Propagation of Electromagnetic Waves at MHz Frequencies Through Seawater

Ahmed I. Al-Shamma'a, Andrew Shaw, and Saher Saman

***Abstract*—The nature of the ocean environment and its vast size has necessitated the development of sophisticated equipment and techniques for various underwater applications including diver-to-diver communications, ROV/AUV docking, communications and oil and gas explorations. To facilitate scientific exploration a wide variety of systems and vehicles have been developed to operate within the shallow continental shelf region or in deep oceans. For successful underwater electromagnetic (EM) wave operation, knowledge is required of the wave transmission properties of seawater over all distances both short and long. This information is required for such activities such as: sensor systems, imaging, position fixing, measurement of speed, obstacle detection and avoidance, guidance, communication of data/voice and remote control. This paper presents a new approach of EM wave propagation through seawater. The experimental results conducted in the laboratory and the real environment of seawater is presented.**

***Index Terms*—Attenuation, conductivity and transmitter and receiver systems, electromagnetic (EM) waves, Maxwell's equations, underwater communications.**

I. Introduction

PRESENT systems involve the transmission of information in the form of light, sound or electric and magnetic fields. However each of these techniques have advantages and limitations. Optical systems are generally limited to extremely short distances because of backscatter and absorption. In the Irish Sea, for example, visibility is often zero or at best 1–2 m due to suspended matter in the water. Acoustic systems are the most versatile and widely used technique. Both optical and acoustic systems, however, are unable to penetrate behind an object and suffer from shadow zones. In shallow water, the use of acoustic techniques can be severely affected by multipath propagation in water due to reflection and refraction. The comparatively slow speed of acoustic propagation in water, of the order of 1500 m/s, is another limiting factor in terms of transmission data rates. Where as optical systems fail because of suspended matter, and acoustic systems because of high ambient noise levels, methods using electric and magnetic fields may offer an effective alternative for use over short distances. Maxwell's equations predict the propagation of electromagnetic (EM) waves travelling in seawater. A linearly polarized plane EM wave propagating in

Manuscript received September 26, 2003; revised December 11, 2003.

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Digital Object Identifier 10.1109/TAP.2004.834449

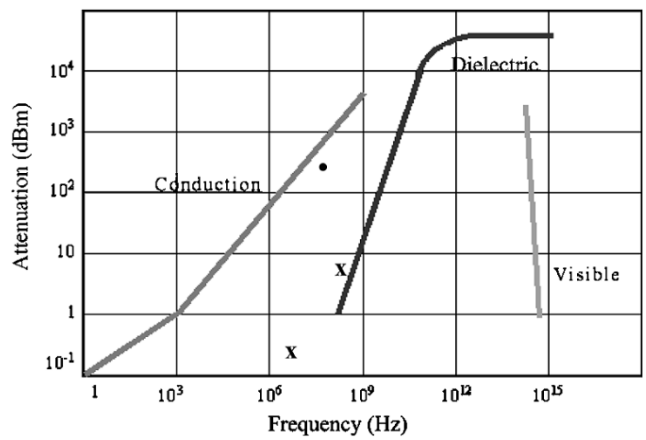

Fig. 1. EM wave propagation in seawater.

the z direction may be described in terms of the electric field strength E_x and the magnetic field strength H_y with

$$E_x = E_o \exp^{(j\omega t - \gamma z)} \quad (1)$$

$$H_y = H_o \exp^{(j\omega t - \gamma z)}. \quad (2)$$

The propagation constant (γ) is expressed in terms of the permittivity (ε), permeability (μ) and conductivity (σ) by

$$\gamma = j\omega\sqrt{\varepsilon\mu - j\frac{\sigma\mu}{\omega}} = \alpha + j\beta \quad (3)$$

