ELECTRICAL AND ELECTROMAGNETIC METHODS FOR SUBMARINE MASSIVE SULFIDE EXPLORATION: A CASE STUDY OF THE PALINURO SEAMOUNT, TYRRHENIAN SEA

by

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ABSTRACT

Recent years have seen increasing interest in exploring for mineral resources on the seafloor. I examine the capabilities of two geophysical methods in exploring for and characterizing seafloor massive sulfide (SMS) deposits: the electromagnetic (EM) and the self-potential (SP) methods.

Working with a team from the Helmholtz Center for Ocean Research Kiel (GEOMAR) in Germany, I carried out a first test of a new marine EM configuration consisting of a towed-loop inductive source transmitter and remote ocean-bottom electric dipole receivers. The system was tested at the Palinuro Seamount, offshore Italy, where shallowly buried massive sulfides had previously been recovered from drill cores. Data from the first test of this EM configuration were collected using a horizontal loop transmitter, and analysis of the data found higher apparent conductivities when the transmitter was in proximity to the zone of known mineralization, suggesting that the buried massive sulfides were detected by the system. I also carried out 3D forward modeling which suggests that this configuration is sensitive to a shallowly buried conductive target of dimensions consistent with the drilling zone at a remote receiver up to $\sim 100$ m away from the transmitter when the target is located in line between the transmitter and receiver.

I used both 1D and 3D forward modeling to compare the sensitivity of a horizontal loop transmitter vs a vertical loop transmitter in the marine EM configuration. The horizontal loop was found to be more sensitive than the vertical loop to the thickness of the target, which is advantageous in attempting to characterize the depth extent of mineralization. The vertical loop is more sensitive than the horizontal loop to a resistive target, such as a gas hydrate deposit. The vertical loop is also less affected by changes in the transmitter towing depth caused by the bathymetry of the field area.
In addition to EM, I investigated the SP method in exploring for SMS deposits. A test of a marine SP system consisting of two perpendicular electrode pairs towed above the seafloor was carried out at the Palinuro study area. To my knowledge this was the first test of a marine SP system at a buried SMS site. The SP data showed elevated electric field strengths on the order of 1–3 mV/m over the zone of known mineralization, demonstrating that a shallowly buried massive sulfide occurrence can be detected by a marine SP system.

My results show that both the marine SP and EM methods have applications in the exploration for SMS occurrences. Furthermore, data collected with the EM and SP systems both suggest that the mineralization at Palinuro extends southward of the drilling zone by \(\sim 40\) m, which demonstrates that these methods are not only useful in detecting SMS deposits, but in characterizing their size and geometry as well.
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LIST OF SYMBOLS

Radius of loop transmitter ........................................... \( a \)
Apparent conductivity scaling constant ................................ \( c \)
Layer thickness .......................................................... \( d \)
Total horizontal electric field magnitude ................................. \( E_h \)
X (northward) component of electric field ............................... \( E_x \)
Y (eastward) component of electric field ................................ \( E_y \)
Z (vertical) component of electric field .................................. \( E_z \)
Tangential component of electric field .................................. \( E_\phi \)
Transmitter current ......................................................... \( I \)
Bessel function of the first kind ......................................... \( J_1 \)
Vertical current density .................................................. \( J_z \)
Mean of apparent conductivities .......................................... \( m \)
3D distance from transmitter .............................................. \( R \)
2D horizontal distance from transmitter .................................. \( r \)
Laplace variable, standard deviation ..................................... \( s \)
Z-score ............................... .......................... \( Z \)
Hankel variable ........................................................... \( \lambda \)
Magnetic permeability of free space .................................... \( \mu_0 \)
Electrical conductivity .................................................... \( \sigma \)
Electromagnetic diffusion time constant .................................. \( \tau \)
LIST OF ABBREVIATIONS

Controlled Source Electromagnetic .............................. CSEM
Electromagnetic ..................................................... EM
Marine Transient Electromagnetic System ....................... MARTEMIS
Remotely Operated Underwater Vehicle .......................... ROV
Receiver ............................................................... RX
Seafloor Massive Sulfide ........................................... SMS
Self-potential .......................................................... SP
Trans-Atlantic Geotraverse ......................................... TAG
Transverse Electric .................................................... TE
Transient Electromagnetic .......................................... TEM
Transverse Magnetic .................................................. TM
Transmitter ............................................................ TX
Volcanogenic Massive Sulfide ....................................... VMS
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CHAPTER 1
INTRODUCTION

In recent years, the number of new discoveries of base and precious metal resources has decreased, while known deposits continue to be depleted through active mining [1, 2]. At the same time, interest has increased in exploring for mineral resources on the seafloor. Among these resources, seafloor massive sulfide (SMS) occurrences are of particular interest as they are often enriched in both base and precious metals [3]. At least 237 SMS occurrences have been identified to date throughout the world’s oceans [4, 5], many of which are enriched in Pb, Zn, Cu, Ag and Au.

Volcanogenic massive sulfide (VMS) deposits found on land, which are often mined for base and precious metals, are actually ancient SMS deposits which originally formed in a marine environment. These onshore VMS deposits account for approximately 50% of the world’s zinc production, 40% of lead production, and 15% of copper production [3]. In contrast, the majority of discovered marine SMS sites are too small to be economically exploited. Hannington et al. [6] have estimated that active SMS deposits globally could contain up to 600 Mt of ore, including 30 Mt Cu. By comparison, the total global production of Cu in 2015 is estimated at 19.1 Mt [7]. While it seems unlikely that production from marine sources will ever parallel that of land-based production, a few larger sites such as the Solwara 1 resource in the Bismark Sea may have economic potential [8]. In addition, most of the SMS occurrences identified to date are associated with active hydrothermal venting; the economic potential of fully mature inactive sites that are buried under sediment is possibly higher than that of the younger active sites [9]. Exploration for SMS deposits of base and precious metals thus remains an interesting problem.

It is much easier to identify hydrothermally-active SMS occurrences than inactive ones. The presence of hydrothermal fluids at active sites produces chemical traces which can be
detected in the water column using marine geochemical methods, and subsequent seafloor surveys can then be used to identify nearby massive sulfide mounds or chimney structures [10]. However, mining at SMS deposits associated with active hydrothermal venting raises environmental concerns: these sites are home to isolated ecosystems of unique chemosynthetic organisms [11]. A more environmentally friendly strategy would be to exploit older SMS occurrences which are no longer hydrothermally active or associated with a vent ecosystem. Inactive sites cannot be detected in the water column and are typically buried under layers of hemipelagic or pelagic sediment; thus geophysical methods are necessary to explore for and characterize these sites.

SMS deposits have several distinguishing petrophysical properties: they are denser than typical host rock, they are often highly electrically conductive, and alteration of the host rock at SMS sites causes magnetite destruction, resulting in magnetic lows over the deposits [10]. Magnetic and electromagnetic (EM) methods are both well suited tools which have been applied in the search for SMS deposits in various settings around the world [eg. 10, 12–20].

EM methods work by producing a primary time-varying electric and magnetic field and then measuring the diffusive electric fields or secondary magnetic fields associated with eddy currents induced within nearby conductive material. These data are then interpreted to make inferences about the electrical conductivity structure of the seafloor. In the case of SMS deposits, the target typically has a much higher conductivity than the surrounding unmineralized host rock [21] and can thus be detected with EM methods.

Another electrical method which shows some promise at detecting SMS occurrences is the self-potential (SP) method. This passive source method detects naturally occurring highs and lows in the electrical potential. On land, massive sulfide deposits are often associated with SP anomalies [62]. When the redox potential is higher at the top of a buried conductive ore body, electrons flow from the bottom to the top of the ore body and produce a build up of charges much like in a galvanic cell. This results in a local low in the electrical potential above the ore body. The SP method has been shown to work in marine environments;
both graphite and massive sulfide bodies have been detected by marine SP systems [22–25]. However, prior to this study, marine SP had not been tested at a buried, inactive SMS site.

For my dissertation project I have chosen to focus on investigating the potential of both EM and SP methods in exploring for and characterizing SMS occurrences. In addition to theoretical modeling studies, this project includes analysis of both EM and SP data collected at the Palinuro Seamount in the Tyrrhenian Sea, offshore Italy (Figure 1.1). Minor amounts of hydrothermal activity have been detected at Palinuro [26–28], but no active chimneys have been discovered. The western part of the seamount hosts a known SMS site. This mineralization was first sampled by Minniti and Bonavia [29], and Petersen et al. [30] later carried out shallow drilling at the site to a maximum depth of 4.85 m. Massive sulfides were recovered from 11 drill holes and were typically buried under several meters of sediment. Thus Palinuro makes a good site for testing geophysical methods in detecting and characterizing buried SMS mineralization in the absence of high-temperature hydrothermal venting. Previous geophysical data sets collected at the Palinuro test site include detailed bathymetry, gravity, magnetics, and sonar backscatter reflectivity [15, 16], but electrical and electromagnetic methods had not been attempted prior to this study.

My project focuses on testing a new EM configuration which had not previously been attempted in a marine setting. The configuration, referred to hereafter as the “Coil2Dipole”, consists of an inductive source loop transmitter and coincident-loop receiver that are towed behind a ship, and remote electric dipole receivers placed on the seafloor throughout the area of interest. An on-board altimeter is used to maintain the transmitter height at an altitude of 5 – 10 m above the seafloor. Transmissions are made at various sites as the transmitter is towed around the study area. These transmissions are recorded by the remote dipole receivers. The dipole receivers consist of two pairs of perpendicular arms 10 m long with Ag-AgCl electrodes on each end which measure both horizontal components of the electric field. This configuration is advantageous because the data from the towed EM system are most sensitive to the seafloor conductivity structure directly below the transmitter and can
Figure 1.1: Map of the location of the Palinuro Seamount in the Tyrrhenian Sea, modified after Petersen et al. [30]
be used to pinpoint the location of targets, while the data from the remote receivers on the seafloor are more broadly sensitive to the conductivity structure of the entire study area, and are also sensitive to greater depths due to the transmitter-receiver offset distance. Combined together, these two data sets can provide a more complete picture of the study area than could be obtained by using only a towed EM system. In my project, I focus on the data acquired by the remote receivers in the Coil2Dipole configuration.

1.1 Overview of Thesis

My thesis consists of three papers, two of which have been published in Geophysics, and one which has been submitted to Geophysical Prospecting and is in review at the time of writing this document.

The first paper included in this thesis document studies the capabilities of the Coil2Dipole configuration using 1D forward modeling [31]. For a horizontal loop transmitter, the method described in Swidinsky et al. [32] is used to calculate the electric field magnitude at a seafloor receiver 100 m away from the transmitter for a variety of 1D models containing a buried conductive layer. A method for calculating the electric fields from a vertical loop transmitter is also derived. The sensitivity of the horizontal and vertical loop configurations to target layers of varying conductivity, thickness, and burial depth are then compared using these 1D forward modeling methods.

The second paper in this thesis examines the Coil2Dipole configuration using 3D forward modeling. A 3D time-domain EM code developed at the University of British Columbia is used to model the bathymetry of the Palinuro study area, and a shallowly buried conductive target block is included in the model in the same area where massive sulfides were recovered from the drill cores. The sensitivity of both a horizontal and vertical loop transmitter is tested against two variables which could not be examined by 1D modeling: the lateral extents of the target block, and the distance of the transmitter from the edge of the target. The use of 3D modeling also allows us to visualize how bathymetry affects the diffusion of the electric fields across the seafloor surface. This paper includes a preliminary analysis of
data collected by the first test of the Coil2Dipole system at the Palinuro Seamount. The
data are examined with an apparent conductivity method and compared to 3D models with
a range of target block extents.

The final paper in this thesis examines SP data collected at the Palinuro study area [33]. Two perpendicular pairs of electrodes towed behind a ship at an altitude of 5 m were used to collect measurements of the naturally occurring electric fields close to the seafloor. The use of two perpendicular pairs of electrodes allows the total horizontal component of the electric field to be calculated, unlike most traditional marine SP experiments which use a single towed line of electrodes. The data collected in this novel experiment show that a zone of high electric field strength correlates well with the location of known massive sulfides from the drill cores. A second zone of high electric fields to the north of the drilling area is also identified in the data; the presence of massive sulfides at this site was later confirmed by the collection of a gravity core sample.

