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Nonlinear least square approach for range estimation based on attenuation of EM waves in seawater using world ocean data from 1955 to 2012

Muhammad Tahir[1] | **Piao Yan**[1] | **Mohsin Raza Jafri**[2]

[1]School of Electronics and Information Engineering, Changchun University of Science and Technology, Changchun, China

[2]Department of Environmental Sciences, Informatics and Statistics, Università Ca' Foscari, Venice, Italy

Correspondence
Piao Yan, School of Electronics and Information Engineering, Changchun University of Science and Technology, Changchun, China.
Email: piaoyan@cust.edu.cn

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Summary

In this research paper, we estimated absorption loss (L_α) and spreading loss (L_o) based on electromagnetic (EM) waves propagation, considering multiple seawater depth (1101) points from surface to 5500 m distributed uniformly with 5-m difference. Estimation of parameters aforementioned was done based on world ocean data (WOD13) from the National Center for Environmental Information (NCEI) averaged between 1955 and 2012 along decades for basic parameters of seawater T (C^o) and S (ppt) up to 5500-m depth vertically and also across (41 088) latitude/longitude points for all oceans that includes Indian, Pacific, Southern, Atlantic, and Arctic horizontally. We also computed another important factor that contributes in overall path loss (L_{UW}), loss due to polarization of EM fields between transmitter T_x and receiver R_x such as antenna polarization factor (L_ϕ). L_ϕ (dB) along with L_α (dB) and L_o (dB) by substituting into basic propagation model for EM waves in seawater helps us to predict efficiently accurate achievable range (R_{est}) using nonlinear least square (NLLS) approximation combined with Lambert transformation considering nonlinear exponential P_T (dBm) decay. Moreover, predicted R_{est} (m) helps us to minimize mean error ($mean(e(t))$) by adapting to actual range R (m) using NLLS approach. Simulation tool MATLAB has been used for implementation of NLLS approach and performance analysis.

KEYWORDS

absorption loss L_α, estimated range R_{est}, nonlinear least square (NLLS) approximation, polarization factor L_φ, seawater, spreading loss L_o

1 | INTRODUCTION

In seawater, electromagnetic (EM) waves propagation provides a great deal of advantage over conventional communication techniques like acoustic and optical wave propagation. Advantages of EM communication in seawater include high-bandwidth B (MHz), higher data rate C (Mbps), low transmission loss across sea/air boundary, and improved performance in error-prone seawater conditions.[1] Previously, EM communication ignored in seawater because of high attenuation (α) at megahertz frequencies with propagation velocity ($\approx 3 \times 10^7$) (m/s). However, Al-Shammaa et al[2] claim effectiveness of EM communication over a distance of approximately 100 m in seawater. They emphasize that although rate of α (dB/m) faces sudden exponential decay along depth due to conduction current in near-field region, α (dB/m) reaches minimum value after few meters ($\approx$5 m) in far-field region, which approximately remains constant due to displacement current. Recently, short R (m) and high B (MHz) communication systems based on EM waves have drawn attention of underwater communication research community because of their applications in oil industry, ocean navigation, undersea communication, geophysical exploration, and military operations. Given EM-based communication systems provides reliable transmission for short R data applications and underwater (seawater) localization/tracking. Underwater localization/tracking techniques based on EM propagation are highly useful due to their accuracy in tracking location of remotely operated vehicles/autonomous underwater vehicles (ROV/AUV) and randomly deployed underwater sensor nodes. Therefore, it is necessary to evaluate performance of EM transmission and EM-based localization in seawater.[3]

Electromagnetic waves can cross sea/air boundary easily, but still, whether or not waves can be detected at far distance with minimum given T_x, R_x antennas gains (G_T, G_R [dB]) and lower transmission power (P_T [dB]) is still a hot topic.[4] In deep oceans, acoustic communication systems can provide long R (m) and limited B (kHz). However, in shallow water (≈100 m), acoustic communication is unreliable due to reflections from sea surface. Optical communication in seawater also received attention recently; however, it requires strictly line-of-sight (LOS) propagation and highly directive T_x, R_x antennas. Robust communication capabilities in shallow (≈100 m) and deep waters allow us to re-evaluate EM-based communication, where both acoustic and optical communications are not reliable for short range. Propagation of EM waves in seawater is a complex phenomenon than that of free space, due to conductive nature that causes frequency-dependent α (dB/m) along multiple depths of seawater.[5]

Underwater channel sounder (UCS) enables us to estimate radio frequency (RF) propagation through multiple input multiple output (MIMO) in depths up to 500 m. UCS also has a capability to use MIMO at receiver and single T_x antenna. UCS also helped to estimate input reflection coefficient (S11) and forward transmission coefficient (S21) parameters at multiple depths up to 500 m. UCS also uses RF signal in remote sensing to increase channel capacity and increase resolution.[6] Seawater sensing and networking using EM wave have become key topics in marine communication. Proper antennas significantly affect performance of EM wave transmission in seawater and also across sea/air interface. It is also found that performance of horizontal electric dipole is better than vertical electric dipole in seawater and that also seawater depth can hardly affect EM propagation.[7]

