Modeling and simulation of SWARA path loss model for underwater acoustic communication in multipath environment

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Modeling and simulation of SWARA path loss model for underwater acoustic communication in multipath environment

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Abstract:- **The propagation loss varies with underwater channel conditions which might considered to be random phenomena. Modeling propagation loss will become meaningful iff mathematical model includes parameters namely viz projector's transmit voltage response (TVR), hydrophone's open circuit receiving response (OCRR), directivity patterns of both, channel parameters such as salinity, temperature, pressure, enclosure boundary conditions along with placements of Tx & Rx nodes & their operating frequency. To best of our knowledge, existing simulators are unable to trace eigen rays for very short range i.e. less than 0.1 km and therefore they are not suitable for computation of such short-range propagation losses. We have made an attempt to overcome limitations of existing simulators wherein we proposed mathematical model SWARA which includes parameters as mentioned above to study very short-range propagation losses using plane wave theory. To validate simulated propagation loss, we conducted tank trials at UWAA Lab, CARE, IIT Delhi to investigate effects of placements of projector & hydrophone on occurrence of transmission loss. The Simulated results of SWARA mathematical model shows that simulated maximum transmission loss is -0.18 to 0.10 times experimental maximum transmission loss, whereas simulated minimum transmission loss is -0.36 to 0.19 times experimental minimum transmission loss for placements of projector (ITC 1042) and hydrophone (Keltron 8240000001) at depths varying from 0.3m-1.2m & range varying from 2m-3.2m in uw tank facility of 3.85m long 2.4 wide 2m deep for 30kHz chirp signal (10kHz bandwidth) under static channel conditions.**

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I. INTRODUCTION

When acoustic signal travels from one point to another, there is an occurrence of transmission loss (TL) which reduces overall strength of acoustic signal at receiver end. This transmission loss is modeled in terms of path loss, which is function of absorption, spreading, scattering, reverberation, reflection, refraction, diffraction happened along the traveling of path in given uw channel. It is necessity of any robust propagation model that adopt real-time channel conditions along with transmitter & receiver's properties to build accurate propagation loss which can be used as basis for evaluating performance metrics of deployed nodes.

The accurate prediction of propagation loss minimizes cost of experimentation required to test researcher's hardware, prototype, or design or to test performance metrics of communication protocols or network to improve network's throughput & reliability. To achieve this, we require design of environment aware protocol which can adjust parameters of excitation signal as per the need of uw channel's time and space variations. The parameters are mainly transmission frequency, bandwidth (BW) & power. The choice of transmission frequency depends on amount of absorption happened at operating frequency (kHz). Transmission BW is selected as per theoretical upper bound set by Shannon's channel capacity theorem. Whereas transmission power is adjusted desired Signal to Noise ratio (SNR) level greater than noise level to meet the requirements of successful transmission at range 'r' m. Therefore, there is need of 1. Characterization of underwater acoustic (uwa) channel using CTD instrument at Tx/Rx nodes, 2. Registration of channel conditions at Tx/Rx nodes, 3. Analysis of propagation loss for acquired channel conditions at Tx/Rx node, 4. Selection of optimum transmission frequency, bandwidth (BW) & power to fulfill the successful transmission & reception.

Shallow water exhibit higher propagation loss due it's varying nature of channel boundaries. Hence occurrence of propagation loss is more due to higher rate of change in reflection & refraction coefficients of path reaching towards receiver. Whereas in deep sea water, propagation loss is moderate due to slower rate of change in reflection & refraction coefficients. Hence nature of boundary enclosure plays important role in adding propagation loss at receiver side.

Depending upon state of channel conditions modeling approach is changing. Nowadays, most of authors are trying to develop computationally efficient models which delivers closed approximations of simulated estimates of propagation loss compared to real-time experimental propagation loss for assumed channel condition. In last 20 years, following are standard propagation models used for studying propagation losses as 1. Ray tracing 2. Normal mode theory, 3. Green's function, 4. Parabolic equation & 5. Plane wave theory. All 5 models are derived from homogeneous Helmholtz equation.

Ray theory gives an insight of how source energy is propagating in given uw channel. Where the analysis of propagation loss is done in two parts 1. By considering fan of all rays of source. Let's consider an Omni directional source where one can study range dependent propagation loss & 2. By considering selected windowed region among all fans of rays (termed as eigen analysis) which aims at depth dependent propagation loss [1].

This theory has advantage that it delivers a ray trace in static as well as in dynamic channel conditions by including source directionality. But for range dependent analysis, in order to produce reasonable energy, spread of source, ray computations performed at all ranges up to receiver range which increases its time complexity as no of channel parameters are changing wrt time. Also, it is applicable only for high frequency approximations, which means that the rate of change of boundary should be as slow as possible as compared to wavelength of source operating frequency (i.e. high frequency) [2].

Normal mode is method of separation of Helmholtz equation in to one dimensional depth & range equation. It is expressed as sum of discrete normal modes with one or more branch integrals for assumed vertical stratification & cylindrical symmetry of uw channel. One dimensional mode will be giving loss analysis of surface-bottom going rays of higher wave number whereas branch integral will be giving loss analysis of steeper rays of lower wave number [3].

The normal modes are calculated by choosing trial values of horizontal wave number & Runge-Kutta numerical approach. This theory is applicable for short range applications and adiabatic approximations (slowly varying)/(where the sound velocity profile (SSP) remains constant or slightly varying wrt range & depth). It includes effects of changing SSP, boundary enclosure, and water properties to evaluate transmission loss at receiver end [3].

Green's function provides complete solution to Helmholtz equation for channel comprises of mixed liquids & solids using Hankel transform at any range including near field. The limitations of this theory are 1. It can be applied to horizontally stratified medium 2. It takes more time for computation of propagation loss [4]. Parabolic equation approach overcome the limitations of Green's function by considering effects of horizontal variation of SSP wrt depth & provides closed approximation to 3-dimensional modeling of transmission loss [4].

Plane wave theory deals with far field analysis of sound wave travelling in direction let say 'x' where sound pressure or intensity is calculated at distance greater than 3 times a wavelength (far field distance) from source. For plane wave propagation in direction 'x', sound pressure and particle velocity in other directions (y & z) are assumed in phase so that overall sound pressure or intensity depends on one spatial variable (i.e. x in this case) at a time. Therefore 3D-Helmholtz equation is simplified to 1D-Helmholtz equation to represent sound pressure or intensity as a function of direction of propagation 'x' & time 't'. Thus, time complexity gets reduced as compared to conventional ray theory and normal mode theory. This theory is applicable to static tank channels where the properties of channel are not changing much wrt time [5].

From available literature, we found that empirical models are easily verified than advanced models because it is impossible to measure all channel parameters (such as salinity, temperature, pressure, water density, boundary conditions, wind speed, ocean currents, noise) using equipped sensor facility at Tx/Rx nodes & also it is difficult to validate its applicability in order to fulfill all channel conditions demanded by advance propagation model. Whereas in case of empirical model, it is possible to validate its applicability because the experimentation is carried out in controlled environment & measurement task is manageable due to limited no of channel parameters demanded by empirical model than advanced model.

Therefore, there is a scope for development of new empirical model : Shallow Water Acoustics for Random Area (SWARA) which adopts 1.channel's physical properties, 2.source & receiver's properties & 3.noise properties to identify optimum placements of projectors & hydrophones in tank by applying plane wave theory. It delivers brief idea about quickly setting up preliminary testing environment without doing actual deployment of nodes which minimizes cost of experimentation in terms of involvement of time, human resources, & money. Such model is required at sonar operational sites, where performance of any sonar systems critically depends on prevention of TL especially in case of shallow water applications.

This paper proposes new mathematical model: SWARA in Section II, applicable for studying underwater propagation losses of Indian tank channels. Plane wave theory is used for modeling these uw propagation losses. The simulation of propagation loss is modeled for all possible depths and range placements of projector and hydrophone, to find optimum placement where channel performance can be improved.