This dissertation project examines how marine EM and SP methods can be applied in exploring for and characterizing SMS occurrences. These geophysical tools have the potential to assist in identifying SMS mineralization that is hydrothermally inactive and buried under sediment. EM and SP methods can also provide valuable data in characterizing the size and depth extent of known SMS occurrences to make inferences about their economic potential. The data and modeling presented in this thesis demonstrate some of the capabilities and limitations of these methods as applied to marine mineral exploration.
CHAPTER 2
LITERATURE REVIEW

This review of relevant literature is divided into four subsections: SMS and VMS deposits, marine EM methods, marine SP methods, and the geological setting of the Palinuro Seamount.

2.1 SMS and VMS Deposits

SMS deposits are the modern-day analogue of the ancient VMS deposits found on land. Onshore VMS deposits are a major source of global production of Pb, Zn, Cu, Ag and Au, with over 800 economically viable VMS sites discovered worldwide [3, 34]. An excellent review of the tectonic and geochemical processes which form VMS deposits is given by Franklin et al. [35]. While global demand for base and precious metal continues to increase, the discovery rate and development cost of metal production on land has decreased over the past several decades [1]. There has thus been speculation that SMS deposits could potentially provide an additional resource of the base and precious metals which are vital to the global economy.

SMS deposits occur primarily in three tectonic settings associated with submarine volcanism: mid-ocean ridges, back-arc basins, and submarine volcanic arcs and related rifts [36]. These deposits form when hot hydrothermal fluids rise up through the crust and mix with cold seawater, precipitating polymetallic massive sulfides at or near the seafloor surface [3]. Detailed reviews of the anatomy and formation processes of SMS deposits have been written by Herzig and Hannington [37] and Herzig [38].

There is disagreement as to the actual economic potential of SMS resources. It has been estimated that SMS deposits worldwide may contain up to 30 million tons of Cu and Zn [6]. A few of the discovered SMS sites may be large enough to be economically extracted, such as the Solwara 1 deposit in the Bismark Sea [8]. However, Petersen et al. [9] argue
that most of the currently discovered SMS occurrences are too small to individually be of economic interest. Aside from base and precious metal resources, the minor element content of SMS deposits is estimated to be small [5].

The majority of currently discovered SMS occurrences are at geologically young, hydrothermally active sites [36]. The potential for additional resources in buried, inactive sites which are larger and geologically mature presents an incentive for continued exploration of SMS resources. Furthermore, mining at hydrothermally active SMS sites presents environmental concerns, as these sites are home to a number of unique chemosynthetic organisms [11, 39]. In contrast, inactive sites present fewer environmental concerns, as these sites are typically buried under sediment and do not host unique ecosystems. Exploring for inactive SMS deposits is more challenging than exploring for active sites; while active sites can be detected in bathymetry data and by chemical tracers in the water column, detection of inactive sites requires geophysical tools [10].

2.2 Marine EM Methods

Marine EM has been applied in the oil and gas industry; good reviews of marine EM for offshore hydrocarbon exploration have been written by Edwards [40], Constable and Srnka [41], and Constable [42, 43]. Yuan and Edwards [44] and Weitemeyer et al. [45, 46] cover the use of marine EM in detecting shallow gas hydrates for mitigating drilling hazards. More recently, interest has increased in using EM methods to explore for SMS deposits. Massive sulfides are more conductive than typical host rock [21, 47], and are thus well-suited for EM exploration methods.

Traditional marine EM systems have often used an electric dipole transmitter which is either towed behind a ship or attached to an ROV. In an early experiment on the application of marine EM to massive sulfide exploration, Wolfgram et al. [12] developed and tested a system consisting of a long vertical wire transmitter and magnetometer receivers placed on the seafloor to investigate a known SMS occurrence at the Juan de Fuca Ridge. Cairns et al. [13] tested a system consisting of a dipole transmitter and dipole receivers placed on
the seafloor by an ROV to investigate the conductivity structure of the TAG hydrothermal mound on the Mid-Atlantic Ridge.

In land-based exploration for minerals, airborne EM systems using an ungrounded transmitter coil as an inductive source have been used extensively. These systems are carried by either a helicopter or small airplane [48]. Marine EM systems which use an inductive source transmitter have also shown some success in detecting and characterizing SMS deposits. A Vancouver-based marine geophysical company, Ocean Floor Geophysics, developed a system with a vertical loop transmitter mounted on an ROV and a dipole receiver which measures the current density below the loop. This system was used to map the Solwara 1 deposit in the Bismark Sea [10, 49], and the data acquired was used by Nautilus Minerals in making the case for the economic potential of the deposit [8]. Lee et al. [50] used an ROV-mounted concentric-loop system to detect a metal rod placed on the seafloor. The BGR-developed GOLDEN EYE system, an in-loop EM system which is lowered from a ship and placed on the seafloor, successfully detected both active and inactive SMS sites at the Central Indian Ridge [20, 51]. The GEOMAR MARTEMIS system, a ship-towed coincident-loop system, was tested over known SMS mineralization at the Palinuro Seamount, offshore Italy [17, 31, 52]. Nakayama and Saito [18] and Asakawa et al. [19] tested an ROV-towed in-loop system with a magnetometer receiver at the Okinawa Trench and detected high conductivities over a known SMS site. Endo et al. [53] recently tested a coincident-loop system towed by an ROV over an SMS site off the coast of Japan.

To our knowledge, the "Coil2Dipole" configuration described in Chapter 1, consisting of an inductive source transmitter and remote dipole receivers, has not yet been tested in a marine setting. However, a system with a similar configuration has been tested on land by Macnae et al. [54–56], who used a large ungrounded wire loop transmitter and an array of grounded electric dipole receivers to successfully detect mineralization at the Gidginbung gold mine in Australia. However, loop or magnetometer receivers are more typically used in EM surveys on land because in many geologic settings, contact resistance is very high. This
is not an issue in a marine setting, as electrodes couple well with seafloor when immersed in salty conductive seawater.

Mathematical modeling has also been employed in predicting the capabilities and limitations of marine EM systems. Cheesman et al. [57] derived double halfspace solutions for a variety of marine EM configurations with both electric and magnetic dipole transmitters and receivers. Evans and Everett [58] use 2D forward modeling to examine the potential to detect marine SMS deposits with EM methods. Chave [59] derived a 1D forward modeling method to calculate the electric and magnetic fields produced by a vertical or horizontal electric or magnetic dipole source in the frequency domain. Swidinsky et al. [32] derived a 1D forward modeling method for a concentric or in-loop marine EM system in the time domain. Jang and Kim [60] developed a 1D method to model the magnetic fields from both a horizontal and vertical in-loop system in the time domain. Safipour et al. [31] derived a 1D forward modeling method for a time domain system with either a horizontal or vertical transmitter and remote dipole receivers.

2.3 Marine SP Methods

The SP method has been a successful tool in land-based mineral exploration, with anomalies of up to -10 V being discovered in association with some deposits [61]. The most widely accepted explanation for SP anomalies on land is a stratification of the redox potential caused by the water table bisecting conductive mineralization, resulting in a flow of electrons from the bottom to the top of the orebody [62]. While a water table is not present in a marine setting, stratification of the redox potential in the upper layers of marine sediment has been observed [22], so the presence of an SP anomaly at a conductive SMS deposit is possible. In addition, streaming potentials and corresponding SP anomalies can be caused by groundwater flow and hydrothermal circulation [63]; the latter is a common feature at active SMS sites.

Very few experiments with marine SP systems have been carried out. Corwin [22] tested a system consisting of two electrodes towed behind a ship off the coast of Maine and detected
anomalies of up to -300 mV above known mineralized zones. Von Herzen et al. [64] collected SP measurements with both vertical and horizontal electrode pairs towed behind an ROV at the TAG hydrothermal mound. Heinson et al. [23, 24] tested a system consisting of a line of towed electrodes off the coasts of Australia and California. Beltenev et al. [25, 65], Cherkashov et al. [66], and Shilov et al. [67] all used a ship-towed systems to detect SP anomalies at known SMS sites on the Mid-Atlantic Ridge. Cherkashev et al. [68] also found SP anomalies in association with massive sulfides at the Mid-Atlantic Ridge where no hydrothermal activity was present. Safipour et al. [33] carried out a test of a towed two-component SP system over an SMS site that is both inactive and buried under sediment, where anomalous electric field strengths of up to 3 mV/m were recorded above and in proximity to the zone of known SMS mineralization.

2.4 The Palinuro Seamount

The study area where we tested both our EM and SP systems is the Palinuro Seamount in the Tyrrhenian Sea, offshore Italy. This volcanic seamount, located at the northern end of the Aeolian Volcanic Arc, was formed during subduction and subsequent rollback of the Adriatic-Ionian slab, although Colantoni et al. [69] argue that Palinuro may in fact be part of a transcurrent E-W fault system which extends into Italy rather than a northern extension of the Aeolian Arc. Detailed tectonic histories of the region have been written by Kastens and Mascle [70] and Argnani and Savelli [71].

Detailed bathymetric data collected at the Palinuro study area indicate what appears to be a collapsed volcanic caldera in the western part of the seamount [16, 72]; this caldera zone is the focus of our studies. Magnetic surveys have shown that zones of hydrothermal alteration at Palinuro are associated with magnetic lows, as hydrothermal fluids cause magnetite destruction in the host rock [15, 16, 73, 74]. The zone of known SMS mineralization is similarly associated with a magnetic low [74]. Demagnetized zones also occur in a circular pattern around the caldera walls, leading to speculation of ring faults around the caldera which led to its collapse [15, 16, 73]. Gravity and seafloor backscatter reflectivity data data
indicate that hydrothermal alteration at Palinuro is associated with reduced rock densities and increased seafloor roughness [16].

Massive sulfide samples were first discovered in the western part of the Palinuro Seamount by Minniti and Bonavia in 1984 using gravity coring [29]. Petersen et al. [30] later carried out shallow drilling several km to the east, within the volcanic caldera where this study is focused. 11 drill holes yielded a total of 13.5 m of core, with the deepest hole penetrating 4.85 m into the seafloor. The drill cores confirmed the presence of massive sulfides and also indicated that the mineralization was typically buried under several meters of volcaniclastic sediment.

Chimneys and active hydrothermal venting have never been detected at Palinuro, although diffuse seepage of hydrothermal fluids at the site is indicated by chemical tracers in the water column [27] and by the presence of tubeworm colonies [28]. The lack of black-smoker type hydrothermal activity makes Palinuro a good test site for the exploration of buried SMS deposits that are not associated with high-temperature venting.
CHAPTER 3
ON ELECTRIC FIELDS PRODUCED BY INDUCTIVE SOURCES ON THE SEAFLOOR

Roxana Safipour, Sebastian Hölz, Marion Jegen, Andrei Swidinsky

3.1 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.

### 3.2 Introduction

In a marine setting, electromagnetic systems have been applied successfully in exploring for oil and gas reserves (see [42] for a review), gas hydrates [44, 45, 75–77], and submarine massive sulfide (SMS) deposits [8, 10, 13, 17, 20, 78, 79]. SMS deposits contain valuable resources of Cu, Pb, Zn, Au, and Ag [3], and some of these deposits, such as the Solwara 1 deposit in the Bismark Sea [8], 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. [57] showed that such systems could theoretically detect changes in seafloor conductivity in a marine setting. More recently, Swidinsky et al. [32] 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 [60] 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. [14] 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. [17] 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 [18] and Asakawa et al. [19] both used an ROV-mounted system to detect high conductivities at known SMS deposits in the Okinawa hydrothermal area. Their system consisted of a horizon-
tal 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 [44, 45, 75–77].

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. [17, 79]). 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. [12] 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. [77] 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 [55, 56]. 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 \( \sim 10 \text{ m} \) 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 (Figure 3.1). 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. [17] 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 (Figure 3.1). 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.

