Development of an Underwater Electric Field Modem

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***Abstract*—An overview of electromagnetic propagation in seawater is discussed with some applications found in the literature. An experiment involving vertical dipoles submerged in seawater was performed to measure the frequency response at different ranges. The experimental results indicate that this dipole configuration can be effectively modeled as two vertical dipoles in a homogenous medium. Lastly, we provide a brief description of the current state of development of our underwater electric field modem.**

I. Introduction

One of the major advantages of underwater acoustic communication is the extended ranges attainable using a high bit-rate acoustic modem which results from the low attenuation of underwater acoustic energy. The effectiveness of propagation of acoustic signals between a source and receiver is inevitably accompanied by the unwanted effects of multipath, reverberation, and ambient noise. Consequently, these factors require intense signal processing to account for the acoustic propagation effects in the transmitted data. Conversely, electromagnetic (EM) signals transmitted in the ocean are heavily attenuated by the conducting medium of seawater with attenuation increasing with frequency. This limited range in propagation implies multipath and reverberation are also minimized, unlike in acoustics. Therefore, an underwater EM modem could potentially have a simpler, cost-efficient design, with the trade-off in range of propagation. Multiple pairs of EM modems could simultaneously exchange data without causing interference with neighboring modems. This potentially could lead to increased network throughput.

The propagation of EM energy through a dissipative medium such as in seawater or underground has been studied extensively. In fact, an entire issue of IEEE Transactions on Antennas and Propagation [1] is devoted to the subject of EM waves in the earth. As the conductivity of a medium increases so does the loss experienced by a propagating EM wave in that medium. In seawater, the conductivity, σ, depends on temperature and salinity such that an increase in either of these quantities results in a linear increase in conductivity [2]. In the world's oceans, conductivities tend to be low in the Arctic Ocean or near the coast where river outflows are found. In contrast, conductivities are relatively higher in the Mediterranean and Red Seas where precipitation is low and water temperatures are high. The generation (or reception) of EM signals in seawater is typically achieved by using a current source to form either an electric dipole consisting of a pair of separated electrodes submerged in seawater or a magnetic dipole in which an insulated conductor or loop is submerged. This paper will focus on the use of separated electrodes for the transmission and reception of signals.

Let's consider a single conducting layer model consisting of half-spaces of seawater and air with transmit and receive antennas submerged in seawater. In the literature, two possible ways are identified whereby EM signals propagate from transmitter to receiver. The first, and by the far the most investigated, is the so-called 'up-over-down' mechanism [3], [4]. In this case EM signals initially propagate from the transmitter almost vertically to the sea-air interface. Across the interface, the EM signals are refracted such that the almost horizontal electric field in seawater is now almost vertical (slightly forward pointing) in air. The EM wave then propagates through the air with little loss. Part of the losses experienced by the EM wave travelling through the air over the sea is associated with a slightly downward oriented Poynting vector that implies some energy propagates from the air into the sea. This tiny amount of EM energy resulting from refraction of the almost horizontal propagation in air to almost vertical propagation in seawater gives rise to a small, almost horizontal, electric field vector arriving at the receiver. Evidently, if submerged electric dipoles are used as transmit and receive antennas then a horizontal collinear arrangement of the dipole axes provides the optimal configuration. The 'up-over-down' mechanism is one aspect of a more general investigation conducted by Moore [3], [4] in the context of communication with submarines using the following three scenarios: surface to submarine, submarine to surface, and submarine to submarine. As an order of magnitude, Moore showed for sufficiently low communication rates, that tens of kilometers in range could be achieved between submerged transmit and receive antennas located at depths up to 5 m with antenna lengths up to 100 m, frequencies in the tens of kilohertz, and transmitted power in the tens of kilowatts.