where α is the attenuation factor, β is the phase factor, and $\omega = 2\,\pi f$ is the angular frequency. The term $\varepsilon\mu$ arises from the displacement current and the term $\sigma\mu$/w from conduction current. It is convenient to consider the solutions for the conduction band $(\sigma/\omega > \varepsilon)$ and the dielectric band $(\varepsilon > \sigma/\text{w})$. Investigations of the parameters σ and $\varepsilon(=\varepsilon^1 - j\varepsilon^{11})$ over the full EM frequency spectrum have been obtained in electrolytic solutions by using a wide variety of experimental techniques. The more popular techniques of EM wave propagation involve the use of coaxial transmission lines and waveguide cavities [1], [2]. If the seawater is in direct contact with the walls of the line or cavity then the conduction band losses apply. For example [3], a coaxial transmission line filled with seawater gave an attenuation coefficient $\alpha = 300$ dB/m for $f = 67$ MHz which is in 96% agreement with the conduction band calculations as shown in Fig. 1. This result is shown by the symbol (•). In experiments where the seawater is placed in an insulating container [4] within the waveguide shown in Fig. 1, the conduction losses are extremely small and the dielectric solution applies and these results are shown by the symbol x. Hence, combining these two experimental techniques will allow the simultaneous evaluation of a range parameters for sea water such as σ, ε^1, and ε^{11} and the wave velocities ν_σ and ν_ε. Such an investigation will allow detailed documentation of the properties of coastal seawater (clear, murky, and polluted) to be calculated for a wide range of temperatures, depths and frequencies. As the EM waves used in this study have longer wavelengths, it is anticipated that the effect of murky water or pollutants will be less severe than for the optical systems.

A literature survey of EM wave propagation has shown that such measurements are scarce, but limited investigations only for horizontal propagation have shown that short-range propagation between a transmitter and a receiver is possible. Propagation in seawater at 7 MHz [5] has produced a transmission distance of 460 m at a depth of 76 m. Measurements at 150 [5] and 14 MHz [6] have measured propagation over a distance of 30 m with the far-field attenuation coefficient (α) of 2.6 dB/m respectively. These results have shown that when EM waves are propagated through seawater, the attenuation can be reasonable and as expected from the dielectric theory. However, the launching and recovery of the wave into the water using conventional metal antennae occurs within the conduction band theory and may result in a loss as high as 80 dB for a 14 MHz frequency [6]. Therefore it appears that the propagation of EM waves into seawater depends on the launching technique used. Therefore the authors undertook a confirmatory experiment described in the following sections.

II. A New Approach

Experiments were classified as type A, B, or C as illustrated in Fig. 2. For type A, the transmitter and receiver antenna were placed in direct contact with the seawater. For type B, the seawater was contained in an insulating container and the antennae placed in air but close to the container walls. For type C, both the antenna were coated with an insulator and placed within the sea for horizontal water transmissions. A type D configuration only allows vertical water transmissions. Previous experiments had shown that type A experiments exhibit a large attenuation as shown in Fig. 3 and illustrated by the conduction curve of Fig. 1. Further research was therefore undertaken using type B, C, and D configurations. For type B experiments the propagation measurements of EM waves within a dielectric lined rectangular waveguide was undertaken. The system is shown in Fig. 4. A section of S band waveguide of 300 mm length and 86 mm by 43 mm cross-section was lined with Perspex of 6 mm thickness. The loop transmitting and receiving antennas were also dielectrically coated. The range of propagation frequencies was analyzed by using a HP Spectrum Analyzer 8594 E (9 kHz–2.9 GHz). The results for resonances in air are given in Fig. 5. The lowest resonance frequency is 1.612 GHz and this is followed by a series of resonances approximately represented by

$$f_{\rm res} = c\left[\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2 + \left(\frac{p}{l}\right)^2\right]^{\frac{1}{2}} \tag{4}$$

where c being the velocity of light and $f_{\rm res}$ is the resonant frequency. The cavity dimensions are (a) and (b) and the cavity length is (l). For any particular set of values of m, n, and p there is an E-type or an H-type mode of EM waves having the same resonance frequency. The lowest mode is TE_{010} and

$$f_{\rm res} = \frac{c}{2a} = 1.744 \text{ GHz}. \tag{5}$$

The actual experimental value is 1.612 GHz and this is lower because of the dielectric lining of the cavity. This reduces the resonance frequency because the dielectric constant of Perspex liner is of the order of 2.28 compared with a value of 1 for air. The spectral response for distilled water is shown in Fig. 6 for frequencies 0 to 1000 MHz. The peak propagation frequency was about 500 MHz and the signal strength was 226 mV. However the lowest resonance frequency has now reduced to 355 MHz. This represents a reduction of 4.54 when compared with the result for air given in Fig. 5. Simple theory would expect the lowest resonance frequency to be $f_{\rm res}/\sqrt{\varepsilon_{\rm water}} = 179$ MHz because the dielectric constant of water is 81, i.e., a reduction of 9 in the frequency. This result would indicate that at high frequencies the microwaves might prefer to propagate via the Perspex lining rather than the water. When seawater simulant, equivalent mixture of seawater constituents including sodium chloride of BS3900 and BS2011 (British Standard), with conductivity $\sigma = 4$ S/m was used then a response curve of similar shape was obtained but with a lower peak value of 22.6 mV as shown in Fig. 7. When the conductivity of the water was increased to

