Remote Sensing of 3-D Conducting Objects in a Layered Medium Using Electromagnetic Surface Waves

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Abstract—Antennas that are located on or near the boundary between two electrically different media, such as air and earth, or seawater and rock, are used as prospective tools for remote sensing and geophysical exploration. As an example, this letter examines the electromagnetic (EM) response of a metallic object that is submerged in a conducting layer of seawater that is situated between an infinite half-space of air and a seabed of lower electrical conductivity. When the source and the object are at some distance away in the water, the primary EM propagation mode is on the interfaces because the surface waves are less attenuated than those following the direct or reflected propagation paths. The simulation tool that predicts the performances of the EM detection system uses the method-of-moments integral equation technique. The method is validated and applied to calculate the scattered fields from a submerged perfectly conducting cylinder. The numerical results are then compared with experimental data that are obtained by towing a steel cylinder through an imposed field that is produced by a horizontal electric source.

Index Terms—Electromagnetic scattering, method of moments (MoM), scattering measurements, stratified medium.

I. INTRODUCTION

Unlike acoustic devices operating in shallow water that appear to suffer from multipath effects, electromagnetic (EM) systems use boundaries for the detection and identification of submerged objects [1]–[3], and underwater communications [4]. The air and seawater and/or seawater and rock interfaces act as leaky waveguides that allow the EM fields to reach a range in the ocean that is much greater than that for signals propagating along direct paths through the water. When both the transmitting and receiving antennas are placed in the water layer, the lateral (or surface) waves are usually interpreted as the waves that relate the source—observer propagation via the air and the seabed media. From the source, they travel approximately vertically to the boundaries and then radially in the air or the seabed before “diving” again to the observation point. Skin depth attenuation is only experienced during the vertical path that is usually much shorter than the direct path from the source to the observer through the water. Note that the reflections between the interfaces also play an important role and need to be considered in the scattering solution.

The scattering of EM waves by submerged or buried objects of arbitrary shape is an important research topic that is extensively treated in the literature. In this field, considerable effort has been directed in developing numerical models for a geometry where the scattering object is placed within a general planar layered media [5]–[13]. The mathematical techniques that are used for the scattering part of the problem are various integral equation (IE) formulations with different method of moments (MoM) concepts [14]. Even if the aforementioned theoretical treatments imposed no limitation for the arrangement of the source, object, and receiver in the horizontally layered structure, these models were mainly applied to subsurface sensing of buried objects where the plane wave or finite sources are located in the top layer (air) above the embedding lossy media [5], [7], [11]–[13].

This letter investigates a different situation where the transmitting electric source and the scattering object are submerged in salt water that is situated between an infinite half-space of air and a seabed of lower electrical conductivity. At certain distance, the incident field is a surface wave and not an EM wave that is incident at an arbitrary angle. The scattered field from the metallic object is strongly influenced by the proximity of the boundaries.

The use of surface EM waves for finding a buried or submerged metal wire was presented in [1]–[3], where only the air–water interface was considered (half-space). A more complicated situation that is treated here appears when a second interface is created between the seawater and a sediment layer of lower electrical conductivity. In this case, there is an additional boundary that generates reflections and on which the EM waves can propagate.

Unlike the previous studies [1]–[3] where the wire approximation was used, the present scattering object is a 3-D perfectly conducting (PEC) object. The induced electric currents on the PEC surface are determined from the magnetic field IE (MFIE) using the MoM [14]. Then, the scattering fields are expressed as surface integrals on the scattering object surface. The integrands of these integrals consist of scalar products between the surface current density and a dyadic Green’s function [6].

As mentioned previously, the techniques that are used here to simulate the scattering from a general submerged PEC target have been published elsewhere [6], [7], [14]. However, the use of the EM surface waves as valuable tools for remote sensing in shallow waters justifies this investigation. The literature presents few theoretical studies on the phenomenology underlying this application. It is worth mentioning that, while the literature is abundant in treating the surface-wave propagation, it is scarce in presenting the surface propagation in conjunction
with a scattering object that is placed in a layered structure. The main goal of this letter is to present example results. Since, to our knowledge, similar results have not been published previously, the data that are presented here will be of interest for further development of this application. These results, which are being supported by experimental data, will serve also for comparison to other computational algorithms.

II. NUMERICAL PROCEDURE AND THEORETICAL STUDY

Consider a PEC object of arbitrary shape that is embedded in a horizontally layered medium that is assumed to be laterally infinite. The layers are separated by planar interfaces that are parallel to the X–Y plane of a Cartesian coordinate system. This is the plane in which the structure is in its EM parameters. For the purpose of this letter, it is assumed that all layers are nonmagnetic, i.e., the permeability is \( \mu_0 \) everywhere. The layers may be lossy, i.e., the permittivity of the layers may be complex. The forcing current has a sinusoidal temporal dependence, and thus, the time dependence factor \( \exp(-j\omega t) \) is suppressed throughout.