2 | MATHEMATICAL MODELING OF PATH LOSS BASED ON EM COMMUNICATION IN SEAWATER

In this section, we will develop fundamental propagation model for EM waves in seawater using Maxwell's equation, Frii's law, and Helmholtz' model considering basic parameters that constitute as input to overall loss, ϵ (F/m) and σ (S/m) estimated based on Debye's theory and Stogryn's model as follows. We also used basic mathematical models that constitute for estimating basic parameters of communication given in this section as follows. Maxwell's equations[8] as described in Equations (1) and 2 explain transmission of transverse (where E and H are perpendicular to each other) EM (TEM) waves in seawater (conducting medium) propagating in z direction. Electric field (E_x) and magnetic field (H_y) propagating in x and y directions, respectively, can be estimated as

$$E_x = E_o e^{j\omega t - \gamma z}, \tag{1}$$

$$H_y = H_o e^{j\omega t - \gamma z}. \tag{2}$$

Here, γ represents propagation constant of given medium and ω, angular frequency. γ for traveling EM wave defined in Equation (3) represented as combination of frequency f (Hz), conductivity σ (S/m), permittivity ϵ (F/m), and permiability μ (H/m) for seawater. Moreover, α (Np/m) and phase constant (β [rad/m]) mainly contribute in estimating absorption loss L_α (dB); phase and propagation delay, respectively, for EM wave as it crosses sea/air boundary are also represented with basic parameters separately.[8]

$$\gamma = j2\pi f\sqrt{\mu(\epsilon - j\sigma/2\pi f)} = \alpha + j\beta = (j\omega\sqrt{\mu\epsilon} + 1/2\sigma\sqrt{\mu\epsilon}) + ((1+j)\sqrt{f\pi\mu\sigma}) \tag{3}$$

Fundamental Maxwell (Equation 1) is represented in more elaborative way for a given condition of seawater communication in Equation (4). As we can see, there are three main components of E-field radiated using dipole antenna with given ($\lambda/2$) length, which includes E_r, E_θ, and H_ϕ. In far field, most effective part of E-field tangential component (E_θ) is used to determine EM field in seawater.[9]

$$E_\theta = E_o e^{-\alpha z} e^{-j\beta z} \tag{4}$$

Here, in Equation (4), $e^{-\alpha z}$ represents absorption loss L_α (dB), whereas $e^{-j\beta z}$ represents propagation delay and also contributes in estimation of phase of E_θ as it crosses sea/air boundary. Assuming no elevation and inclination losses in seawater, L_α (dB) along with L_o (dB) based on Frii's law and L_ϕ loss due to polarization $\cos^2$, antenna properties, ie, G_T and G_R, determine total path loss in seawater L_{UW} from surface to multiple depths of oceans[10] as described in Equation (5).

$$L_{UW} = P_R/P_T = G_T \times G_R \times (\lambda/4\pi R)^2 \times e^{-2\alpha R} \times cos^2(\phi) \tag{5}$$

Here, in Equation (5), P_R (dB) and P_T (dB) represent receiver (R_x) and transmitter (T_x) power, respectively, while wavelength λ (m) is based on respective V_p (m/s) at multiple depths and frequency range. To estimate α (dB/m) in developed model for total path loss as mentioned in Equation (5), we need mathematical model for basic parameters ϵ (F/m), μ (H/m), and σ (S/m). μ (H/m) of seawater is the same as of free space, ie, ($4\pi \times 10^{-7}$ [H/m]). Complex permittivity ϵ (F/m) can be expressed as real and imaginary part[8] described in Equation (6),

$$\epsilon = \epsilon' - j\epsilon''. \tag{6}$$

Real part of ϵ (F/m) as mentioned in Equation (6), ϵ', is referred to as dielectric constant that represents stored energy when material is exposed to E_θ. Imaginary part of ϵ (F/m) dielectric loss factor (ϵ'') influences energy absorption L_α (dB) and also loss in medium due to damping of vibrating dipole (dielectric damping) along with free charge conduction. ϵ (F/m) related to relative permittivity (ϵ_r) is expressed as a ratio[8] relative to permittivity of vacuum (ϵ_o) (F/m) as depicted in Equation (7),

$$\epsilon = \epsilon_o \epsilon_r. \tag{7}$$

To calculate ϵ (F/m), we first need to estimate ϵ_r.ϵ_r for lossy dielectric materials; in our case, seawater is described by Debye's model in Equation (8) as depicted below.[11]

$$\epsilon_r = (\epsilon_\infty + (\epsilon_s - \epsilon_\infty)/(1 + jw\tau)) - j\sigma/w\epsilon_o = \epsilon_r' - j\epsilon_r'' \tag{8}$$

In Equation (8), value of ϵ (F/m) at optical frequencies (ϵ_∞) is 4.9, while ϵ_s (F/m) represents static ϵ (F/m) at low frequencies. Relaxation time (τ) is depicted in Equation (9) in seconds, time taken for dielectric to reach state of equilibrium.[8]

$$\tau = \epsilon/\sigma \tag{9}$$

α (dB/m) is considered to be an important factor to compute the overall L_{UW} depicted in Equation (5) as a loss of energy E_θ is suffered by EM wave due to absorption and scattering as it passes through seawater computed in Equation (10) based on Helmholtz model. β (rad/m), another important factor as depicted in Equation (3), represents change in phase per unit length at any instant that contributes in estimating V_p (m/s). β (rad/m) can be estimated using Helmholtz model depicted in Equation (11). Another important factor in seawater communication, V_p (m/s), normally considered constant in literature can be computed using the model given in Equation (12) based on previously estimated parameter β (rad/m).[8]

$$\alpha = w\sqrt{\mu\epsilon/2[\sqrt{1 + [\sigma/w\epsilon]^2}] - 1} \tag{10}$$

$$\beta = w\sqrt{\mu\epsilon/2[\sqrt{1 + [\sigma/w\epsilon]^2}] + 1} \tag{11}$$

$$V_p = w/\beta \tag{12}$$

Another important factor to determine seawater communication channel characteristics, transition frequency f_T (Hz), that helps in determining whether seawater behaves like conductor or insulator for a particular range of frequencies can be estimated by the given Equation (13). f_T (Hz) can be computed only when σ (S/m) and ϵ (F/m) are known.[8]

$$f_T = \sigma/2\pi\epsilon \tag{13}$$

Characteristics impedance Z (ohms) of seawater can be estimated based on free space impedance ($Z_o \approx 377$ ohms), along with σ (S/m) and ϵ (F/m) for various frequencies of EM waves[8] computed as follows with the given model in Equation (14).

