Propagation of Electromagnetic Waves in Seawater

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Abstract:

Electromagnetic communication through seawater has advantages over acoustic and optical communication. Propagation in seawater (conducting medium) dependence on f(Hz), ϵ (F/m), and σ (S/m) of transmission medium. In this paper the propagation of electromagnetic waves in seawater is discussed. The study classified the conducting medium into three areas, good conductor, normal conductor, and good dielectric, depending on loss tangent value. In order to obtained more accuracy, general equations and complex permittivity are applied for the three cases. The paper illustrates EM frequency communication for seawater from 10kHz to 100 GHz range and also provides comprehensive performance analysis using MATLAB simulation tool.

1. Introduction

Underwater communications have attracted significant interest in recent years since they have a wide range of applications including coastline protection, underwater environmental observation for exploration, off-shore oil/gas field monitoring, oceanographic data collection, autonomous underwater vehicles (AUVs) and remotely operated vehicles (ROVs), etc., [2]. Seawater communications have traditionally been carried out using acoustic and optical technologies, all of which have advantages and disadvantages.

Acoustic communications, for example, are commonly used in the underwater environment, but multipath propagation has a major effect on their performance in shallow waters. Another drawback of acoustic communications is the low propagation velocity(1500ms^{-1}) of acoustic waves in water. On the contrary, laser based optical systems have significantly higher propagation speed than underwater acoustic waves. However, strong backscattering caused by suspended particles in water always limits the application of optical systems to very short distances[2].

EM waves propagates faster in water than acoustic waves by more than 4 orders of magnitude($\approx 3x10^7 ms^{-1}$). The high attenuation caused by water's conductivity is the primary disadvantage of EM wave propagation in seawater. Seawater is considered a high-loss medium due to the fact that it is highly conductive. The conductivity of seawater is almost 400 times greater compared to freshwater[8].

This study focuses on investigation of electromagnetic waves propagating in seawater. Loss tangent parameter of seawater has been determined on wide range of frequency. The value of loss tangent specifies the conductivity of seawater. Table(1) classified seawater conductivity loss tangent value.

Table(1) shows classification of seawater conductivity

	Good conductor	Normal conductor	Good dielectric
Loss tangent	>100	100-0.01	<0.01

The attenuation and propagating velocity of EM wave in seawater is investigated. General equation for attenuation(12) is used to obtained accurate result.

2. Theoretical Background

To derive a governing equation for The properties of an electromagnetic wave (wave propagation, velocity of propagation, frequency, attenuation, etc.), we start with Maxwell's equations:

$\nabla E_S = 0$ (1)

$\nabla . H_S = 0$ (2)

$\nabla \mathrm{X} E_S = -\mu H_S$ (3)

$\nabla H_S = (\sigma + j\omega\varepsilon)\, E_S$ (4)

Where μ and ϵ are permeability and permittivity of the medium.

From this set of equations, we can derive a Helmholtz's equation and investigate the wave properties through seawater. Taking the curl of both sides of equation (3) with application of vector identity and invocation of equation (1) and (4) we obtain homogenous vector Helmholtz's equation

$\nabla^2 E_S - \gamma^2 E_S = 0$ (5)

$\nabla^2 H_S - \gamma^2 H_S = 0$ (6)

The complex constant γ is defined as the propagation constant

$$\gamma = \sqrt{j\omega\mu(\sigma + j\omega\varepsilon)} \quad (7)$$

3. Parameter variation with frequency and conductivity

The propagation of electromagnetic wave through a uniform, linear, homogenous medium is described by the propagation constant

$$\gamma = \sqrt{j\omega\mu(\sigma + j\omega\varepsilon)} = \alpha + j\beta \quad (8)$$

Where σ is the medium conductivity, $\epsilon=\epsilon_0\epsilon_r$ is the medium permittivity, and $\mu=\mu_0\mu_r$ is the medium permeability[7].