The second mechanism of propagation between submerged transmit and receive antennas uses the direct path through the conducting medium—this will be the subject of the experiment discussed in the next section. This mechanism is rarely considered since the typical frequencies of interest have high attenuations that severely degrade the direct path signals. As a result, useable ranges between transmitter and receiver are significantly reduced. In order to minimize these limitations low carrier frequencies are necessary for implementing this approach. For any underwater transmit-receive scenario both 'up-over-down' and direct paths exist. The relevance of each path is dictated by the amount of received EM energy from these contributions. The 'up-over-down' method is usually applied to frequencies in the upper very-low-frequency (VLF

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3–30 kHz) band and lower part of the low-frequency (LF 30–300 kHz) band with ranges in the tens of kilometers and shallow antenna depths. The cumulative loss experienced by EM signals in the 'up-over-down' method primarily consists of the vertical (up/down) attenuation through seawater, and interface losses at each sea-air transition wherein most of the energy is reflected and only a small portion is refracted. For shallow antenna depths and long ranges, the 'up-over-down' path is optimal since direct path attenuation through seawater is far higher. At ultra-low-frequencies (ULF 300–3000 Hz), using vertical electric dipoles, and short ranges (<100 m) the optimal path becomes the direct path through the conducting medium. This will be the case for the electric field modem presented in a subsequent section.

An alternative propagation path for antennas in conducting media, which is in the spirit of the 'up-over-down' mechanism, has been suggested that involves placing antennas at or near a layer with extremely low conductivity. In seawater, antennas placed on a low conductivity seabed have been shown to transmit ULF/ELF EM signals further than the same antennas in seawater of infinite extent [5]. Furthermore, at greater depths below the earth's surface there appears to be a waveguide that exists over a great deal of the earth, from 2–20 km deep, with conductivities ranging from 10^{-11}–10^{-6} S/m that is bounded above by the more conductive surface layer of the earth and bounded below by the increasing conductivity resulting from increasing temperatures. Radio wave propagation over very long distances, through this waveguide, from land to submarines on the seafloor has been proposed [6].

There are a number of references dealing with the theory of EM signal propagation in lossy media along with an analysis of submerged electric or magnetic antennas [3], [7], [8], to name a few. Weaver [9] found solutions for the electric and magnetic fields of a vertical or horizontal electric dipole embedded in a conducting medium (sea) of finite thickness that is bounded below by another conducting half-space (seabed) and above by free space. Weaver's work generalized previous results focussing on EM propagation in a single conducting half-space (sea-air) to a two-layer conducting half-space (seabed-sea-air). A verification of the Weaver model has been demonstrated [10] in a recent at-sea experiment performed in shallow water. Vertical and horizontal electric dipoles were used as transmitters and the amplitude of the magnetic field was measured at ranges up to 682 m showing good agreement with the Weaver model. A variety of applications of EM waves in seawater are reviewed in [11]. These include the Omega system used for near surface submarine positioning and navigation, triggering of a remote release mechanism, an obstacle detection system for a ship, and a guidance system using magnetic fields. In a modern application involving communication among a large number of autonomous underwater vehicles (AUVs), a simulation was performed [12] that compared the use of EM versus acoustic signalling where it was shown that up to an order of magnitude increase in network throughput could be achieved using EM signalling for an appropriately chosen density and scale of an AUV network. EM communication through sea and rock have been commercialized by Wireless Fibre Systems and Ultra Electronics, respectively.

EM propagation in any medium, including seawater, is governed by Maxwell's equations. It is worthwhile briefly reviewing some of the fundamental equations of EM propagation in a conducting medium. Consider the following Maxwell (–Ampère) equation in SI units

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \ , \tag{1}$$

where $\mathbf{H}$ (A/m) is the magnetic field intensity, $\mathbf{J}$ (A/m^2) is the electric current density that is a sum of conduction and impressed currents, and $\mathbf{D}$ (C/m^2) is the electric displacement. The right hand side of (1) contains the sources that drive EM propagation. For a dipole antenna in air the first term on the right hand side of (1) is negligible whereas the displacement current generated by the second term results in the radiation of EM waves. However, in a conducting medium such as seawater the displacement currents are negligible whereas the electric currents appearing in the first term of the right hand side of (1) drive EM propagation in the sea. This explains why the term 'conduction current signalling' encountered in the literature is used synonymously for EM propagation in seawater.

