layer:

$$U_i = \frac{\theta_i}{\sigma_i}\left[\frac{\theta_i \tanh(\theta_i d_i) + \sigma_i U_{i+1}}{\theta_i + \sigma_i U_{i+1} \tanh(\theta_i d_i)}\right] \tag{A-37}$$

At the top of the lower halfspace, the halfspace thickness $d_N = \infty$ and we can thus start the recursion relation with $U_N = \theta_N/\sigma_N$.

If we define $z = 0$ as the bottom of the ith layer, and considering that the current density, $j_z = \sigma e_z$, is continuous across the layer boundaries, we have from (A-27):

$$e_{z,i}\big|_{z=0} = \frac{j_{z,i}}{\sigma_i} = \frac{j_{z,i+1}}{\sigma_i} = C \tag{A-38}$$

By a similar procedure to the derivation of (A-13), we can derive a downward recursion relation for j_z:

$$\begin{aligned} j_{z,i+1} &= j_{z,i}\left[\frac{\theta_i \operatorname{sech}(\theta_i d_i)}{\theta_i + \sigma_i U_{i+1} \tanh(\theta_i d_i)}\right] \\ &= j_{z,i} L^U_{i+1} \end{aligned} \tag{A-39}$$

where L^U is the "ladder operator" defined by the recursion relation:

$$L^U_i = \frac{\theta_{i-1} \operatorname{sech}(\theta_{i-1} d_{i-1})}{\theta_{i-1} + \sigma_{i-1} U_i \tanh(\theta_{i-1} d_{i-1})} \tag{A-40}$$

If j_z is to be calculated in the plane of the dipole source, $i = 1$ and by definition $L^U_1 \equiv 1$. For any layer i, $e_{y,i}$ can be calculated from $j_{z,i}$ and the definition of U:

$$e_{y,i} = \left(\frac{U_i \sigma_i i q}{p^2 + q^2}\right) e_{z,i} = \left(\frac{U_i i q}{p^2 + q^2}\right) j_{z,i} \tag{A-41}$$

e_x can be related to e_y by Faraday's Law (B-10):

$$e_{x,i} = \left(\frac{p}{q}\right) e_{y,i} = \left(\frac{U_i ip}{p^2+q^2}\right) j_{z,i} \tag{A-42}$$

Similar to U, we can derive a recursion relation V for the layers above the dipole source. We calculate the change in e_y across the plane of the dipole source from (A-41) as:

$$\delta e_y = e_y^+ - e_y^- = (U_1+V_1)\left(\frac{iq\sigma_1 e_{z,1}}{p^2+q^2}\right) = (U_1+V_1)\left(\frac{iqj_{z,1}}{p^2+q^2}\right) \tag{A-43}$$

If we equate (A-43) to (A-33) we can solve for j_z in the plane of the dipole source:

$$j_{z,1} = -iq(i\omega\mu_0)m\left(\frac{1}{U_1+V_1}\right) \tag{A-44}$$

We convert to the Hankel domain, making use of relation (B-15):

$$J_{z,1}(r,\phi) = \frac{-i\omega\mu_0 m}{2\pi\sigma_1}\sin(\phi)\int_0^\infty \left(\frac{1}{U_1+V_1}\right)\lambda^2 J_1(\lambda r)d\lambda \tag{A-45}$$

Note: The vertical current density J_z should not be confused with the Bessel function J_1 inside the integral.

We can solve for e_y by substituting (A-44) into (A-41):

$$e_{y,1} = \frac{q^2 i\omega\mu_0 m}{p^2+q^2}\left(\frac{U_1}{U_1+V_1}\right) \tag{A-46}$$

Converting to the Hankel domain, making use of relation (B-16):

$$E_{y,1}(r,\phi) = \frac{i\omega\mu_0 m}{2\pi}\left[\sin^2(\phi)\int_0^\infty \left(\frac{U_1}{U_1+V_1}\right)\lambda J_1'(\lambda r)d\lambda + \frac{\cos^2(\phi)}{r}\int_0^\infty \left(\frac{U_1}{U_1+V_1}\right)J_1(\lambda r)d\lambda\right] \tag{A-47}$$