According to the characteristics of the medium (μ,ϵ,σ) we may evaluate the attenuation and phase constant equations.

$$\gamma^2 = j\omega\mu(\sigma + j\omega\varepsilon) = (\alpha + j\beta)^2 = \alpha^2 + j2\alpha\beta - \beta^2 \quad (9)$$

$$Re\gamma^2 = \alpha^2 - \beta^2 = -\omega^2\mu\varepsilon \quad (10)$$

$$Im\gamma^2 = 2\alpha\beta = \omega\mu\sigma \qquad (11)$$

$$\alpha = \omega[\frac{\mu\varepsilon}{2}(\sqrt{1+\left[\frac{\sigma}{\omega\varepsilon}\right]^2}) - 1]^{1/2} \qquad (12)$$

$$\beta = \omega[\frac{\mu\varepsilon}{2}\left(\sqrt{1+\left[\frac{\sigma}{\omega\varepsilon}\right]^2}\right) + 1]^{1/2} \qquad (13)$$

The parameter α describes the attenuation expressed as Ne per m^{-1} (usually converted to dB m^{-1}). The parameter β describes the phase change with distance, expressed as rad m^{-1}.[7].

4. Calculating the wave parameters of different frequencies in seawater

4.1. Loss tangent

Loss tangent is a parameter of a medium that quantifies dissipation of electromagnetic energy. The value of loss tangent ($\frac{\sigma}{\omega\varepsilon}$) judge whether or not the medium is good or bad conductor comparing to unity. The loss tangent value (τ) expressed by equation (14).

$$\tau = \frac{\sigma}{\omega\varepsilon} = tan\delta \qquad (14)$$

Medium considered as good conductor for loss tangent much bigger than unity. Medium has loss tangent much smaller than unity considered as lossy dielectric. For more specific, mediums have loss tangent bigger than 100 classified as a good conductor, mediums have loss tangent less than 0.01 classified as lossy dielectric, the range between 0.01 and 100 classified as normal conductor. Clearly, loss tangent depends on frequency, that means the frequency of transmitted EM wave can determine the conductivity of the medium.

4.2. Complex permittivity

Permittivity is a quantity used to describe dielectric properties that influence reflection of electromagnetic waves at interfaces and the attenuation of wave energy within materials[10]. In lossy dielectrics complex relative permittivity ε_c of a material can be expressed in the following form:

$$\varepsilon_c = \varepsilon' - j\varepsilon" \qquad (15)$$

$$\varepsilon' = \varepsilon_r\,\varepsilon_0 \qquad (16)$$

Where ε_r is the relative permittivity of medium, for seawater is about (81), ε_0 is the permittivity of free space ($8.854x10^{-12}$F/m).

$$\varepsilon" = \frac{\sigma}{\omega} \qquad (17)$$

The imaginary part of permittivity (ε") is called the loss factor and is a measure of how dissipative or lossy a material is to an external electric field.

For getting accurate results, complex permittivity is used to calculate loss tangent instead of absolute permittivity.

$$tan\delta = \frac{\sigma}{\omega\varepsilon_c} \qquad (18)$$

4.3. Attenuation

Electromagnetic wave weaken when passing through a medium. Attenuation can provide a reasonable estimate of how much power will be lost after Z distance. The value of attenuation depending on medium that wave propagates through. Frequency has direct effect on attenuation amount where attenuation increases with increasing of frequency. The general attenuation equation (12) is applied to obtain the precise attenuation of signal in seawater.

4.4. Velocity

The velocity of sound underwater is 1500 m/s, which is slow when compared to the velocity of EM signals in the same medium. Thus, EM waves are faster than acoustic waves, hence yielding less propagation delays and enabling fast communication [8]. The propagation velocity is expressed in Equation (19).

$$v = \frac{\omega}{\beta} \qquad (19)$$

Where ω is the angular frequency in (radians/s), and β is the phase constant in (radians/m).

5. Results

The loss tangent as well as attenuation for a plane wave propagating through seawater is analyzed in the frequency range of 10 kHz to 100 GHz. The frequency spectrum covers frequencies from the VLF(used in submarine communications) to the UHF band. The conductivity is set to 4 S/m while the permittivity is a function of frequency(complex permittivity) to obtain accurate results. Matlab was utilized to get the data. Results were achieved for various EM signal frequencies.

The Loss Tangent was simulated using equation (14), the permittivity considered as complex. **Figure 1** illustrates the loss tangent in seawater. Value if loss tangent is large for low frequencies and tended to decline as the frequency of the signal increased.