In Section III, methodology of path loss calculation is explained. Section IV, analysis of simulation performed using SWARA Matlab code is explained. The study is applicable for small size rectangular tank of size 3.85m long 2.4m wide and 2m deep. In section V, verification & validation of simulated transmission loss is discussed. Section VI describes comparative analysis & observations of simulated & experimental results of TL followed by Section VII, conclusion.

II. MATHEMATICAL MODEL SWARA OF TRANSMISSION LOSS USING PLANE WAVE THEORY

Shallow water channel has its own significance due to its randomly varying (temporal and spatial) nature. It behaves like waveguide structure for uw tank channel where acoustic signal radiating from source spreads out spherically at receiver which is located at distance less than depth of uw tank whereas signal spreads out cylindrically for receiver which is located at a distance more than depth of uw tank. For static channel condition, sound rays radiating from source are travelling straight due to no change in SSP among water layers of uw tank. These rays are normal to the wave fronts & are travelling in direction of propagation of the wave fronts as shown in figure 1 below.

The propagation of acoustic wave in water is governed by the laws of fluid mechanics and is described using plane wave theory as below. When source radiates at frequency f_0 kHz. The wave fronts are travelling in all directions with particle velocity U_r m/s. U_r is particle velocity in radial direction from source acoustic centre. In far field, (Kr >> 1) the force gets exerted on another consequent water particle and its motion will follow law of conservation of momentum. let say between Kr (wave number for distance coverage of 'r' m) & Kr+ΔKr the sum of forces acting on water element is equal to change of momentum as shown in figure 1 above.

$$(Ps)_{kr} - (Ps)_{kr+\Delta kr} = Ps\frac{dU_r}{dt}\Delta kr \tag{1}$$

P is acoustic pressure; s is area of an infinitesimal water element. The rate of change of velocity $\frac{dU_r}{dt}$ is described as

$$\frac{dU_r}{dt} = \frac{\partial U_r}{\partial t} + \frac{\partial U_r}{\partial kr}\frac{\partial kr}{\partial t} \tag{2}$$

$\vec{U}_r$ is particle velocity of water which is rate change of displacement wrt time hence we can rewrite above equation as

$$\frac{dU_r}{dt} = \frac{\partial U_r}{\partial t} + \frac{\partial U_r}{\partial Kr}U_r \tag{3}$$

Note that above expression is referred as Lagrangian description for motion of a mass of water element at Δkr. Now more precise momentum balance can be expressed by Euler description as

$$-\frac{\partial p}{\partial Kr} = \frac{D\rho_w U_r}{Dt} = \rho\frac{DU_r}{Dt} \tag{4}$$

p is total acoustic pressure given by addition of static pressure p_{sta} with fluctuating pressure p_{flc} induced by small

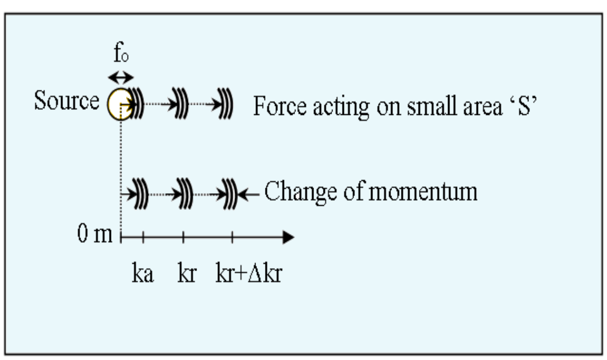

Fig. 1. Relation between force & motion of water element in tank expressing balance of momentum

fluctuations of water particles. Whereas ρ is total water density given by addition of static density ρ_{sta} & fluctuating density ρ_{flc}.

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + U_r\frac{\partial}{\partial Kr} \tag{5}$$

$\frac{D}{Dt}$ is called as total derivative where first term represents rate of change wrt time and second term represents change wrt space as sound moves along 'r' with velocity U_r. For uw channel, tank static pressure p_{sta} & density ρ_{sta} do not vary much in space & time as compared to sea channel states. Then equation (4) becomes

$$\frac{\partial p_{flc}}{\partial Kr} = \rho_{sta}\frac{\partial U_r}{\partial t} \tag{6}$$

this proves that change in acoustic pressure p_{flc} across small distance kr causes water element of unit volume ρ_{sta} to move with acceleration $\frac{\partial U_r}{\partial t}$. This equation generally referred as linearized Euler equation which states that change in fluctuating pressure makes water particle to move. Using conservation of mass principle (relation between density and fluid particle velocity) & from equation (4) & (6) we get

$$\frac{\partial \rho_{flc}}{\partial t} = -\rho_{sta}\frac{\partial U_r}{\partial Kr} \tag{7}$$

which represents relation between water fluctuating density (ρ_{flc}) and water particle velocity (U_r) which implies higher compression rate in time makes a steeper negative velocity gradient in space. From laws of thermodynamics change in acoustic fluctuating pressure causes change in water fluctuating density and its entropy.

$$\frac{p_{flc}}{\rho_{flc}} = \frac{Blk}{\rho_{sta}} = {C_w}^2 \tag{8}$$

Blk is bulk modulus of water, $C_w$is speed of sound in water medium. Above equation expresses how fluctuating acoustic pressure relates with fluctuating water density. It states that speed of propagation depends on the characteristics of the medium. Hence from equation (6), (7) & (8) we obtain

$$\frac{\partial^2 p_{flc}}{\partial^2 Kr} = \frac{1}{{C_w}^2}\frac{\partial^2 p_{flc}}{\partial^2 t} \tag{9}$$

which represents general one-dimensional wave equation of sound. This states that plane wave theory simplifies 3-dimensional wave equation to 1 dimensional wave. Source type is omnidirectional and therefore spherical coordinate system will be more convenient for pressure calculations in far field. Type of coordinate system changes with type of source [6]. We adopt spherical coordinate system conveniently to represent pressure at any point p (x, y, z) ranged at 'r' m from source in uw tank. It also satisfies the governing equation and holds superposition principle true for each component of spherical coordinate system (r, Θ, φ) [6]. Considering isotropic medium, the solution to above wave equation for a point source radiating at frequency f_0 at range 'r' m is given by reduced spherical wave equation as

$$P_{(r,t)} = \frac{p_{sta}}{r}e^{\left[jw\left(t-\frac{r}{c}\right)+\phi\right]} = \left(\frac{a}{r}\right)^2 p_{sta}\, e^{[j(wt-kr+\phi)]} \tag{10}$$

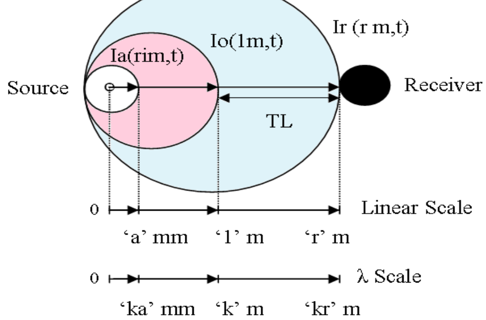

Fig. 2. Far field intensity analysis of sound wave using plane wave theory

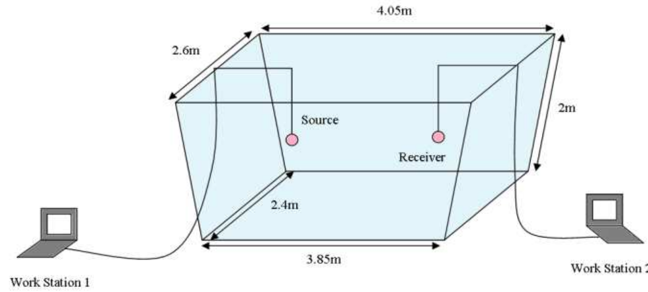

Fig. 3. Acoustic set-up with underwater tank facility

$P_{(r,t)}$ is magnitude of acoustic pressure of sound wave travelling in direction of 'r' with initial phase $'\phi'$ as a function of time t. p_{sta} is static pressure & kr is wavelength in terms of λ to cover distance of' 'r' m.