If an electric field intensity $\mathbf{E}$, or magnetic field intensity $\mathbf{H}$, is a applied to a medium that responds with a proportionate polarization vector $\mathbf{P}$, or magnetization vector $\mathbf{M}$, respectively, then the medium is called linear. In this case, we can write the displacement $\mathbf{D} = \epsilon\mathbf{E}$, and the magnetic flux density $\mathbf{B} = \mu\mathbf{H}$. The electric and magnetic properties of the medium are contained in the permittivity ϵ and permeability μ; for seawater $\epsilon = 7.08 \times 10^{-10}$ F/m and $\mu = 4\pi \times 10^{-7}$ H/m. Furthermore, if the medium satisfies Ohm's law then $\mathbf{J} = \sigma\mathbf{E}$, where σ is the conductivity of the medium. A typical value of $\sigma = 4$ S/m is used for seawater. Assuming a linear medium that is conducting and satisfies Ohm's law, as we do for seawater in this paper, then from (1) along with the other Maxwell equations it can be shown that $\mathbf{E}$, and similarly $\mathbf{H}$, satisfies the following propagation equation

$$\nabla^2\mathbf{E} - \mu\epsilon\frac{\partial^2\mathbf{E}}{\partial t^2} - \mu\sigma\frac{\partial\mathbf{E}}{\partial t} = 0 \ . \tag{2}$$

In air, the conductivity $\sigma \approx 0$ S/m therefore (2) reduces to the wave equation for $\mathbf{E}$. In a conducting medium such as seawater where $\sigma \approx 4$ S/m and the frequencies of interest are sufficiently low then the third term on the left hand side of (2) dominates the second term and therefore (2) approximates the heat equation for $\mathbf{E}$. Evidently, EM propagation in seawater is similar to a diffusion process at low frequencies. The condition on frequency arises from solutions of (2) with a time harmonic variation, ω, so that every ∂_t accumulates a factor ω. Therefore, the relative magnitude of displacement currents to conduction currents, or similarly the medium behaving as a dielectric or conductor depends on the relative magnitude of $\omega\epsilon$ to σ, respectively. A typical requirement for a medium to be conducting is $\sigma \gg \omega\epsilon$, we note for seawater with $\sigma = 4$ S/m that displacement currents and conduction currents are comparable at approximately 900 MHz, which is far higher than any frequencies considered in this paper (up to 20 kHz). Consider a plane wave solution of (2) travelling in the x-direction

$$E = E_0 e^{\jmath\omega t - \gamma x} = E_0 e^{-\alpha x} e^{\jmath(\omega t - \beta x)} \ , \tag{3}$$

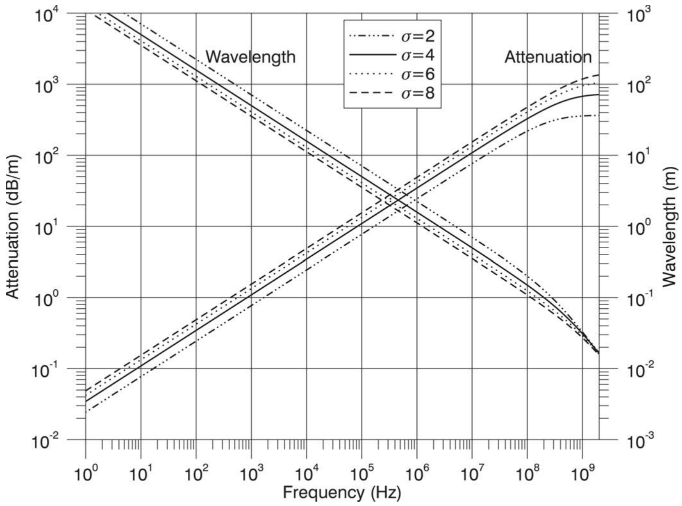

Fig. 1. Attenuation and wavelength of a plane wave propagating in seawater with varying conductivities.