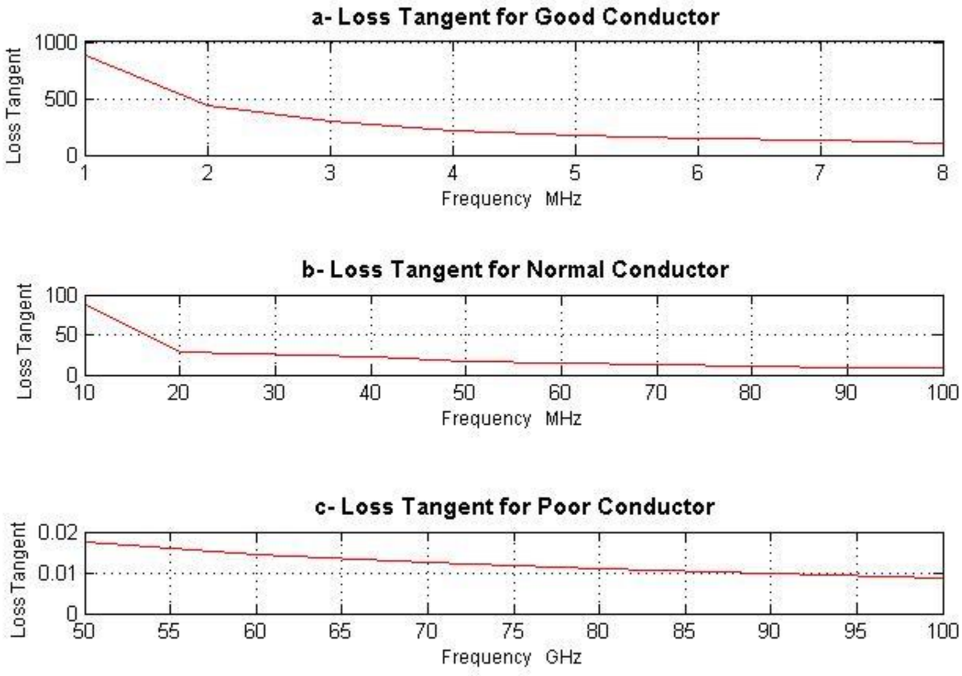

Figure 1 shows loss tangent values corresponding to frequency for (a) good conductor, (b) normal conductor, (c) poor conductor.

Figure 1-a shows the loss tangent for a good conductor medium which frequency value is less than 8MHz which gives value of 109.8 of loss tangent. **Figure 1-b** shows the loss tangent for a normal conductor medium started from 87.86 which corresponding to 10 MHz. **Figure 1-c** shows the loss tangent for a poor conductor medium. At 50 GHz the loss tangent falls to 0.0176 which considered as poor conductor . as shown in the figure frequency almost has no effect on loss tangent at frequencies above 50MHz.

A higher value of loss tangent means that the signal tends to be more a conductor than a dielectric. When the loss tangent is decreased to be smaller, the signal appears to be more dielectric.

General attenuation is calculated as in equation (12). Also, the permittivity compensated as complex in the equation. **Figure 2** illustrates the attenuation expressed in dB/m of the propagation of EM wave through seawater. It can be noticed that the attenuation increases with the increasing of frequency. From the other side, lower frequency signals experience lower attenuation values.

Figure 2-a illustrates attenuation for good conductor medium, frequencies less than 8MHz have loss less than 62.83 dB/m. **Figure 2-b** illustrates attenuation of frequency between 10MHz and 100MHz , the corresponding attenuation is 70.24 dB/m and 221.6 dB/m respectively which classified as normal conductor. **Figure 2-c** illustrates attenuation of frequency above 1GHz. As shown in the figure, at 50GHz the medium become poor conductor (good dielectric).

