Seawater salinity modelling based on electromagnetic wave characterization

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ABSTRACT

Wireless communications have experienced tremendous growth, and improving their performance based on specific parameters requires an accurate model. Salt seawater, being an abundant resource, could play a crucial role in various applications such as enhancing electrical conductivity, monitoring security, improving battery power efficiency, and creating liquid antennas. Salinity is an essential factor to consider when developing these applications. This paper focused on investigating the electromagnetic properties of seawater salinity in the context of marine wireless communications. The results of the study showed that salinity has a significant impact on the Fresnel reflection coefficient in terms of magnitude, phase shift, and polarization, and can either constructively or destructively affect it. The new model paved the way for the development of an integrated salt seawater model that addressed the complex salinity issues involved in these applications.

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1. INTRODUCTION

Wireless communication witnessed immense growth rapidly over the last decades, and that gives a paramount role to the telecommunication company when thinking to implement designs and planning in different environments, particularly in seawater which is cover more than 70% [1]. Due to the tremendous information era, high data rates become inevitable in modernization, where signal behavior would contribute that revolutionizing digitalization. As stated before, studying deeply the wavelength phenomenon electromagnetically in an open water environment that covers above to two-thirds of universally, whereas saltwater particularly represents more than 95% of the water resources available to serve the modern upcoming life consider unavoidable and should become in front of the scene [2], [3].

Accurate propagation should be known for each specific environment to tackle mainly the various parameters such as path loss and fading which affect the coverage area and improve receiver sensitivity, respectively [4]. Each up to now the wireless model has its own applicability standards and limitations, including various antenna's specification [5], but up to the present, no study takes care of the gradient seawater salinity despite the area such as the Gulf region and others having a distinguished environment and stark salinity that has been variating from place to another inside the water [6], [7]. This phenomenon gives a crucial warning when considering the coastline link design to investigate the signal behavior well when bouncing from the salt seawater and diffusely reflected in many directions.

Previously, different studies investigated weather challenges particularly in the Gulf region [8], [9] while seawater under various circumstances and traditional approach have been done, for example, the famous experiment which was conducted by Marconi in 1901 demonstrated that the signal could provide a connection with ships sailing on the English Channel, and then followed by the two ray communication and broadcasting which were developed in 1930 and 1940 [9]. After that, the cellular concept started to develop in the 1960s and 1970s in Bell Laboratories until reached the first generation of wireless mobile communication in the 1980s [10]. While specific to the sea communication, Kamal *et al.* [11] proposed a process to characterize a wide-band channel over the sea wave propagation to measure the mobile channel at 1.9 GHz with little attention has been paid to the water composition types which influence the signal behavior. However, to improve the model and make it more reliable, the multipath effects need to be incorporated into the channel model [12], particularly the diversity techniques to achieve high performance [13]. Also, the propagation has been analyzed in [14] at 5 GHz to measure line-of-sight (LoS) near the sea surface, but the channel model could be improved by taking into account the surface configuration added to the error rate along with signal strength at the receiver [15]. As much as in [16], it was interesting to view millimeter wave propagation over the sea environment that was analyzed, but to get better channel modelling, the sea surface should be included as a parameter according to the connection link, and receiver sensitivity. Furthermore, for more precise and robust modelling, the specification of seawater type should also be considered [17], [18].

Another study has discussed antenna material [19] followed by [20] that could be used in wireless applications based on material permittivity, while trough gathering more electrical properties could achieve notable power radiation. Nevertheless, in [21] the liquid material characterization had been explored via dielectric characterization with unadvisable measurement of liquid samples due to the repetitive process of opening and closing the lid of the cavity that could lead to errors in the measurement process. Whereas the dielectric dense patch antenna was proposed in [22] to study Zamzam and distilled water at 5 GHz applications, and the significant result demonstrated a return loss between 4.41-5.52 GHz that reaches up to -10 dB, hence the strongest aspects of the study is considering the water composition which is could play a vital role in terms of propagation performance. Due to that, our study takes into account covering wide salinity levels in a variety of water including ocean and seawater to avoid the various hurdles that previous studies explored considering structure, and surface formation, in addition to that, the accuracy of seawater propagation looking to involve more parameters such as salinity with considering it in a wide range to cover various location and water types. Consequently, the objective of the study takes care to offer a comprehensive solution and provides a contribution wireless seawater model to serve different sectors such as environmental, electrical conductivity, and water communications, whereas the following subsection provides the model's description and analysis for an adequate propagation technique covering signal attitude and polarization with a range of salinity levels.