### 3.3 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 [80]. 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 [81]. Swidinsky et al. [32] 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, $E_\phi$, 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. [32] equation A-13:

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

(3.1)

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:

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

(3.2)

and

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

(3.3)

where $\theta_i$ is defined as $\sqrt{\lambda^2 + s\mu_0\sigma_i}$ for the $i$th seafloor layer, $\theta_j$ is defined as $\sqrt{\lambda^2 + s\mu_0\sigma_j}$ for the $j$th seawater layer, $d_i$ and $d_j$ denote the thickness of each layer, $\sigma_i$ and $\sigma_j$ denote the conductivity of each layer, $\mu_0$ 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 [32]. The parameter $L_i^F$ is the "ladder operator" which must be repeatedly applied as a product:

$$L_i^F = \frac{\theta_i-1 F_{i-1} \text{sech}(\theta_i-1 d_i-1)}{\theta_i-1 F_i + \mu_0 \tanh(\theta_i-1 d_i-1)}$$

(3.4)
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 [81]. 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 \( \phi \), 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:

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

\((3.5)\)

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

\((3.6)\)
\[ J_z(r, \phi) = -\frac{\mu_0 I a^2}{2} \sin(\phi) \int_0^\infty \left( \frac{1}{U_1 + V_1} \right) \prod_{i=1}^{K} L^U_i \lambda^2 J_1(\lambda r) d\lambda \quad (3.7) \]

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):

\[
U_i = \frac{\theta_i}{\sigma_i} \left[ \frac{\sigma_i U_{i+1} + \theta_i \tanh(\theta_i d_i)}{\theta_i + \sigma_i U_{i+1} \tanh(\theta_i d_i)} \right] \qquad (3.8)
\]

\[
V_j = \frac{\theta_j}{\sigma_j} \left[ \frac{\sigma_j V_{j+1} + \theta_j \tanh(\theta_j d_j)}{\theta_j + \sigma_j V_{j+1} \tanh(\theta_j d_j)} \right] \qquad (3.9)
\]

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:

\[
L^U_i = \frac{\theta_{i-1} \text{sech}(\theta_{i-1} d_{i-1})}{\theta_{i-1} + \sigma_{i-1} U_i \tanh(\theta_{i-1} d_{i-1})} \quad (3.10)
\]

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 \( L^U_1 \equiv 1 \) (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 3.1 for the horizontal loop is derived from a finite horizontal loop current source, equations 3.5 – 3.7 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 $\mu_0$ 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.

### 3.4 A Forward Modeling Study

Using equations 3.5 – 3.7, 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 whitespace derived by Ward and Hohmann [82]. Next we
chose a simple layered model of the seafloor. Our model (Figure 3.2) 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 [80], with the field attenuating as it
spreads outward and downward from the transmitter site (Figure 3.3a). 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 (Figure 3.3b), while the vertical field, $E_z$, is strongest at locations
Figure 3.2: 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.
perpendicular to the loop axis (Figure 3.3c).

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 (Figure 3.4a). 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 (Figure 3.4b). $E_z$ 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 (Figure 3.4c).

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 $37^\circ$ 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 (Figure 3.5a) 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 (Figure 3.5b) 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,
Figure 3.3: Snapshots in map view of the electric field magnitude at $5 \times 10^{-5}$, $3 \times 10^{-4}$, and $1 \times 10^{-3}$ seconds after the transmitter is turned on (left, middle, and right, respectively). We use the basic geometry and parameters depicted in Figure 3.2 with a homogeneous seafloor ($\sigma_2 = 0.1 \text{ S/m}$). 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 3.4: Snapshots in cross section view of the electric field magnitude at $5 \times 10^{-5}$, $3 \times 10^{-4}$, and $1 \times 10^{-3}$ seconds after the transmitter is turned on. We use the basic geometry and parameters depicted in Figure 3.2 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.
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 Figure 3.5b. 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 (Figure 3.5c) 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 (Figure 3.6a) is sensitive to the target burial depth up to $\sim 50$ 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 3.6b) 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 (Figure 3.6c) 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
Figure 3.5: Plots of electric field magnitude modeled using the basic geometry depicted in Figure 3.2, 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 \(2 \times 10^{-8}\) 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.
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 (Figure 3.7a) is sensitive to the target layer thickness up to $\sim30$ m, while both $E_h$ and $E_z$ for the vertical loop system (Figure 3.7b and c) are only sensitive up to $\sim10$ m thickness. With $E_h$ for the vertical loop system we see similar behavior as in Figure 3.5b: 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.

### 3.5 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 [29] at a depth of $\sim650$ m. Shallow drilling carried out by Petersen et al. [30] 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 [15, 16], 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 (Figure 3.8a). The receivers consisted of two perpendicular arms 10 m in length with Ag-AgCl electrodes on the ends (Figure 3.8b). 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
Figure 3.6: Plots of electric field magnitude modeled using the basic geometry depicted in Figure 3.2, 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 ($2 \times 10^{-8}$ 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 3.7: Plots of electric field magnitude modeled using the basic geometry depicted in Figure 3.2, 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 ($2 \times 10^{-8}$ 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.
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 [17]. 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.

![Image](image_url)

Figure 3.8: The horizontal loop transmitter, and B) a dipole receiver used in the experiment at the Palinuro volcanic complex.

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 (Figure 3.9). 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 \( \sigma \) 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 effect 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 $\sim 7^\circ$ 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 (Figure 3.10). 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 3.2 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 (Figure 3.10a), 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 (Figure 3.10b), 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 (Figure 3.10c), 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
Figure 3.9: A map of the transmission sites (blue circles) and the locations of receivers RX09 and RX11 (red crosses). The zone of previously-drilled massive sulfide mineralization is indicated by the green square. Bathymetry is indicated by the black contours.
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.

3.6 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.
Figure 3.10: 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, $\tau$. 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.
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.

3.7 Acknowledgments

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CHAPTER 4
A FIRST APPLICATION OF A MARINE INDUCTIVE SOURCE EM
CONFIGURATION WITH REMOTE ELECTRIC DIPOLE RECEIVERS: LESSONS
LEARNED FROM 3D FORWARD MODELING

A paper submitted to *Geophysical Prospecting*
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4.1 Abstract

We study a new marine electromagnetic configuration which consists of a ship-towed inductive source transmitter and a series of remote electric dipole receivers placed on the seafloor. The approach was tested at the Palinuro Seamount in the southern Tyrrhenian Sea, at a site where massive sulfide mineralization has been previously identified by shallow drilling. A 3D model of the Palinuro study area was created using bathymetry data, and forward modeling of the electric field diffusion was carried out using a finite volume method. These numerical results suggest that the remote receivers can theoretically detect a block of shallowly-buried conductive material at up to $\sim 100$ m away when the transmitter is located directly above the target. We also compared the sensitivity of the method using either a horizontal loop transmitter or a vertical loop transmitter and found that when either transmitter is located directly above the mineralized zone, the vertical loop transmitter has sensitivity to the target at a farther distance than the horizontal loop transmitter in the broadside direction by a few 10s of meters. Furthermore, the vertical loop transmitter is more effective at distinguishing the seafloor conductivity structure when the vertical separation between transmitter and receiver is large due to the bathymetry. As a horizontal transmitter is logistically easier to deploy, we conducted a first test of the method with a horizontal transmitter. Apparent conductivities are calculated from the electric field transients recorded at the remote receivers. The analysis indicates higher apparent seafloor conductivities when
the transmitter is located near the mineralized zone. Forward modeling suggests that the best match to the apparent conductivity data is obtained when the mineralized zone is extended southward by 40 m beyond the zone of previous drilling. Our results demonstrate that the method adds value to the exploration and characterization of seafloor massive sulfide deposits.

4.2 Introduction

Seafloor massive sulfide (SMS) deposits are a potential source of base and precious metal resources, and lately interest in exploring for and economically exploiting these deposits has been increasing [10]. Transient electromagnetic (TEM) and controlled-source electromagnetic (CSEM) surveys have both played a role in the exploration and investigation of these marine mineral resources. Marine TEM methods typically employ an inductive source loop transmitter and coincident or in-loop receiver that is either mounted on a remotely operated vehicle (ROV) or towed behind a ship. Marine TEM systems have been applied to detecting and characterizing SMS deposits [10, 17–19]. Marine CSEM systems typically employ a ship-towed electric dipole transmitter and electric dipole receivers placed on the seafloor. Marine CSEM methods have been successfully applied in detecting and characterizing SMS deposits and other small targets [12, 13], oil and gas reserves (see [42] for a review), and gas hydrates [44, 45, 75–77, 79, 83].

We describe a new marine EM configuration which combines the advantages of TEM and CSEM systems. TEM systems with the receiver either coincident or concentric to the transmitter are primarily sensitive to the seafloor conductivity structure directly below or close to the system, which is a useful property when attempting to pinpoint the location of a small target. Conversely, a CSEM system with an array of remote dipole receivers covering the area of interest has a broader sensitivity to the structure of the seafloor throughout the survey area. It should also be noted that CSEM systems use galvanic (electric dipole) sources as opposed to inductive (magnetic dipole) sources, and based on the different underlying physics, have different sensitivity to subsurface structure. Our configuration, referred to as
“Coil2Dipole”, consists of a transmitter and coincident receiver loop towed behind a ship and an array of dipole receivers placed on the seafloor (Figure 4.1) [31]. The data recorded by the towed receiver loop provide narrowly-sensitive data along the towing path, while the remote receivers provide data which are broadly sensitive to the conductivity structure of the whole survey area. In addition, the remote receivers are sensitive to greater depths within the seafloor than the towed loop receiver, because of the effect of offset between transmitter and receiver. Thus the configuration has the capability to both pinpoint the location of small targets and detect additional targets which are not close enough to the towing path or too deep to be detected by a standard TEM system. Potential targets identified in the data from the remote receivers could then be investigated in detail by towing the system directly over them in a follow-up survey.

Figure 4.1: Illustration of the Coil2Dipole configuration, consisting of a horizontally suspended square frame housing a loop transmitter that is towed by a ship. Remote two-component electric dipole receivers are deployed on the seafloor.
Previously, a marine system which combines a self-contained towed system with remote receivers has been tested in gas hydrate exploration; Constable et al. [77] developed and tested a CSEM system consisting of a galvanic electric dipole transmitter and an array of self-contained 3-component dipole receivers towed behind a ship with additional stationary dipole receivers placed on the seafloor. A TEM system consisting of a loop transmitter and remote electric dipole receivers has been tested in land-based applications [55, 56]. However, to our knowledge, a system consisting of an inductive source transmitter and remote dipole receivers has not been tested in a marine setting prior to this study.

In a previous paper, we studied the theoretical capabilities of the Coil2Dipole configuration and briefly examined the remote receiver data from our first test of the configuration using a 1D forward modeling approach [31]. However, a more thorough interpretation of the data requires a 3D approach, as the bathymetry of the study area and the 3D nature of the SMS target are not considered in a 1D model. In this study we examine the theoretical capabilities of the Coil2Dipole configuration using 3D forward modeling. We compare the capabilities of the configuration using either a horizontal or vertical loop transmitter, and we examine the effect of the transmitter position relative to the edge of a buried conductive target body. Finally, we use an apparent conductivity method to interpret the data recorded by the remote receivers during the first test of the configuration.

4.3 A First Test of the Coil2Dipole Configuration

The transmitter of the Coil2Dipole configuration is a square frame 4.3 x 4.3 m containing two windings of wire with a current of 38 A that is suspended horizontally 15 m below a cubical container for the system electronics (Figure 4.2). The coincident-loop receiver and data logger are also affixed to the square frame. The transmitter is lowered off the back of the ship via an A-frame winch, and an on-board altimeter tracks the height of the system above the seafloor; during deployment the cable length is constantly adjusted to maintain the transmitter altitude between 5 – 10 m. Prior to deploying the frame, ocean-bottom receivers consisting of two perpendicular arms 10 m in length with Ag-AgCl electrodes on
the ends are deployed throughout the survey area (Figure 3.8b). The ocean-bottom receivers are affixed to a titanium frame with buoyant foam blocks and are kept on the seafloor by concrete slab anchors. When the survey is complete, acoustic pings are used to signal the receivers to release their anchors and float back to the surface where they can be recovered. The electric field transients recorded by the receivers are stacked to obtain a single transient decay curve for each transmission. The system electronics are described in detail by Hölz et al. [17].