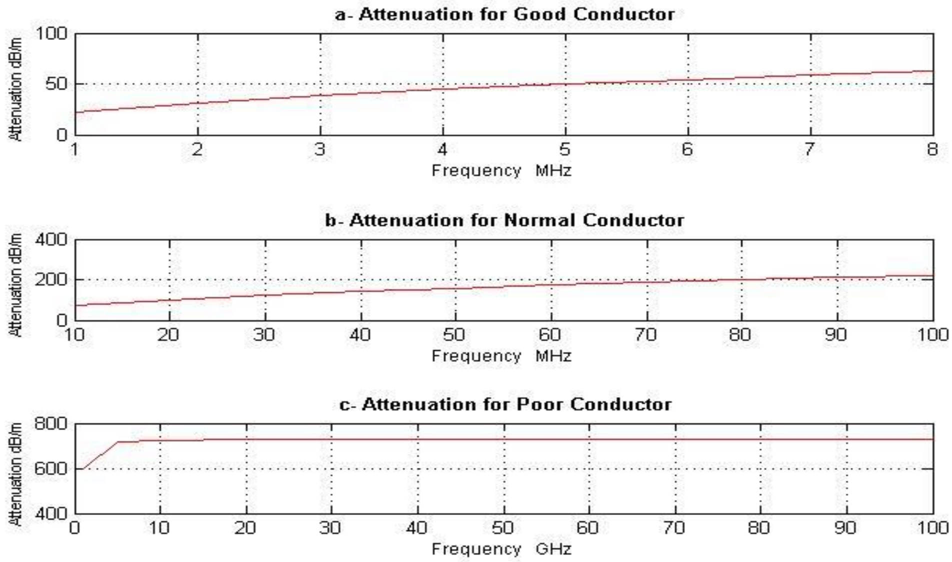

Figure 2 shows the attenuation corresponding to frequency for (a) good conductor, (b) normal conductor, (c) poor conductor.

The speed of the EM wave when it propagates in seawater is derived by the equation given in Equation (22). **Figure 3** illustrates the velocity values for an EM signal propagating across seawater. For various frequencies, the values are determined. As shown in **Figure 3** , with an increase in frequency, the velocity increases.

6. CONCLUSIONS

In this paper, we discuss the propagation of electromagnetic waves in sea water analyzing the loss tangent, attenuation and the propagation speed in a medium with complex permittivity and general equations of wave propagation, in order to accurately characterize a wireless propagation medium. MATLAB was used to obtain the results. Data were obtained for frequency range from 10kHz to 100GHz.

Loss tangent value determine whether seawater is a good conductor or a good dielectric depending on frequency of propagating wave. From the study, values of loss tangent bigger than 109.8 considered as a good conductor. On other hand, values less than 0.0176 considered as a poor conductor. Values between 109.8 and 0.0176 are normal conductor.

At 8MHz the attenuation is 62.83dB/m. frequencies less than 8MHz considered as good conductor and the attenuation will be smaller than 62.83dB/m. Normal conductor frequency will be between range of 10MHz and 100MHz, the corresponding attenuation are 70.24dB/m and 221.6dB/m. At frequency of 50GHz the attenuation is 472.3dB/m which is very high the value of loss tangent 0.0176, the medium become a poor conductor. For all frequencies above 50GHz medium considered as good dielectric.

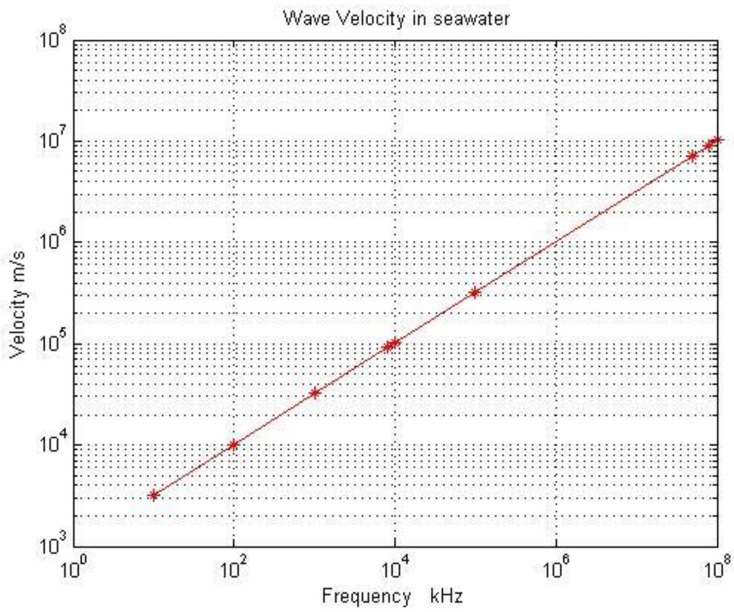

Figure 3 shows the velocity values for an EM signal propagating across seawater.

Velocity of the wave propagating through seawater increases with frequency rapidly. From the results, the velocity of the wave in seawater is 3.21×10^3m/s at 10kHz. The speed of the wave start increasing with increasing of frequency until reach 1.0154×10^7m/s at 0.1GHz.

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