Underwater Electromagnetic Communications Using Conduction – Channel Characterization

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ABSTRACT

This paper explores the properties of short-range broadband wireless communications for underwater operations using electric conduction. Electric field in the water is generated by a pair of electrodes with opposite current and detected by two receiving electrodes. Ranges of operation can be shorter than 1 m, suitable for contactless data collection by remotely operated vehicles (ROVs), and even as short as 1-10 cm, suitable for contactless riser health monitoring for deep sea drilling sensors. Experiments were conducted at frequencies between 100 kHz and 6.5 MHz, using orthogonal frequency division multiplexing (OFDM). Our lab tests were performed in a plastic tank filled with salt water, and our sea test at the ocean surface and 5 m depth (boundary free). Magnitude and phase delay of the channel transfer function were modeled based on inference from dipole radiation theory in a conducting medium. An exponential attenuation model fitted to the lab measurements indicated inverse cubic range dependence (near-field compliant). A rational-polynomial model provided the best match for the recorded magnitude, especially at low frequencies. The phase characteristic obtained from the ocean measurements exhibited a minimum around 2 MHz, which agrees with theory.

Categories and Subject Descriptors

I.6.5 [Simulation and Modeling]: Model Development – Modeling methodologies

General Terms
Measurement, Experimentation, Theory, Verification

Keywords
Underwater RF, electric dipole, conducting medium

1. INTRODUCTION

Possible applications of electromagnetic field in underwater communications are short range communications (<100m) and very short range (<1m), very high speed, communications. One application is for contactless data transfer between sensor-equipped sections of a deep sea drill riser. Radio Frequency (RF) conduction antenna system can be made small enough to fit between riser sections. This technology supports the vision of a subsea positioning system – a network of devices scattered across the seafloor that is used to guide ROVs to data collection sites mounted on production assets. When the vehicle is within close proximity of a data collection port it can transfer information at tens or hundreds Mbps.

In [1], the authors state that the effective range in an RF conduction system is not a function of power but of current. While radiated power represents a product of current and square of the radiation resistance of the antenna, the RF conduction method relies on voltage between receiving electrodes rather than the received power. Increased spacing between electrodes implies higher voltage with same current. Two technically feasible designs for voice communication underwater were reported in [1]: one for divers (150 m range with 6 W of power), and the other for manned submersibles (1 km range with 280 W of power). Center frequency reported in the paper was 1.2 kHz, with bandwidth 1.5 kHz.

Over the recent years, a variety of products for underwater electromagnetic communication has been offered by Wireless Fibre Systems (WFS) Technologies [2]. They have developed a line of products for data rates 1-100 bps that can perform at ranges out to 30 m. Another one of their designs are 25-156 kbps systems, optimized for ranges between 2 m and 10 m. WFS Technologies have also been offering an underwater electromagnetic communication system that can transfer up to 1 Mbps at ranges less than 10 m. Their current line of products use loop antennas. The size of their square-shaped loop antenna for high data rates is 25 cm × 15 cm.

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In this paper, we study characteristics of a wide-band RF conduction channel based on a set of measurements from a site off-shore coastal Massachusetts. The paper is organized as follows. Section 2 summarizes the principles of electromagnetic wave propagation in conducting media based on electric dipole antenna model. In Section 3 we describe the equipment and methodology used in the experiment. Our probing signals are based on Orthogonal Frequency Division Multiplexing (OFDM). Section 4 presents the channel frequency response.

2. PROPAGATION MODEL

There are three electromagnetic field components of a linear dipole antenna, electric fields \( E_r \) and \( E_\theta \), and magnetic field \( H_\phi \). In the far field, \( E_\theta \) can be used to determine the radiated electromagnetic power. In the near field, \( E_\theta \) is the field component that is related to the received voltage signal.