Our first test of the Coil2Dipole configuration was carried out at the Palinuro Seamount in the Tyrrhenian Sea (Figure 1.1) during the research cruise POS483 (R/V Poseidon, Mar. 28 - Apr. 15, 2015). Massive sulfide samples were first discovered at Palinuro by Minniti and Bonavia [29] and shallow drilling carried out by Petersen et al. [30] recovered sulfides in 11 drill cores. The drill cores indicate that the massive sulfides are typically buried under several meters of mud, making Palinuro a good test site for the exploration of a shallowly buried deposit. Gravity, magnetic, sonar backscatter reflectivity, and detailed bathymetry data had previously been collected over the area of the sulfides [15, 16]. In addition, during the POS509 research cruise in February 2017, a self-potential experiment detected high natural electric field strengths over the massive sulfide mineralization [33], and heat flow data collected at the site indicated elevated seafloor temperatures over the known mineralization and extending ∼35 m southward [52]. Electromagnetic methods had not been tested at Palinuro prior to these cruises.

For the test at Palinuro, ocean-bottom receivers were deployed throughout the survey area; unfortunately, due to a failure of the data cards only two receivers recorded electric fields during the experiment, RX09 and RX11. The transmitter loop was lowered to a height of 5 – 10 m above the seafloor and towed past the site of the known SMS mineralization, and 84 transmissions were made along the towing path which were recorded by the two receivers (Figure 3.9). The separation distance between transmission sites and receivers ranged from 80 m to 300 m. Transients were recorded by both RX09 and RX11 for most of
Figure 4.2: A diagram of the Coil2Dipole transmitter.
the transmissions, though at some of the largest separation distances a transient could not be clearly identified in the data. A total of 111 transients of good quality were recorded by the remote receivers (Figure 4.3), while 57 of the transmitter-receiver combinations had too large of an offset for a transient to be detected. The orientation of the receivers’ electrode arms is arbitrary, however, since the electrode arms are perpendicular, we can calculate the magnitude of the total horizontal electric field, $E_h$, from the fields $E_1$ and $E_2$ recorded by the two electrode arms:

$$E_h = \sqrt{E_1^2 + E_2^2} \quad (4.1)$$

In this study, we work with the quantity described in equation 4.1 as the basic measurement of the Coil2Dipole configuration, and examine the data recorded by the remote receivers. An examination of the data from the coincident-loop receiver, known individually as the Marine Transient Electromagnetic (MARTEMIS) System, is covered by Hölz et al. [17].

4.4 A 3D Forward Modeling Approach

We gained access to a finite-volume 3D time-domain EM forward modeling code produced at the University of British Columbia [84]. Using this code we created a 3D block model of the Palinuro survey area using the bathymetry data (Figure 4.4). We assigned the seawater a conductivity of 4.6 S/m which is consistent with the seawater conductivity measured by CTD probe during the experiment. The seafloor conductivity was set to 1 S/m to represent host rock saturated with seawater. To include the effect of the sulfides, we placed a block with a conductivity of 10 S/m with dimensions 55 m x 35 m x 30 m thick buried at 5 m below the seafloor surface at the site of the previously drilled massive sulfide mineralization, indicated by the green square in Figure 3.9. The lateral dimensions of this block correspond to the extents of the area where massive sulfides were recovered from drill holes, however, the true lateral extents of the mineralization are unknown and could be larger, hence the
Figure 4.3: All transients recorded during the Coil2Dipole experiment at Palinuro by RX09 (blue curves) and RX11 (red curves).
purpose of the geophysical surveys in the area. The depth extent of the mineralization is also unconstrained by the drill holes. The burial depth of 5 m was chosen because the drill holes indicated the mineralization was buried under several meters of mud. We ran the forward model with a transmitter of 2 m radius and 50 A current located 10 m above the seafloor directly above the center of the buried conductive block.

Figure 4.4: 3D block model of the bathymetry of the Palinuro study area, created with an octree mesh using Geosoft software.

The electric fields were calculated at a grid of receivers on the seafloor surface spaced 50 m apart. In this way we were able to model and visualize how the total horizontal electric field moves outward from the transmitter across the seafloor topography for both a horizontal transmitter (Figure 4.5) and a vertical transmitter with the loop axis aligned in an E-W direction (Figure 4.6). While the actual experiment at Palinuro was conducted with only a horizontal loop transmitter, modeling both a horizontal and vertical transmitter allows us to make some theoretical inferences about the relative sensitivity of the two systems. The pattern of electric field diffusion across the seafloor is similar for both the vertical and
horizontal loop transmitters, although with a vertical transmitter the fields diffuse outward slightly faster in the direction broadside to the transmitter loop axis.

As a reference, we also modeled the horizontal electric field magnitude for a purely homogeneous seafloor. Figure 4.7 and Figure 4.8 show the absolute difference in horizontal electric field magnitude between the homogeneous seafloor model and the model containing the 10 S/m conductive mineralized block. To assess the detectability of the target by our instrumentation, we include a red contour line on the images that indicates a field strength of $2 \times 10^{-8}$ V/m, which is the approximate noise floor of our receivers. From the modeling we see that the system is sensitive to the presence of the conductive block at distances up to $\sim100$ m away from the target, and the vertical loop system is sensitive to a few 10s of meters farther distances than the horizontal loop system in the N-S direction. We next ran the models with the transmitter located 50 m to the east of the edge of the mineralized zone. The conductive block is still detectable, but now only at closer distances to the target ($\sim50$ m away), and the sensitivity appears about the same for both the horizontal and vertical loop transmitters. Finally, we ran the models with the transmitter located 100 m to the east of the edge of the mineralized zone (Figure 4.9 and Figure 4.10). For this case the conductive block is only detectable by a receiver located directly above the mineralized zone.

Safipour et al. [31] investigated the vertical bounds of detectability of a layered deposit using 1D analysis. With 3D modeling we can now extend this analysis to characterize lateral bounds of detectability. In particular, we examined the horizontal electric field transients for a horizontal transmitter with a 2 m radius and 50 A current at a receiver located on the seafloor directly centered over the buried conductive block. We model the conductive target block with lateral extents confined to the drilling zone (green square in Figure 3.9), and also with the eastern boundary of the conductive target extended by 20 m, 40 m, and 60 m and with the western boundary of the target extended by 20 m, 40 m, and 60 m. Figure 4.11c shows the transients when the transmitter is located 10 m above the seafloor 100 m to the east of the receiver. Due to the relatively flat bathymetry east of the target (Figure 4.11a),
Figure 4.5: Forward model of the diffusion of the total horizontal electric field magnitude across the bathymetry of the Palinuro study area at six timesteps after transmitter turn-off: horizontal loop transmitter, indicated by the pink asterisk, located directly above the center of the mineralized zone.
Figure 4.6: Forward model of the diffusion of the total horizontal electric field magnitude across the bathymetry of the Palinuro study area at six timesteps after transmitter turn-off: vertical loop transmitter, indicated by the pink asterisk, located directly above the center of the mineralized zone indicated by the pink asterisk.
Figure 4.7: Forward model of the absolute difference in the total horizontal electric field magnitude for a homogeneous seafloor model vs. the model which includes the conductive target block, displayed on the bathymetry of the Palinuro study area at six timesteps after transmitter turn-off: horizontal loop transmitter, indicated by the pink asterisk, located directly above the center of the mineralized zone. Red contour indicates the noise floor of the receivers used in the experiment at $2 \times 10^{-8}$ V/m.
Figure 4.8: Forward model of the absolute difference in the total horizontal electric field magnitude for a homogeneous seafloor model vs. the model which includes the conductive target block, displayed on the bathymetry of the Palinuro study area at six timesteps after transmitter turn-off: vertical loop transmitter, indicated by the pink asterisk, located directly above the center of the mineralized zone. Red contour indicates the noise floor of the receivers used in the experiment at $2 \times 10^{-8}$ V/m.
Figure 4.9: Forward model of the absolute difference in the total horizontal electric field magnitude for a homogeneous seafloor model vs. the model which includes the conductive target block, displayed on the bathymetry of the Palinuro study area at six timesteps after transmitter turn-off: horizontal loop transmitter, indicated by the pink asterisk, located 100 m to the east of the edge of the mineralized zone. Red contour indicates the noise floor of the receivers used in the experiment at $2 \times 10^{-8}$ V/m.
Figure 4.10: Forward model of the absolute difference in the total horizontal electric field magnitude for a homogeneous seafloor model vs. the model which includes the conductive target block, displayed on the bathymetry of the Palinuro study area at six timesteps after transmitter turn-off: vertical loop transmitter, indicated by the pink asterisk, located 100 m to the east of the edge of the mineralized zone. Red contour indicates the noise floor of the receivers used in the experiment at $2 \times 10^{-8}$ V/m.
the transmitter has a height of 10 m above the height of the receiver. The system cannot
distinguish between the case of the target confined to the drilling zone and the extension
of the target to the west, which is not a surprising result given that the system should be
mostly sensitive to the seafloor conductivity structure between the transmitter and receiver.
However, the system can distinguish between the drilling zone target and the target which is
extended to the east by 60 m, as the difference in amplitude of the transient is greater than
the approximate measurement error of the receivers at $2 \times 10^{-8}$ V/m. Figure 4.11d shows
the transients when the transmitter is located 10 m above the seafloor 100 m to the west
of the receiver. The bathymetry is uphill to the west of the target (Figure 4.11b), so the
transmitter now has a height of 40 m above the height of the receiver, and the burial depth
of the target increases to the west. In this case, the system cannot distinguish between the
conductive block confined to the drilling zone and the conductive block that is extended to
the west. The increased target burial depth and increased height of the transmitter above
the receiver, both resulting from the bathymetry, are likely factors that cause the system to
be less sensitive to the changes in the target boundaries when the transmitter is west of the
target, as opposed to when it is east of the target.

We also examine the horizontal electric field transients for a vertical loop transmitter
with its axis aligned in an E-W direction with a 2 m radius and 50 A current at a receiver
located on the seafloor directly centered over the buried conductive block. Figure 4.11e shows
the transients for the case when the transmitter is located 10 m above the seafloor 100 m
east of the receiver, and Figure 4.11f shows the transients for the case when the transmitter
is located 10 m above the seafloor 100 m west of the receiver. Unlike with the horizontal
transmitter, the system can now distinguish between the conductive target that is confined
to the drilling zone and the target that is extended to the west when the transmitter is
located 100 m west of the receiver, and the system does a better job of distinguishing the
various eastward target extensions when the transmitter is located 100 m east of the receiver.
This suggests that the vertical transmitter is less sensitive to the effects of the underlying
Figure 4.11: Plots of the total horizontal electric field magnitude, $E_h$, vs time at a receiver located on the seafloor centered over the conductive target. Green lines indicate a model with the target boundary extended to the east by 20 m, 40 m, and 60 m. Blue lines indicate a model with the target boundary extended to the west by 20 m, 40 m, and 60 m. Black lines indicate a model with the target boundary confined to the drilling zone (green square in Figure 3.9). The approximate measurement error of the receivers used in the experiment, $2 \times 10^{-8}$ V/m, is indicated by the gray line. A) Cross section of the model with transmitter located 100 m east of receiver. B) Cross section of the model with transmitter located 100 m west of receiver. C) Horizontal transmitter located 10 m above the seafloor 100 m east of receiver. D) Horizontal transmitter located 10 m above the seafloor 100 m west of receiver. E) Vertical transmitter located 10 m above the seafloor 100 m east of receiver. F) Vertical transmitter located 10 m above the seafloor 100 m west of receiver.
bathymetry and increased height between the transmitter and receiver caused by moving the transmitter uphill, which may result from the larger vertical component of the electric field induced by the vertical transmitter.