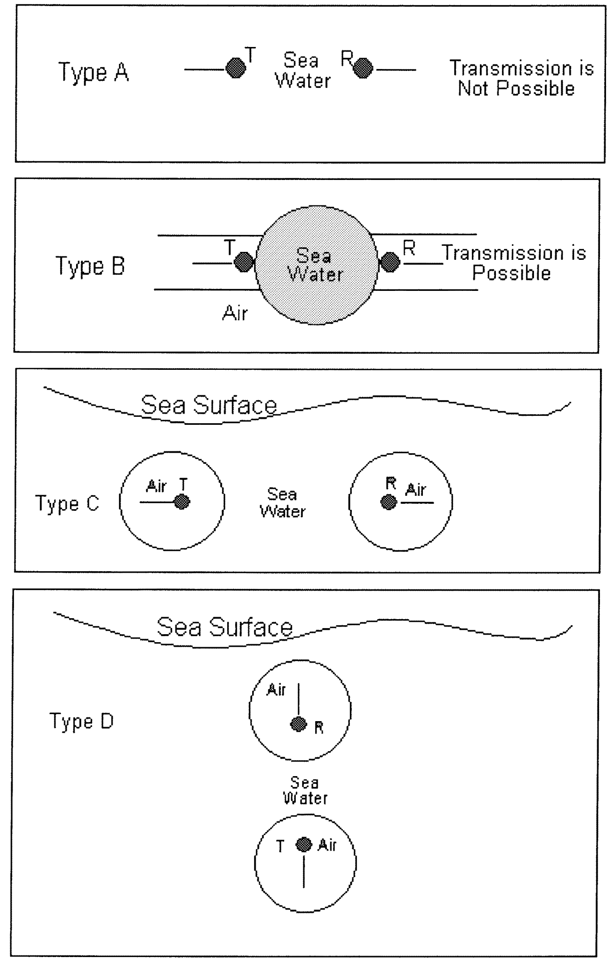

Fig. 2. Antenna configurations where T is the transmitter and R is the receiver.

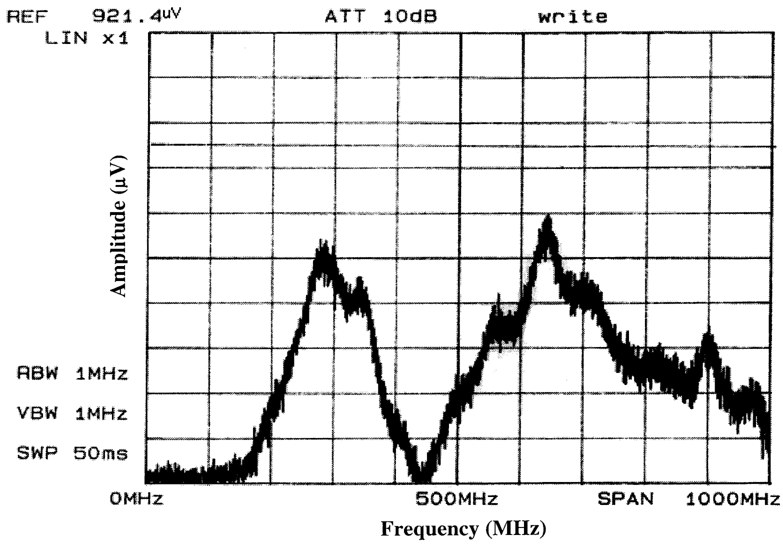

Fig. 3. Weak seawater simulant has been used with conductivity level of 1 S/m. The transmission distance was 300 mm.

10 S/m the peak voltage actually increased to 31.2 mV at a frequency of 370 MHz as shown in Fig. 8. The estimated signal attenuation was 16 dB for the enhanced seawater when compared with distilled water and this measured value was clearly much lower than the expected value from (1) of 600 dB. Propagation was also shown to be possible at 1000 MHz, and the signal attenuation is well below the predicted value of 2000 dB over the short distance of 30 cm. The signal was clearly shown to be passing through the seawater by introducing an inflated balloon at the center of the waveguide, which totally blocked the transmission path. These results clearly show that the propagation loss in seawater is very much lower than expected and distances of the order of meters and not mm are possible.