$$Z = Z_o \times \sqrt{(\mu_r/\epsilon_r)} \times \sqrt{(\omega\epsilon/\sigma)} \tag{14}$$

Mismatch between Z (ohms) for seawater and Z_o (ohms) for free space causes significant reflections at sea/air boundary. This effect indicated below by reflection coefficient ($\gamma_{reflection}$) and transmission coefficient ($T_{transmission}$) is depicted in Equations (15) and (16), respectively.[8]

$$\gamma_{reflection} = (Z_o - Z)/(Z_o + Z) \tag{15}$$

$$T_{transmission} = 2Z_o/(Z_o + Z) \tag{16}$$

Debye's model formulation for ϵ' (F/m) and ϵ'' (F/m) as depicted in Equations (17) and (18) contributes in estimating α and β, respectively. Regression equations for seawater σ (S/m) expressed in Equations (19) and (20) contribute in determining $L_\alpha(dB)$ with given $\Delta = 25 - T$.[12]

$$\epsilon'(f, T, S) = \epsilon_\infty(T, S) + (\epsilon_s(T, S) - \epsilon_\infty(T, S)/1 + 4\pi^2 f^2 \tau^2(T, S)) \tag{17}$$

$$\epsilon''(f, T, S) = (\epsilon_s(T, S) - \epsilon_\infty(T, S))2\pi f \tau(T, S)/(1 + 4\pi^2 f^2 \tau^2(T, S)) + \sigma(T, S)/2\pi\epsilon_o f \tag{18}$$

$$\sigma(T, S) = \sigma(25, S)exp(-\Delta c) \tag{19}$$

$$c = 0.020 + 1.26 \times 10^{-4}\Delta + 2.464 \times 10^{-6}\Delta^2 - S(1.894 \times 10^{-5} - 2.551 \times 10^{-7}\Delta + 2.551 \times 10^{-8}\Delta^2) \tag{20}$$

$$\sigma(25, S) = S(0.182 - 0.001S + 2.093 \times 10^{-5}S^2 - 1.282 \times 10^{-7}S^3)$$

Stogryn's specific form of polynomial to estimate ϵ_s is expressed in Equations (21) and (22) based on previous regression equations.[12]

$$\epsilon_s(T, S) = \epsilon_s a(T, S) \tag{21}$$

$$\epsilon_s = 87.134 - 0.194T - 0.012T^2 + 2.249 \times 10^{-4}T^3 \tag{22}$$

$$a(T, S) = 1 + 1.613 \times 10^{-4}ST - 0.003S + 3.2 \times 10^{-4}S^2 - 4.232 \times 10^{-7}S^3$$

Stogryn's model for estimating τ (s) is given in Equation (23) to compute ϵ (F/m) and σ (S/m).[12]

$$\tau(T, S) = \tau(T, 0)b(S, T) \tag{23}$$

$$\begin{aligned} \tau(T, 0) &= 1.768 \times 10^{-11} - 10^{-12}T + 10^{-13}T^2 - 10^{-16}T^3 \\ b(S, T) &= 1 + 2.282 \times 10^{-5}ST - 0.0007S - 7.760 \times 10^{-6}S^2 \\ &\quad + 1.105 \times 10^{-8}S^3 \end{aligned}$$

3 | NONLINEAR LEAST SQUARE APPROXIMATION FOR RANGE ESTIMATION BASED ON ATTENUATION OF EM WAVES IN SEAWATER

Least square approach minimizes squared difference between $x(t)$ (in our case, R_{est} [m]) and $y(t)$ (R [m]) as depicted in Figure 1. Given figure describes overall process of nonlinear least square (NLLS) approach considering input and output and also models inaccuracies considering system noise. In our case, $x(t)$ represents summation of perturbed version (model inaccuracies) like (L_α, L_o, L_ϕ) and N_o or P_n, further based on θ accounts for input frequency, P_T, G_T, and modulation schemes (BPSK, QPSK, or FSK) in given case. Input $y(t)$ in our case R is actual distance between T_x and R_x, while $x(t)$ generated by the model given in Equation (5) based on θ is described as perturbation on input sequence of information $y(t)$. Closeness is measured by minimizing LS error criteria[13] as represented in Equation (24).

