Analysis of Loop Antenna with Ground Plane for Underwater Communications

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***Abstract*—Transmission and reception of high-speed short range signal is important for successful underwater water communications between an Autonomous Underwater Vehicle (AUV) or Remote Operated Vehicles (ROVs) and a docking station or underwater sensor nodes during a survey mission. The need for this form of application is currently receiving global attention from scientific groups and industries. Hence, underwater antennas are therefore required to provide these links and achieve good data rates and propagation distances for these applications either in fresh or sea water scenario.**

In this paper, the performance of loop antenna placed at a specified distance and parallel to the ground plane is assessed through simulation for usage in fresh water and operating in the High Frequency (HF) band. Three variations of this antenna namely; the circular loop, the square loop and the delta loop antennas has been placed on two different ground plane shapes (circular and square) for analyses of their performances. These antennas were designed in FEKO, an electromagnetic simulation software and their performance is assessed in terms of bandwidth and directivity. The results obtained shows that the antennas exhibit wideband and high directivity with square loop antenna placed on a square ground plane having slight advantages over the other antennas with respect to their bandwidth and directivity. Experimental results added for the same antenna, confirmed its performance in terms of the measured parameters are in good agreement with simulation results.

***Index Terms*—Autonomous Underwater Vehicle; Underwater Antennas; data rates; propagation distance; loop antenna; ground plane; directivity; bandwidth.**

I. Introduction

RF underwater communications finds applications in coastline protection and surveillance, off-shore oil and gas field monitoring, underwater environmental observation for exploration as well as oceanographic data collection [1], [2]. In these applications, communications requires downloading of mission data from the AUV to the docking station, successful docking of the AUV at the station for recharging through wireless power transfer [3], exchange of data between AUVs and underwater wireless sensor nodes. Critical Consideration of the three underwater technologies shows that despite the capability of acoustics and ultrasonic signals to be used for long range communications, the technology suffers from poor immunity to noise, low data-rates and high round-trip channel latency and thereby remain unfit for real-time and broadband underwater communications [2], [4], [5]. Another underwater technology is optical communication signals, which delivers high data-rates and low latency. However, this technology are affected by suspended particles in water and marine fouling and also requires strong alignment [4]–[6]. Electromagnetic (EM) signals is the last of the three established underwater technologies, it can delivers data rates up to 10 Mbps though at very short distances and their propagation does not require strong alignments and are neither limited by water conditions (clean or dirty) [7]. One main disadvantage of this technology is attenuation and it increases with increasing operating frequency, which imposes limits on its usage for underwater communications [8]. Therefore, antennas designed for underwater communications should comply with; bandwidth requirements to enable the support of real-time data exchange between underwater bodies (Autonomous Underwater Vehicles (AUVs), docking stations and underwater sensor nodes), propagating at low operating frequency (High Frequency bands) to reduce the effect of attenuation on the systems and achieving the maximum propagation distance which will inherently reduce the number of antennas needed for a desired link. Thus, the antenna for consideration is a full wave loop antenna, which are designed at the resonance frequency of 50 MHz. Three variations of the antenna designed are: the circular loop, the square loop and the delta or triangular loop antennas. The remainder of this paper is organised in the following order: section II presents e;ectromagnetic waves propagation in water and propagation model; in section III analyses of the designed antennas is presented; this is followed by the simulation results in section IV; in section V the experimental results are presented and compared with the simulation results and the conclusions are addressed in section VI.

II. Electromagnetic Propagation in water and the Propagation Model

The dimensions of underwater antennas can be calculated by employing the parameters that are important for calculating their wavelengths. According to [9], permittivity in lossy medium becomes complex and can be given as

$$\epsilon = \epsilon_r \epsilon_0 - j\frac{\sigma}{\omega} = \epsilon' - j\epsilon'' \text{ F/m} \tag{1}$$

where ϵ_r is the permittivity of the medium, ϵ_0 is the permittivity in free space, j is the imaginary unit (=$\sqrt{-1}$), ω is the angular frequency of the radiation (=$2\pi f$) and ϵ' and ϵ'' are the real and imaginary parts of the permittivity, respectively. It is pertinent to note that ϵ_r depends on several factors like the salinity, temperature as well as the operating frequency. The details of which were described by the Cole-Cole equation [10], [11] and Debye model [12]. Thus at 25°C permittivity in water is 81, however, at the same temperature, relative permeability of the medium equals that of the air, which means designing of underwater antennas are independent of this element. Another important parameter for calculating the antenna dimension is the conductivity of the medium which also responsible for determining the expected attenuation when e-m waves is propagating in lossy medium. Thus, it is important to note that attenuation increases with increasing frequency and conductivity, which therefore necessitate that antennas are designed at lower frequencies to ensure that the effect of attenuation is minimal on the performance of the antennas. Similarly at 25°C the conductivity in fresh water is 0.05 S/m, whereas in sea water it is 4 S/m [4], [5].