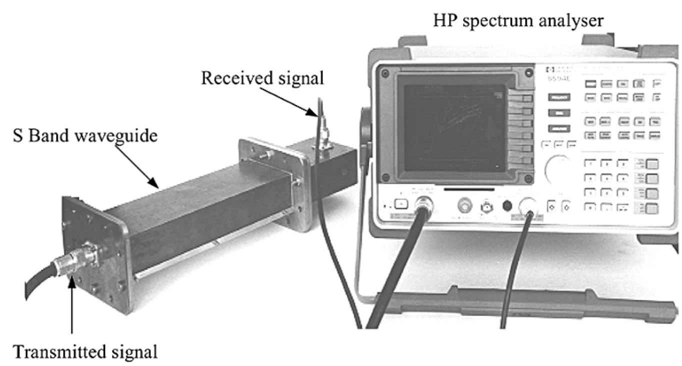

Fig. 4. Experimental setup for a rectangular waveguide.

III. Laboratory Tank and Dock Trials

The next step was to undertake a type C experiment in order to achieve propagation at longer distances by using antennae in open water. A stand alone, battery operated, loop antenna transmitter and receiver were constructed as shown in Fig. 9. Coated antennae were used with PVC containers, which housed the electronics. Crystal oscillators with additional amplification provided the transmitted signal at fixed frequencies in the range 1 to 66 MHz. The receiver was an identical antenna directly connected to the HP spectrum analyzer. Further amplification of 23 dB could be used within the container. A range of different types of antennae was investigated including loop, multiple loop, dipole and folded dipole. The propagation between these antennae was initially measured as a function of distance within a small testing tank filled with water having conductivities varying from 0 to 4 S/m. The transmitter power was 10 dBm and the receiver had no additional amplifier. The testing tank was constructed from fiberglass and had dimensions of 2 m (W), 1.5 m (H), and 2.5 m (L). The transmitter and receiver were mounted from a gantry on moveable supports, which allowed the antennae to be placed at a depth of 0.5 m to 1.5 m with antenna separation of 1 m, as illustrated in Fig. 10. The results for a lower salt concentration ($\sigma = 1$ S/m) are given in Fig. 11. These results show that the attenuation increases with distance, with a rapid attenuation at low distances (near field) and a more gradual attenuation at the longer distances (far field). The rapid gradient results show the attenuation between the antennae follows Maxwell's equation:

$$E = E_o \exp^{(-\alpha x)} \tag{6}$$

where x is the distance between the transmitter and receiver.

With

$$\alpha = 35\sqrt{\frac{\sigma f}{4}} \quad \text{(dBm)} \tag{7}$$

$$\lambda = 1.56\sqrt{\frac{4}{\sigma f}} \quad \text{(m)} \tag{8}$$

and

$$\alpha\lambda = 54.6 \quad \text{(dB)} \tag{9}$$

where σ is the conductivity in S/m, f the signal frequency in MHz, and λ the wavelength in meter. The results show that the rapid attenuation is severe with between 60 dB and 80 dB of signal being lost in launching the EM wave into seawater.

Further trials were undertaken within a dock "real seawater environment." The transmitter power was increased to 5 W (+37 dBm). Initially the transmitting and receiving antennae were submerged in seawater, about 1.5 m below the surface

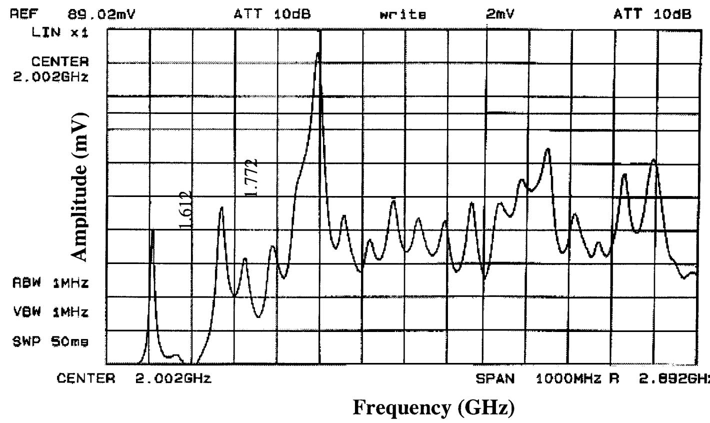

Fig. 5. Metal waveguide lined with Perspex, empty, i.e., dielectric is air.