We can solve for e_x by substituting (A-44) into (A-42) and convert to the Hankel domain, making use of relation (B-17):

$$e_{x,1} = \frac{pqi\omega\mu_0 m}{p^2+q^2}\left(\frac{U_1}{U_1+V_1}\right) \tag{A-48}$$

$$E_{x,1}(r,\phi) = \frac{i\omega\mu_0 m}{2\pi}\cos(\phi)\sin(\phi)\left[\int_0^\infty \left(\frac{U_1}{U_1+V_1}\right)\lambda J_1'(\lambda r)d\lambda - \frac{1}{r}\int_0^\infty \left(\frac{U_1}{U_1+V_1}\right)J_1(\lambda r)d\lambda\right] \tag{A-49}$$

If we wish to calculate the fields at a layer interface K below the transmitter, we must include the ladder operator (A-40) which must be repeatedly applied as a product for each layer interface i until the desired interface K is reached. Also note that as per (A-41) and (A-41) for e_x and e_y we must use U_K in place of U_1 in the numerator of the integral kernel:

$$J_{z,K}(r,\phi) = \frac{-i\omega\mu_0 m}{2\pi}\sin(\phi)\int_0^\infty \left(\frac{1}{U_1+V_1}\right)\prod_{i=1}^{K} L_i^U \lambda^2 J_1(\lambda r)d\lambda \tag{A-50}$$

$$\begin{aligned} E_{x,K}(r,\phi) =& \frac{i\omega\mu_0 m}{2\pi}\cos(\phi)\sin(\phi)\Bigg[\int_0^\infty \left(\frac{U_K}{U_1+V_1}\right)\left(\frac{\sigma_K}{\sigma_1}\right)\prod_{i=1}^{K} L_i^U \lambda J_1'(\lambda r)d\lambda \\ & - \frac{1}{r}\int_0^\infty \left(\frac{U_K}{U_1+V_1}\right)\left(\frac{\sigma_K}{\sigma_1}\right)\prod_{i=1}^{K} L_i^U J_1(\lambda r)d\lambda\Bigg] \end{aligned} \tag{A-51}$$

$$\begin{aligned} E_{y,K}(r,\phi) =& \frac{i\omega\mu_0 m}{2\pi}\Bigg[\sin^2(\phi)\int_0^\infty \left(\frac{U_K}{U_1+V_1}\right)\left(\frac{\sigma_K}{\sigma_1}\right)\prod_{i=1}^{K} L_i^U \lambda J_1'(\lambda r)d\lambda \\ & + \frac{\cos^2(\phi)}{r}\int_0^\infty \left(\frac{U_K}{U_1+V_1}\right)\left(\frac{\sigma_K}{\sigma_1}\right)\prod_{i=1}^{K} L_i^U J_1(\lambda r)d\lambda\Bigg] \end{aligned} \tag{A-52}$$

Combining the TE and TM modes

To get the full solutions for E_x and E_y we simply add the TE and TM parts. The full solution for E_x is given by (A-24) + (A-51), and the full solution for E_y is given by (A-25) + (A-52).

The magnetic moment of a wire loop is given by the current in the loop times the area of the loop, so for our vertical loop source we replace the magnetic moment m in the above equations with $I\pi a^2$ where a is the radius of the loop and I is the current.

In the case of time-domain EM, our source is a step function of the current. To get the response from our source in the Laplace domain, we multiply the expressions for E_x, E_y, and J_z by the Laplace transform of a step function, $1/s$, where s is the Laplace variable $s = i\omega$. This yields the final expressions for E_x, E_y, and J_z in the Laplace domain given in equations 5,6, and 7.