$$J(\theta) = \sum_{n=0}^{N-1}[x(t) - y(t)]^2 \tag{24}$$

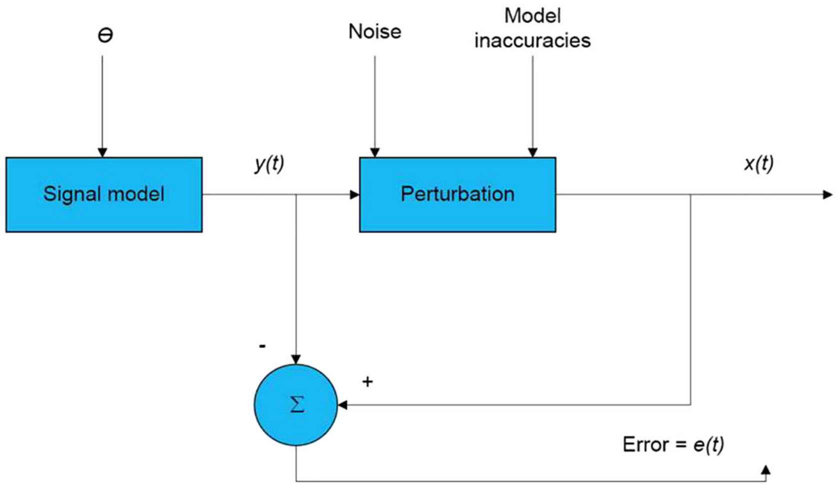

FIGURE 1 Nonlinear least square (NLLS) estimation approach

Here, in Equation (24), observational interval assumed between $n = 0, 1, \dots, N-1$ and dependence of J (Jacobian matrix) is on θ via $y(t)$. No probabilistic assumptions are made about $x(t)$, so given method is equally valid for Gaussian and non-Gaussian channel. Performance of NLLS scheme depends on noise corruption (N_o or P_n) and modeling errors as described in Equation (5). Computation of $y(t) = H\,\theta$ leads to simple linear problem; however, $y(t)$ rather considered as nonlinear N-dimensional matrix in general scenarios. We discussed first one-to-one transformation, which produces linear model[13] in a new space as depicted in Equation (25).

$$A = g(\theta). \tag{25}$$

Here, g is p-dimensional matrix in Equation (25), whose inverse[13] can lead easily to computation of linear least square estimation (LSE) of A and thus non-LSE of θ as depicted in Equations (26) to (28).

$$y(g^{-1}(A)) = HA \tag{26}$$

$$\theta = g^{-1}(A) \tag{27}$$

$$A = (H^T H)^{-1}(H^T x) \tag{28}$$

Underwater range sensor model (URSM) describes overall path loss L_{UW} (dB) as a function of range R (m) mentioned in Equation (5). As T_x transmits EM signal with known P_T (dB), difference between P_R and $P_T = RSS$ (dB) that receives signal strength[14] can be formulated by the model given in Equation (29).

$$RSS = -20log10(R) - 20log10(R\alpha log_{10}e) + \gamma_{offsetfactor} \tag{29}$$

Here, in Equation (30), offset factor ($\gamma_{offsetfactor}$) (dBm) represents antennas and environmental influences. $\gamma_{offsetfactor}$ (dBm) can be estimated if variables such as G_T, G_R, and L_ϕ (dB) and loss factor $20 * log(\lambda/4 * \pi)$ (dB) are known. Model parameters R_{est} (m) can be computed by fitting given RSS (dB) using NLLS approach. Estimation of R_{est} (m) performed with the help of Lambert W transformation as a function of P_R (dB) taking into consideration of nonlinear and exponential property[14] of Equation (5) is depicted in Equation (30).

$$\gamma_{offsetfactor} = (G_T + G_R + 20 \times log(\lambda/4 \times \pi) + L_\phi) + 30 \tag{30}$$

$$R_{est} = (1/(\alpha \times log_{10}e * ln10)) \times W[\alpha \times log_{10}e \times ln e^{-ln10/20(P_R-P_T)-\gamma ln10/20}]$$

Lambert W function $W(y)$ is also known as omega function, namely, branches of inverse relation of function $f(x) = x \times e^x$, where e^x is an exponential function in our case L_α (dB) and x is α (dB/m), a complex number. $W(y)$, which is an inverse of given exponential decaying overall path loss[14] of seawater L_{UW} (dB), is described in Equation (31).

$$f^{-1}(x) = y = W(y) \tag{31}$$

4 | SIMULATION RESULTS AND DISCUSSION

In this research work, we defined three main problem motivations: (a) characterizing seawater communication channel at megahertz frequency, (b) using NLLS approach for range estimation based on attenuation (α) of EM waves that helps to minimize difference between R_{est} (m) and R (m), and (c) adjusting configurations P_T, G_T, and G_R (dB) for T_x and R_x accordingly. Table 1 represents list of symbols used frequently in this paper. To achieve these aforementioned tasks, we used real-time-averaged data along decades for T (C^o) and S (ppt) from 1955 to 2012 at multiple depths of oceans[15] up to 5500 m. We used MATLAB as simulation tool for analysis and performance evaluation in terms of R_{est} (m), mean value ($mean(R_{est})$), standard deviation ($SD(R_{est})$), variance ($var(R_{est})$), and BER probability P_e (probability of error) for different modulation schemes, ie, BPSK/QPSK (coherent) and FSK (coherent and noncoherent). Table 2 represents simulation parameters for analysis and range estimation based on α of EM waves. Data for T (C^o) and S (ppt) from 1955 to 2012 averaged across multiple decades for (41 088) latitude/longitude points along with depth from surface to 5500 m distributed nonuniformly across 102 points have been used. Data across nonuniformly distributed seawater depth mapped into (1101) depth points up to 5500 m with uniform distribution of depth (5 m) difference with frequency range of 1 to 20 MHz, $P_T = 30$ dBm, $d_{Rayleigh}$ ($\approx$5 m), and $G_T, G_R = 10$ dB.