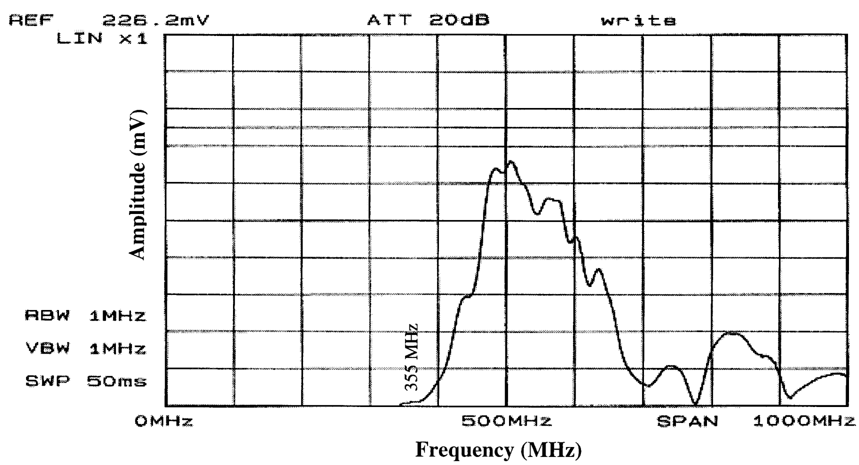

Fig. 6. Distilled water has been used and the transmission distance was 300 mm. Propagation is clearly shown.

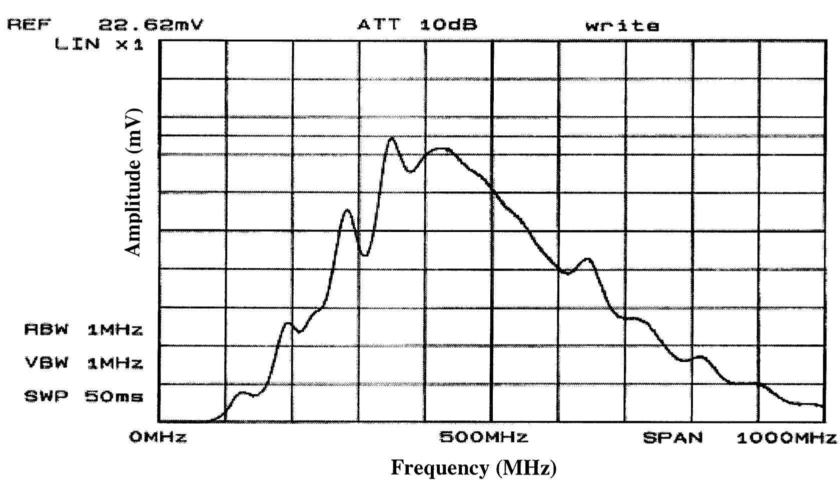

Fig. 7. Standard seawater simulant has been used (0.4 gm mole/l). The distance is 300 mm and transmission is clearly possible.

and separated vertically by a distance of 3 m. The results given in Fig. 12 show that the loop antenna performs better than the dipole but both need impedance matching to the seawater and further amplification. At 1 MHz the slower rate of attenuation occurs after a minimum distance of 2.5 m. The results given in Fig. 13 were obtained horizontally in water with the antennae placed at variable depths of between 2 and 3 meters. The propagation distance was found to increase to 10 m. For optimum signal strength it was necessary to maintain impedance matching of the loop antennae to the 50 Ω system impedances. The slower rate of attenuation is observed for distances greater than 3 m. No signal was received when the receiver circuit container was lifted out of the water. In fact, careful checking for "through-air" transmission was carried out at all stages of the measurement procedure. A few longer distances were then examined up to a separation of 60 m. The signal strength was