2. MODELLING VIEW

The signal could spread via a smooth flat reflection surface and then be modelled with direct and reflected rays of the electric field while ignoring surface wave components when the height of the transmitting antenna is many wavelengths or more above the reflection plane [23], [24]. This type of model relied on coherent direct and specular reflection and ignores non-coherent components that result from diffuse scattering due to a rough reflecting surface. If assume $H_{V,H}$ be the narrow band radio channel transfer functions for vertical and horizontal polarization, respectively. The description of vertical or horizontal polarization follows the usually used attitude with the vector of the electric field $\vec{E}$ being either parallel or normal to the incidence plane, respectively. The incidence plane contains a normal vector $\vec{n}$, directions of the incident, and reflection rays, whereas the more surface rougher the more signal diffuse and vice versa the less surface rougher the more coherent signal specular [25], [26]. The upcoming figures demonstrate the concept; Figure 1 illustrates a valuable contribution to smooth surfaces with normal specifications while neglecting the other surface types which are affecting the signal performance. Figures 2, 3, and 4 show the three surface classifications. Usually, the reflection plane is the earth's surface in the ground communication and open-source water such as the sea in terms of seawater communication, while according to the papers [27]–[29], that have been explained the behavior of magnitude $\rho_{V,H}$ and phase $\psi_{V,H}$ at small grazing angles from the plane wave Fresnel reflection coefficient which could be equal to $R_{V,H} = \rho_{V,H}e^{j\Psi_{V,H}}$ for both vertical and horizontal polarization, and can be written as (1).

$$R_{V,H} = \rho_{V,H}e^{-j\psi_{V,H}} = \frac{\sin\psi - a_{V,H}\sqrt{\varepsilon - \cos^2\psi}}{\sin\psi + a_{V,H}\sqrt{\varepsilon - \cos^2\psi}} \quad (1)$$

where ψ is the grazing angle on reflecting surface, $\varepsilon = \varepsilon_r - j60\lambda\sigma$, ε_r and σ are relative permittivity and electrical conductivity of reflecting surface, $a_V = 1/\varepsilon$ for vertical polarization transmission and $a_H = 1$ for horizontal polarization transmission.

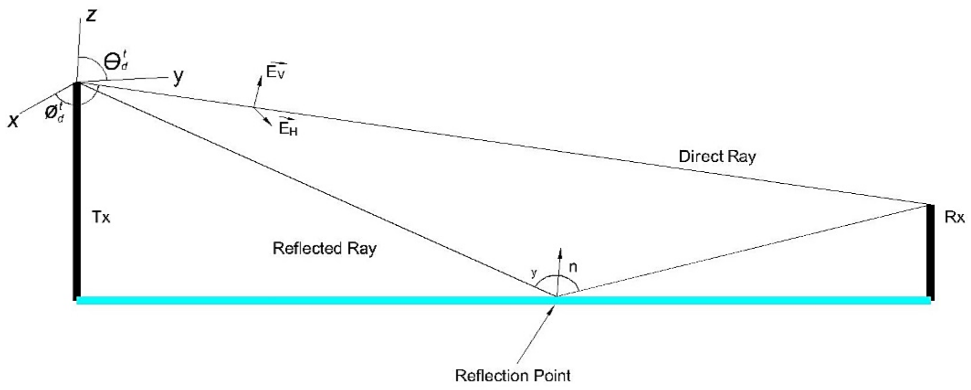


Figure 1. Propagation paths of the two-rays

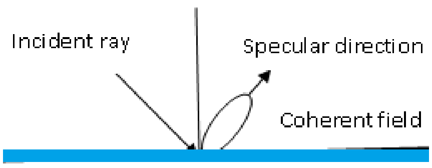


Figure 2. Smooth surface

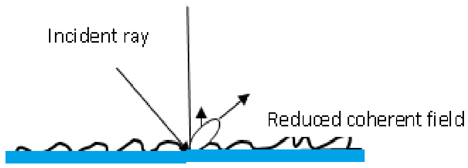


Figure 3. Rough surface

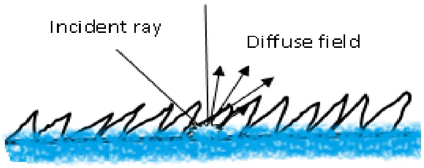


Figure 4. A very rough surface

The propagation of EM waves in seawater is significantly different from that on air because seawater has distinct electrical properties that severely impact the signal propagation. When the electromagnetic wave propagates, it is exposed to two types of losses; the first one when the dielectric is slightly conducting and the second one due to the energy dissipation via the polarization process. The salinity has a clear impact on the conductivity of the reflection surface. The relationship between salinity (ϕ) in ppt and conductivity σ in (S/m) shown in given by [30], [31] as (2).

$$\sigma = 0.001 * e^{4.99+0.05\,\phi} \quad (2)$$

where σ conductivity, and ϕ is the salinity, however, the (2) shows the clear exponential relation between conductivity and salinity which are both considered part of seawater [32], [33].