The total electric (\( \mathbf{E} \)) and magnetic (\( \mathbf{H} \)) fields at the observation point are the sums of the incident (primary) fields from the source and the anomalous (secondary) fields from the PEC object, i.e., \( \mathbf{E} = \mathbf{E}' + \mathbf{E}^* \) and \( \mathbf{H} = \mathbf{H}' + \mathbf{H}^* \). The incident \( \mathbf{E}' \) and \( \mathbf{H}' \) fields are the wave propagation solutions satisfying the horizontally stratified geometry without the scattering object. The scattering contributions from the object, i.e., \( \mathbf{E}^* \) and \( \mathbf{H}^* \), also satisfy the layered geometry. This means that all multiple scattering effects coupling the sources and the interfaces are taken into account.

Using the notation \( \mathbf{A} \) for the (magnetic) vector potential, the EM fields in the \( m \)th layer are written as

\[
\mathbf{E}_m = -j\omega \mathbf{A}_m - \frac{j}{\omega \mu_0} \nabla (\nabla \cdot \mathbf{A}_m), \quad \mathbf{H}_m = \frac{1}{\mu_0} \nabla \times \mathbf{A}_m. \tag{1}
\]

If the PEC object is placed in the \( m \)th layer, the vector potential \( \mathbf{A}_m \) in the \( m \)th layer is given by the integral over the surface of the object \( S \)

\[
\mathbf{A}_m(r) = \int_S \mathbf{G}^A(r, r') \cdot \mathbf{J}_n(r') dS', \tag{2}
\]

where \( \mathbf{G}^A(r, r') \) is the dyadic Green's function in the selected stratified geometry. The unknown current density \( \mathbf{J}_n(r) \) on the surface of the PEC object is obtained by forcing the boundary condition, i.e.,

\[
\mathbf{J}_n(r) = \mathbf{n}(r) \times [\mathbf{H}'(r) + \mathbf{H}^*(r)], \quad r \in S \tag{3}
\]

where \( \mathbf{n} \) is the unit outward normal vector to \( S \). This condition generates an IE of the second kind called the MFIE, i.e.,

\[
\frac{1}{2} \mathbf{J}_n(r) = \mathbf{n}(r) \times \mathbf{H}'(r) - \frac{1}{\mu_0} \mathbf{n}(r) \times \nabla \times \int_S \mathbf{G}^A(r, r') \cdot \mathbf{J}_n(r') dS'(r'), \quad r \in S \tag{4}
\]

which is solved by MoM [14]. The resulting current components are essentially electric dipoles that radiate in the presence of the interfaces of the stratified structure.

One approach to calculate the Green's function in a layered structure is given by Michalski and Zheng [6], where the solution is obtained by numerical evaluation of the Sommerfeld integrals. In the present calculation, the so-called Formulation-C in [6] was used. Once the Green's function for a layered media is available, one can use (1) and (2) to compute the incident fields and to express the scattered fields in terms of the current density on the surface of the PEC object.

A. Cylinder in a Half-Space Medium

To validate the preceding numerical method, the EM scattering calculation was applied to investigate the response of a submerged metallic cylinder with a length of \( 2L = 100 \) m and a diameter of \( 2R = 12.5 \) m. The problem was analyzed analytically by King [3] for a half-space medium and thin-wire approximation. The same geometry will be used here for easy comparison of the results. The X-direction and Y-direction denote the horizontal plane. The vertical Z direction is pointing downward, and the origin of this Cartesian reference frame is located on the interface between the two media. A conducting medium (region 1) occupies the half-space \( Z > 0 \) of the rectangular coordinate system and has the conductivity \( \sigma_1 = 4 \) S/m. Region \( Z < 0 \) is taken to be free space (\( \sigma_0 = 0 \)).

In the proposed geometry [3], the cylinder is horizontally oriented with its axis along the X-direction. It is submerged at a depth of \( H = 100 \) m (from its axis to water level), and its center is at 3000-m separation distance from the electric source. The surface of the cylinder was modeled with 1272 patches, each one with an area of about 3 m². The source illuminating the cylinder is a horizontal electric dipole with an electric moment of 1 A·m that carries a sine wave current with a constant frequency of 25 Hz. It was placed at the origin of the X–Y plane at \( h = 1 \) m depth in water and oriented in the X-direction. The sensor line is placed in water parallel to the cylinder axis at 1-m depth.