where $\gamma = \alpha + \jmath\beta$ is the propagation constant whose real part is the attenuation factor and imaginary part is the phase factor,

$$\gamma = \sqrt{\jmath\omega\mu(\sigma + \jmath\omega\epsilon)} \ , \tag{4}$$

$$\alpha = \sqrt{\frac{\omega\mu\sigma}{2}} \left[-\frac{\omega\epsilon}{\sigma} + \sqrt{1 + \left(\frac{\omega\epsilon}{\sigma}\right)^2} \right]^{\frac{1}{2}} \ , \tag{5}$$

$$\beta = \sqrt{\frac{\omega\mu\sigma}{2}} \left[\frac{\omega\epsilon}{\sigma} + \sqrt{1 + \left(\frac{\omega\epsilon}{\sigma}\right)^2} \right]^{\frac{1}{2}} \ . \tag{6}$$

The plane wave travels with a phase velocity $v = \omega/\beta$. In a conducting medium such as seawater where $\sigma \gg \omega\epsilon$ we have that attenuation and phase factors are approximately equal, $\alpha = \beta = \sqrt{\omega\mu\sigma/2}$.

Figure 1 graphs the attenuation factor from (5), and wavelength for a plane wave travelling in a medium with conductivities varying from 2–8 S/m; these are typical values for seawater. As the conductivity increases, so does the attenuation. Moreover, the higher the conductivity the slower the EM propagation speed which results in a corresponding decrease in wavelength. Clearly, anything beyond LF results in attenuation over 20 dB/m; thus, severely limiting the range of direct path conduction current signalling. The electric field modem presented in a subsequent section has a carrier frequency of 2 kHz, so from Figure 1 plane wave propagation gives an attenuation of 1–2 dB/m. The flattening of the attenuation curves in Figure 1 is associated with the seawater transitioning from a conductor to a dielectric. As we stated previously, for seawater with $\sigma = 4$ S/m, the transition is at approximately 900 MHz. It is important to note that the assumption that seawater is a linear medium no longer holds at high frequencies since ϵ decreases at frequencies above 5 GHz. In addition, σ increases above 2 GHz, so the curves in Figure 1 would be inaccurate if continued beyond these values because this frequency dependence is not taken into account [13], [14].

II. Experimental Results

The electric field modem discussed in this paper consists of a pair of separated electrodes representing an electric dipole for both transmitting and receiving. In order to investigate the performance of this modem we conducted an experiment that measured the magnitude of the frequency response between two vertical dipoles in seawater whose centers were at a depth of 10 m in a water depth of 40 m. Each dipole consists of a pair of zinc electrodes with 1 m separation. One dipole was used as the transmitter and the other as the receiver, and a swept sine with frequency ranging from 50 Hz to 20 kHz was transmitted. The frequency response was measured as the dipole separation ranged from 1 m to 20 m in increments of 1 m. Since the fields of each vertical dipole are minimized along the dipole axis then interaction with the surface and bottom is also minimized. In this case, the vertical dipole has been described [15] as generating a quadrupole at the air-sea interface that is essentially out of phase and thus does not radiate well into the air. In contrast, a horizontal electric dipole is the optimal transmitter/receiver for the up-over-down method since it radiates better into the air. Therefore, we simplify the problem by neglecting the air/seabed half-spaces and assume the dipoles are in a homogeneous conducting medium. In this geometric configuration we are investigating EM propagation via the direct seawater path. A similar experiment measuring the frequency response was performed in [16] where horizontal electric dipoles were used for transmitting and receiving. The receiver was placed at a fixed 2 m depth while, directly below, the range from a parallel horizontal transmitter was adjusted. Seven frequencies were sampled from 500 Hz–32 kHz at ranges of 4, 6, 8, 10 m. Their results show that the measured frequency response consistently underestimates the theoretical response and as the transmitter approaches the receiver the discrepancy increases. The difference at 4 m was attributed to the increased effect of the boundary surface [16]. Using the notation of [16] we assume an extended vertical dipole at the centre of a spherical coordinate system. Assuming the dipole axis is aligned with the z-axis, then the non-vanishing electric field components are along the radial E_r and polar E_θ directions, and the only magnetic field component is along the azimuthal direction H_ϕ [7]. A second extended dipole parallel to the first, with centre in the x–y plane, will measure the following voltage arising from E_θ as