We also ran all of the models for the case where the transmitter is located 10 m directly above the receiver, centered over the conductive target. For both the horizontal and vertical loop transmitters, the system is unable to distinguish between any of the models with the target boundaries extended to the east or west. This is an expected result, as when the transmitter is located directly above the receiver the system is primarily sensitive to the seafloor conductivity structure directly below the receiver and has limited lateral imaging ability.

4.5 Apparent Conductivity Analysis

We conduct a preliminary analysis of the data recorded by the remote receivers by calculating apparent conductivities. We use the method derived by [79], where for a 1D double halfspace model the apparent conductivity of the lower halfspace can be calculated from the arrival time of the peak of the $E_h$ transient. We are only interested in the apparent conductivity of the lower halfspace, which represents the seafloor, while the upper halfspace representing the seawater is assumed to be of relatively constant conductivity throughout the survey area. The apparent conductivity of the seafloor, $\sigma$, is calculated from the arrival time of the peak of the transient, $\tau$, and the 3D separation distance between the transmitter and receiver, $R$, as:

$$\sigma = \frac{\tau c}{\mu R^2} \quad (4.2)$$

Where $\mu$ is the permeability of free space and $c$ is a scaling constant. For any given double halfspace model, $c$ can be calculated numerically via 1D forward modeling. We use a double halfspace model with an upper halfspace conductivity of 4.6 S/m, which is consistent with the seawater conductivity measured at Palinuro, and a lower halfspace conductivity of 1 S/m,
representing the seafloor. For each transmitter and receiver pair, the transient is forward modeled using the routine from [31] and the value of \( c \) needed to return the correct apparent conductivity of 1 S/m is calculated. The peak arrival time is then picked from the real data for the same transmitter-receiver pair, and an apparent conductivity is calculated using this numerically derived value of \( c \).

As the calculation of \( c \) is somewhat dependent on the initial guess at seafloor conductivity used in the 1D forward model, apparent conductivities are best for making inferences about the relative conductivity of the seafloor throughout the survey area rather than identifying the true conductivity. Thus after calculating an apparent conductivity for each transmitter-receiver pair, we convert each apparent conductivity, \( \sigma_n \), to a Z-score, \( Z_n \), representing how many standard deviations the apparent conductivity is above or below the mean of the data [eg. 85]:

\[
Z_n = \frac{\sigma_n - m}{s} \tag{4.3}
\]

Where \( m \) is the mean of the apparent conductivities and \( s \) is the standard deviation. The use of Z-scores allows us to identify where the apparent conductivity of the seafloor is higher or lower than average. We plot the Z-scores of apparent conductivity at the midpoint between each transmitter-receiver pair, as the apparent conductivity is most sensitive to the conductivity structure of the seafloor between the transmitter and receiver (Figure 4.12).

From the Z-scores for RX09 we find that seafloor apparent conductivity appears to be relatively highest when the transmitter was over or near to the zone of previously drilled mineralization (green square in Figure 4.12). This suggests that the conductive massive sulfides were successfully detected by the system. For RX11 the seafloor apparent conductivity is also slightly elevated when the transmitter was over the mineralization, though the effect is not as prominent as for RX09. This is likely because RX09 is located closer to the mineralization and therefore more sensitive to it.
Figure 4.12: Z-scores of apparent conductivity of the seafloor calculated from the transients recorded by RX09 and RX11. Transmitter locations are indicated by the gray circles and receiver locations are indicated by the red crosses. The zone of previously-drilled massive sulfide mineralization is indicated by the green square. Bathymetry is indicated by the black contours.
Using the 3D forward modeling code, we calculate the expected apparent conductivities at RX09 for the 10 transmitter locations closest to the mineralized zone with a model consisting of 4.6 S/m seawater, 1 S/m seafloor, and a 30 m thick 10 S/m conductive block buried 5 m below the seafloor with lateral extents of 35 x 55 m (indicated by the solid-outlined green square in Figure 4.12). This is the same model used in generating Figure 4.5 – Figure 4.10. Figure 4.13 shows the difference in apparent conductivity Z-score between the forward modeling results and the real data. We find that the apparent conductivity Z-scores generated by this model are too low when compared to the data (Figure 4.13a). We then increased the southward extent of the conductive block in increments of 10 m; Figure 4.13b-d indicate a southward extension of the conductive block by 20 m, 40 m, and 60 m. We find that the best match to the apparent conductivity Z-scores of the real data occurs when the conductive block is extended 40 m to the south (Figure 4.13c); when the mean absolute difference between modeled apparent conductivity Z-score and data is calculated, the minimum value of 0.471 occurs when the conductive target is extended southward by 40 m. This suggests that the mineralization at Palinuro extends to the south of the drilling zone by a few 10s of meters, which is consistent with the footprint of the self-potential signal measured at the mineralized zone [33]. In addition, this southward extension of mineralization is also consistent with heat flow measurements taken of the seafloor sediment during the POS509 research cruise in February 2017, which found elevated temperatures of up to 35.6 °C extending southward of the drilling zone by ~35 m [52].

The use of Z-scores in our analysis allows us to determine areas where the seafloor appears to be relatively more or less conductive compared to the background seafloor conductivity, which is useful in exploring for targets such as massive sulfides which are highly conductive compare to unmineralized rock. Matching of actual apparent conductivities in the data is a difficult exercise using a forward modeling approach; a 3D inversion of the data would be a better approach when there is a desire to estimate the actual, rather than relative, seafloor conductivity structure. However, a 3D inversion is computationally expensive compared to
Figure 4.13: Difference in Z-scores of apparent conductivity between forward model and data. Transmitter locations are indicated by the gray circles and receiver RX09 location is indicated by the red cross. The zone of previously-drilled massive sulfide mineralization is indicated by the solid-line green square. Green dashed lines indicate the southward extension of the conductive target block in the model. Mean absolute difference in Z-score is indicated in the lower left of each panel. A) No southward extension. B) 20 m southward extension. C) 40 m southward extension. D) 60 m southward extension.
our approach. Furthermore, the data set analyzed in this study has only 2 receivers and is too sparse to provide a proper base for a full 3D inversion of the seafloor conductivity structure. A second data set was collected with the Coil2Dipole configuration during the POS509 research cruise using 10 receivers; the data from that deployment is currently being processed and will form the basis of a full 3D interpretation of the seafloor structure at Palinuro [52].

4.6 Conclusions

We conducted a first test of the Coil2Dipole configuration, which is capable of collecting data from both a ship-towed coincident-loop receiver and remote electric dipole receivers placed on the seafloor. A 3D model of the Palinuro study area was created using bathymetry data, and 3D forward modeling results suggest that the Coil2Dipole configuration should be capable of detecting a shallowly-buried 10 S/m conductive target block of dimensions consistent with a zone of previously drilled massive sulfide mineralization. The conductive target can be detected at receivers located up to $\sim$100 m away when the transmitter is located directly above the mineralized zone, and the use of a vertical transmitter over a horizontal transmitter would extend the sensitivity to the conductive target by a few 10s of meters broadside to the transmitter loop. The sensitivity of the configuration to the conductive target decreases as the transmitter is moved away from the mineralized zone, and when the transmitter is located 100 m from the edge of the mineralization the receivers are only sensitive to the target when they are located directly above it. The configuration is only sensitive to the conductivity structure of the seafloor between the transmitter and the receiver. When a vertical transmitter is used, the configuration is less affected by changes in height between the transmitter and receiver and target burial depth caused by the bathymetry of the study area compared to a horizontal transmitter.

Data recorded by the remote receivers during the test of the configuration at the Palinuro Seamount were analyzed using an apparent conductivity method; results indicate higher apparent conductivities when the transmitter was close to the zone of previously drilled
massive sulfide mineralization. Forward modeling also indicates a conductive target block that extends 40 m to the south of the drilling zone, suggesting that massive sulfide mineralization at Palinuro extends southward of the drilling zone by a few 10s of meters. This southward extension of the mineralization is consistent with self-potential and heat flow data collected at the site. Our experiment at Palinuro demonstrates that the inclusion of remote receivers in the Coil2Dipole configuration can have useful applications in the exploration of shallowly-buried electrically conductive massive sulfide mineral deposits on the seafloor.

4.7 Acknowledgments

We wish to thank the Newmont Mining Corporation, Eldad Haber, and David Wynn for access to and assistance with the UBC forward modeling code. This project received funding from GEOMAR, The Colorado School of Mines, and the European Union as part of the Blue Mining project: Grant No. 604500, ”Breakthrough Solutions for the Sustainable Exploration and Extraction of Deep Sea Mineral Resources”. This is an EU-FP7 project.
5.1 Abstract

The self-potential (SP) method detects naturally occurring electric fields which may be produced by electrically conductive mineral deposits such as massive sulfides. Recently, there has been increasing interest in applying this method in a marine environment to explore for seafloor massive sulfide (SMS) deposits which may contain economic resources of base and precious metals. While SMS sites that are associated with active venting and are not buried under sediment cover are known to produce an SP signal, the effectiveness of the method at detecting inactive and sediment-covered deposits remained an outstanding question. We built an instrument capable of recording SP data in a marine setting. We carried out a test of the instrument at the Palinuro Seamount in the Tyrrhenian Sea. Palinuro is one of only a few known sites containing an SMS occurrence which is buried under sediment and not associated with active hydrothermal venting, although diffuse seepage of hydrothermal fluids is known to occur at the site. Elevated electric field strengths recorded in and near the site of previously drilled massive sulfide samples are on the order of 1–3 mV/m. A second zone of high field strengths was detected by us to the north of the drilling area where gravity coring later confirmed the existence of massive sulfides. Our observations indicate that an SP signal can be observed at the site of SMS mineralization even when the mineralized zone is shallowly buried and active hydrothermal venting is not present. These observations could
aid in the planning of future marine research expeditions which use the SP method in the exploration of seafloor massive sulfides.

5.2 Introduction

In recent years, interest has increased in exploring for massive sulfide deposits on the seafloor, as evidence suggests these deposits may provide an economic resource of base and precious metals [6, 8]. Seafloor massive sulfide (SMS) mineralization typically occurs at marine plate boundaries such as mid-ocean ridges, volcanic arcs, and back-arc basins, where hydrothermal fluids rise from deep in the crust, mix with cold seawater, and precipitate minerals on or below the seafloor [36]. 237 SMS deposits are currently known to exist throughout the world’s oceans [4, 5]. Most of these sites are small and economically not of interest. However, the economic potential of occurrences that are buried underneath a blanket of sediments is likely much higher [9].

Magnetic and electromagnetic methods have been applied in the search for SMS deposits [10, 12–16, 74]. A less commonly used method is the self-potential (SP) method, which looks for naturally occurring anomalies in electrical potential which can arise from buried conductive bodies (e.g., massive sulfides, graphite shear zones) [62] or from streaming potentials caused by fluid flow (e.g., groundwater) [63]. The SP method has been shown to work in marine environments, where both graphite and massive sulfide bodies have been detected by marine SP systems [22–25, 64–68, 86]. In a few cases, massive sulfides at the Mid-Atlantic Ridge were found to produce an SP anomaly even where no hydrothermal activity was present [68]. However, prior to our study, the SP method had not been tested over a hydrothermally inactive SMS site which is buried under sediment.

Marine SP data have typically been acquired via electrodes towed in-line behind a ship (e.g. [23, 68]). Rather than measuring the electrical potential with respect to a remote reference point as is commonly done on land, for logistical reasons these systems measure the electric field strength, which is the spatial derivative of the electrical potential. Most systems tested in the past only measured the horizontal electric field component aligned with
the towing direction of the ship, although VonHerzen et al. [64] measured the vertical electric field in an experiment at the Trans-Atlantic Geotraverse (TAG) hydrothermal mound. The horizontal component of the electric field perpendicular to the towing direction has typically not been measured.

We built and tested a new marine SP system (Figure 5.1a) which was mounted onto a larger carrier system for EM measurements. A data logger and two pairs of Ag-AgCl electrodes manufactured by Silvion were attached onto a lower fiberglass-reinforced plastic frame (4.3 m x 4.3 m), which allowed us to measure both components of the horizontal electrical field. The frame was suspended 15 m beneath a second frame, which held the electronics for active EM experiments, which are not considered in the scope of this paper. The entire system can be raised or lowered with a winch, and an altimeter was used to measure the height of the system above the seafloor. For positioning we used a Posidonia USBL system (IXSea).