Acoustic waves often referred as longitudinal waves where particle velocity of medium moves in direction of propagation of sound wave fronts. These wave fronts are in spherical shape initially (Kr~1) and later becomes plane in far filed (Kr >> 1) where pressure amplitude decreases by factor of 1/R due to spherical spread of sound which implies sound pressure is inversely proportional to distance from source in far field [7].Consider Omni directional point source with input power W watts radiates sound in all directions with same intensity at distance 'r' m from centre of source as shown in figure 2 above.

The sound propagation is strongly influenced by structure of channel physical aspects & geometry which consists of uw tank sidewalls, bottom type, type of water, nature of sediment at bottom present at the time of communication. Absorption losses in normal water are very low for moderate range of frequency but it increases with increase in frequency [8]. Therefore, absorption losses shall be considered for higher frequency of operation.

The plane wave theory is applicable for finding complete mathematical solution to acoustic wave equation in far field for all boundary conditions. This theory includes projector, hydrophone's properties along with channel conditions to calculate transmission loss. The transmission loss is nothing but difference in acoustic signal's intensity from source to receiver as shown in figure 2 above. For effective radiation at source, Ka should be greater than 1 in far field region (distance greater than 3λ) and choice of operating frequency depends on factor Ka (wavelength in terms of λ to cover distance of 'a' m). Then active average (mean) intensity at distance 'r' m from source is calculated as

$$\left|I_{r\,(r,t)}\right| = \frac{1}{2}\mathrm{Re}\{P_r U_r^*\} \qquad W/m^2 \qquad (11)$$

the velocity potential at distance 'r' m is given by

$$U_{r(r,t)} = U_0\left(\frac{1-jKr}{1-jKa}\right)\left(\frac{a}{r}\right)^2 e^{(j(wt-k(r-a)+\phi_u))} \quad m/s \quad (12)$$

U_0 is $p_{sta}/\rho_w c_w$, $\left(\frac{1-jKr}{1-jKa}\right)$ is radiation impedance, $\left(\frac{a}{r}\right)$ is spreading loss factor. The acoustic pressure at distance 'r' m is given by

$$P_{r(r,t)} = \rho_w c_w U_0\left(\frac{-jKa}{1-jKa}\right)\left(\frac{a}{r}\right)^2 e^{(j(wt-k(r-a)+\phi_p))} \quad Pa \quad (13)$$

Where $\rho_w c_w$ is characteristic impedance of channel and $\left(\frac{-jKa}{1-jKa}\right)$ is radiation impedance. Here equation (12) & (13) are valid if 'r' is larger than 'a'. Using equation (12) and (13) we obtain equation (11) as

$$I_{r\,(r,t)} = \frac{1}{2}\rho_w c_w\, U_0^2\left(\frac{a}{r}\right)^4\left(\frac{1}{1+\left(\frac{1}{ka}\right)^2}\right)e^{j(\phi_{p_r}-\phi_{u_r})} \qquad (14)$$

$$I_{0\,(1,t)} = \frac{1}{2}\rho_w c_w\, U_0^2(a)^4\left(\frac{1}{1+\left(\frac{1}{ka}\right)^2}\right)e^{j(\phi_{p_0}-\phi_{u_0})} \qquad (15)$$

therefore, we get

$$\left|I_{r\,(r,t)}\right| = \frac{1}{2}\rho_w c_w\, U_0^2\left(\frac{a}{r}\right)^4\left(\frac{1}{1+\left(\frac{1}{ka}\right)^2}\right) \quad W/m^2 \quad (16)$$

$$\left|I_{0\,(1,t)}\right| = \frac{1}{2}\rho_w c_w\, U_0^2(a)^4\left(\frac{1}{1+\left(\frac{1}{ka}\right)^2}\right) \quad W/m^2 \quad (17)$$

where

P_r : Acoustic pressure at distance 'r' m in far field
U_r^*: Complex conjugate of water particle velocity at distance 'r' m from source
U_o: Water particle velocity at distance 1m from source
$\rho_w c_w$: Characteristic impedance of channel
I_0: Average mean intensity at distance 1m from source
$\frac{1}{2}$ factor: Averaging intensity and

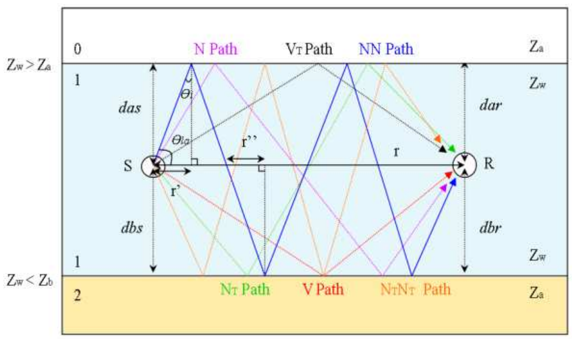

Fig. 4. Types of eigen rays

$$\left(\frac{1}{1+\left(\frac{1}{ka}\right)^2}\right): \text{Effective radiation factor}$$

Radiation mainly dominated by relative size of radiator (Ka) compared to wavelength (λ). The radiated sound field is mainly governed by relative distance (Kr) from radiator compared to wavelength of interest (λ) [9]. Therefore, in order to study propagation of sound wave in 3-dimensional space one should understand the transmission & reflection phenomena at boundaries (surface, bottom & sidewalls) of uw tank.

Whenever there is change of medium occurs it gives impedance mismatch which further leads to mismatch in amount of reflection & transmission of pressure or energy bouncing on flat surface of discontinuity. Consider tub shaped rectangular uw tank of size (surface : 4.05m x 2.6m x 2m & bottom : 3.85m x 2.4m x 2m) shown in figure 3 above. Where an Omni source radiates at frequency f_0 kHz with supplied input power of W watts in all direction then sound rays are travelling from source to receiver with several multi-paths.

In this modeling, we considered only eigen paths which are dominant multi-paths reaching towards receiver proximity. Now such paths are grouped in 6 types as below. At eigen ray travelling from source to receiver via surface (water-air) boundary will lead to occurrence of V^T, N, NN paths & via bottom (water-concrete bottom) boundary will lead to occurrence of V, N^T, N^TN^T paths as shown in figure 4 below.

When acoustic signal travels from source to receiver through any of above mentioned eigen paths, at surface or bottom boundary we assume velocity of water particles must be continuous so that resultant velocity due to incident and reflected pressure wave must be same as that of transmitted pressure wave. The pressure and velocity continuity equations can be written as

$$P_{inc} + P_{relf} = P_{trans} \tag{18}$$

$$U_{inc} - U_{refl} = U_{trans} \tag{19}$$

Where P_{inc} is incident pressure wave, P_{relf} is reflected pressure wave, P_{trans} is transmitted pressure wave. Similarly, U_{inc} is incident particle velocity, U_{refl} is reflected particle velocity and U_{trans} is transmitted particle velocity. The minus sign arises due 180° phase shift occurring every time when path bounces off from surface, bottom & sidewalls of uw tank [10]. Where acoustic pressure is a scalar quantity and it does not depend on direction of propagation whereas water particle velocity is vector quantity therefore we must consider direction of propagation. Applying plane wave theory to equation (18) we can write for surface boundary:

$$\frac{P_{inc}}{Z_w} + \frac{P_{relf}}{Z_w} = \frac{P_{trans}}{Z_a} \tag{20}$$

similarly for bottom boundary:

$$\frac{P_{inc}}{Z_w} + \frac{P_{relf}}{Z_w} = \frac{P_{trans}}{Z_b} \tag{21}$$

where $Z_w = \rho_w c_w$, $Z_a = \rho_a c_a$ & $Z_b = \rho_b c_b$ are far field characteristic impedances of water, air & bottom respectively. Now reflection coefficient for surface & bottom discontinuity is defined by taking ratio of P_{inc}/P_{relf}. Therefore, from equation (20) we get reflection coefficient for surface discontinuity as

$$R_{wa} = \frac{Z_a - Z_w}{Z_a + Z_w} \tag{22}$$

and reflection coefficient for bottom discontinuity as for convenience we denote R_{wa} as R_{10} and R_{wb} as R_{12}.

$$R_{wb} = \frac{Z_b - Z_w}{Z_b + Z_w} \tag{23}$$

Where R_{10} & R_{12} are reflection coefficient for surface and bottom discontinuity defined from oblique wave impedances of water-air & water-bottom respectively.