It can be shown [5] that the tangential component of the electric field radiated by the infinitesimal dipole, at radial distance \( r \) from the source, is given by:

\[
E_\theta = j\eta \frac{k I_0 \sin \theta}{4\pi r} \left(1 + \frac{1}{jk r} - \frac{1}{(kr)^2}\right) e^{-jkr} \tag{1}
\]

where \( l \) is the antenna length and \( I_0 \) the current. The propagation constant \( k \) is a function of radial frequency \( \omega \), given by

\[
k = \beta - j\alpha = \sqrt{\mu \varepsilon \left(1 - \frac{j\sigma}{\omega \varepsilon}\right)} \tag{2}
\]

where \( \mu, \varepsilon, \) and \( \sigma \) are the permeability, permittivity and conductivity of the propagation medium, respectively. The characteristic impedance \( \eta \) of the medium is given by

\[
\eta = \sqrt{\frac{\mu}{\varepsilon} \left(1 - \frac{j\sigma}{\omega \varepsilon}\right)^{-1}} \tag{3}
\]

The electric field (1) can be expressed as

\[E_\theta = E(\omega, r) e^{-\sigma r} e^{-j(\beta r + \theta(\omega, r))}\]

For a given range \( r \), \( E(\omega, r) \) has rational polynomial form in terms of \( \omega \). The product \( \beta r \) represents propagation delay of the electromagnetic wave, while \( \beta r + \theta(\omega, r) \) is the phase of the electric field.

Frequency variation of the magnitude of tangential electric field component between 0 Hz and 6.5 MHz is illustrated in Figure 1. We can see that the peak frequency decreases, approaching zero, as range increases. That trend is consistent with the notion of attenuating plane waves,

\[E \sim E_\theta \exp(-\alpha_0 f) \tag{4}\]

as far-field approximation in terms of frequency \( f \).

At frequencies such that \( \sigma >> 2\pi f \varepsilon\), \( \alpha \) and \( \beta \) can be approximated as

\[\alpha = \beta \approx \frac{2\pi f}{\mu_0} \tag{5}\]

The theoretical value of exponential attenuation constant, with \( \mu = \mu_0 = 4\pi \times 10^{-7} \text{ H/m and } \sigma = 4.3 \text{ S/m} \), is then

\[\alpha_0 = \sqrt{\frac{\pi \mu_0 \sigma}{4.12}} \approx 4.12 (\text{m MHz}^{-1}) \tag{6}\]

Finally, the wavelength underwater is defined as

\[\lambda = \frac{2\pi}{\beta} \tag{8}\]

With the approximation (5), \( \lambda \approx \sqrt{\frac{4\pi f \mu_\sigma}{\mu_0}} \). Again, with \( \mu = \mu_0 = 4\pi \times 10^{-7} \text{ H/m} \),

\[\lambda \approx \frac{10}{\sqrt{f \text{ MHz} \sigma}} \tag{9}\]

where \( f_{\text{MHz}} \) denotes frequency in MHz.
3. EXPERIMENT DESCRIPTION

The goal of our experiment was to measure the channel frequency response of an RF conduction channel. To this end, we transmitted and received data at multiple frequencies. The waveforms were designed in Matlab and hard-coded into the transmitter’s FPGA module. Following the reception through the data capture board in the receiving unit, the received signals were post-processed in Matlab to obtain the channel frequency response.

Our lab tests were conducted in a plastic tank filled with salt water, shown in Figure 3. The conductivity of the water in the tank was measured to be 1.3 S/m. The results presented in Section 4 correspond to the distances between the transmitter and the receiver of 35 cm and 50 cm.

![Figure 3. Lab tank.](image)

The experiment in the ocean was carried out at a depth of approximately 5 m. (Skin depth at 100 kHz is approximately 0.77 m.) We also performed a set of measurements very close to the surface. The conductivity of the sea water was measured to be 4.3 S/m. For the sea test, the transmitter and receiver containers were mounted on a steel frame, as shown in Figure 4. The separation distance between the tips of the electrodes of the transmitter and the receiver was about 10 cm. The entire frame was lowered into the water from a small boat to collect data.

![Figure 4. The frame holding the transmitter (smaller tube) and the receiver.](image)

3.1 Probing Signals

For our channel frequency response measurements, we used OFDM signals with \( K = 128 \) carriers, total bandwidth \( B = 6.25 \) MHz, lower band edge \( f_0 = 100 \) kHz, sub-carrier spacing \( \Delta f = 48.83 \) kHz, and QPSK modulation.