$$V_\theta = \frac{I l_r l_t}{4\pi r^3 \sigma} \left(1 + \gamma r + \gamma^2 r^2\right) e^{-\gamma r} \ , \tag{7}$$

where l_t and l_r are the lengths of the transmitting and receiving dipoles respectively, whose centres are separated by a range r, I is the impressed current generated by a harmonically time varying transmitting dipole at the origin with frequency ω, and γ is the propagation constant defined in (4). Equation (7) holds as long as l_t is much less than a wavelength. A measurement of the conductivity at 10 m depth during our experiment gave $\sigma = 3$ S/m, which we use in the remaining. To leading order, the measured voltage V_θ falls off as r^{-3}, and increases proportionally with an increase in driving current, or lengths of the transmitter or receiver dipoles. Using $l_r = l_t = 1$ m, and a nominal value of $I = 1$ A r.m.s we plot the measured and theoretical magnitude of V_θ/I in Figure 2. This gives the

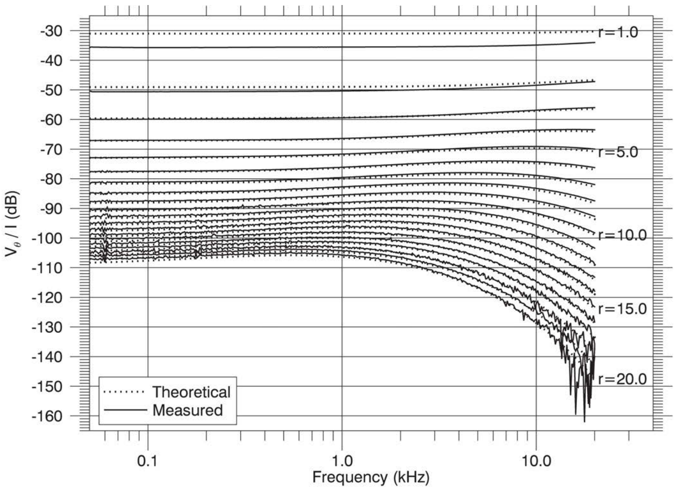

Fig. 2. Theoretical and measured values of the frequency response for vertical electric dipoles used as a transmitter and receiver at 10 m depth in seawater.

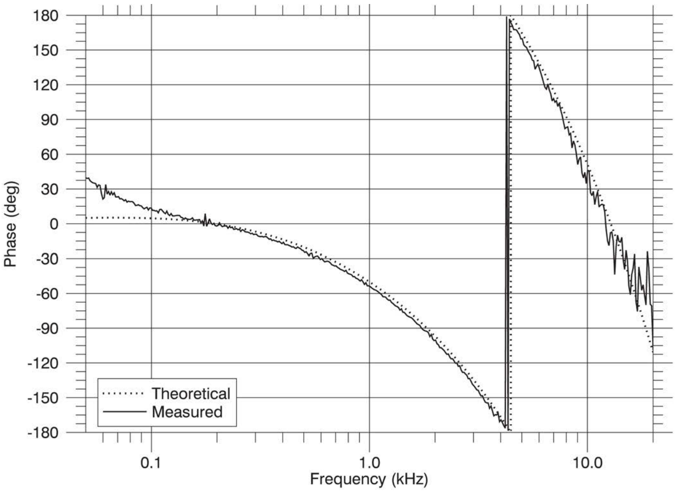

Fig. 3. Theoretical and measured values of the phase response for vertical electric dipoles used as a transmitter and receiver at a 10 m depth in seawater and a range of 20 m.

frequency response of the vertical electric dipole transmitter-receiver system in seawater.