SWARA model considers specular reflection phenomena to analyze angle-based transmission loss of only those eigen paths which are reaching to receiver proximity. This method saves computation time and need not require calculating transmission loss at every angle like existing simulators does. Also, In order to simplify the implementation of the simulation code, several assumptions are made about the environment (uw tank channel) as below.

1. The water of uw tank is homogeneous, isothermal, isotropic & non viscous. We assume that there are no such layers present of differing temperatures, salinity, pressures, or sound speeds in both horizontal and vertical water columns.
2. Sound pressure fields are uniform in far field.
3. No skimming is handled in the simulation code at this time.
4. The source & receiver are stationary while sending and receiving acoustic signal.
5. No another source of noise and obstacle is present in between or around source & receiver placements.
6. Only ambient noise due to platform will be present & its effects will be considered.

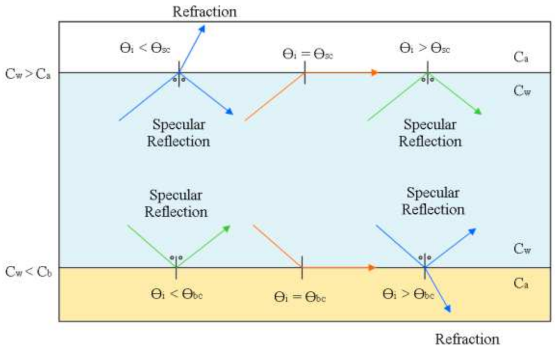

Fig. 5. Region of applicability of snell's law

TABLE I: TABLE OF CRITERION OF SURFACE AND BOTTOM REFLECTION COEFFICIENT

Table of Criterion		
1. Surface Reflection Coefficient R_{10}		
Boundary Conditions	**Snell's Law Condition**	**Formula For Reflection Coefficient**
At Water To Air Interface (Surface)	$\theta_{inc} < \theta_{sc}$	$R_{10} = \frac{(\rho_a . c_a . \cos\theta_{inc} - \rho_w . c_w . \cos\theta_{refl})}{(\rho_a . c_a . \cos\theta_{inc} + \rho_w . c_w . \cos\theta_{refl})}$ (24)
	$\theta_{inc} > \theta_{sc}$	$R_{10} = \frac{(m.\cos\theta_{inc} - i\sqrt{\sin^2\theta_{inc} - n^2})}{(m.\cos\theta_{inc} + i\sqrt{\sin^2\theta_{inc} - n^2})}$ (25) $m = (\frac{\rho_a}{\rho_w}) < 1$ $n^2 = (\frac{c_a^2}{c_w^2}) < 1$
2. Surface Reflection Coefficient R_{12}		
At Water To Bottom Interface (Bottom)	$\theta_{inc} < \theta_{bc}$	$R_{12} = \frac{(m.\cos\theta_{inc} - i\sqrt{n^2 - \sin^2\theta_{inc}})}{(m.\cos\theta_{inc} + i\sqrt{n^2 - \sin^2\theta_{inc}})}$ (26) $m = (\frac{\rho_b}{\rho_w}) > 1$ $n^2 = (\frac{c_b^2}{c_w^2}) > 1$
	$\theta_{inc} > \theta_{bc}$	$R_{12} = \frac{(\rho_b . c_b . \cos\theta_{inc} - \rho_w . c_w . g_r)}{(\rho_b . c_b . \cos\theta_{inc} + \rho_w . c_w . g_r)}$ (27) $g_r = \sqrt{\left[\left(\frac{c_b}{c_w}\right)^2 . \sin^2\theta_{inc} - 1\right]}$

To study sound propagation in uw tank we applied Snell's law at flat interface [11]. Therefore, incident pressure wave which is bouncing on flat interface with any arbitrary incident angle θ_{inc} satisfies linear wave propagation in all three mediums (i.e. air, water & concrete bottom) of uw tank. Total internal reflection occurs for $\theta_{inc} < \theta_{sc}$, $\theta_{inc} > \theta_{sc}$, $\theta_{inc} < \theta_{bc}$, $\theta_{inc} > \theta_{bc}$ where $\theta_{sc}$is critical angle for surface interface and θ_{bc} is critical angle for bottom interface. At $\theta_{inc} = \theta_{sc}$ & $\theta_{inc} = \theta_{bc}$ total internal reflection gets failed and hence snell's law is not applicable to analyze the transmission of pressure wave for such condition. The region of applicability of snell's law to fulfill specular reflection is shown in figure 5.

For uw tank, interface will be either water-air interface or water-concrete bottom interface. The values of reflection coefficient R_{10} & R_{12} are defined by applying snell's law with oblique incidence and are stated in table 1 above [12]. Therefore, when sound pressure wave meets at any surface or bottom interface it gets reflected and transmitted as shown in figure 5. Degree of reflection & transmission totally depends on characteristic impedance of mediums [13].

III. METHODOLOGY FOR CALCULATION OF PATH LOSS ATTENUATION FOR MEASURED CHANNEL CONDITIONS

To calculate transmission loss for each eigen path we followed steps as below:

1. To consider a scenario of projector & hydrophone are to be placed at equidistant depths 'Z' m at range 'r' m.

We considered placements of source and receiver as per table III shown below. Here we chose placements in such a way to avoid near field effects.

2. To apply initial boundary conditions by measuring channel parameters with help of instrument. The channel parameters are as stated below.

In order to apply snell's law and boundary conditions using plane wave theory to calculate respective reflection coefficients we need to measure parameters such as salinity, temperature, pressure, fluid density of water and air with help of available equipments at UWAA lab. The measured channel parameters are as below:

$$c_a = 343\frac{m}{s}, c_w = 1500\frac{m}{s}, c_b = 3000\frac{m}{s},$$

$$\rho_a = 1.03\frac{kg}{m^3}, \rho_w = 1000\frac{kg}{m^3}, \rho_b = 2400\frac{kg}{m^3}$$

3. To Identify the reliable multipath reaching towards receiver proximity for given placements of combination of projector & hydrophone.