The primary field is created by the submerged electric source close to the water–air interface. At a distance that is larger than a few skin depths (\( \delta = 50 \) m), the EM field propagating directly through the water is practically completely attenuated. Since both the cylinder and the sensors are in a similar location (submerged) at a distant point from the source, the received EM field is a surface wave propagating along the boundary in the air where the propagation distance is much bigger than that in the homogeneous infinite medium of water. This particularity makes the method suitable for remote sensing of submerged bodies.

The secondary EM field from the metallic object is significant only when an axial current is induced in the cylinder, so that the electric source and the cylinder were placed on the same line. Using the moment method, the X-component of the secondary electric field signal is computed on a 200-m-long observation (sensor) line. The amplitude and the phase of this field are presented in Fig. 1. Directly above the cylinder at \( X = 3000 \) m, \( Y = 0 \) m, and \( Z = 1 \) m, the calculated has
a magnitude of $6.05 \cdot 10^{-15}$ V/m and a phase of $-6^\circ$ in very good agreement with the analytical results. [3, eq. (26a)] gives a scattered field amplitude of $5.23 \cdot 10^{-15}$ V/m and a phase of $-8.6^\circ$. The difference between the two results may be caused by the different mathematical approaches in the calculation of the scattering field. The wire approximating the cylinder in [3] is placed at exactly 100-m depth, whereas in the present calculation, the cylinder preserves its 3-D shape with an upper surface at 93.75 m.

In order to detect the presence of the cylinder, the secondary field at the receiver must be differentiated from the primary field, whose $X$-component of the electric field at the point directly above the center of the cylinder at 1-m depth is $(1.1415 + j0.0056) \cdot 10^{-12}$ V/m.

B. Cylinder in a Layered Structure

To illustrate the influence of the second boundary on the propagation of the EM surface waves, it is advantageous to modify the preceding geometry by introducing a simplified sea bottom (region 2) so thick that reflections from other layers beyond it are negligible. The model that is presented here as an example consists of the 110-m-thick layer of water that is situated between an infinite half-space of air and a seabed with conductivity of $\sigma = 0.01$ S/m. In this way, the electric source and the sensors are close to the air–water interface as before, and the metallic cylinder is close to the water–seabed interface. Characteristic for this geometry is the appearance of the second surface wave propagating via the seabed of low electrical conductivity. Because the vertical path of both propagation modes, i.e., the upper and lower surface waves, to the metallic cylinder is approximately the same, the intensity of the EM field illuminating the object is almost double compared to the previous case. This situation is reflected in the amplitude of the $X$-component of the scattered field that is recorded at the sensor line, which is presented in Fig. 2, together with its phase. In comparison to Fig. 1, the amplitude of the secondary field at the point above the center of the cylinder increased about 1.8 to $10.7 \cdot 10^{-15}$ V/m.

As before, this field must be detected in the presence of the primary field from the source that was calculated to be $(1.1462 + j0.026) \cdot 10^{-12}$ V/m at the same point. The values

III. EXPERIMENTAL RESULT

In this section, the preceding calculation is applied to interpret the data that are collected during an experiment that investigated the EM scattering response of a moving submerged metallic cylinder. The experiment was carried out in Esquimalt Harbor, Victoria, BC, Canada, and its geometry is shown in Fig. 3. The $X$-axis is oriented toward the north, the $Y$-axis is oriented toward the east, and the $Z$-axis is oriented downward with zero value at the surface of the water. When real data are used, one must acknowledge the errors in the geometrical parameters due to the positioning inaccuracy, particularly, when all the equipment is placed underwater on an uneven seabed. The errors in the position of the source and sensor, their alignment and orientation, imply that the “true” values in this
letter are only approximated. The seawater conductivity was measured to be 3 S/m and had a depth of \( d = 13 \text{ m} \).

An iron pipe with a length of 7 m and a diameter of 0.8 m was towed horizontally at a depth of \( H = 6 \text{ m} \), which represents the distance from the water level to the central axis of the cylinder. The towing speed was approximately 1.5 m/s. This object was illuminated by a horizontal electric source, which is 20 m long with a current of 5 A, placed on the seafloor \( (h = 12.9 \text{ m}) \), and oriented at about \(-30^\circ\) from the \( X \)-direction. The source emitted a continuous sine wave with a frequency of 327 Hz (wavelength in water of \( \lambda_1 = 100 \text{ m} \) and skin depth of \( \delta = 16 \text{ m} \)). The scattered fields were measured on horizontal seabed-mounted two-axis electric field sensors that are built with Ag/AgCl electrodes, each axis being 3.0 m long. The arrangement was asymmetrical, so that there was a 36-m separation between source and sensor in the \( X \)-direction and 18-m separation in the \( Y \)-direction. In this experiment, the distances were close to the skin depth, so that the direct wave may still propagate. However, the primary propagation mode is along the seafloor interface that is located at a small distance (in skin depth) from the source, cylinder, and receiver, particularly, when the scattering object is in the range of 40–50 m from the transmitter.