The field area chosen for this study is the Palinuro Seamount in the southeastern Tyrrhenian Sea, located at 39.5° N, 14.7° E (Figure 5.1b). Massive sulfide samples were collected first from the western part of Palinuro by Minniti and Bonavia [29] and later by Petersen et al. [30] a few km to the east in our study area. Gravity, magnetic, sonar backscatter reflectivity, and detailed bathymetric data have been collected over this area [15, 16, 30, 74], but electrical and electromagnetic methods had not been attempted prior to this study. Diffuse seepage of low-temperature hydrothermal fluids has been detected at Palinuro [27, 28], but no active chimneys have been discovered. Shallow drilling carried out by Petersen et al. [30] indicates that the massive sulfide mineralization is typically buried under up to several meters of volcaniclastic sediment, making this a good test site for the exploration of buried deposits which lack black-smoker type hydrothermal activity.

5.3 Data Collection and Processing

The system was tested at Palinuro during the research cruise POS509 (R/V Poseidon, Feb. 15 - Mar. 3, 2017). SP data were collected over two days: on the first day the frame
Figure 5.1: A) Photo of the marine SP system. A 4.3 by 4.3 m square frame holding two pairs of electrodes is horizontally suspended 15 m below a cube containing the system electronics, which is in turn suspended from a cable to a winch on board the ship. B) A regional map showing the location of the Palinuro Seamount.
was towed along seven N-S profiles and on the second day along twelve E-W profiles over the study area. The system was towed at a very low speed of 0.4 knots (0.2 m/s) while the cable length was adjusted to keep the frame between 5–10 m above the seafloor as determined by the on-board altimeter. At the beginning and end of each profile, the system was raised to a height of 100 m above the seafloor and kept at this height for 5 minutes to measure the background noise without any geologic signal from the seafloor. These periods were used as control points to correct for temporal electrode drift.

Voltages were recorded by the two pairs of electrodes every 1 second. The voltages measured by the electrode pairs were converted to electric fields, $E_1$ and $E_2$, by dividing by the separation distance of the electrodes (4.3 m). Tilt sensors attached to the frame show that pitch and roll were on average $1.2^\circ \pm 4.0^\circ @ 2\sigma$ and $2.4^\circ \pm 4.4^\circ @ 2\sigma$, respectively; since the tilt angles were small at all times, $E_1$ and $E_2$ are effectively horizontal.

The data were smoothed using a moving average with a window size of 60 s to remove oscillations in the data caused by the transmitter from the EM experiment which was being carried out simultaneously. A temporal electrode-drift curve was calculated by fitting a 2nd order polynomial through the control points when the system was high in the water column, and consequently removed from the data. When the ship winch was moving the system up or down in the water column, the vertical movement of the cable produced electrical noise; thus the data during vertical instrument movement were trimmed. For the E-W profiles, an overall shift was apparent in the data from the eastward-towed lines versus the westward-towed lines, with the eastward-towed lines showing fields on average 222 $\mu$V/m higher than the westward-towed lines for $E_1$ and 397 $\mu$V/m higher for $E_2$. While we are unsure of the exact cause of this shift, we theorize that it may be related to the interaction of the towing cable with the Earth’s magnetic field; this theory is supported by the fact that no apparent shift is seen between the northward-towed and southward-towed lines on the N-S profiles when the system is being towed mostly parallel to the Earth’s magnetic field. To remove this effect, the data from the eastward towed and westward towed lines were leveled to each
other by subtracting half the average difference from the eastward towed lines and adding half the average difference to the westward towed lines for each electrode pair. The data processing steps are summarized in Figure 5.2.

Figure 5.2: The data processing steps: 1. Smoothing with a 60-s moving average to remove oscillations from the EM system transmitter. 2. Removal of temporal electrode drift and trimming of times when the system was high in the water column. 3. Removal of the apparent shift between the eastward-towed transects and westward-towed transects and trimming of times during vertical winch movement. A) The full time series of $E_2$ for the E-W profiles. B) A close-up of a zone of anomalously high field strength, indicated by the pink bar labeled “1” in part A of this figure and also by location number 1 in Figure 5.3.

Since the system is free to rotate horizontally about the winch cable, $E_1$ and $E_2$ represent arbitrary orthogonal directions at any given time. We calculated the magnitude of the total horizontal field, $E_h$, as $\sqrt{E_1^2 + E_2^2}$, which is independent of the orientation of the system (Figure 5.3). In addition, heading data from an on-board compass with a sampling rate of $\sim 1.6$ Hz were used to trigonometrically calculate the northward and eastward components of the horizontal electric field, referred to as $E_x$ and $E_y$, respectively.
Figure 5.3: Magnitude of the horizontal electric field, $E_h$. The area containing previously drilled massive sulfide samples is indicated by the green rectangle. A gravity core sediment sample containing a thick layer of massive sulfides is indicated by the green asterisk. Bathymetry is indicated by the black contours. A) Full survey area. B) A close-up of the zone around the massive sulfide samples, indicated by the black square in part A.

### 5.4 Data Analysis

Several areas at Palinuro were found to have elevated $E_h$ values on the order of 1–3 mV/m, which is an order of magnitude greater than the background $E_h$ values of a few hundred $\mu$V/m (Figure 5.3). Most of the areas of high $E_h$ values can be spatially correlated with massive sulfide samples collected at Palinuro. Previous shallow drilling has recovered 11 core samples containing massive sulfides in the northwestern part of the crater [30]. The location of these drill core samples, indicated by the green bounding box in Figure 5.3, corresponds spatially with high $E_h$ values on both the N-S and E-W profiles. On the N-S profiles, high $E_h$ values are seen to occur both to the NW and SE of the drilling site, which is consistent with our working hypothesis that a possible NW-SE trending fault structure can be interpreted from the bathymetry at the drilling site. In addition, high $E_h$ values are observed $\sim$200 m to the north of the drilling site on both the N-S and E-W profiles, located outside of the crater hosting the drilled mineralization. After observing these anomalies in
the SP data, a gravity coring device was used to collect samples of seafloor sediment in the area of the anomalies. A gravity-corer sample indicated by the green asterisk on Figure 5.3, located between high $E_h$ values on the N-W profiles and proximal to elevated $E_h$ values on an E-W profile, contained a thick layer (>1 m) of sediments bearing massive sulfides starting at 180 cm below the seafloor. Two additional zones of high $E_h$ values in the SW part of the field area observed on the E-W profiles correspond with areas which have not been sampled at this time.

The spatial correlation between high $E_h$ values and massive sulfide sampling suggests that the high $E_h$ values are produced by a geologic source. The source of these electric fields could be the presence of highly conductive massive sulfide bodies spanning a vertical redox potential gradient in the seafloor, consistent with the explanation suggested by Sato and Mooney [62] for SP anomalies on land. Alternatively, while active high-temperature venting of hydrothermal fluids is not present at Palinuro, the electric fields could result from the diffuse seepage of hydrothermal fluids through the seafloor in the mineralized zone or by geochemical reactions between the sulfides and the porewaters.

Further evidence that these electric fields result from a geologic source is obtained by examining $E_x$ and $E_y$ (Figure 5.4). We consider an SP anomaly produced by a massive sulfide occurrence; for a vertical conductor, such anomalies typically consist of a local low in the electrical potential [62] (Figure 5.4). A system is towed from west to east across the potential low and measures the electric field components $E_x$ and $E_y$, which are the negative spatial derivatives $-d/dx$ and $-d/dy$ of the electrical potential. If the system passes to the north of the ”bullseye” of the potential low, $E_x$ will be negative at all times, with a minimum occurring when the system passes due north of the bullseye. Conversely, $E_y$ will be positive before passing due north of the bullseye, zero at the point due north of the bullseye, and negative after passing due north of the bullseye. Indeed, this pattern is observed in the data in several places on the E-W profiles; one example is shown in detail in Figure 5.4b. On the N-S profiles, we expect to see the opposite pattern, with a sign change occurring in $E_x$ but
not in \( E_y \). This pattern is also observed in several places in the N-S profiles; one example is shown in detail in Figure 5.4c. In this example, two zero crossings occur in \( E_x \), suggesting that the system was towed across two local lows in the electrical potential located close together. The presence of these patterns in the \( E_x \) and \( E_y \) data suggests that the elevated electric field measurements are the result of local lows in the electrical potential, which are likely produced by geology or diffuse hydrothermal fluid seepage in the seafloor. In addition, this suggests that with densely sampled data, analysis of the relative strengths of the \( E_x \) and \( E_y \) components could be used to vector in on the bullseye of the electrical potential, which would be useful from an exploration standpoint.

5.5 Conclusions

We performed a marine self-potential (SP) experiment which recorded both horizontal components of the electric field. The system was tested over an area of known sediment-covered massive sulfide mineralization with only diffuse low-temperature hydrothermal fluid seepage at the Palinuro Seamount in the southeastern Tyrrhenian Sea. Zones of elevated horizontal electric field strengths were observed in close proximity to locations where massive sulfide cores have been collected from the seafloor. These elevated field strengths may result from the presence of electrically conductive massive sulfide bodies in the seafloor, or from the seepage of hydrothermal fluids through the seafloor in the mineralized zone. Past experiments have demonstrated that seafloor massive sulfide occurrences can produce natural electric fields even when no hydrothermal activity is present; however, this study represents the first test of an SP system over a seafloor massive sulfide occurrence which is buried beneath sediment cover. The magnitudes of the elevated field strengths observed at Palinuro are on the order of 1–3 mV/m. These field strengths are comparable to the SP anomalies observed over massive sulfide occurrences which are not buried, where anomalies of a few mV/m in the electric field have also been observed. Patterns observed in the northward and eastward components of the electric field are indicative of local lows in the electrical potential, which is consistent with the typical SP signal produced by massive sulfide deposits on land. Our
Figure 5.4: A theoretical depiction of the expected $-d/dy$ and $-d/dx$ derivatives measured by a system towed across a local low in a potential field. B) A 90-m segment of $E_x$ and $E_y$ data from the E-W profiles indicated by location number 1 in Figure 5.3. C) A 90-m segment of $E_x$ and $E_y$ data from the N-S profiles indicated by location number 2 in Figure 5.3.
experiment at Palinuro demonstrates that the marine SP method is a useful exploration tool at shallowly buried seafloor massive sulfide occurrences with only diffuse hydrothermal activity.

5.6 Acknowledgments

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CHAPTER 6
CONCLUSIONS

This project has examined the capabilities of marine EM and SP methods as applied to the exploration of SMS resources. In particular, I have examined in detail an EM configuration consisting of a ship-towed inductive source transmitter and remote electric dipole receivers placed on the seafloor, which I refer to as the Coil2Dipole configuration. This configuration has the potential to augment the data recorded by a more traditional airborne-style coincident loop receiver because measurements from the remote receivers are sensitive to greater distances from the transmitter towing path and also to greater depths within the seafloor. I have carried out a preliminary examination of the data from a first test of the Coil2Dipole configuration at the Palinuro Seamount, which contains a zone of known SMS mineralization. I also have examined data collected in a novel marine SP experiment consisting of two perpendicular pairs of electrodes towed close to the seafloor over the Palinuro Seamount SMS site. The data and modeling presented in this study can be used to draw some conclusions about the sensitivity and utility of these methods.

The 1D forward modeling study presented in Chapter 3 demonstrates that the Coil2Dipole EM configuration is sensitive to shallowly buried conductive targets. The use of a horizontal loop transmitter has greater sensitivity than a vertical loop transmitter to the conductive layer thickness, which is useful when attempting to estimate the depth extent of a target body. The horizontal loop system also experiences less attenuation of the signal than a vertical loop system when the conductive target is not buried, but rather exposed at the seafloor surface. These factors imply that a horizontal loop transmitter is favorable to a vertical loop transmitter in exploring for SMS occurrences. However, only the vertical loop transmitter is sensitive to a buried resistive layer, which means a vertical loop transmitter would be favorable in exploring for resistive targets such as gas hydrate deposits or pockets.
of shallow gas.