Previous studies show that T (C^o) and S (ppt) values are chosen normally between 20 to 25 C^o and 30 to 35 ppt, respectively, for analysis of the seawater. Real-time-averaged data show that these parameters lie in range of 3.07 to 13.83 C^o and 34.083 to 34.337 ppt. Experimental and theoretical results show that σ (S/m) lies approximately near 4 S/m. Estimation of σ (S/m) using Stogryn's model in Equation (20) shows that given parameter lies between 4.415 to 3.003 (S/m) and 5500-m depth with mean value $mean(\sigma) = 3.366$ and standard deviation $SD(\sigma) = 0.428$. This rejects possibility of assuming constant σ (S/m) for seawater.[16] Table 3 depicts estimated parameters based on real-time data from 1955 to 2012, required

TABLE 1 List of symbols

L_α	**Absorption Loss**
L_o	Spreading loss
L_ϕ	Loss due to polarization
R_{est}	Estimated range
$NLLS$	Nonlinear least square
α	Attenuation constant
β	Phase constant
γ	Propagation constant
L_{UW}	Total underwater loss
$\gamma_{reflection}$	Reflection loss
$T_{transmission}$	Transmission loss
P_n	Noise power
LSE	Least square error
RSS	Received signal strength
$\gamma_{offsetfactor}$	Offset factor
$Lambert - W$	Lambert W transformation

TABLE 2 Simulation parameters for analysis

T (C^o) and S (ppt)	1955 → 2012	**Averaged Data (Averaged Decades)**
Oceans	5	Indian, Pacific, Southern, Atlantic, Arctic
OceanDepth	0 → 5500 (m)	Average seawater depth of 3500
Latitude	0 → ±90	North or south of equator
Longitude	0 → ±180	East or west of Greenwich
VerticalPoints	1 → 1101	Seawater depth up to 5500 m divided into 1101 depth points
HorizentalPoints	1 → 41088	Seawater latitude and longitude divided into 41 088 points
$f_{transmission}$	1 → 20 MHz	Frequency range for transmission
P_T	30 dBm	Source power for transmission
$G_{T,R}$ (dipole)	10 dB	Gain for both transmitter and receiver
$d_{rayleigh}$	≤5 m	Rayleigh distance

TABLE 3 Estimated parameters at multiple seawater depths

Parameter	**0 m**	**50 m**	**100 m**	**350 m**	**700 m**	**1200 m**	**1700 m**	**2400 m**	**3400 m**	**4400 m**	**5500 m**
$T\ (C^o)$	13.838	12.957	11.451	7.548	4.880	3.067	2.285	1.756	1.422	1.456	3.070
S (ppt)	34.083	34.515	34.735	34.762	34.630	34.694	34.771	34.831	34.866	34.988	34.337
α (dB/m)	10.645	10.619	10.546	10.312	10.143	10.033	9.987	9.955	9.929	9.921	9.936
σ (S/m)	4.145	4.097	3.963	3.562	3.299	3.139	3.074	3.028	2.994	2.982	3.003
ϵ_r''	$1.342 * 10^4$	$1.327 * 10^4$	$1.283 * 10^4$	$1.154 * 10^4$	$1.068 * 10^4$	$1.017 * 10^4$	$9.958 * 10^3$	$9.812 * 10^3$	$9.201 * 10^3$	$9.662 * 10^3$	$9.732 * 10^3$
ϵ_r'	68.223	68.174	68.479	69.645	70.394	70.737	70.838	70.903	70.970	71.004	70.976
$\gamma_{offsetfactor}(dBm)$	22.606	22.644	22.784	23.223	23.550	23.784	23.881	23.944	23.955	24.017	23.986
Z (ohms)	1.916	1.932	2.008	2.252	2.445	2.576	2.633	2.673	2.705	2.716	2.697
β (rad/m)	12.542	12.471	12.267	11.648	11.209	10.938	10.825	10.747	10.687	10.666	10.703
$V_p(m/Sec)(* 10^6)$	5.759	4.780	4.866	5.123	5.326	5.458	5.519	5.555	5.586	5.597	5.577
τ (s) $(* 10^{-11})$	1.181	1.206	1.243	1.348	1.458	1.544	1.584	1.613	1.633	1.639	1.625
f_T (Hz)	$1.093 * 10^9$	$1.081 * 10^9$	$1.041 * 10^9$	$9.207 * 10^8$	$8.436 * 10^8$	$7.988 * 10^8$	$7.811 * 10^8$	$7.689 * 10^8$	$7.595 * 10^8$	$7.561 * 10^8$	$7.617 * 10^8$
$T_{transmission}$	1.989	1.986	1.989	1.988	1.987	1.986	1.986	1.985	1.985	1.985	1.985

to compute L_α (dB) and L_o (dB) across selective seawater depths and contribute in estimating R_{est} (m). This also makes a clear indication that we cannot assume constant σ (S/m), ϵ (F/m), τ (s), and V_p (m/s) across multiple seawater depth as normally pointed out in literature.

In seawater, ϵ_r' contributes to energy absorption and is assumed approximately 81. Estimation by using Deby's theory formulation using Stogryn's model as depicted in Equations (17) and (18) shows that it lies between 68.223 and 70.976 with $mean(\epsilon_r') = 70.0878$ and $SD(\epsilon_r') = 1.0871$. ϵ_r'' estimation shows that this parameter lies between $1.342 * 10^4$ and $9.732 * 10^3$ with $mean(\epsilon_r'') = 1.0906 * 10^4$ and $SD(\epsilon_r'') = 1.3876 * 10^3$, whereas Z lies between 1.916 and 2.697 ohms with $mean(Z) = 2.42$ and $SD(Z) = 0.300$. Free-space Z_o is approximately 377 ohms while for a smooth transition at sea/air boundary, Z (ohms) should be approximately equal to free-space Z_o. Similarly, v_p lies between $4.780 * 10^6$ and $5.597 * 10^6$ m/s with $mean(v_p) = 5.3028 * 10^6$ and $SD(v_p)$=$3.1192 * 10^5$. Figure 2 represents α (dB/m) estimate based on Equation (10) and contributes in L_α of seawater against number of occurrences. We can clearly see that a maximum number of occurrences for multiple depths and frequencies lie in the range of 9 to 10.5 dB/m that helps to assume value α (dB/m) in this range on average. Given simulation results also shows normal distribution fit for α (dB/m). We can also clearly see that less values of α occur less frequently that helps to predict real-time L_α for multiple depths up to 5500 m.