The propagation constant, γ in a conducting medium is given as [13]

$$\gamma = \sqrt{j\omega\mu(j\omega\epsilon + \sigma)} = \alpha + j\beta \tag{2}$$

here, ω is the angular frequency measured in radian per second, μ is the absolute permeability (μ=$\mu_0\mu_r$), ϵ is the absolute permittivity(ϵ=$\epsilon_r\epsilon_0$), σ is the conductivity measured in Siemens per metre, α is the attenuation constant measured in Neper per metre and β is the phase constant measured in radians per unit length.

The parameters in the Right Hand Side (RHS) of equation (1) (α and β) are further defined and are given as equation (2) and (3) respectively [2].

$$\alpha = \omega\sqrt{\mu\epsilon}\sqrt{1/2(\sqrt{1 + (\sigma/\omega\epsilon)^2} - 1)} \tag{3}$$

$$\beta = \omega\sqrt{\mu\epsilon}\sqrt{1/2(\sqrt{1 + (\sigma/\omega\epsilon)^2} + 1)} \tag{4}$$

For full wave loop antenna, the calculated wavelength is equivalent to the perimeter, which is calculated from equation (5)

$$\lambda = 2\pi/\beta \tag{5}$$

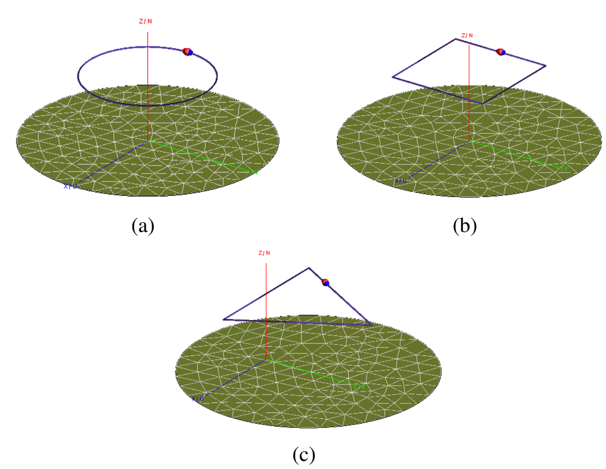
III. Analyses of the Designed Antennas

In one of the previous works on the analysis of underwater antennas in this group [14], performance of the cirular loop antenna have been duly analyzed, alongside dipole and J-pole antennas. In the analysis, the loop antenna has a bandwidth of 13.94 MHz and the maximum directivity of 5.2 dB in fresh water, similarly, the radiation pattern is bi-directional in the plane perpendicular to the plane of the loop. But, to ensure that the antenna radiates in one direction only, thereby making it an highly unidirectional antenna with improved propagation distance in the chosen direction [15] and also with higher bandwidth which is important for improved data rates, a ground plane (reflector) is placed perpendicular to the antenna through parametric analysis but at a distance not greater than λ/4 [16], [17]. Thus, three variations of the full wave loop antennas designed and analysed in this paper are; the circular loop antenna, the square loop antenna and the delta loop antenna. Similarly, two dimensions of ground plane used in this work are the circular and the square ground plane. Thus, the models of these antennas, which are designed in FEKO software, are presented in Fig. 1 & 2 showing the circular, square and the delta loops placed perpendicular on circular and square ground plane respectively with a distance of 14 cm apart. The three antennas designed to propagate at the same operating frequency, in that respect, the circumfrence of the circular loop antenna is equivalent to the perimeter of; the square loop and delta loop antennas. Likewise, the circumfrence of the circular ground plane is equal to the perimeter of the square ground plane.