The study needs to investigate the behavior of $\rho_{V,H}$ and $\Psi_{V,H}$ as a function of salinity as both $\rho_{V,H}$ and $\Psi_{V,H}$ are function of $\varepsilon = \varepsilon_r - j60\lambda\sigma$ as mention earlier. The impact of salinity takes place in permittivity ε through its relation with conductivity σ. Hence, the relationship between permittivity ε and salinity ϕ can be written as (3).

$$\varepsilon = \varepsilon_r - j0.060\lambda e^{4.99+0.05\,\phi} \quad (3)$$

3. RESULTS AND DISCUSSION

A wide range has been accommodated to serve a comprehensive seawater surfaces model that could use in various areas not only in stark salinity regions. The study covers a salinity parameter in the gulf region and more that are from 10 ppt to 90 ppt to contribute to the model with a real seawater conductivity span, vertical and horizontal polarization, and distinct frequency. Figure 5 shows evidence of the strong correlation between salinity and conductivity. Whereas, the next Figure 6 shows the salinity had an impact on the signal polarizations which could be applied for radar and remote sensing on the magnitude Figure 6(a) and phase Figure 6(b) of Fresnel reflection coefficient for vertical polarization transmission using frequency of 10 MHz. While the next Figure 7 illustrates the influence of salinity on the magnitude Figure 7(a) and phase Figure 7(b) of Fresnel reflection coefficient for horizontal polarization transmission using frequency of 10 MHz and offer a robust sound that salinity of seawater could cause the refractive index to change and this might, which can affect the polarization of the various radar signals.