The experiment involved recording (primary plus secondary) electric field data at the horizontal vector sensor during the transit of the cylinder between the source and the sensors. Simultaneously, a signal that is proportional to the current in the transmitter was recorded and used as the reference in the calculation of the amplitude and phase of the scattered signal. Unlike its phase, the amplitude of the forcing current was not constant during the experiment. For this reason, a signal that is proportional to the amplitude of the scattered field was obtained by dividing the envelope of the signal at the receiver to the envelope of the impressed current. The envelopes of the signals were calculated as the absolute values of their Hilbert transform. The segment of data representing the relative amplitude and the phase of the scattered field that are recorded in two directions when the cylinder was moving between the transmitter and receiver is plotted in Fig. 4(a) and (b). The longitudinal direction is parallel to the \( X \)-axis, and the transverse direction is perpendicular to it. The actual position of the cylinder relative to the sensor is not known, so that the horizontal scale of Fig. 4 represents a virtual distance that is given by the product of time and velocity.

In modeling the experiment, a three-layer model was assumed to be valid. The seafloor of the Esquimalt harbor is rocky, so that the sediment layer was set to have a conductivity of 0.03 S/m. The transmitter was modeled as an extended dipole.

The surface of the cylinder was modeled with 288 patches. The model was placed at various positions along the \( X \)-axis, and the scattered field was calculated for each position to generate the amplitude and phase plots that are shown in Fig. 5(a) and (b) for the longitudinal and transverse fields, respectively. Figs. 4 and 5 show that there is a good agreement between the experimental and calculated results for both the amplitudes and phases.

The phase of the scattered signal is plotted in these figures in absolute values, so that it is easier to be compared. The best results were obtained for the phase of the transverse electric field. The measured and calculated values are very close, and the two maxima that they present are separated by a distance of about 37.5 m. The calculated phase of the longitudinal field differs from the measurement by about \( 20^\circ \). It was noticed during the computation that the phase of the secondary electric field has high sensitivity to the sensor orientation, so that the difference may be explained by the errors in the geometry, as shown previously. However, there are similarities between the plots of the measured and calculated phases of the longitudinal scattered field. For example, both phases tend to have a minimum when the object moves toward the sensor, and the overall phase variation is of tenths of a degree. Then, in both Figs. 4 and 5, the minimum of the phase of the longitudinal field is delayed relative to the minimum of the transverse field.

Fluctuations in the parameters of the detection system made impossible an absolute comparison between the experimental and calculated amplitudes of the scattered field. From the measurements that are taken during this experiment, it could be concluded that the main source of noise affecting the signal amplitude was the environment. The littoral water is a mixture of salt and fresh water. The transmitting antenna was an electric dipole consisting of an insulated cable with two pieces of zinc.
as bare end terminations. The driving-point impedance of such antenna is proportional to the wave number of the surrounding media, which is seawater in this case. Any variation of the water conductivity due to the underwater currents, for example, will translate into low-frequency (tents of heriz) fluctuations of the driving current, provided that the voltage at the feed point is constant. The same effect may generate signal fluctuations at the receiving antenna as well, but here, it depends also on the input impedance of the preamplifier. Other sources of environment noise such as the low-frequency EM fields due to the water waves and swell would affect only the mean value of the scattered signal. With all the limitations due to the noise, the plots in Figs. 4 and 5 show close similarities between the experimental and calculated amplitudes of the scattered field. In this case, the calculated results reproduce better the experimental data for the longitudinal electric field.

IV. Conclusion

A rigorous MoM analysis has been performed for determining the frequency response of PEC 3-D objects in a layered structure. The metallic object is submerged in a conducting layer of seawater that is situated between an infinite half-space of air and a seabed of lower electrical conductivity. The source is a submerged horizontal electric dipole (line) that is placed near the boundary between electrically different regions. Because of the high conductivity of seawater, it is shown that the EM propagation on interfaces plays an important role in the remote sensing of the submerged object. The results underscore the benefit of rigorous modeling, with which such phenomena can be predicted and exploited for remote sensing applications.

The determination of the scattered electric field can be used to detect the presence of a cylinder that is located in a conducting layer of seawater. An actual working system that gives an indication on the various problems involving the method for locating a submerged object from measurements of the scattered field was presented. Model results and experimental data were in good agreement. The anomalous intensity is typically a few percent of the primary field, so that the noise in the system is an important factor. The experiment demonstrates that the measurement errors of the phase of the scattered signal may be caused by the geometrical factors, while the amplitude errors are due to the environment noise. From this viewpoint, the phase shift seems to be a more sensitive quantity than the amplitude variation for detection of the metallic object.

REFERENCES