The 3D modeling study presented in Chapter 4 demonstrates that the Coil2Dipole configuration should be capable of detecting a shallowly-buried 10 S/m conductive target block whose dimensions are consistent with the zone of SMS mineralization recovered in drill cores at Palinuro. The modeling results indicate that a target of this size could be detected at remote receivers up to $\sim 100$ m away when the transmitter is directly above the target. The results also show that a vertical loop transmitter, when compared to a horizontal loop transmitter, is less affected by changes in the transmitter altitude caused by the bathymetry of the study area. This suggests that the use of a vertical transmitter may be advantageous in areas where bathymetry is steep.

The data from the first test of the Coil2Dipole configuration, collected using a horizontal transmitter, are analyzed in Chapter 4 using an apparent conductivity method. Higher apparent conductivities are seen when the transmitter was close to the zone of known SMS mineralization. When the data are compared to 3D forward modeling, they are found to be more consistent with a conductive target block that extends 40 m to the south of the drilling zone; this, in conjunction with heat flow data collected at the site, suggests that mineralization at Palinuro extends to the south. The test of the Coil2Dipole configuration at Palinuro demonstrates the utility of including remote receivers in a marine towed-loop EM survey.

Chapter 5 covers a test of a novel marine SP system at the Palinuro study area, which measures both horizontal components of the electric field. High electric field strengths are observed which correspond spatially to locations of known shallowly buried SMS mineralization. These high field strength extend to both the southeast and the northwest of the known SMS occurrence by $\sim 50$ m. Whether these high field strengths result directly from the presence of electrically conductive massive sulfides or from the seepage of hydrothermal fluids through the seafloor remains an open question. While previous marine SP experiments have demonstrated success at SMS occurrences, this study represents the first successful test
of such a system at a buried SMS site. The use of two perpendicular electrode pairs in measuring the electric fields allows the northward and eastward components of the electric field to be calculated. Patterns observed in these northward and eastward components indicate local lows in the electrical potential, which is consistent with the typical SP signal observed at massive sulfide deposits on land. Analysis of the northward and eastward components of the electric field can also be used to determine the direction towards the center of the electrical potential low, which could be useful in trying to pinpoint the center of a target body.

The Coil2Dipole data and the SP data both suggest that the SMS occurrence at Palinuro may extend beyond the bounds of the drilled mineralization. These results demonstrate how both EM and SP data can be used to characterize the lateral extents of near-surface SMS mineralization. The marine EM and SP methods examined in this project may have a wide range of applications in both the exploration for new SMS sites and the characterization of known deposits. It is my hope that the data presented here demonstrate the capabilities and limitations of these methods to the extent that better informed decisions can be made in how to apply these tools in the search for mineral resources on the seafloor.

6.1 Future Work

It would be useful to collect SP data at the Palinuro study area with more closely spaced tow lines. This would provide a more complete dataset and would likely reveal some additional zones of anomalously high field strengths. These targets could then be tested using either shallow drilling or gravity core sampling to determine if they contain massive sulfides. This additional ground-truthing of the SP data would confirm if zones of high field strength are always correlated with mineralization. Furthermore, sampling done in areas of low field strengths could determine the efficacy of the system at detecting all massive sulfides in the area. Ultimately, it would be interesting to also test the SP system at a different site of buried massive sulfides where no hydrothermal fluid seepage of any kind exists in the seafloor, as this would determine whether low-level hydrothermal activity is the source of
the electric fields detected at Palinuro, and if the system is effective at a fully inactive SMS site. Discovering such a site at which to test the system remains a major challenge.

In addition, the large data set collected with the Coil2Dipole configuration during the POS509 research cruise in February 2017 will shed additional light on the potential of this method to determine the seafloor conductivity structure. These data were acquired with ten functional ocean-bottom receivers, as opposed to the two receivers used in this study. A data set of this size has the potential to be fully inverted with a 3D inversion code. The seafloor conductivity model recovered from this inversion could then be compared to the SP data, drilling, and gravity core sampling at Palinuro. Such a comparison could determine if the inversion results are geologically reasonable and consistently show higher conductivities in areas of SP anomalies or known sampled mineralization. SP data can easily be acquired at the same time as the Coil2Dipole data by simply including two perpendicular pairs of electrodes affixed to the Coil2Dipole frame, so it would be useful to further investigate how the data sets collected by these two methods can be used in tandem to explore for and characterize a mineralized zone of the seafloor.
REFERENCES CITED


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 (Figure A.1).

![Coordinate system](Figure A.1: Coordinate system used throughout this derivation.)

A vertical loop of current can be represented by a horizontal magnetic dipole which produces both an electric and magnetic field (Figure A.2).

![Electric and Magnetic Fields](Figure A.2: The electric (E) and magnetic (B) fields produced by a horizontal magnetic dipole in a uniform media.)

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 $b_z$:

$$\frac{\partial^2 b_z}{\partial z^2} - \theta^2 b_z = 0 \quad (A.1)$$

where

$$\theta^2 = p^2 + q^2 + i\omega\mu_0\sigma \quad (A.2)$$

A solution to this differential equation has the form:

$$b_z = Ce^{(-\theta|z|)} + De^{(\theta|z|)} \quad (A.3)$$

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

$$b_z = Ce^{(-\theta|z|)} \quad (A.4)$$

From Ward and Hohmann [82] equation 4.104 we have the solution for the primary vertical magnetic field produced by a horizontal magnetic dipole at a depth $z$:

$$b_{z\text{ primary}} = \mu_0 h_{z\text{ primary}} = \pm \frac{\mu_0 i pm}{2} e^{-\theta z} \quad (A.5)$$

where $m$ is the magnetic moment of the dipole and $\mu_0$ is the permeability of free space. By substituting A.4 into A.5 we find that $C = \pm \frac{\mu_0 i pm}{2}$. $b_z$ is discontinuous across the plane of the dipole source, and we solve for the change in $b_z$ across the source:

$$\delta b_z = b_z^+ - b_z^- = 2C = \mu_0 ipm \quad (A.6)$$
For a layered earth model, a solution to A.1 within a layer i has the form:

\[ b_{z,i} = C \cosh(\theta_i z) + D \sinh(\theta_i z) \]  

(A.7)

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

\[
b_{y,i} = \frac{-iq}{p^2 + q^2} \frac{\partial b_z}{\partial z} = \frac{-iq}{p^2 + q^2} \theta_i \left[ C \sinh(\theta_i z) + D \cosh(\theta_i z) \right]
\]  

(A.8)

We define a variable \( F \) as:

\[
F = \frac{iq}{p^2 + q^2} \frac{b_z}{b_y}
\]  

(A.9)

For the i\textsuperscript{th} layer, from A.7 and A.8 we have:

\[
F_i = -\frac{1}{\theta_i} \left[ C \cosh(\theta_i z) + D \sinh(\theta_i z) \right]
\]

\[
= -\frac{1}{\theta_i} \left[ C \sinh(\theta_i z) + D \cosh(\theta_i z) \right]
\]

(A.10)

If we define the z-axis to coincide with the bottom of the i\textsuperscript{th} layer, and considering that \( F \) is continuous across the layer:

\[
F_i = F_{i+1} = -\frac{1}{\theta_i} \frac{C}{D}
\]

\[
\frac{C}{D} = -\theta_i F_{i+1}
\]

(A.11)

Now we substitute A.11 into A.10 to define an upward recursion relation, where \( z = d_i \) is the thickness of the i\textsuperscript{th} layer:

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

(A.12)
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 $i$th layer, and considering $b_z$ is continuous across the layer boundaries, we have from A.2:

\[ b_{z,i} \big|_{z=0} = b_{z,i+1} = C \]  \hspace{1cm} (A.13)

Substituting A.13 into A.11 we have:

\[ D = \frac{b_{z,i+1}}{-\theta_i F_{i+1}} \] \hspace{1cm} (A.14)

Now we set $z = -d_i$ for the bottom of the $(i + 1)$th layer. By substituting A.13 and A.14 into A.7 we derive a downward recursion relation to define $b_z$ at any layer interface below the source:

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

\[ b_{z,i+1} = b_{z,i} \left[ \frac{\theta_i F_{i+1} \text{sech}(\theta_i d_i)}{\theta_i F_{i+1} + \tanh(\theta_i d_i)} \right] \] \hspace{1cm} (A.15)

Substituting the relationship between $b_y$ and $b_z$ defined in A.9 we get:

\[ \left( \frac{p^2 + q^2}{iq} \right) F_{i+1} b_{y,i+1} = \left( \frac{p^2 + q^2}{iq} \right) F_i b_{y,i} \left[ \frac{\theta_i F_{i+1} \text{sech}(\theta_i d_i)}{\theta_i F_{i+1} + \tanh(\theta_i d_i)} \right] \] \hspace{1cm} (A.16)

\[ b_{y,i+1} = b_{y,i} \left[ \frac{\theta_i F_i \text{sech}(\theta_i d_i)}{\theta_i F_{i+1} + \tanh(\theta_i d_i)} \right] \]

\[ = b_{y,i} L^F_{i+1} \] \hspace{1cm} (A.17)

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

\[ L^F_i = \frac{\theta_{i-1} F_{i-1} \text{sech}(\theta_{i-1} d_{i-1})}{\theta_{i-1} F_i + \tanh(\theta_{i-1} d_{i-1})} \] \hspace{1cm} (A.18)
If $b_y$ is to be calculated in the plane of the dipole source, $i = 1$ and by definition $L_1^F \equiv 1$. 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:

$$e_{x,i} = i\omega b_{z,i} \left( \frac{iq}{p^2 + q^2} \right) = F_i i\omega b_{y,i}\quad (A.19)$$

$$e_{y,i} = i\omega b_{z,i} \left( \frac{-ip}{p^2 + q^2} \right) = F_i i\omega b_{y,i}\quad (A.20)$$

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.9 as:

$$\delta b_z = b_z^+ - b_z^- = (F_1 + G_1) \left( \frac{p^2 + q^2}{iq} \right) b_{y,1}\quad (A.21)$$

By equating A.21 to A.6, we find that:

$$b_{y,1} = \left( \frac{1}{F_1 + G_1} \right) \left( \frac{-\mu_0 p q m}{p^2 + q^2} \right)\quad (A.22)$$

We find the electric field components using the relations in A.19 and A.20:

$$e_{x,1} = F_1 i\omega \left( \frac{1}{F_1 + G_1} \right) \left( \frac{-\mu_0 p q m}{p^2 + q^2} \right)\quad (A.23)$$

$$e_{y,1} = F_1 i\omega \left( \frac{1}{F_1 + G_1} \right) \left( \frac{\mu_0 p^2 m}{p^2 + q^2} \right)\quad (A.24)$$

We transform A.23 and A.24 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:

$$E_{x,1}(r, \phi) = \frac{-\mu_0 m i\omega}{2\pi} \cos(\phi) \sin(\phi) \left[ \int_0^\infty \left( \frac{F_1}{F_1 + G_1} \right) \lambda J'_1(\lambda r) d\lambda - \frac{1}{r} \int_0^\infty \left( \frac{F_1}{F_1 + G_1} \right) J_1(\lambda r) d\lambda \right]\quad (A.25)$$
\[ E_{y,1}(r, \phi) = \frac{\mu_0 m \omega}{2\pi} \left[ \cos^2(\phi) \int_0^\infty \left( \frac{F_1}{F_1 + G_1} \right) \lambda J'_1(\lambda r) d\lambda + \frac{\sin^2(\phi)}{r} \int_0^\infty \left( \frac{F_1}{F_1 + G_1} \right) J_1(\lambda r) d\lambda \right] \]

(A.26)

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.19 and A.20 we must use \( F_K \) in place of \( F_1 \) in the numerator of the integral kernel:

\[ E_{x,K}(r, \phi) = -\frac{\mu_0 m \omega}{2\pi} \cos(\phi) \sin(\phi) \left[ \int_0^\infty \left( \frac{F_K}{F_1 + G_1} \right) \prod_{i=1}^K L^F_i \lambda J'_1(\lambda r) d\lambda - \frac{1}{r} \int_0^\infty \left( \frac{F_K}{F_1 + G_1} \right) \prod_{i=1}^K L^F_i J_1(\lambda r) d\lambda \right] \]