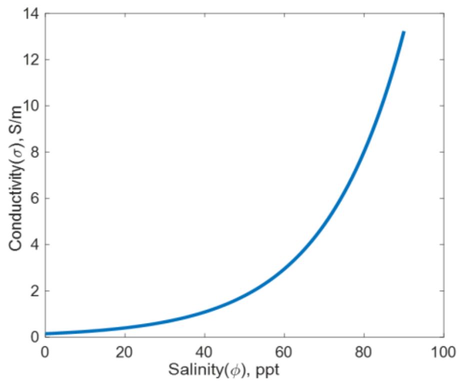


Figure 5. Salinity vs conductivity

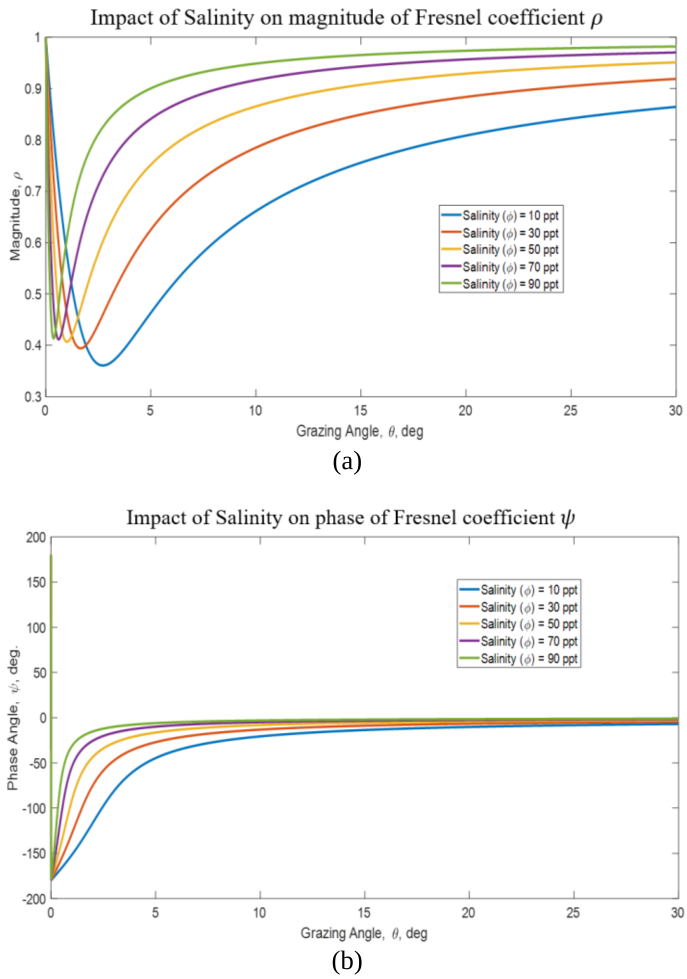
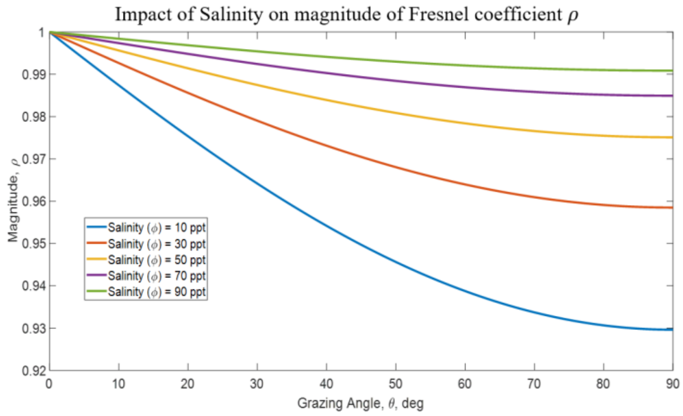
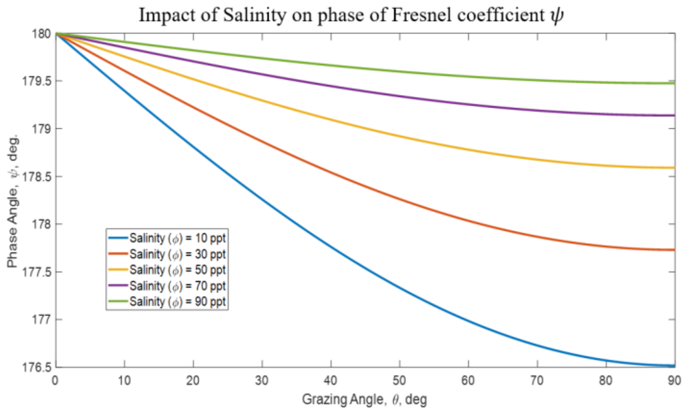


Figure 6. Vertical polarization under different salinity levels (a) at magnitude and (b) at phase



(a)



(b)

Figure 7. Horizontal polarization under different salinity levels (a) at magnitude and (b) at phase

From the result perspective, the unprecedented relation between conductivity and salinity could massively contribute to various applications such as liquid antenna as being safer for marine life, can be used to discreetly monitor a country's borders, when it works by identifying the best techniques for integrating salt seawater into propagating electromagnetic signals. While from the analysis aspect, the Fresnel reflection coefficient for vertical polarization transmission demonstrates that the little slop in all salinity grades clearly with the notable gradation from 90 ppt to 10 ppt, has made some disturbances in signal propagation, and then rise up to the receiver directly, while the increasing up with the steady spread of the signal at all salinity levels occurred and provide constructive interference at the phase of the coefficient propagation. Whereas the Fresnel reflection coefficient for horizontal transmission indicates clearly gradation under salinity grade 90 ppt with a dramatically gap when reaching 10 ppt and hence give a sound to the high impact of the magnitude when Fresnel reflection coefficient at the horizontal transmission. However, the phase of the Fresnel coefficient is more severe and could lead to a destructive signal when considering the reflection coefficient in the horizontal transmission.

4. CONCLUSION

Salinity is a major contributor to water quality problems in many areas of the world. However, in certain circumstances seawater could serve a useful purpose for service providers when other materials are unavailable. The paper investigated assessing the comparative strengths and weaknesses of different water types modelling for creating large-scale practical seawater wireless connections. The result shows that salinity is a major parameter in terms of the wireless design, particularly on the coast with the care of water composition. The variation at the salinity grade could play a crucial role when analyzing the effective propagation parameters such as phase shift, magnitude, and vertical or horizontal polarization transmission, which leads to signal influences constructively or destructively. Comprehensively, the study offers a sound to incorporate the salinity levels in wireless maritime design tools to accommodate the electrical properties and predict the unusual signal propagation.

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