Although in literature τ lies near $8.2 * 10^{-12}$ s, however its estimated values lie between $1.203 * 10^{-11}$ and $1.639 * 10^{-11}$ s with $mean(\tau) = 1.4694 * 10^{-11}$ and $SD(\tau) = 1.6912 * 10^{-12}$. Similarly, f_T lies near 888 MHz previously while its estimated values lie between $1.093 * 10^9$ and $7.595 * 10^8$ Hz with $mean(f_T) = 8.6646 * 10^8$ and $SD(f_T) = 1.2500 * 10^8$. On the basis of varying V_p (m/s), estimated L_o lies between 41.373 and 100.963 dB. However, for the constant assumption of V_p (m/s), it lies from 24.802 to 85.630 dB. Difference between L_o (dB) estimated based on real data and constant v_p (m/s) lies between 16.570 and 15.333 dB. Similarly, transmission coefficient $T_{transmission}$ lies between 1.985 and 1.989 with $mean(T_{transmission}) = 1.987$ and $SD(T_{transmission}) = 0.001$. Figure 3 represents β (rad/m) estimate based on Equation (11) and contributes in L_β of seawater against number of occurrences. We can clearly see that a maximum number of occurrences for multiple depths and frequencies lie in the range of 8 to 12.5 rad/m that helps to assume β (rad/m) in this range on average. Given simulation results also shows normal distribution fit for β (rad/m). We can also clearly see that less values of β (rad/m) occur less frequently that helps to predict real-time phase and propagation delay of signal for multiple depths up to 5500 m.

P_R (dB) computed using Equation (5) is based on principle for vertical communication that all parameters across latitude/longitude (41 088 points) averaged vertically along seawater depth (102 points). Seawater depth points that are nonlinearly distributed from 0 to 5500 m are mapped into linear distribution of (1101 points) while difference between any two points is 5 m. $T\,(C^o)$ and S (ppt) data are distributed among different depth points, which are newly created based on average principle between two successive depth points uniformly. T_x location from 0th position (seawater surface) is

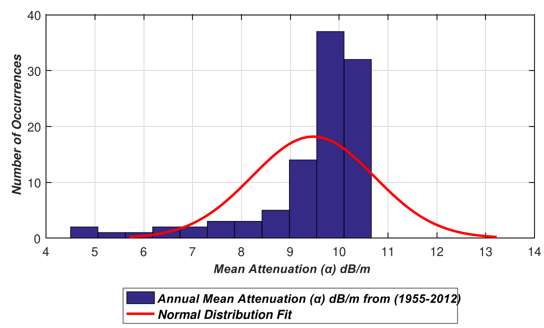

FIGURE 2 Mean attenuation α versus number of occurrences

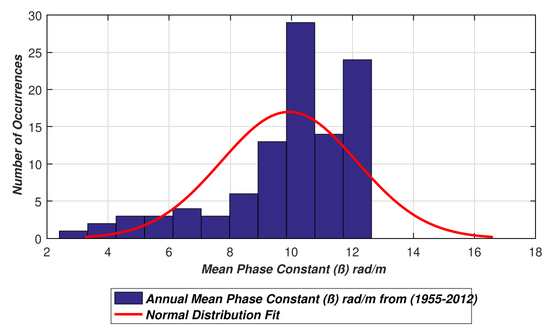

FIGURE 3 Mean phase constant β versus number of occurrences

moved uniformly with 5-m depth steps to see the effect of launching EM wave in seawater at each depth point up to 5495 m (41 087 iterations done). After whole process of T_x movement is completed along depth, average P_R (dB) is estimated at multiple points (1101 points) of seawater depth. Estimation of $\gamma_{offsetfactor}$ (dB) representing antenna and environmental influences can be estimated if variables such as G_T, G_R, and L_ϕ (dB) assuming $\phi = 0$ and loss factor $20 * log(\lambda/4 * \pi)$ (dB) are known based on Equation (29). In Figure 4, we can see that $\gamma_{offsetfactor}$ (dB) versus number of occurrences varies from −7.934 to −6.104 dB linearly after 0 dB approximately with $mean(\gamma_{offsetfactor}) = -13.83$ and $SD(\gamma_{offsetfactor}) = 0.293$.

$\gamma_{offsetfactor}$ (dB) helps to compute RSS (dB) based on Equation (30). Moreover, fitting RSS (dB) with NLLS approach helps to estimate R_{est} (m) with help of Lambert W transformation based on Equation (31). As we can see in Figure 5, R_{est} (m) approximated at different frequencies versus number of occurrences shows that it varies from 0 to 200 m in a nonlinear way. For certain frequencies, R_{est} (m) stricts to 50 m but for low frequencies goes up to 200 m based on parameters like ϵ_r and σ (S/m), which vary across seawater depth. EM-based range estimation in seawater gives us near to actual range that also helps to minimize error to reach actual R; rather than acoustic waves that suffer from man-made noise, slow propagation speed, and Doppler spread and optical waves that suffers from dirty water conditions, back scattering also requires LOS link. Error $e(t)$ between actual R (m) and predicted location R_{est} (m) of T_x based on NLLS varies from 0 to 400 m as shown in Figure 6. However, at low frequencies and lower seawater depth, error remains minimum that helps