(A.27)

\[ E_{y,K}(r, \phi) = \frac{\mu_0 m \omega}{2\pi} \left[ \cos^2(\phi) \int_0^\infty \left( \frac{F_K}{F_1 + G_1} \right) \prod_{i=1}^K L^F_i \lambda J'_1(\lambda r) d\lambda + \frac{\sin^2(\phi)}{r} \int_0^\infty \left( \frac{F_K}{F_1 + G_1} \right) \prod_{i=1}^K L^F_i J_1(\lambda r) d\lambda \right] \]

(A.28)

**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 \( e_z \):

\[ \frac{\partial^2 e_z}{\partial z^2} - \theta^2 e_z = 0 \]

(A.29)

Similar to A.1, a solution to this equation has the form:

\[ e_z = C e^{(-\theta |z|)} \]

(A.30)
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 [82]:

$$e_{z,primary} = \pm \left( \frac{iq(i\omega\mu_0)m}{2\theta} \right) e^{-\theta z} \quad (A.31)$$

where $m$ is the magnetic moment of the dipole source and $\mu_0$ 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 $e_y$:

$$e_x = \left( \frac{-ip}{p^2 + q^2} \right) \frac{\partial e_z}{\partial z} \quad (A.32)$$

$$e_y = \left( \frac{-iq}{p^2 + q^2} \right) \frac{\partial e_z}{\partial z} \quad (A.33)$$

From A.31 we find $\frac{\partial e_z}{\partial z}$:

$$\frac{\partial e_z}{\partial z} = \pm \left( \frac{iq(i\omega\mu_0)m}{2} \right) e^{-\theta z} \quad (A.34)$$

By substituting A.34 into A.33 we get:

$$e_y = \pm \left( \frac{q^2i\omega\mu_0m}{2(p^2 + q^2)} \right) e^{-\theta z} \quad (A.35)$$

$e_y$ 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:

$$\delta e_y = e_y^+ - e_y^- = \frac{q^2i\omega\mu_0m}{p^2 + q^2} \quad (A.36)$$

Now we consider the layered earth model. A solution to A.29 within each layer $i$ has the form:

$$e_{z,i} = C \cosh(\theta_i z) + D \sinh(\theta_i z) \quad (A.37)$$
Substituting A.37 into A.33 we get:

\[ e_y = \left( \frac{-iq}{p^2 + q^2} \right) \theta [C \sinh(\theta z) + D \cosh(\theta z)] \quad (A.38) \]

With \( \sigma \) being the electrical conductivity, we define a variable \( U \) as:

\[ U = \left( \frac{p^2 + q^2}{i q} \right) \left( \frac{e_y}{\sigma e_z} \right) \quad (A.39) \]

Similar to the derivation of \( F \) in A.12, we derive an upward recursion relation for \( U \), where \( z = d_i \) is the thickness of the \( i \)th layer:

\[ U_i = \frac{\theta_i}{\sigma_i} \left[ \frac{\theta_i \tanh(\theta_i d_i) + \sigma_i U_{i+1}}{\theta_i + \sigma_i U_{i+1} \tanh(\theta_i d_i)} \right] \quad (A.40) \]

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 \( i \)th layer, and considering that the current density, \( j_z = \sigma e_z \), is continuous across the layer boundaries, we have from A.30:

\[ e_{z,i} \big|_{z=0} = \frac{j_{z,i}}{\sigma_i} = \frac{j_{z,i+1}}{\sigma_i} = C \quad (A.41) \]

By a similar procedure to the derivation of A.15, we can derive a downward recursion relation for \( j_z \):

\[ j_{z,i+1} = j_{z,i} \left[ \frac{\theta_i \text{sech}(\theta_i d_i)}{\theta_i + \sigma_i U_{i+1} \tanh(\theta_i d_i)} \right] = j_{z,i} L^U_{i+1} \quad (A.42) \]

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

\[ L^U_{i} = \frac{\theta_{i-1} \text{sech}(\theta_{i-1} d_{i-1})}{\theta_{i-1} + \sigma_{i-1} U_{i} \tanh(\theta_{i-1} d_{i-1})} \quad (A.43) \]
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 \( U \):

\[
e_{y,i} = \left( \frac{U_i \sigma_i q}{p^2 + q^2} \right) e_{z,i} = \left( \frac{U_i q}{p^2 + q^2} \right) j_{z,i} \quad (A.44)
\]

\( e_x \) can be related to \( e_y \) by Faraday’s Law B.10:

\[
e_{x,i} = \left( \frac{p}{q} \right) e_{y,i} = \left( \frac{U_i q p}{p^2 + q^2} \right) j_{z,i} \quad (A.45)
\]

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.44 as:

\[
\delta e_y = e^+_y - e^-_y = (U_1 + V_1) \left( \frac{i q \sigma_1 e_{z,1}}{p^2 + q^2} \right) = (U_1 + V_1) \left( \frac{i q j_{z,1}}{p^2 + q^2} \right) \quad (A.46)
\]

If we equate A.46 to A.36 we can solve for \( j_z \) in the plane of the dipole source:

\[
j_{z,1} = -i q (i \omega \mu_0) m \left( \frac{1}{U_1 + V_1} \right) \quad (A.47)
\]

We convert to the Hankel domain, making use of relation B.15:

\[
J_{z,1}(r, \phi) = -\frac{i \omega \mu_0 m}{2 \pi \sigma_1} \sin(\phi) \int_0^\infty \left( \frac{1}{U_1 + V_1} \right) \lambda^2 J_1(\lambda r) d\lambda \quad (A.48)
\]

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.47 into A.44:

\[
e_{y,1} = \frac{q^2 i \omega \mu_0 m}{p^2 + q^2} \left( \frac{U_1}{U_1 + V_1} \right) \quad (A.49)
\]

Converting to the Hankel domain, making use of relation B.16:
\[ E_{y,1}(r, \phi) = \frac{i\omega \mu_0 m}{2\pi} \left[ \sin^2(\phi) \int_0^\infty \left( \frac{U_1}{U_1 + V_1} \right) \lambda J'_1(\lambda r) d\lambda + \frac{\cos^2(\phi)}{r} \int_0^\infty \left( \frac{U_1}{U_1 + V_1} \right) J_1(\lambda r) d\lambda \right] \quad (A.50) \]

We can solve for \( e_x \) by substituting A.47 into A.45 and convert to the Hankel domain, making use of relation B.17:

\[ e_{x,1} = \frac{pq i \omega \mu_0 m}{p^2 + q^2} \left( \frac{U_1}{U_1 + V_1} \right) \quad (A.51) \]

\[ E_{x,1}(r, \phi) = \frac{i\omega \mu_0 m}{2\pi} \cos(\phi) \sin(\phi) \left[ \int_0^\infty \left( \frac{U_1}{U_1 + V_1} \right) \lambda J'_1(\lambda r) d\lambda - \frac{1}{r} \int_0^\infty \left( \frac{U_1}{U_1 + V_1} \right) J_1(\lambda r) d\lambda \right] \quad (A.52) \]

If we wish to calculate the fields at a layer interface \( K \) below the transmitter, we must include the ladder operator A.43 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.44 and A.45 for \( e_x \) and \( e_y \) we must use \( U_K \) in place of \( U_1 \) in the numerator of the integral kernel:

\[ J_{z,K}(r, \phi) = -\frac{i\omega \mu_0 m}{2\pi} \sin(\phi) \int_0^\infty \left( \frac{1}{U_1 + V_1} \right) \prod_{i=1}^K L_i^U \lambda^2 J_1(\lambda r) d\lambda \quad (A.53) \]

\[ E_{x,K}(r, \phi) = \frac{i\omega \mu_0 m}{2\pi} \cos(\phi) \sin(\phi) \left[ \int_0^\infty \left( \frac{U_K}{U_1 + V_1} \right) \left( \frac{\sigma_K}{\sigma_1} \right) \prod_{i=1}^K L_i^U \lambda J'_1(\lambda r) d\lambda \right. \]

\[ \left. - \frac{1}{r} \int_0^\infty \left( \frac{U_K}{U_1 + V_1} \right) \left( \frac{\sigma_K}{\sigma_1} \right) \prod_{i=1}^K L_i^U J_1(\lambda r) d\lambda \right] \quad (A.54) \]

\[ E_{y,K}(r, \phi) = \frac{i\omega \mu_0 m}{2\pi} \left[ \sin^2(\phi) \int_0^\infty \left( \frac{U_K}{U_1 + V_1} \right) \left( \frac{\sigma_K}{\sigma_1} \right) \prod_{i=1}^K L_i^U \lambda J'_1(\lambda r) d\lambda \right. \]

\[ + \frac{\cos^2(\phi)}{r} \int_0^\infty \left( \frac{U_K}{U_1 + V_1} \right) \left( \frac{\sigma_K}{\sigma_1} \right) \prod_{i=1}^K L_i^U J_1(\lambda r) d\lambda \right] \quad (A.55) \]

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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 $A.27 + A.54$, and the full solution for $E_y$ is given by $A.28 + A.55$.

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 3.5, 3.6, and 3.7.
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:

\[ ipe_x + iqe_y = \frac{\partial e_z}{\partial z} \]  \hspace{1cm} (B.1)

Gauss’ Law for magnetics in the Fourier domain:

\[ ipb_x + iqb_y = \frac{\partial b_z}{\partial z} \]  \hspace{1cm} (B.2)

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

\[ -ipe_y + iqe_x = -i\omega b_z \]  \hspace{1cm} (B.3)

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

\[ -ipb_y + iqb_x = \mu_0 j_z + \mu_0 \epsilon_0 i\omega e_z \]  \hspace{1cm} (B.4)

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

\[ pb_y = qb_x \]  \hspace{1cm} (B.5)

\[ pe_x = -qe_y \]  \hspace{1cm} (B.6)

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

\[ b_y = \frac{-iq \frac{\partial b_z}{\partial z}}{p^2 + q^2} \]  \hspace{1cm} (B.7)
In the TE mode, by substituting (B-6) into (B-3) we have:

\[ e_x = \left( \frac{iq}{p^2 + q^2} \right) i\omega b_z \]  
\[ e_y = \left( \frac{-ip}{p^2 + q^2} \right) i\omega b_z \]  
\[ \text{(B.8)} \]

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

\[ pe_y = qe_x \]  
\[ \text{(B.10)} \]

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

\[ e_x = \left( \frac{-ip}{p^2 + q^2} \right) \frac{\partial e_z}{\partial z} \] 
\[ e_y = \left( \frac{-iq}{p^2 + q^2} \right) \frac{\partial e_z}{\partial z} \]  
\[ \text{(B.11)} \]

Useful derivatives:

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

\[ \frac{\partial^2}{\partial x^2} \int_0^\infty f(\lambda) \lambda J_0(\lambda r) d\lambda = -\cos^2(\phi) \int_0^\infty f(\lambda) \lambda^3 J'_1(\lambda r) d\lambda - \frac{\sin^2(\phi)}{r} \int_0^\infty f(\lambda) \lambda^2 J_1(\lambda r) d\lambda \] 
\[ \text{(B.14)} \]

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

\[ \frac{\partial^2}{\partial y^2} \int_0^\infty f(\lambda) \lambda J_0(\lambda r) d\lambda = -\sin^2(\phi) \int_0^\infty f(\lambda) \lambda^3 J'_1(\lambda r) d\lambda - \frac{\cos^2(\phi)}{r} \int_0^\infty f(\lambda) \lambda^2 J_1(\lambda r) d\lambda \] 
\[ \text{(B.16)} \]
\[ \frac{\partial^2}{\partial x \partial y} \int_0^\infty f(\lambda) \lambda J_0(\lambda r) d\lambda = -\cos(\phi) \sin(\phi) \left[ \int_0^\infty f(\lambda) \lambda^2 J_1(\lambda r) d\lambda - \frac{1}{r} \int_0^\infty f(\lambda) \lambda J_1(\lambda r) d\lambda \right] \]  

(B.17)