The antennas are designed at the operating frequency of 50 MHz, at this frequency it has been shown in [18] that the attenuation is minimal both in fresh and sea water and also that the antenna in fresh water operates in a dielectric medium. If the antennas are to be operated in both fresh and sea water, different dimensions will be required as the operating frequency depends on the conductivity of the medium. But the concern of this paper is operating the antennas in fresh water scenario only. Thus, the dimensions of the antennas are given in Table I. Here, the raidu of the circular loop antenna is given as 136.67 mm, the length of each side of the square loop antenna is given as 215 mm and the length of each side of the delta loop antenna is given as 286.63 mm. Similarly, the radius of the circular groun plane is given as 258 mm and the length of each side of the square ground plane is 400.00 mm. The thickness of the wires used in the design of the antennas is 3 mm, the wires are covered with insulating material with thickness of 50 μm and relative permittivity of 3.

IV. Simulation Results

The antennas were simulated in fresh water scenario and the results corresponding to the reflection coefficient as a function of frequency, when the antennas were simulated with circular ground plane and square ground plane are presented in Fig. 3 and Fig. 4 respectively. The terms CC, SC and DC in Fig. 3 are used to represent the Circular loop antenna on Circular ground plane, Square loop antenna on Circular



(a) (b) (c)

Fig. 1. The antennas placed perpendicular to circular ground planes

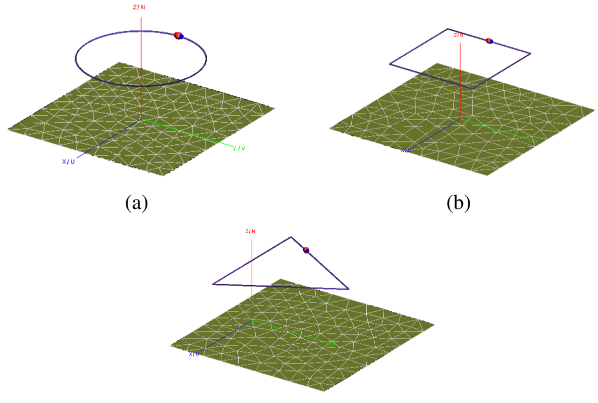


Fig. 2. The antennas placed perpendicular to square ground planes

TABLE I
DIMENSION OF THE ANTENNAS

S /No.	Parameters (mm)	Dimensions (mm)
	Antennas	
1	Radius of Circular Loop Antenna	136.87
2	Side of the Square loop Antenna	215.00
3	Side of the Delta Loop Antenna	286.63
	Ground Planes	
4	Radius of Circular Ground Plane	258.00
5	side of the Square Ground Plane	400.00

ground plane and Delta loop antenna on Circular ground plane respectively. Similarly, the terms CS, SS and DS in Fig. 4 are used to represent Circular loop antenna on Square ground plane, Square loop antenna on a Square ground plane and Delta loop antenna on a Square ground plane respectively. The bandwidth is measured at -10 db and the results shows that antennas achieved wideband which spanned between 32 MHz and 167 MHz both on the antennas with circular ground plane and the square ground plane in the three antennas. It is also clearly observed that change in the ground plane shape (circular to square) has little or no effect on the performance of the antennas as the reflection coefficient results obtained for the antennas in both ground planes are very similar.

Based on these analyses, the antennas on the square ground plane were further analysed to determine their directivity characteristics in the frequency bands from 40 MHz and 100 MHz incrementing by 10 MHz and the results are presented in Table II. The results in the table were used to generate plots of directivity as a function of frequency, which is presented in Fig. 5. These results shows that the directivities of the antennas within the frequencies of observation are higher than what was obtained for J-pole antenna in the same medium, which was presented in [14]. Also, the three antennas has their respective highest directivity at 60 MHz and the Square loop Antenna has slightly higher directivity than other antennas. This are important results when considering the usage of these antennas for underwater operations, especially when both data rates and propagation distance are been considered.