3.2 Hardware Description

Transmitter was a completely self-contained unit, battery powered with no connection to the outside world. A waveform generator, controlled by the Field-Programmable Gate Array (FPGA), was used to form the signals. After D/A conversion (DAC), the signals were smoothed using a filter and presented to the output driver. The output driver produced 1A amplitude output current to supply the electrodes. The dynamic range of the DAC component was 2Vp-p. The electronics and batteries sufficient to drive the transmitter over several hours (10 NiMH batteries) were placed inside a 4-inch PVC pipe container which was sealed to make it pressure-resistant to 5 meter depths. The electrodes were small pieces of plugged ¼ inch bronze pipe. The separation was set by the mechanical constraints of the package and the length of the electrodes was set so as not to exceed the current drive of the transmitter. The transmitter was capable of producing waveforms up to 10 MHz. A Spartan FPGA was used as the arbitrary waveform generator with clock frequency of 51.6096 MHz.

The receiver utilized a data capture 14 bit acquisition card from Linear Technologies and a Fiber Optic USB connection so that no copper connection was made to the receiver. External 50 MHz clock source was designed and implemented by GE Research. The electronics were battery powered and capable of several hours of operation. A pre-amplifier, model ZFL-1000LN+ (15 V) by Mini-Circuits, was included to keep the input signal within range of the ADC (1.5Vp-p). According to the product specifications, the Low Noise Amplifier (LNA) gain was 23.56 dB, and its noise figure was 2.9 dB, across the frequency range.

4. CHANNEL FREQUENCY RESPONSE

Since our experimental signals represent voltage between the receiving electrodes, we expect that the measured channel frequency response should match the electric field function discussed in Section 2. We investigate this match by fitting the measured data to parametric models devised from (1) and (4).

Not counting the noise, the transmitted and the received signal are related by

\[
Y(r_0, f) = H(r_0, f)X(f)
\]

where \( Y(r_0, f) \) is the signal on the receiving end of the channel, at range \( r_0 \), \( X(f) \) is the transmitted signal, and \( H(r_0, f) \) is the channel transfer function. For shorter notation, we write \( H(f) = H(r_0, f) \), or sometimes just \( H \). Our goal here is to model the function

\[
H(f) = |H(f)|e^{j\phi(f)}
\]

4.1 Magnitude of the Channel Frequency Response

The simplest propagation model known in theory is the exponentially attenuating wave approximation. Referring to (4), we assume

\[
|H| = A_0e^{-\alpha_1 f}
\]
where $A_0$ and $\alpha_1$ represent the model. This approximation is notably valid when the receiver is in the far-field. The relation between (4) and (10) suggests $\alpha_1 \sim \alpha_0 \sigma$. It can be seen from (9) that, if the frequency is not higher than 10 MHz and $\sigma \approx 4$ S/m, the wavelength is not shorter than half a meter. The far-field boundaries at 100 kHz and 6.35 MHz, respectively, are $5m/2\pi = 80cm$ and $0.6m/2\pi = 10cm$. Since our measurements correspond to ranges on the order of 10 cm – 50 cm, we can see that the receiving antenna was in a combination of near- and far-fields.

If the propagation medium is not treated strictly as highly conducting, (2) suggests that we can assume linear frequency dependence of the exponential attenuation constant. Another simple model is then given by

$$|H| = A_0 e^{-\alpha_2 f}$$

(11)

where $A_0$ and $\alpha_2$ are the representing parameters. A more general model can be formulated as

$$|H| = \frac{p_1 f^2 + p_2 f + p_3}{q_1 f^2 + q_2 f + q_3} e^{-\alpha_2 f}$$

(12)

The rational-polynomial part of this model was derived by substituting (2) in (1) and finding the magnitude. This model is better suited to near-field situations than (10) and (11) in the sense that it allows for magnitude dependence on frequency.

### 4.2 Phase Delay Model

Referring to the expression (7), when $\omega \epsilon << \sigma$, as it is the case in well conducting medium such as sea water, we have that

$$\cot^{-1} \frac{\omega \epsilon}{\sigma} \approx \frac{\pi}{2} - \frac{\omega \epsilon}{\sigma} \approx \frac{\pi}{2}$$

Furthermore, effect of the $\tan^{-1}$ component of the phase delay function (7) can be captured by a linear function of frequency $f$. Incorporating these approximations into the expression (7) leads to a relatively simple model for channel phase delay:

$$\varphi(f) = -b_1 \sqrt{f} + cf + d$$

(13)

where $b_1$, $c$, and $d$ represent fitting parameters of the model. Specifically, the first term in (13) is associated with $\beta r$ in well-conducting medium, while the second term is intended to model the influence of the $\tan^{-1}$ component. Function $\cot^{-1} 2\pi \epsilon/\sigma$ is assumed constant for low argument values, which again corresponds to well-conducting medium.