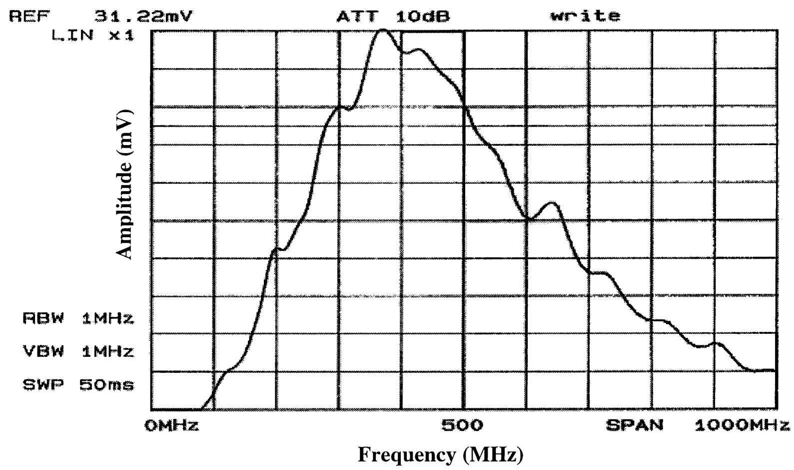

Fig. 8. Extra strong seawater simulant has been used (1 gm mole/l). Although this concentration is 2.5 times standard seawater, transmission is clearly possible. The transmission distance is 300 mm.

Fig. 9. Loop antennas with associated electronic housing. The larger system contains additional amplifiers for undertaking dock trials.

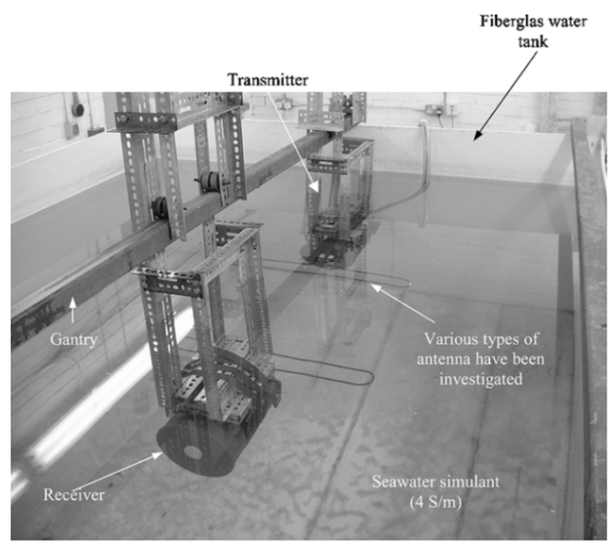

Fig. 10. Testing tank of 2 m (W), 1.5 m (H), and 2.5 m (L).

almost constant but at the longest distance the receiver was at the dock wall and hence would benefit from the signal strength reflected from the wall. The received signal was amplified by a 23 dB Mini-Circuits amplifier, type MAN-1LN, placed after the matching circuit in the submerged receiving container. The received signal strength was measured to be between 100 and 200 mV at the longer distance of 10 m's. A further transmission test was concluded in a shallow open seawater bay with a water depth of 6 m and conductivity of 4.1 S/m. Fig. 14 shows an experimental repeated test of EM wave propagations when both the transmitter and receiving antennae were submerged in seawater and separated by a depth of 6 m in Liverpool Dock "open seawater". Further horizontal measurements have been carried out for distances of more than 50 m. The receiver was suspended in the water at a distance of about 10 m from the dock wall and the transmitter, placed 2 m below the surface, suspended from a small boat at varying distances away from the transmitter. The measurements exhibited a similar attenuation profile but with slightly more attenuation in the far field as shown in Fig. 15. The results show rather more scatter because of the difficulty of accurately controlling the boat position.

IV. Conclusion

Seawater has a molecular dipole lossy dielectric structure as well as a conductivity of approximately 4 S/m. In the near field, because of the proximity of the electrodes, conduction currents exist, while in the far field, the influence of the electrodes is minimal and under these conditions dielectric molecular dipole displacement (nullification) currents exist. This is illustrated in Fig. 16. Conduction is a continual loss process whilst nullification is a single and much smaller loss process in response to a change of electric field. Its magnitude is given by the Debye equation [7]. Table I shows the estimated attenuation in both the near and far fields with allowance for diffraction losses. For example at 5 MHz, a signal loss of −131 dB will be attained mainly through near field loss and the far field diffraction loss. The through water attenuation is only estimated to be a few dBs. Various techniques and methods of propagating an EM waves through seawater have been studied as

TABLE I
PROPAGATION CAPABILITIES OF EM WAVES.