TABLE II
DIRECTIVITIES OF THE ANTENNAS VERSUS OPERATING FREQUENCIES

		Directivity (dB)		
S /No.	Frequencies (MHz)	CS	SS	DS
1	40.00	15.38	16.84	14.41
2	50.00	16.73	18.22	15.69
3	60.00	16.98	18.79	16.01
4	70.00	16.12	17.82	15.24
5	80.00	14.62	16.15	14.36
6	90.00	14.11	15.78	13.64
7	100.00	13.79	15.18	13.21

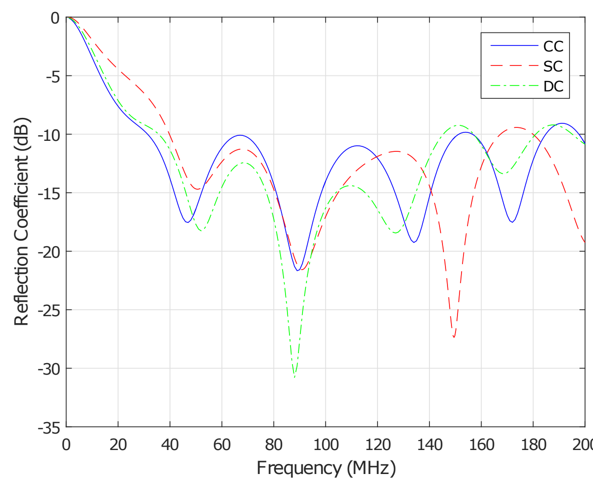


Fig. 3. Reflection coefficient against frequency for the antennas on circular ground plane

V. EXPERIMENTAL RESULTS

In manufacturing the square loop antenna on the square ground plane, the simulation results and ease of fabrication were taken into consideration. Thus, the antennae was fabricated using the dimensions as presented in Table I; thickness of copper wires used is 3 mm and thickness of the aluminum ground plane is 5 μm. The manufactured antenna is presented in . Baluns were added to the manufactured antenna which is presented in 6, this is to reduce undesired radiation on the coaxial cables, which could interfere with the radiation of the antennas and thereby altering the radiation charateristics of the antennas.

The experimental measurements for the bandwidths and radiation pattern was set up in a freshwater pool owned by INESC TEC, with the antennas at a depth of 2.5 m from the surface and placed on the centre of the tank (which has dimensions of 10 m $\times$ 6 m $\times$ 5.5 m and the conductivity of water was 0.0487 S/m at 25°C). Thus, the entire set up used in the measurements are presented in Fig. 7. The simulation results for the reflection coefficient as a function of operating frequencies are compared with the measured results, which are presented in Fig.8. These results confirmed that Loop antenna with ground plane actually achieved wideband. The difference between the measured and the simulated can be due the attenuation through cable loss or as a result of reflection

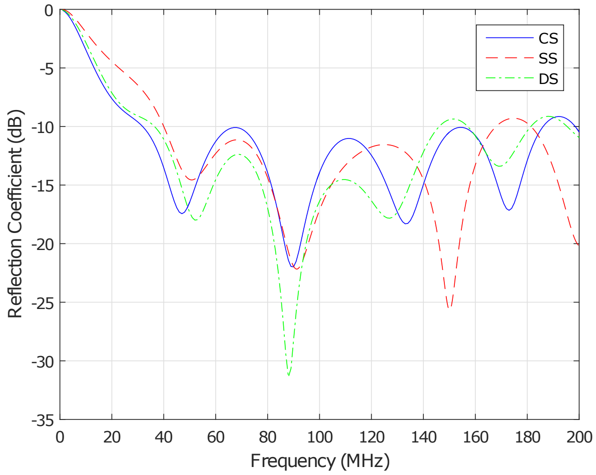


Fig. 4. Reflection coefficient against frequency for the antennas on square ground plane

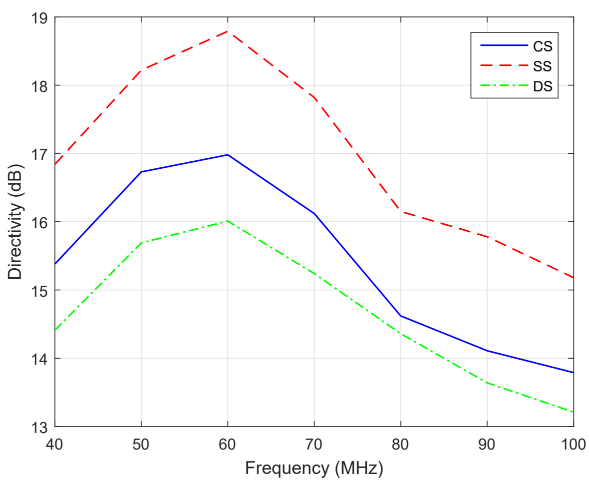
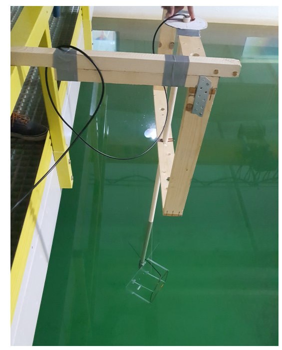