In general, we find good agreement at each range step and frequency between the measured values and equation (7), giving errors typically less than 1 dB. However, at the short ranges of 1 and 2 m the errors are higher, closer to 5 and 2 dB, respectively. We attribute these increased errors at the short ranges to perturbations in separation between the two dipoles being a significant fraction of the range r. These range errors are likely since the dipoles were suspended from cables to a depth of 10 m. At 20 m, a measurement of the phase response of the system was performed and compared with the theoretical phase of V_θ/I. Figure 3 shows the comparison of the phase response, and the generally good agreement between measured and theoretical values.

One of the primary limitations in underwater EM communication is the EM noise in the atmosphere from natural and man-made sources that penetrates through the sea and reduces signal-to-noise ratio at the receiver. Seasonal data for

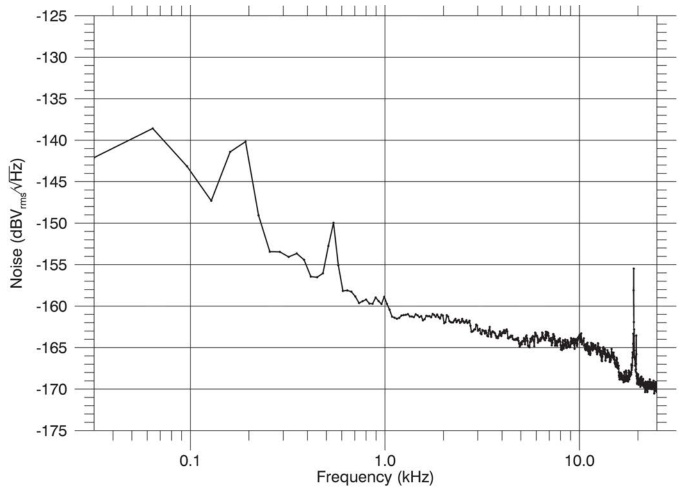

Fig. 4. Electric field noise power measured by the vertical receiving dipole at a depth of 10 m.

noise in the atmosphere, at different locations on the earth, has been studied [17], [18] and may be used to determine EM noise at an underwater dipole receiver located at a specified depth. In Figure 4, we provide a measure of the noise at our vertical electric dipole receiver located at a depth of 10 m in Halifax harbour. The frequencies sampled in Figure 4 range from 32 Hz–25 kHz and show an increase in noise at 60 Hz and some of its odd harmonics. In addition, at the 2 kHz carrier frequency of our electric field modem we find a noise power spectral density of approximately -162 $\mathrm{dBV_{rms}}/\sqrt{\mathrm{Hz}}$ or $8\,\mathrm{nV_{rms}}/\sqrt{\mathrm{Hz}}$ across our 1 m receiving electrodes. These are simply rough estimates of noise power, and any proper noise measurements would require multiple spectral averages over an extended period of time and at multiple locations.

III. Electric Field Modem

In order to investigate the benefits of electric field communications Defence Research & Development Canada - Atlantic Research Centre (DRDC Atlantic Research Centre) has been developing an underwater electric field modem in a project referred to as Low Complexity Access Network (LCAN). Figure 5 shows a diagram of the electric field modem which consists of an aluminum frame supporting two canisters, one for batteries and the other for the electronics. Below the electronics canister is a cable going to a pair of platinum coated electrodes (not shown), separated by 10 m, and used as an electric dipole for transmit and receive. Platinum is used for the electrodes because of its minimal corrosion in seawater which will result in a low, constant impedance presented to the electronics.