Appendix B: Useful Mathematical Relations

Consider that for a magnetic dipole, by Gauss' law the divergence of the electric field is zero, from which we can derive the following in the Fourier domain:

$$ipe_x + iqe_y = \frac{\partial e_z}{\partial z} \tag{B-1}$$

Gauss' Law for magnetics in the Fourier domain:

$$ipb_x + iqb_y = \frac{\partial b_z}{\partial z} \tag{B-2}$$

The z-component of Faraday's Law in the Fourier domain:

$$-ipe_y + iqe_x = -i\omega b_z \tag{B-3}$$

The z-component of Ampere's Law in the Fourier domain:

$$-ipb_y + iqb_x = \mu_0 j_z + \mu_0 \epsilon_0 i\omega e_z \tag{B-4}$$

In the TE mode, $e_z = 0$ and $j_z = 0$, so we have from (B-1) and (B-4):

$$pb_y = qb_x \tag{B-5}$$

$$pe_x = -qe_y \tag{B-6}$$

In the TE mode, by substituting (B-5) into (B-2) we have:

$$b_y = \frac{-iq}{p^2 + q^2} \frac{\partial b_z}{\partial z} \tag{B-7}$$

In the TE mode, by substituting (B-6) into (B-3) we have:

$$e_x = \left(\frac{iq}{p^2+q^2}\right) i\omega b_z \tag{B-8}$$

$$e_y = \left(\frac{-ip}{p^2+q^2}\right) i\omega b_z \tag{B-9}$$

In the TM mode, $b_z = 0$ and we have from (B-3):

$$pe_y = qe_x \tag{B-10}$$

In the TM mode, by substituting (B-10) into (B-1) we have:

$$e_x = \left(\frac{-ip}{p^2+q^2}\right) \frac{\partial e_z}{\partial z} \tag{B-11}$$

$$e_y = \left(\frac{-iq}{p^2+q^2}\right) \frac{\partial e_z}{\partial z} \tag{B-12}$$

Useful derivatives:

$$\frac{\partial}{\partial x}\int_0^\infty f(\lambda)\lambda J_0(\lambda r)d\lambda = -\cos(\phi)\int_0^\infty f(\lambda)\lambda^2 J_1(\lambda r)d\lambda \tag{B-13}$$

$$\frac{\partial^2}{\partial x^2}\int_0^\infty f(\lambda)\lambda J_0(\lambda r)d\lambda = -\cos^2(\phi)\int_0^\infty f(\lambda)\lambda^3 J_1'(\lambda r)d\lambda - \frac{\sin^2(\phi)}{r}\int_0^\infty f(\lambda)\lambda^2 J_1(\lambda r)d\lambda \tag{B-14}$$

$$\frac{\partial}{\partial y}\int_0^\infty f(\lambda)\lambda J_0(\lambda r)d\lambda = -\sin(\phi)\int_0^\infty f(\lambda)\lambda^2 J_1(\lambda r)d\lambda \tag{B-15}$$

$$\frac{\partial^2}{\partial y^2}\int_0^\infty f(\lambda)\lambda J_0(\lambda r)d\lambda = -\sin^2(\phi)\int_0^\infty f(\lambda)\lambda^3 J_1'(\lambda r)d\lambda - \frac{\cos^2(\phi)}{r}\int_0^\infty f(\lambda)\lambda^2 J_1(\lambda r)d\lambda \tag{B-16}$$

$$\frac{\partial^2}{\partial x\partial y}\int_0^\infty f(\lambda)\lambda J_0(\lambda r)d\lambda = -\cos(\phi)\sin(\phi)\left[\int_0^\infty f(\lambda)\lambda^3 J_1'(\lambda r)d\lambda - \frac{1}{r}\int_0^\infty f(\lambda)\lambda^2 J_1(\lambda r)d\lambda\right] \tag{B-17}$$

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Figure Captions

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.

Figure 2: The 1D layered model used in this study. The seawater has a conductivity of 3 S/m, and the background seafloor has a conductivity of 0.1 S/m. Various layers of different thicknesses and conductivities can be included within the seafloor. The transmitter consists of either a horizontal or vertical loop with radius of 2 m and a current of 50 A. The transmitter is located at a height of 10 m above the seafloor at the point x = 0 m, y = 0 m. The receiver is located on the seafloor at the point x = 80 m, y = 60 m, such that the horizontal separation between the transmitter and receiver is 100 m.