Frequency f (MHz)	Losses for 1000m propagation (dB)			Total Signal Loss (dB)
	Near Field Optimised	Far Field Diffraction	Far Field Attenuation	
0.1	- 60	- 52	0	- 112
1	- 60	- 62	0	- 122
5	- 60	- 69	- 2	- 131
10	- 60	- 72	- 8	- 140
20	- 60	- 75	- 31	- 166

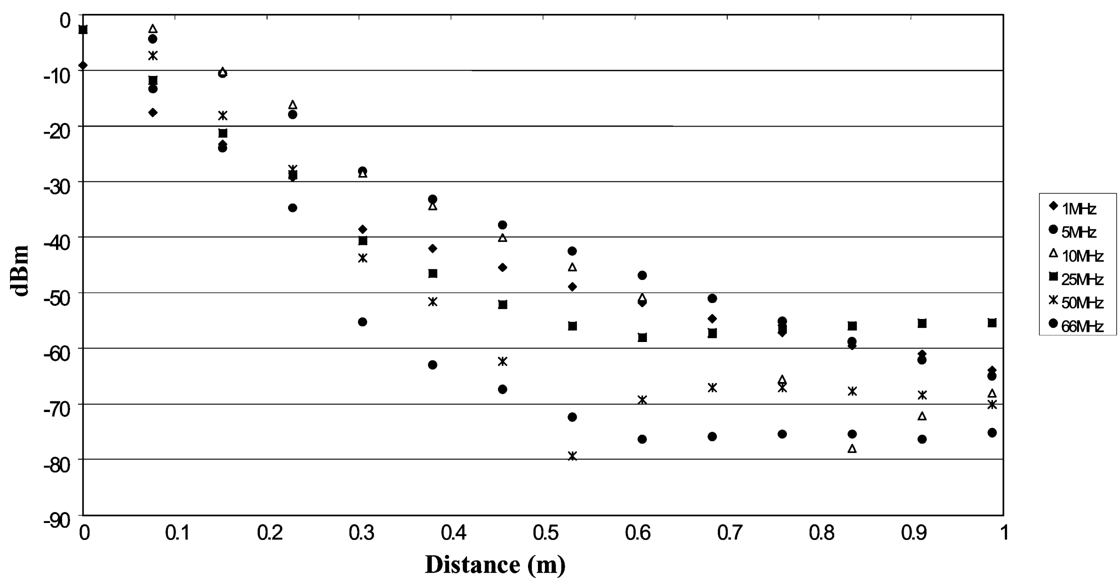

Fig. 11. Results for the full range of frequencies in salt water with conductivity 4 S/m.

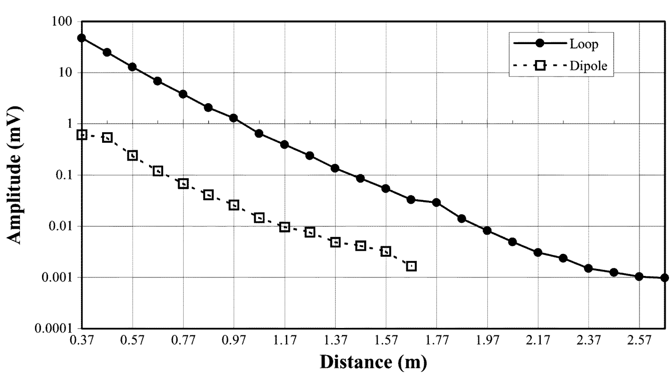

Fig. 12. Results of dock trials at 1 MHz frequency in vertical water.

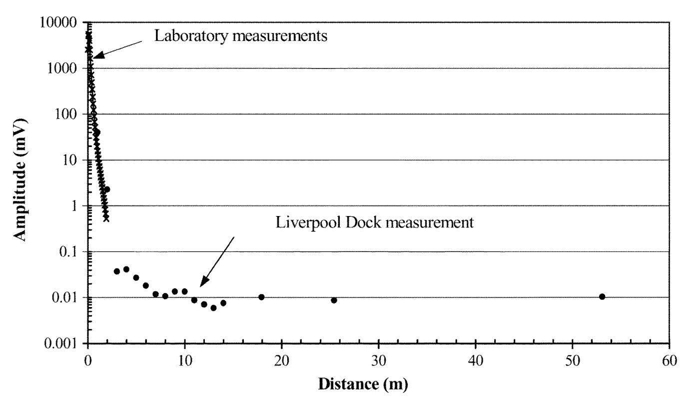

Fig. 13. Signal propagation of 1 MHz and power of 4.75 W in laboratory tank and seawater "Liverpool dock" at a conductivity of 4 S/m.

shown in Fig. 2. Types A to C represent a horizontal propagation while type D represents the vertical (depth) propagations of an EM wave. The effects of a conductive medium in unlined waveguide (cavity resonator) represented by type A. If a small amount of seawater simulant is added, with a conductivity of 1 S/m, into the cavity filled with distilled water then the signals undergo a large attenuation as shown in Fig. 3 with a loss of at least 42 dB per meter. Therefore, it is unlikely that EM wave propagation is possible in normal seawater with a conductivity of 4 S/m. However, successful results were achieved in types B, C, and D. Comprehensive investigation were carried out using various types of antennae including dipole, loop, double loop, and folded dipoles and some shown in Figs. 9, 10, and 12.