We applied trigonometric relations to get incident angle θ_{incs} of first reliable eigen path of surface interface as given below

$$\theta_{incs} = 90^{\circ} - \theta_{flas} \quad (28)$$

$$\theta_{flas} = \tan^{-1}\left(\frac{das}{r/2}\right) \quad (29)$$

r: distance between projector & hydrophone (m), das: distance above source placement (m) Similarly, we obtain

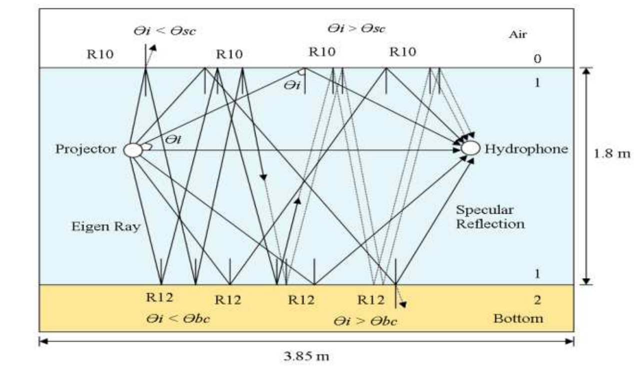

Fig.6. Identification of eigen rays using Snell's law & Pythagoras geometry theorem

$$\theta_{incb} = 90^{\circ} - \theta_{flab} \tag{30}$$

$$\theta_{flab} = \tan^{-1}\left(\frac{dbs}{r/2}\right) \tag{31}$$

dbs: distance below source placement (m), θ_{incb}: incident angle of first reliable eigen path of bottom interface of uw tank. Now once we get θ_{incs} and θ_{incb} then we calculate incident angles of remaining all reliable eigen paths reaching towards receiver proximity from equation given below

$$r' = \frac{dbs}{\tan(la)} \tag{32}$$

$$r'' = \frac{das}{\tan(la)} \tag{33}$$

where for surface interface, range of launch angle starts from θ_{flas} to 89° and for bottom interface it starts from θ_{flab} to 89°. From all these combinations of launch angles we select only those launch angles which satisfies following equation

$$2(r' + r'') \approx r \tag{34}$$

this formula optimizes selection of reliable eigen paths reaching towards receiver by providing selected combinations of incident angles using equation (28) and (30) for given assumed combinations of projector & hydrophone placements in uw tank as shown in Figure 6.

3.1 To decide surface & bottom critical angle (θ_{sc} & θ_{bc}) using Snell's law & calculated path length of each eigen path using Pythagoras theorem.

Here critical angle for surface is given by formula

$$\theta_{sc} = \sin^{-1}\left(\frac{c_a}{c_w}\right) \cong 13^{\circ} \tag{35}$$

critical angle for bottom is given by applying snell's law [14] as below

$$\theta_{bc} = \sin^{-1}\left(\frac{c_w}{c_b}\right) \cong 30^{\circ} \tag{36}$$

3.2 To compute surface reflection coefficient for V^T, N and NN paths & bottom reflection coefficient for V, N^T and $N^T N^T$ paths.

once we identified V^T, N, NN paths based on incident angles obtained from equation (28) to (33) we calculate the path lengths using Pythagoras theorem and trigonometric formulas using equations below.

$$pl_{V^T} = 2\sqrt{das^2 + r'^2} \tag{37}$$

$$pl_N = 2\left[\left(\sqrt{das^2 + r'^2}\right) + \left(\sqrt{dbs^2 + r''^2}\right)\right] \tag{38}$$

$$pl_{NN} = \left(\frac{r}{2(r' + r'')}\right) 2\left[\left(\sqrt{das^2 + r'^2}\right) + \left(\sqrt{dbs^2 + r''^2}\right)\right] \tag{39}$$

Here we considered placements of projector and hydrophone at equidistant depths therefore for bottom case, path lengths for V, N^T and $N^T N^T$ paths can be obtained using equation (37),(38),(39) as

$$pl_V = 2\sqrt{dar^2 + r'^2} \tag{40}$$

$$pl_{N^T} = 2\left[\left(\sqrt{dar^2 + r'^2}\right) + \left(\sqrt{dbr^2 + r''^2}\right)\right] \tag{41}$$

$$pl_{N^T N^T} = \left(\frac{r}{2(r' + r'')}\right) 2\left[\left(\sqrt{dar^2 + r'^2}\right) + \left(\sqrt{dbr^2 + r''^2}\right)\right] \tag{42}$$

for equidistant placements of nodes das = dar & dbs = dbr for above path lengths. where das is distance above source (projector) , dbs is distance below source, dar is distance above receiver (hydrophone) , dbr is distance below receiver as shown in figure 4.

4. To compute path amplitude factor of each eigen ray.

When any eigen ray travels from source to receiver it bounces from any of boundary (either surface or bottom or sidewalls) of uw tank then part of energy gets reduced by factor of paf[15], path amplitude factor denoted by and is calculated by

$$paf_{m,n} = \left(\frac{a}{pl}\right)^2 (R_{10})^m (R_{12})^n \tag{43}$$

a is source radius , pl is path length, and m & n is the order of multipath where respective path has taken finite no. of bounces from boundary. The path amplitude factor plays important role in increasing transmission loss of wave travelling from source to receiver. Greater the paf greater propagation loss.

5. To compute pressure at distance ‘r’ m from rim of source.

Since hydrophone is calibrated in terms of output voltage for an incident sound pressure fields reaching at receiver hydrophone at time t_i. Overall pressure filed at receiver hydrophone distanced by 'r' m will now become

$$P_{Total\ (r,t_i)}{}^2 = \sum_{k=1}^{nop} P_k{}^2(r, t - t_i) \tag{44}$$

Where nop is finite no of eigen paths reaching at receiver at time t_i. Here maximum value of nop will be 4 and minimum will be 2 depending upon interference of sound pressure fields coming from top, bottom or sidewalls of uw tank. Equation 44 represents coherent pressure fields. If two or more pressure waves of same frequency and different phase reaching at time t_i at receiver then overall semi coherent pressure fields at will now become

$$P_{Total\ (r,t_i)}{}^2 = \sum_{k=1}^{nop} P_k{}^2(r, t - t_i) + nop\left[\left(P_{nop}(r, t - t_i)P_{(nop-1)}(r, t - t_i) \ldots . P_{(nop-(nop-1)}(r, t - t_i)\right).\left(\cos\left(\emptyset_{nop} - \emptyset_{nop-1} \ldots \ldots . -\emptyset_{nop-(nop-1)}\right)\right)\right] \tag{45}$$

& incoherent pressure fields will become as equation no (44) [16]. Therefore, using equation (13) we get cumulative pressure $P_{r(r,t_i)}$as

$$P_{r(r,t)} = \left(\frac{a}{r}\right)^2 (R_{10})^m (R_{12})^n \rho_w c_w U_0 \left(\frac{-jKa}{1-jKa}\right) e^{(j(wt-k(r-a)+\phi_c))}\ \mathrm{Pa} \tag{46}$$

6. To compute water particle velocity at distance ‘r’ m from rim of source we use equation (12).

$$U_{r(r,t)} = U_0 \left(\frac{1-jKr}{1-jKa}\right)\left(\frac{a}{r}\right)^2 e^{(j(wt-k(r-a)+\phi_u))}\quad \mathrm{m/s} \tag{47}$$

7. To compute acoustic intensity at a distance ‘r’ m from spherical Omni-source

Using equation (46),and (11) we obtained intensity at distance 'r' m from Omni source radiating at frequency

$$|I_{r\,(r,t)}| = \frac{1}{2}\left(\frac{a}{r}\right)^4 (R_{10})^m (R_{12})^n \left(\rho_w c_w\right) U_0^2 \left(\frac{1}{1+\left(\frac{1}{ka}\right)^2}\right)\quad \mathrm{W/m^2} \tag{48}$$

Similarly intensity distance 1 m from Omni source is given by

$$|I_{0\,(1,t)}| = \frac{1}{2}(a)^4\left(\rho_w c_w\right) U_0^2 \left(\frac{1}{1+\left(\frac{1}{ka}\right)^2}\right)\quad \mathrm{W/m^2} \tag{49}$$

To compute path transmission loss (in dB) of respective eigen ray.

$$TL_{Simulated} = 10\log_{10}\left(\frac{I_{0\,(1,t)}}{I_{r\,(r,t)}}\right) \tag{50}$$

this formula is used to calculate propagation loss for each combination of placements of Tx & Rx nodes [17]. The combinations at which placements of projector & hydrophone are kept for given channel conditions is shown in table III .