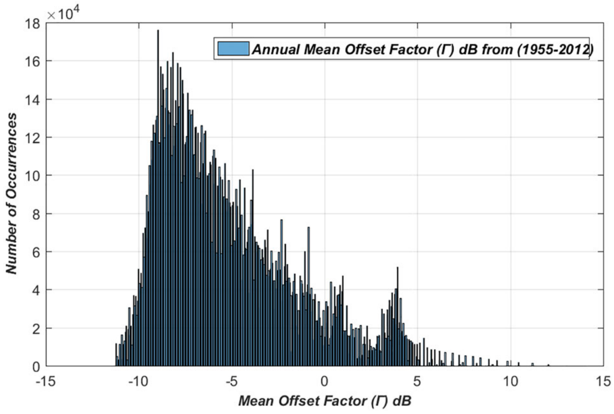

FIGURE 4 Mean offset factor $\gamma_{offsetfactor}$ (dB) versus number of occurrences

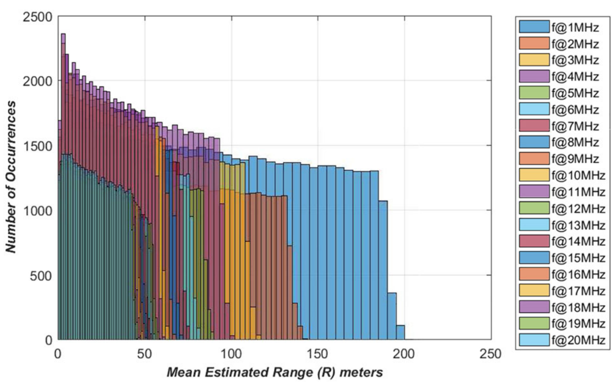

FIGURE 5 Mean estimated range R_{est} (m) versus number of occurrences

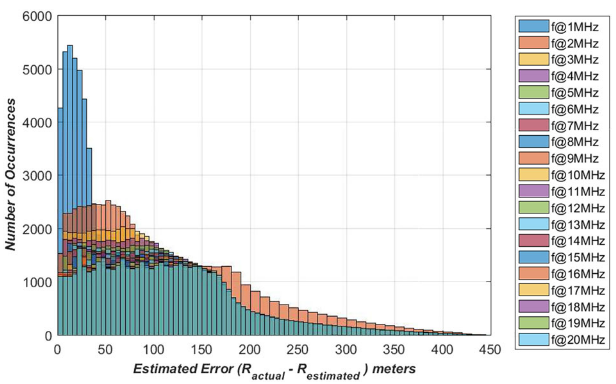

FIGURE 6 Mean estimated error $mean(e(t))$ (m) versus number of occurrences

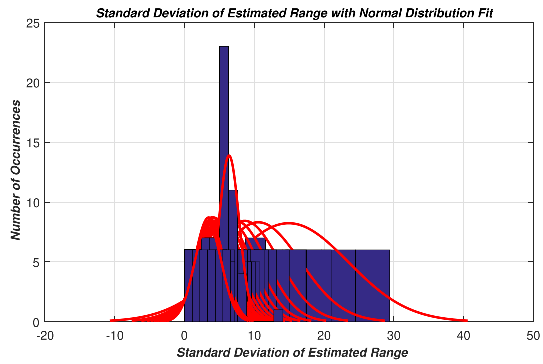

FIGURE 7 Standard deviation of R_{est} (m) with normal distribution fit

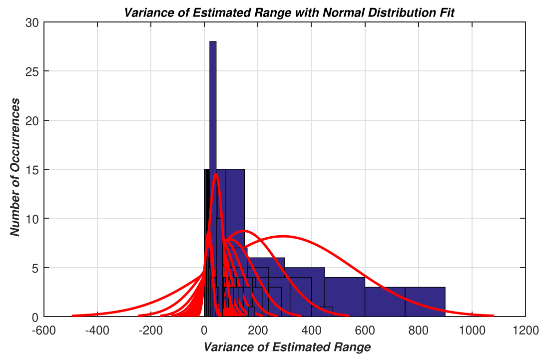

FIGURE 8 Variance of R_{est} (m) with normal distribution fit

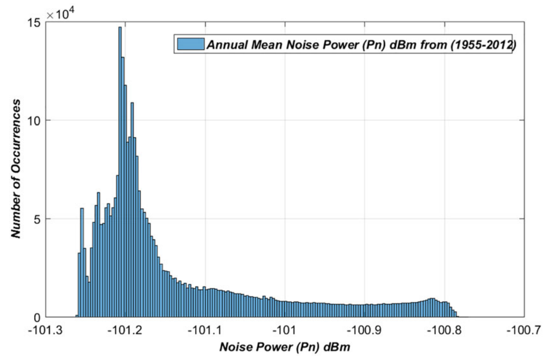

FIGURE 9 Mean noise power $mean(P_n)$ (dBm) versus number of occurrences

to localize underwater nodes and vehicles based on EM waves. Error between R_{est} (m) and R (m) can be minimized by applying principle for higher frequencies and depths as shown in Figure 1, by adjusting input parameter θ (P_T, G_T, f) accordingly.