Fig. 11 shows that EM propagation in laboratory tank at various transmitted frequencies ranging from 1 MHz to 66 MHz. It is clearly shown that this antenna has been matched to propagate at a particular frequency of 25 MHz. In order to achieve a greater distance of EM waves propagation, further test were carried out at Liverpool Dock, which represents a real environment of open seawater. Propagation through seawater at a frequency of MHz over a distance of 85 m appears to be possible as shown in Figs. 13 and 15 for horizontal propagation. There is rapid signal attenuation by seawater conductivity in the vicinity of the antennae, which is of the order of 80 dB over 85 m.

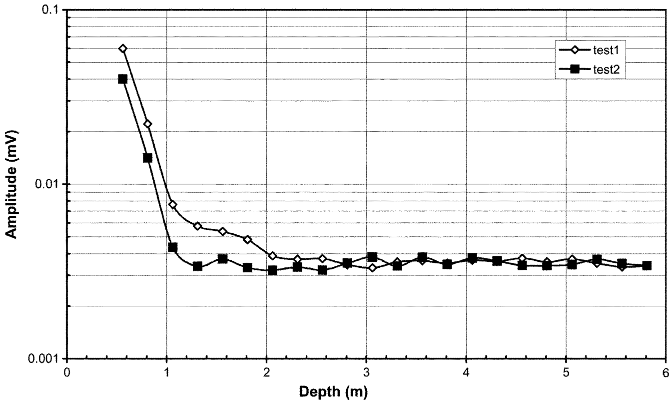

Fig. 14. Measurements in vertical water at seawater conductivity of 4.1 S/m.

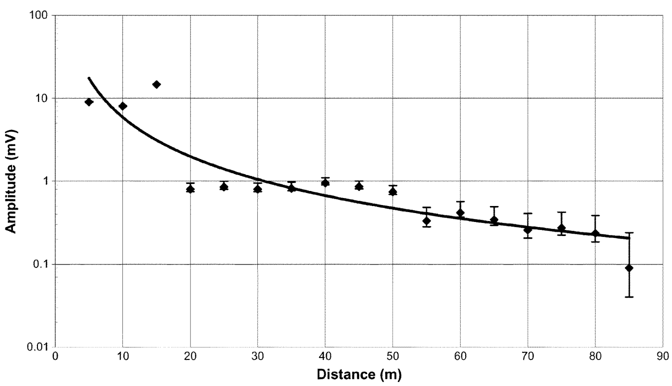

Fig. 15. Liverpool Dock test at frequency of 1 MHz.

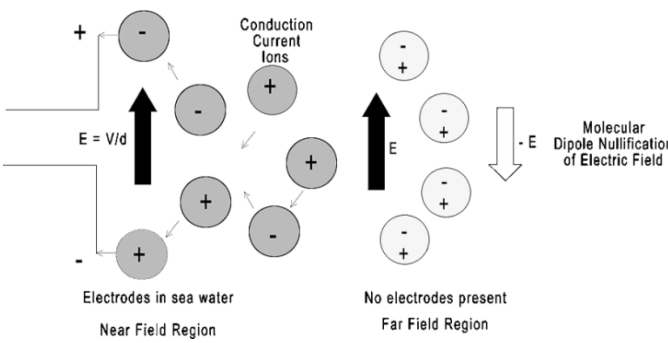

Fig. 16. EM waves in seawater.

After that, the attenuation is vastly reduced and subsequent losses are comparable with diffraction losses. It appears that the effect of conductivity is modest in this region and the attenuation in the far field is comparable with the dielectric loss curve of Fig. 1. Vertical EM waves propagations have been achieved for a depth of only 6 m, as shown in Fig. 14, due to the physical limitation of the dock site. Further experimental measurements are underway to exceed this limitation using various test sites in Loch Linnhe, divers training site, with depths over 30 m. In addition, further investigations will be undertaken to study the effect of the inhomogeneous strata in seawater, e.g., density, composition and temperature effect on the propagated EM wave signals.

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