IV. SIMULATION ANALYSIS OF MODELLED TRANSMISSION LOSS USING SWARA PATH LOSS MODEL

Using channel conditions stated in Table II we developed SWARA path loss model to simulate transmission losses at all possible placements of projector and hydrophone in uw tank facility of UWAA lab IIT Delhi as shown in table III. Using equation (28) to (50), we designed SWARA Matlab code to model effect of placements of source & receiver on occurrence of transmission loss which is stated in table IV below. SWARA Path loss model will be able to deliver following analysis as mentioned below:

TABLE II: PLACEMENTS OF PROJECTOR AND HYDROPHONE SELECTED FOR SIMULATION ANALYSIS USING SWARA PATH LOSS MODEL

Combination Index	Range (m)	Pr Depth (m)	Hd Depth (m)
1	2	0.3	0.3
2	2.5	0.3	0.3
3	2.85	0.3	0.3
4	2	0.5	0.5
5	2.31	0.5	0.5
6	2.9	0.5	0.5
7	3	0.5	0.5
8	2.3	0.5	0.5
9	2.5	0.5	0.5
10	2.6	0.5	0.5
11	3.2	0.5	0.5
12	2	0.9	0.9
13	2.3	0.9	0.9
14	2.3	1.2	1.2
15	2.6	1.2	1.2
16	2.9	1.2	1.2
17	3.2	1.2	1.2

Using SWARA path loss model we can study 1.Overall contribution of surface, bottom & sidewalls in occurrence of transmission loss, 2. Distribution of incident angle, 3. Distribution of surface and bottom reflection coefficients, 4. Path amplitude factor distribution, 5. TL Distribution, 6. Delay arrival, 7. Intensity distribution, 8. Power delay profiles of each multipath, 9. Finite no of paths available for every possible choice of placements of source and receiver.

In this paper we are dealing with effects of change in placements of source and receiver on overall transmission loss as shown in table IV. Where minimum transmission loss is loss occurred due V^T paths. These paths are derived from SR category of paths. Notion of SR is termed as surface reflected paths and BR is termed as bottom reflected paths [18].

The V^T and V paths are occurred due to sidewalls of uw tank.Such paths are derived from LHSDWLR & RHSDWLR category of paths where notion of LHSDWLR is termed as path reflected from left hand sidewall of tank & RHSDWLR is considered as path reflected from right hand sidewall of tank. Now minimum transmission loss is calculated from collective pressure of all possible paths both V^T and V reflecting from surface, bottom & sidewalls using equation (44).

Similarly to calculate maximum transmission loss, SWARA path loss model will use equation (45) to (50) to calculate collective pressure of all possible paths both NN and N^TN^T reflecting from surface, bottom & sidewalls. Depending upon scope of interest we can further include effects of N and N^Tpaths reflecting from surface, bottom & sidewalls to study time dependent transmission losses same as above. It is observed that simulated transmission loss given by SWARA path loss model ranges from 12.48 dB to 88.51 dB for depths varying from 0.3m to 1.2m & range varying from 2m to 3.2m for measured channel conditions mentioned in table II as above.

Our aim to verify & validate these modeled transmission losses given by SWARA Path Loss Model. To conduct experiments for verification & validation of simulated transmission loss stated by SWARA path loss model for given placements of nodes (depths & range) in underwater tank, we required following resources such as

1. UW tank 2. Projectors 3. Hydrophones 4. Pre/Power Amplifiers 5. Power Supply 6. Data Acquisition Card 7. BNC Connectors 8. Co-axial Cables 9. PC 10. Simulation Tools to set up an experiment for doing analysis of simulated results mentioned in table IV. The design of SWARA path loss model is proposed for studying the underwater propagation losses of an Indian tank channels. The plane wave theory is used for modeling propagation losses of acoustic signals.

The transmission loss is analyzed for different depth and range-based placements of projector and hydrophone, in order to find the optimum node placement where the channel performance can be improved especially for Indian shallow water tanks. The simulation is performed for small size

TABLE III: MODELED TLS FOR DIFFERENT PLACEMENTS OF PROJECTOR AND HYDROPHONE USING SWARA MATLAB CODE

Combination Index	Simulated Minimum TL (dB)	Simulated Maximum TL (dB)	Range of Simulated TL (dB)
1	12.48	82.46	69.98
2	17.04	74.3	57.26
3	18.41	88.51	70.1
4	13.71	82.46	68.75
5	16.32	85.05	68.73
6	19.49	69.9	50.41
7	20.4	70.44	50.04
8	16.32	84.82	68.5
9	17.05	86.33	69.28
10	17.82	74.87	57.05
11	21.36	70.15	48.79
12	17.19	82.46	65.27
13	18.63	84.82	66.19
14	16.3	84.82	68.52
15	18.12	86.9	68.78
16	20.22	69.91	49.69
17	20.99	71.14	50.15

TABLE IV: MEASURED CHANNEL CONDITIONS ON JANUARY 23, 2019 USING CTD INSTRUMENT AT UWAA LAB IIT DELHI

Sr. No	Parameters	Values
1.	Depth of Channel	1.8 m
2.	Temperature of Water	20 Degrees
3.	Salinity of Water	0.5 ppt
4.	Speed of Sound in Water (C_w)	1485 m/s
5.	Speed of Sound in Air (C_a)	343 m/s
6.	Speed of Sound at Bottom Surface (C_b)	1700 m/s
7.	Density of Air (ρ_a)	1.03 kg/m3
8.	Density of Water (ρ_w)	1000 kg/m3
9.	Density of Bottom (ρ_b)	2400 kg/m3
10.	Fluid particle velocity at 1m from source (U_0)	2.1e-10 m/s
11.	Type of Projector	ITC 1042 Transducer
12.	Source Radius	17.7mm
13.	Transmit Voltage Sensitivity	127 dB @ 30 kHz
14.	Type of Hydrophone	Keltron Transducer
15.	Receiving Sensitivity	-178 dB @ 30 kHz

rectangular tub shaped tank set up of 3.85m long 2.4m wide and 2m deep.

V. VERIFICATION & VALIDATION OF SIMULATED TRANSMISSION LOSS WITH HELP OF TANK TRAILS CONDUCTED AT UWAA LAB IIT DELHI

The above-mentioned resources were available at UWAA lab of CARE, IIT Delhi. Therefore, we conducted tank trials from 7th January to 28th January 2019 to verify & validate simulated results of SWARA path loss model.

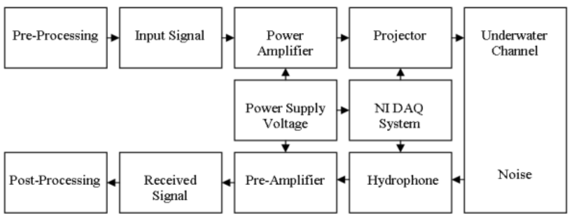

Fig. 7: Experimental set up

For planning experiments, we have followed steps as below.

1. To identify the underwater acoustics lab equipped with acoustic communication set up to perform planned experiments

UWAA lab equipped with 1. UW tank of (3.85m X 2.4m X 2m) 2.Projector : ITC 1042 Omni-directional 3.Hydrophone : Keltron Uni-directional 4.Pre/Power Amplifier : Keltron 5.Power Supply : 5V DC Keltron 6.DAQ Card : NI PCI 6110 7.BNC Connector : NI 2110 8.Co-axial Cables : RG-7 (50 Ω) 9.PC : Intel Xeon V3 @3.60GHz x64 with 32 GB RAM 10.Simulation Tools : Matlab 2017b, LabView 2018. The whole set up comprises as shown below in Figure7.

To investigate transmission losses, we designed chirp signal at 30 kHz center frequency (of 10 kHz bandwidth) & sent from projector (ITC 1042) to hydrophone (Keltron) at mentioned depths table III. These projector & hydrophone are connected to PC through BNC connectors (NI BNC 2110) along with 10m long coaxial cables (of 50 Ω impedance).