Fig. 5. Directivity against frequency for the antennas

Fig. 6. Manufactured Square Loop Antenna with Square Ground Plane

from the wall of the freshwater tank. Similarly, the measured and simulated radiation pattern in the E-plane for the antenna at 50 Mhz, 60 MHz and 70 MHz were presented in Fig.9. It is seen here that at the three frequencies, the simulated and the measured are in good agreememnt and also with minimal back lobe.

(a)



(b)

Fig. 7. Set up for the measurements

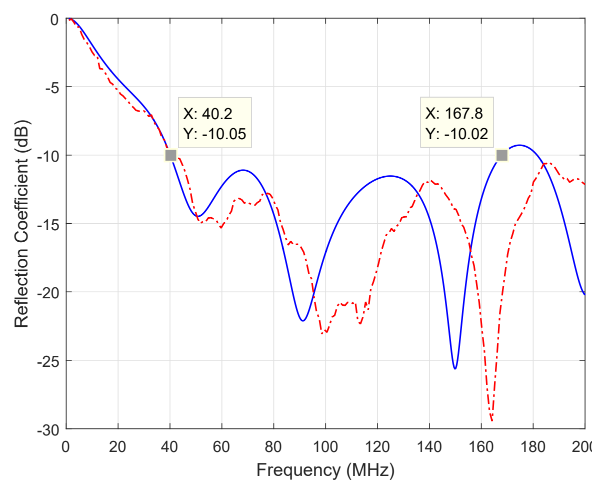
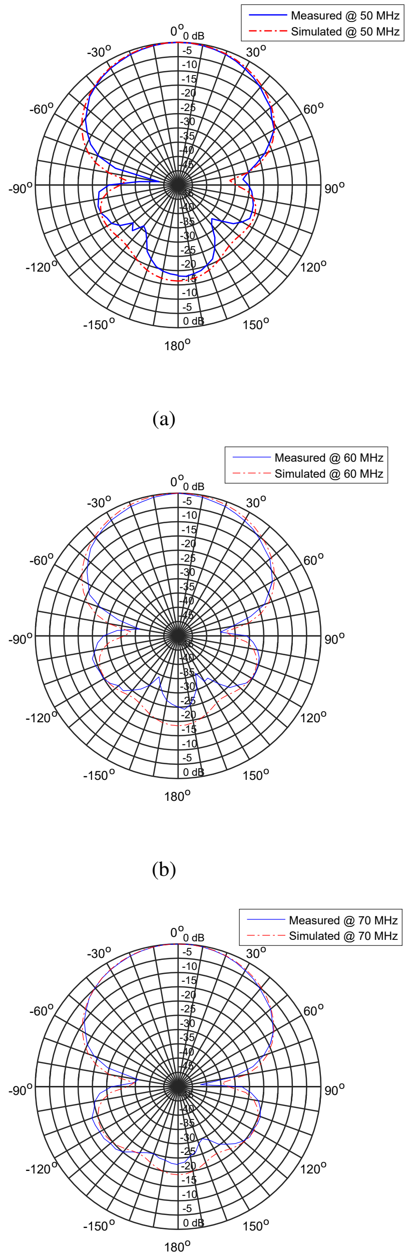


Fig. 8. Simulation versus Measurement Square Loop Antenna with Reflector

VI. Conclusion

Evaluation and analyses of the full wave loop antennas with ground plane have been considered in this paper. Here, three variations of the loop antenna, which are the circular loop, the rectangular loop and the delta loop antennas has been simulated in fresh water on two different shapes of the ground plane. It has also been affirmed from the results that the performance of the antennas is independent of the shape of its ground plane. These antennas exhibits widebands which



(a)

(b)

(c)

Fig. 9. E-plane radiation pattern of the antennas at 50 MHz, 60 MHz and 70 MHz respectively

are important for data rates in any applications including underwater applications. Likewise, the antennas exhibits higher directivities, which is an important parameter for propagation distance for antennas, with the ground plane influence the radiation pattern to be highly directional. Furthermore,the square loop antenna on a square ground plane yielded the best results in terms of bandwidth and directivity among the three antennas. Though, the difference between the results of this antenna and other variations is not really much, but adding ease of fabrication to these makes the square loop antenna on the square ground plane to be manufactured. The measured results conformed with the simulation results both in term of bandwidth and radiation patterns that were presented. Finally, considering these performances in fresh water scenario, further analysis will be considered for designing, simulating and measuring of this antenna type in the sea water.