### 4.3 Data Fitting

We used the measurements from the lab and the field to fit our models, based on non-linear function least-square fitting in Matlab. Figure 5 shows the measured channel characteristics along with the models (10)-(12) for the magnitude and (13) for the phase. The corresponding measurements are taken in the tank, at 35 cm range. The channel magnitude seems to vary between $-54dB$ and $-34dB$ in the given frequency band.

Figure 6 shows the measured channel characteristics, in the tank, at 50 cm range. Again, the magnitude is described by (10)-(12) and the phase is described by (13).

Channel magnitude at 50 cm distance seems to vary between $-60dB$ and $-45dB$, in the given frequency band. If compared to the 35 cm range results, that indicates approximately 6 dB attenuation at the high end of the frequency band and 11 dB at its low end, per 15 cm range.

We notice that the phase at the longer range (Figure 6) is more folded upward than at the shorter range (Figure 5). This tendency can be predicted based on the theory, as illustrated in Figure 2; however, theoretical prediction of the frequency of the minimum phase delay for the given separation distance is significantly lower than the measurement. Therefore, space-constrained environment and the vicinity of the boundaries in the tank may dictate a different phase-delay model than the one given by (1) and (7), which corresponds to boundary-free environment.
Figure 6. Channel magnitude (a) and phase (b): measured values (dots) in the tank and models (10)-(12) for the magnitude and (13) for the phase. Range 50 cm. $\sigma \approx 1.3 \text{ S/m}$.

Figure 7 shows the measured channel characteristics, taken at the ocean surface, and Figure 8 corresponds to 5 m depth. The magnitude is again characterized by (10)-(12) and phase by (13). The channel frequency response close to the surface shows a much lower attenuation, probably because part of the electromagnetic energy was reflected from the ocean-air boundary. In the given frequency band, the channel magnitude seems to vary between $-75$ dB and $-55$ dB at the surface, and between $-100$ dB and $-75$ dB at 5 m depth. Therefore, the proximity of the ocean surface, as a reflecting boundary, results in $25$ dB and $20$ dB stronger signal at the high and low ends, respectively, of the frequency band.

As expected, the rational-polynomial model (12) provides the best match for the recorded magnitude characteristic. This is notably true at low frequencies where the far-field assumption does not hold, and both models (10) and (11) fail to capture the effect. Beyond the peak frequency, model (11) gives a better match than model (10), but is still outperformed by the rational-polynomial model (12).

As for the phase, a minimum can be observed between 2 MHz and 3 MHz, in Figures 7 and 8. According to the theory of electric dipole, that would indicate a separation distance of a few cm, which coincides with the distances between the tips of transmit and receive electrodes in the experiment.

In Figures 5 – 8, the sea test data appear less scattered than the tank test data. In particular, sea test data at 5 m depth appear even less scattered than the sea test data from the surface measurements, which indicates less noise at 5 m depth than at the surface.

Tables 1-4 list the model parameters corresponding to the expressions (10)-(12), with frequency in MHz. Each table contains entries for two lab tests and two sea tests. Results that correspond to the measurements in the tank at 35 cm and 50 cm range are referred to as Lab 1 and Lab 2, respectively, in the tables. Tests Sea 1 and Sea 2 correspond to the measurements at the sea surface and 5 m deep, respectively.
Figure 8. Channel magnitude (a) and phase (b): measured values (dots) at sea, at 5 m depth, and models (10)-(12) for the magnitude and (13) for the phase. Range 10 cm. $\sigma \approx 4.3 \text{ S/m}$.

### Table 1. Channel transfer function magnitude fitting parameter values. Model given by (10).

<table>
<thead>
<tr>
<th></th>
<th>$A_0$</th>
<th>$\alpha_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lab 1</td>
<td>2.55e-2</td>
<td>0.6562</td>
</tr>
<tr>
<td>Lab 2</td>
<td>8.56e-3</td>
<td>0.617</td>
</tr>
<tr>
<td>Sea 1</td>
<td>3.54e-3</td>
<td>1.073</td>
</tr>
<tr>
<td>Sea 2</td>
<td>3.35e-4</td>
<td>1.011</td>
</tr>
</tbody>
</table>

The $A_0$ values for Lab 1 and Lab 2, shown in Tables 1 and 2, indicate $r^3$ dependence, which is in agreement with (1) for $kr \ll 1$, or near-field.