The electronics canister contains an analogue 'front-end' board that includes the amplifiers, filtering, and impedance matching to seawater necessary for transmit and receive. The second board in the electronics canister, interfaced with the front-end, is the embedded modem processor board [19] that was designed and developed by Omnitech Electronics Inc. of Dartmouth, Nova Scotia. Utilizing a 300 MHz ARM processor with 128 MB of RAM running a Linux kernel, it performs all of the digital signal processing. Many of the modem configuration parameters can be adjusted. Experimentation will

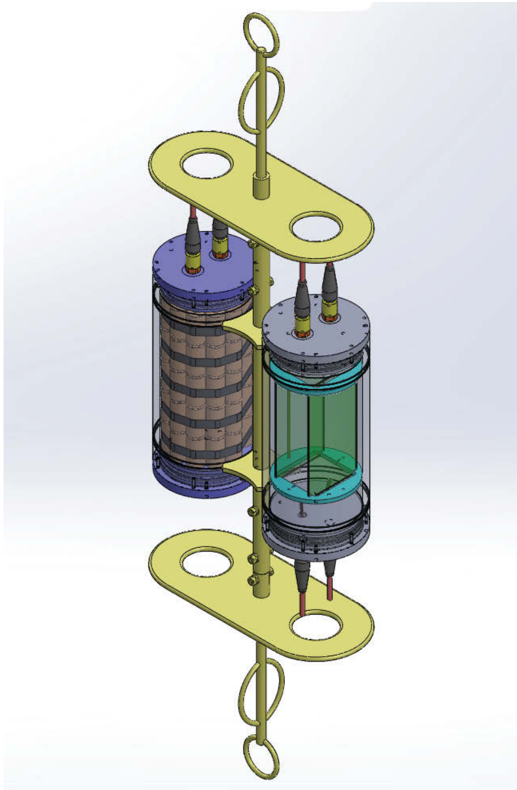

Fig. 5. Battery and processor canisters used in the electric field modem.

be required to determine the optimal configuration parameters for specific modem geometries and environments. By default, the modem uses a 2 kHz carrier frequency that is modulated using differential phase shift keying with 4 symbols in the constellation each representing 2 bits of data at a rate of 300 baud. Each packet contains 64 bytes of data, a 2 byte packet header, and a preamble sequence formed from a barker code of length 11 that is used for packet alignment. The modem can be used with or without an error correcting scheme. However, based on the noise limited channel environment we expect very poor performance without error correction. Implemented error correction schemes include the Hamming (7,4) code, and a rate 1/2 convolutional code. Other convolutional code rates are obtained by puncturing the output of the 1/2 convolutional encoder to give rates 2/3, 3/4, 5/6, and 7/8. The calculated throughput of the modem given these default parameters range from 545 bps for no error correction to 274 bps for a rate 1/2 convolutional code [19]. Currently, a pair of LCAN modems is being assembled at DRDC Atlantic Research Centre with hardware tests planned for later in the year.

IV. Conclusion

The concept of using underwater EM propagation for communication is not new as is evidenced by the vast amount of literature on the subject. In this short paper we have briefly highlighted some of the documented applications and showed that heavy attenuation rates force only low carrier frequencies to be used in any reasonable transmit-receive scheme. It has been shown that for the arrangement of vertical dipoles used in the experiment the effects of the boundaries are negligible. This conclusion follows from the good agreement obtained between the measured and the theoretical frequency response for vertical dipoles in a homogeneous conducting medium. In this simplified EM model the gain of the received voltage signal is directly proportional to the length of the transmit or receive dipoles, and to the current of the transmitter. Apart from the r^{-3} leading order attenuation rate there are indications that ambient EM noise will limit the communication channel. To mitigate the effects of expected low signal-to-noise a number of error correction schemes have been implemented in the ongoing development of an underwater electric field modem.

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