VII. Acknowledgement

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References

[1] H. F. G. Mendez, F. Le Pennec, C. Gac, and C. Person, "High performance underwater uhf radio antenna development," *IEEE OCEANS Conference Jun 06-09, 2011 Santander, SPAIN*.

[2] S. Jiang and S. Georgakopoulos, "Electromagnetic wave propagation into fresh water," International Conference on Detection and Classification of Underwater Targets, France, p. 6, 2012.

[3] L. M. Pessoa, M. R. Pereira, H. M. Santos, and H. M. Salgado, "Simulation and experimental evaluation of a resonant magnetic wireless power transfer system for seawater operation," Oceans2016, Shanghai China, p. 5, 2016.

[4] J. H. Goh, A. Shaw, and A. I. Al-Shamma'a, "Underwater wireless communication system," *Journal of Physics*, p. 6, 2009.

[5] H. Zhang, D. Geng, G. Zhang, and T. A. Gulliver, "The impact of antenna design and frequency on underwater wireless communications," *IEEE Pacific Rim Conference on Communications, Computers and Signal Processing (Pacrim)*, pp. 868–872, univ Victoria, Victoria, CANADA 2011.

[6] X. Che, I. Wells, G. Dickers, and P. Kear, "Tdma frame design for a prototype underwater rf communication network," *Ad Hoc Networks*, vol. 10, no. 3, pp. 317–327, 2012.

[7] J. Lloret, S. Sendra, M. Ardid, and J. J. P. C. Rodrigues, "Underwater wireless sensor communications in the 2.4 GHz ISM frequency band," *Sensors*, vol. 12, no. 4, pp. 4237–4264, 2012.

[8] K. C. David, "Field and wave electromagnetics," *IEE Proceedings-a-Science Measurement and Technology*, vol. 131, no. 8, pp. 660–660, 1984.

[9] F. T. Ulaby, E. Michielssen, and U. Ravaioli, *Fundamentals of Applied Electromagnetic*, 6th ed. Pearson/Prentice Hall, 2013. [Online]. Available: ¡Go to WoS¿://WOS:000241966000013

[10] K. S. Cole and R. H. Cole, "Dispersion and absorption in dielectrics 1. alternating current characteristics," *The Journal of Chemical Physics*, vol. Vol. 9, no. 4, p. 11, 1941.

[11] F. Franks, "The physics and physical chemistry of water," *Springer Science & business Media*, vol. I, 2012.

[12] R. Somaraju and J. Trumpf, "Frequency, temperature and salinity variation of the permittivity of seawater," *Ieee Transactions on Antennas and Propagation*, vol. 54, no. 11, pp. 3441–3448, 2006, somaraju, Ram Trumpf, Jochen 2. [Online]. Available: ¡Go to ISI¿://WOS:000241966000013

[13] K. P. Hunt, J. J. Niemeier, and A. Kruger, "Short paper: Antennas for mussel-based underwater biological sensor networks in rivers," p. 4, 2010.

[14] O. Aboderin, L. M. Pessoa, and H. M. Salgado, "Performance evaluation of antennas for underwater applications," Wireless Days 2017, p. 4, March 2017.
[15] A. A. Ayorinde, S. A. A dekola, and A. I. Mowete, "Performance characteristics of loop antennas above a ground plane of finite extent," p. 6, 2013.
[16] D. Jefferies, "Experiments on loops above ground," *antenneX Online*, no. 106 , p. 8, 2006.
[17] J. Iwashige, "Analysis of loop antenna with circular reflector and its properties," *Electronics and Communications in Japan*, vol. 63-B, no. 11 , p. 7, 1982.
[18] O. Aboderin, S. I. Inácio, H. M. Santos, M. R. Pereira, L. M. Pessoa, and H. M. Salgado, "Analysis of j-pole antenna configurations for underwater communications," Oceans2016, Monterey Califonia, p. 5, 2016.