At hydrophone, signal is acquired at sampling rate of 240 kHz (through NI PCI 6110 DAQ) and is further processed using Labview & Matlab simulation tools. The power amplification is performed in transmitter side & pre amplification is performed at receiver side depending upon channel conditions (calm, moderate, drastic).

2. To identify depths & ranges at which the experiments are to be performed.

The selection of depths & ranges is decided as per table III.

3. To measure the channel conditions we have used the thermometer and CTD instrument.

By applying snell's law and boundary conditions using theses channel parameters to calculate values of reflection coefficients for SWARA path loss model as shown in table II.

4. To identify the source & receiver & their operating frequency range to be used for experimentation.

We used ITC 1042 as projector to send acoustic signal from source to receiver. At receiver we used Keltron 8240000001 as hydrophone to record signals sent from source. The operating band of projector is from 1kHz to 120kHz and for hydrophone is 20kHz to 40kHz. Therefore, the operating frequency should be selected within 20kHz to 40kHz. The identified centre frequency for source's excitation signal is 30kHz with BW of 10kHz (25kHz-35kHz).

5. To identify & design the type of signal to be used for establishing acoustic communication between source & receiver.

We designed linear quadratic chirp signal of 5V peak amplitude at center frequency 30 kHz with bandwidth of 10 kHz referred from [19]. This excitation signal is sent from projector to hydrophone at mentioned depths in Table III. Chirp is a sinusoidal signal of frequency f_c where this frequency increases or decreases over time. The relationship between time and frequency is expressed with a polynomial expression depending upon type of signal (Linear, Log, Exponential). Chirp signals are employed for data transmission schemes due to its advantages [20] such as

5.1 It includes flat amplitude spectrum with independent scalability both in time & frequency domain.

5.2 It includes wide range of frequencies over short interval of time which eliminates influence of low frequency (biological) signals.

5.3 More than 90 percent of energy is present in chirp BW.

5.4 Auto correlation properties of chirps are similar to Impulse response function.

5.5 Shortening of pulse won't affect on general benefits of chirp signals hence pulse compression can be utilized in chirp signals.

5.6 Better Identification of channel impulse response in noisy channel conditions.

5.7 Identification and characterization of transmission parameters like multipath delay spread, coherence time, coherence bandwidth through CIR wiz essential for designing data communication through the available spectrum.

5.8 Chirp spread spectrum is ideal for applications requiring low power usage and needing relatively low data rates (1 mbps or less).

It is commonly used in sonar applications as a chirp spread spectrum technique which is resistant to multi-path fading even when transmitter is operating at very low power. The chirp signal design parameters are as mentioned below in table V. The designed linear chirp signal's time domain representation & frequency v/s time relation is as shown in Figure 8.

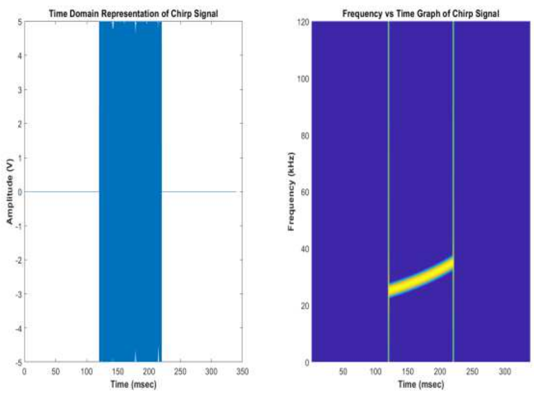

Fig. 8: Time domain chirp signal and its frequency v/s time relationship

TABLE V: CHIRP SIGNAL DESIGN PARAMETERS

Sr.No	Parameters	Value
1	Chirp Start & Stop Frequency	25 kHz to 35 kHz
2	Chirp BW	10 kHz
3	Probe Signal Design	[Silent, Chirp, Silent]
4	Chirp Duration	100 milli-seconds
5	Silent Duration	120 milli-seconds
6	Probe Signal Duration	340 milli-seconds
7	Chirp Amplitude	10 Volts Peak-Peak
8	Sampling Rate (Frequency)	240 kHz
9	Total Sample Points of Probe Signal	81,600 [28,800 + 24,000 + 28,800] Samples

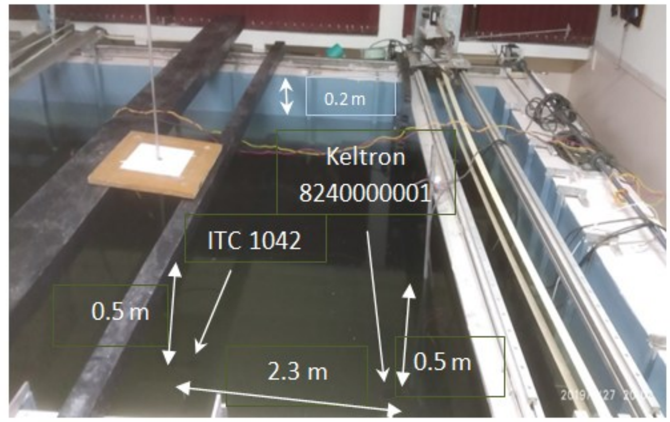

Fig. 9. Execution of experiment for projector & hydrophone placed at 0.5m depth & range 2.3m in channel depth of 1.8m

6. To send & record the signal using projector & hydrophone respectively.

The execution of experiments are trailed in uw tank facility of UWAA Lab, CARE IIT Delhi at specified depths and range combinations as shown in table III. Tank is filled with pure water up to 1.8m height. The average water temperature was 20°c. Power & pre amplification not is performed at transmitter side & at receiver side because the signal to noise ratio was favorable for such static calm channel conditions.

7. To analyze TL experimentally performed at decided placements of source & receiver in uw tank.

To calculate Transmission loss at decided depths and range combinations we require the intensities of sound wave at 1m and 'r' m. The intensity level of sound wave transmitted from ITC 1042 at 1m is calculated from equation given by [21]

$$SI_{1\,m} = TVR_{dB} + V_{in\ Supplied\ dB} \tag{51}$$

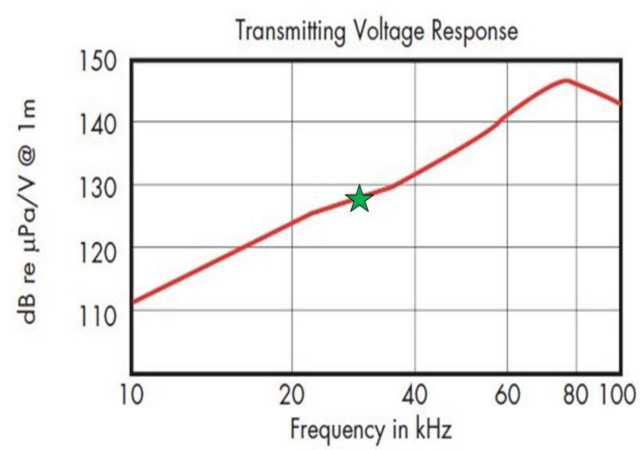

Fig.10. TVR Response of ITC1042 Omni directional projector [22]