Figure 3: Snapshots in map view of the electric field magnitude at 5×10^{-5}, 3×10^{-4}, and 1×10^{-3} seconds after the transmitter is turned on (left, middle, and right, respectively). We use the basic geometry and parameters depicted in Figure 2 with a homogeneous seafloor ($\sigma_2 = 0.1$ S/m). The receiver location is indicated by the pink asterisk. A) Horizontal field for a horizontal loop transmitter. B) Horizontal field for a vertical loop transmitter whose axis is aligned with the x-axis. C) Vertical field for a vertical loop transmitter whose axis is aligned with the x-axis.

Figure 4: Snapshots in cross section view of the electric field magnitude at 5×10^{-5}, 3×10^{-4}, and 1×10^{-3} seconds after the transmitter is turned on. We use the basic geometry and parameters depicted in Figure 2 with a homogeneous seafloor ($\sigma_2 = 0.1$ S/m). The cross section is taken on a line between the transmitter location and the receiver location, indicated by the pink asterisk. A) Horizontal field for a horizontal loop transmitter. B) Horizontal field for a vertical loop transmitter whose axis is aligned with the x-axis. C) Vertical field for a vertical loop transmitter whose axis is aligned with the

x-axis.

Figure 5: Plots of electric field magnitude modeled using the basic geometry depicted in Figure 2, with fixed depth to ($d_1 = 5$ m) and thickness of ($d_2 = 10$ m) the target layer. Electric field transients are plotted for targets with conductivities of 0.001, 0.01, 1, and 10, S/m, 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 gray line. A) Horizontal field for a horizontal loop transmitter. B) Horizontal field for a vertical loop transmitter whose axis is aligned with the x axis. C) Vertical field for a vertical loop transmitter whose axis is aligned with the x axis.

Figure 6: 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 ($\sigma_2 = 10$ S/m). Electric field transients are plotted for various target layer burial depths, d_1, 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 gray line. A) Horizontal field for a horizontal loop transmitter, with burial depths of 0 - 50 m at 5 m intervals. B) Horizontal field for a vertical loop transmitter whose axis is aligned with the x axis, with burial depths of 0 - 50 m at 10 m intervals. C) Vertical field for a vertical loop transmitter whose axis is aligned with the x axis, with burial depths of 0 - 50 m at 5 m intervals.

Figure 7: Plots of electric field magnitude modeled using the basic geometry depicted in Figure 2, with fixed target layer burial depth ($d_1 = 5$ m) and conductivity ($\sigma_2 = 10$ S/m). Electric field transients are plotted for various target layer thicknesses, d_2, 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 gray line. A) Horizontal field for a horizontal loop transmitter, with thicknesses of 5 - 35 m at 5 m intervals. B) Horizontal field for a vertical loop transmitter whose axis is aligned with the x axis, with thicknesses of 1, 5, 10, and 15 m. C) Vertical field for a vertical loop transmitter whose axis is aligned

with the x axis, with thicknesses of 1, 5, 10, and 15 m.

Figure 8: A) The horizontal loop transmitter, and B) a dipole receiver used in the experiment at the Palinuro volcanic complex.

Figure 9: Map of the transmitter (TX) and receiver (RX) locations in the experiment at the Palinuro volcanic complex. Locations of shallow drill holes containing massive sulfides are indicated by the green diamonds. Bathymetry of the seamount is indicated by the black contours.

Figure 10: Horizontal electric field transients from the experiment at the Palinuro volcanic complex recorded by receiver 11 (see figure 9 for receiver and transmitter locations). Transients are plotted with their timescales normalized by the time constant, τ. Transient amplitudes are multiplied by the square of the 3D transmitter-receiver separation distance. Red lines indicate forward modeling of the horizontal electric field using the basic geometry depicted in figure 2 with a seawater conductivity of 4.6 S/m and a background seafloor conductivity of 0.1 S/m. A) Target layer is 10 m thick with 5 m burial depth and conductivity is varied. B) Target layer is 10 m thick with a conductivity of 10 S/m and burial depth is varied. C) Target layer has a conductivity of 10 S/m and a burial depth of 5 m and the layer thickness is varied.

Figure A1: Coordinate system used throughout this derivation.

Figure A2: The electric (E) and magnetic (B) fields produced by a horizontal magnetic dipole in a uniform media.