### Table 2. Channel transfer function magnitude fitting parameter values. Model given by (11).

<table>
<thead>
<tr>
<th></th>
<th>$A_0$</th>
<th>$\alpha_2$</th>
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<tbody>
<tr>
<td>Lab 1</td>
<td>1.8e-2</td>
<td>0.2551</td>
</tr>
<tr>
<td>Lab 2</td>
<td>6.4e-3</td>
<td>0.4652</td>
</tr>
<tr>
<td>Sea 1</td>
<td>2.2e-3</td>
<td>0.4129</td>
</tr>
<tr>
<td>Sea 2</td>
<td>2.1e-4</td>
<td>0.4129</td>
</tr>
</tbody>
</table>

### Table 3. Channel transfer function magnitude fitting parameter values for dipole model given by (12).

<table>
<thead>
<tr>
<th></th>
<th>$p_1$</th>
<th>$p_2$</th>
<th>$p_3$</th>
<th>$q_1$</th>
<th>$q_2$</th>
<th>$q_3$</th>
<th>$\alpha_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lab 1</td>
<td>0.01</td>
<td>0.01</td>
<td>2.4e-3</td>
<td>0.6</td>
<td>0.35</td>
<td>0.23</td>
<td>0.28</td>
</tr>
<tr>
<td>Lab 2</td>
<td>6.6e-3</td>
<td>4.3e-3</td>
<td>1.4e-3</td>
<td>0.8</td>
<td>0.45</td>
<td>0.38</td>
<td>0.32</td>
</tr>
<tr>
<td>Sea 1</td>
<td>-1.9e-5</td>
<td>3.5e-4</td>
<td>3.3e-4</td>
<td>0.1</td>
<td>0.08</td>
<td>0.19</td>
<td>0.16</td>
</tr>
<tr>
<td>Sea 2</td>
<td>3.4e-5</td>
<td>1.2e-4</td>
<td>1.5e-5</td>
<td>0.4</td>
<td>0.22</td>
<td>0.16</td>
<td>0.39</td>
</tr>
</tbody>
</table>

### Table 4. Channel transfer function phase fitting parameter values. Model given by (13).

<table>
<thead>
<tr>
<th></th>
<th>$b$</th>
<th>$c$</th>
<th>$d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lab 1</td>
<td>1.817</td>
<td>0.4464</td>
<td>-0.3061</td>
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<tr>
<td>Lab 2</td>
<td>1.936</td>
<td>0.5326</td>
<td>-0.1996</td>
</tr>
<tr>
<td>Sea 1</td>
<td>2.803</td>
<td>0.8589</td>
<td>1.477</td>
</tr>
<tr>
<td>Sea 2</td>
<td>2.898</td>
<td>0.9342</td>
<td>1.591</td>
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</table>

### 5. CONCLUSION

We measured electromagnetic field radiated by a pair of electrodes in a plastic tank in our lab and in the ocean, and modeled magnitude and phase of the channel transfer function based on the measurements. Dipole radiation theory in conducting medium was helpful in predicting the general form of the channel transfer function.

A rational-polynomial model provided the best match for the recorded magnitude characteristic, especially at low frequencies, where simple exponential models failed to capture the near-field effect. Beyond a peak frequency, exponential model with linear frequency dependence of the attenuation constant gave a better match than one with square root of frequency in the exponent, but was still outperformed by the rational-polynomial model. The simple exponential models were helpful in detecting near-field magnitude behavior.

The phase of the ocean channel exhibited a minimum at around 2MHz, which was in sound agreement with the theory of electric dipole, for a separation distance of a few cm. However, the frequency of the minimum phase delay did not seem to be very
sensitive to range changes, based on the lab measurements. As a part of our future work, we will consider adjusting the propagation model to space-constrained environments such as a lab tank.

The large magnitude variation (20-25 dB) with frequency and time invariance of the channel motivate the design of an OFDM system with unequal bit loading. That will be the direction of our future research.

6. ACKNOWLEDGMENTS

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7. REFERENCES