$$P_n = N_o = (10 * log10(kTB)) + 30 \tag{32}$$

Figures 7 and 8 represent $SD(R_{est})$ and $var(R_{est})$ of estimated R_{est} (m), respectively. $SD(R_{est})$ varies from 0 to 30 with constant number of occurrences, ie, 5, and with a $SD(R_{est}$ of 6 to 7 with highest number of occurrences fitted using normal distribution. Figure 8 shows that $var(R_{est})$ of R_{est} varies from 0 to 900. $var(R_{est})$ represents that actual spread of R_{est} lies between 0 and 200. As P_T (dB) suffers from noise, so considering effect of thermal noise[17] N_o or P_n (dB) that helps to estimate P_R/P_n is based on Equation (32). Here, k is Boltzman's constant $1.380 * 10^{-23}$, $T\,(C^o)$ at each latitude/longitude, and seawater depth with B bandwidth (assumed equal to T_x frequency). Figure 9 shows that noise power level versus number of occurrences varies from −101.34 to −100.8 dBm. Estimated N_o (dB) leads us to compute of P_e for different modulation schemes BPSK/QPSK (coherent) and FSK (coherent and noncoherent). On the basis of the assumption of $(B(Hz) = C(bps))$ for BPSK/QPSK (coherent), Figure 10 shows that P_e decreases from 0.5 to 0.055 up to 100-m depth. After 100- to 200-m depth, on average, it remains constant. For FSK (coherent), P_e decreases from 0.5- to 0.152- up to 100-m depth, and for FSK (noncoherent), P_e decreases from 0.5 to 0.3 up to 100-m depth beyond that approximately remains constant. Figure 11 shows mean L_α (dB) and mean L_o (dB) versus different depths of ocean and frequency. It is clear from the results that at lower depths, both L_α and L_o show minimum value with exponential decay that becomes a suitable choice for short-distance communication but with increasing depth, α increases that causes signal to attenuate at higher

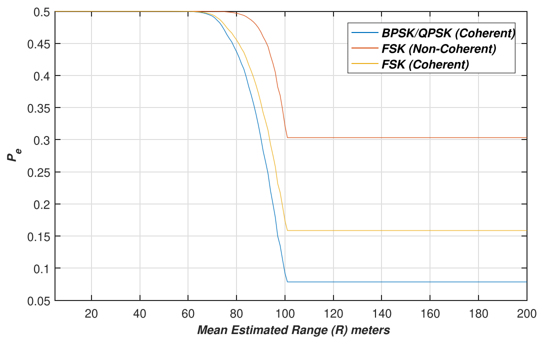

FIGURE 10 Probability of error P_e versus mean estimated $mean(R_{est})$ (m) using different modulation schemes

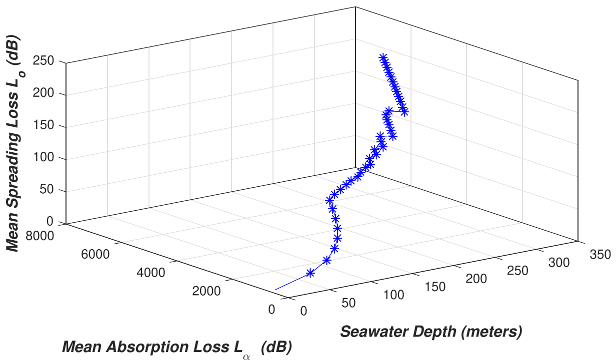

FIGURE 11 Mean L_α (dB) and mean L_o (dB) across multiple seawater depths

rate that becomes less suitable for long-range communication. Another observation we can make for lower (shallow water) and higher depths (deep water) signal attenuates nonlinearly, while in between, α is approximately a linear phenomenon.

5 | CONCLUDING REMARKS

To analyze NLLS implementation for estimation of R_{est} based on attenuation of EM waves, considering localization/tracking and performance evaluation of seawater EM communication, we used real-time data from the National Center for Environmental Information (NCEI) for all oceans. Given data helped us to characterize seawater communication channel for 1- to 20-MHz frequency range at multiple depth points (1-1101) with uniform distribution of 5-m difference in depth. We also implemented Stogryn's model to estimate σ (S/m), ϵ_r (both real and imaginary parts), and α (dB/m) using Helmholtz's model along with other parameters like τ (s), V_p (m/s), Z (ohms), and f_T (Hz). Computed parameters ultimately contribute in estimating L_α (dB), L_o (dB), and L_ϕ (dB) to estimate total underwater path loss for seawater L_{UW} (dB). L_{UW} (dB) also helped us in estimating (R_{est}) (m) by applying Lambert W transformation considering nonlinear exponential decay and minimizing $mean(e(t))$ using NLLS approach. R_{est} (m) using EM waves in seawater was examined for localization/tracking shows that maximum achievable depth is 200 m with maximum $mean(e(t)) = 400$ m, while $SD(R_{est})$ lies in the range of 0 to 40, along with $var(R_{est})$ in 0 to 900. P_e estimation for different modulation schemes BPSK/QPSK (coherent) and FSK (noncoherent) shows that on average, P_e varies between 0.5 to 0.08 and 100 m; however, beyond that, on average, it remains constant up to 200 m. Analysis of mean L_α (dB) and mean L_o (dB) across multiple depths of oceans in 3D plot is a clear indication that at lower depths up to 200 m, both L_α and L_o retain sudden exponential decay and minimum decay in P_T (dB) overall. But with increasing depth beyond 200 m, L_α (dB) and L_o (dB) increases much higher cause signal to α (dB/m) at higher rate and become less suitable for long-range communication in seawater. Another observation we can make from the estimated result that based on real-time data that for shallow water and higher depths (deep water) near to seabed signals α (dB/m) nonlinearly, while in between, α (dB/m) is approximately a linear phenomenon. In the future, we want to look at this problem in the context of e-navigation, bringing existing and new technologies together to improve safety of navigation, commercial efficiency, and security.

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ORCID

Piao Yan https://orcid.org/0000-0002-4668-1193
Mohsin Raza Jafri https://orcid.org/0000-0001-5197-4399

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