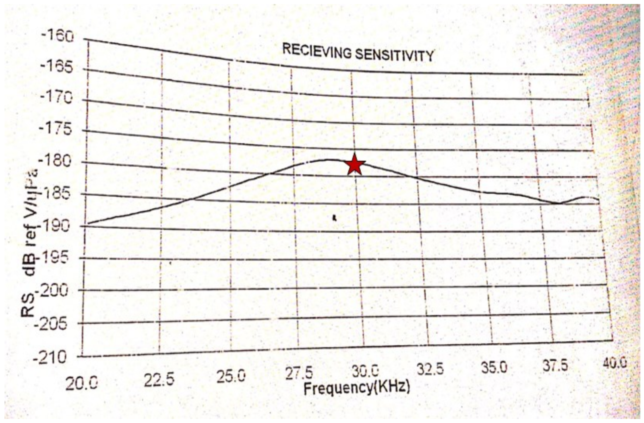

Fig. 11. OCR response of keltron 8240000001 uni directional hydrophone

TABLE VI: EXPERIMENTAL TLS FOR DIFFERENT PLACEMENTS OF PROJECTOR AND HYDROPHONE AT THE TIME OF EXECUTION

Combination Index	Experimental Minimum TL (dB)	Experimental Maximum TL (dB)	Range of Experimental TL (dB)
1	17.03	77.53	60.5
2	16.94	82.1	65.16
3	16.89	84.15	67.26
4	17.17	76.59	59.42
5	16.91	83.09	66.18
6	16.89	76.57	59.68
7	16.94	82.58	65.64
8	16.95	81.21	64.26
9	17.94	77.04	59.1
10	17.79	74.8	57.01
11	17.24	83.4	66.16
12	16.89	82.67	65.78
13	17.23	82.2	64.97
14	16.95	81.35	64.4
15	17.22	82.3	65.08
16	17.05	76.47	59.42
17	17.62	76.56	58.94

transmit voltage response of ITC 1042 at operating frequency of 30 kHz is 127 dB as shown in below Figure 10. TVR is a measure of relative voltage generated at a distance of 1 meter by projector ITC 1042 for supplied 1 micropascal pressure per 1 volt. The sound intensity level at 1m distance from source is 133.98 dB ref 1μPa/1V @1m. The receiver placed at 'r' m is, the intensity level of transmitted signal sent from source ITC 1042 is calculated from equation and given by [21].

$$\mathrm{SI}_{\mathrm{r\,m}} = \mathrm{V}_{\mathrm{Recorded\ dB}} - \mathrm{OCRR}_{\mathrm{dB}} \tag{52}$$

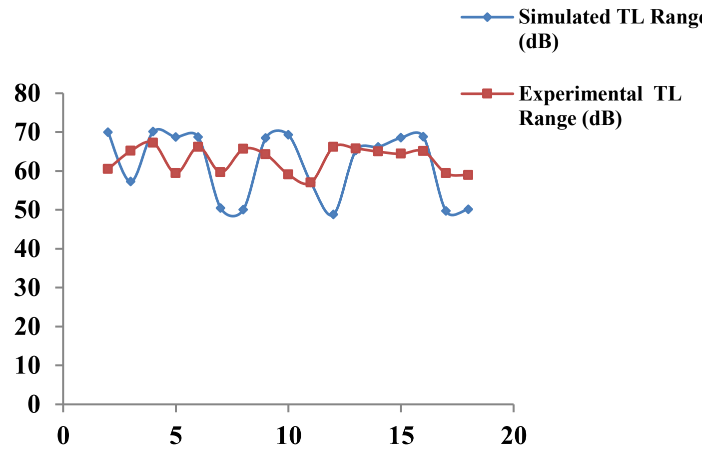

Fig. 12. Comparison of range of simulated TLs & experimental TLs for different placements of projector and hydrophone

The recorded voltage is wrt received pressure at distance 'r' m and Open circuit receiving response of Keltron hydrophone at operating frequency of 30 kHz is -178 dB as shown in figure 11 below. OCRR is a measure of voltage generated at distance 'r' m by hydrophone Keltron for supplied 1 volt per 1 micropascal pressure. The sound intensity level at 'r' m distance from source is 166.73 dB ref $1V/1\mu Pa\ @\ 'r'm$ for one of time instance of recorded voltage samples of combination index 8. Therefore equation for experimental transmission loss is defined using equation (51) & (52) as below

$$\mathrm{TL}_{\mathrm{Experimental}} = \mathrm{SI}_{\mathrm{r\,m}} - \mathrm{SI}_{1\,\mathrm{m}} \tag{53}$$

Using equation (51),(52),&(53), we executed experiment of sending linear chirp signal (of 10 kHz bandwidth) at 30 kHz center frequency from projector (ITC 1042) to hydrophone (Keltron 8240000001)at mentioned depths stated in table III. The transmission loss occurred at mentioned placements of projector and hydrophone are stated in table VI above. The verification & validation of SWARA path loss model is proved based on observing range of experimental TL to range of simulated TL as shown in column no 4 of table VI and IV respectively.

VI. COMPARATIVE ANALYSIS AND OBSERVATION OF EXPERIMETAL TRANSMISSION LOSS WITH SIMULATED TRANSMISSION LOSS

Overall transmission loss depends on surface and bottom reflection, path amplitude factor, water particle velocity, radiation and characteristics impedance as shown in equation (47) to (50). Occurrence of TL depends on instantaneous distribution of these factors. The table VII shows the range of

TABLE VII: CONTRIBUTION OF INCIDENT ANGLE FOR GIVEN COMBINATION INDEX

Sr.No	Type of Boundary	Incident Angle Range (Degree)	
		V^T, N, NN Paths	V, N^T, N^TN^T Paths
1	Surface of tank	48 to73	1 to 3
2	Bottom of tank	34 to 62	2 to 4
3	Sidewalls of tank	40 to 53	1 to 3

incident angles of eigen rays' bounces from surface, bottom and sidewalls to reach at receiver as below. The directivity pattern of projector depends on its transducer equivalent beam pattern [23]. SWARA path loss model also adopts projector's beam pattern, directivity to select orientation of projector and hydrophone to achieve guaranteed reception of acoustic signal from source to destination during deployment.

Following table VII, the beam directivity pattern of projector shall include $17^{\circ}$to 42° for surface bouncing and $28^{\circ}$to 56° for bottom bouncing and $26^{\circ}$to 50° for sidewalls to reach signal at receiver placed for all 17 combinations. Since projector ITC 1042 is of spherical beam type consists of all beams stated as above in its directivity pattern [22].

The surface reflection coefficient plays important role in introducing propagation loss. When a pressure wave bounces at either surface or bottom or sidewalls it undergoes phase shift of 180° which implies negative sign. From simulation it is observed that for bottom boundary R_{10} lies in range of 0.99 to 1, means maximum part of incident acoustic pressure is reflected from surface of uw tank. Whereas for surface boundary R_{10} lies in range of 0.953 to 1 where part of reflected pressure is slightly lesser than of bottom. The bottom reflection coefficient R_{12} is 1 for surface, bottom, and sidewalls except for few N and N^T paths.

The spreading loss depends on distance travelled by respective eigen path. From simulations it is observed that path amplitude factor increases with increase in path lengths. Minimum spreading loss is occurred at V^T and V paths. Maximum spreading loss is occurred at NN and N^TN^T paths.

Path amplitude factor ranges from 1.01e-5 to 9.11e-9, 1.1e-5 to 9.48e-8, and 1.84e-5 to 9.64 e-7 for sidewalls, surface, and bottom boundary respectively. The range of path amplitude factor is lesser for bottom than surface and sidewalls. Following figure 20, 21, and 22 shows above. Simulation study shows that in overall transmission loss contribution of sidewalls is more than surface and bottom of tank. Contribution of bottom gives less transmission loss among all.

TABLE VIII: DEVIATION OF SIMULATED VALUE OF TL COMPARED TO EXPERIMENTAL VALUE OF TL

Combination Index	Deviation of Simulated Values from Experimental Values of TL	
	Minimum TL	Maximum TL
	X	Y
1	-0.36	0.05
2	0.00	-0.10
3	0.08	0.04
4	-0.25	0.07
5	-0.03	0.02
6	0.13	-0.09
7	0.16	-0.17
8	-0.03	0.04
9	-0.05	0.10
10	0.00	0.00
11	0.19	-0.18
12	0.01	-0.00
13	0.07	0.03
14	-0.03	0.04
15	0.04	0.05
16	0.15	-0.09
17	0.16	-0.07

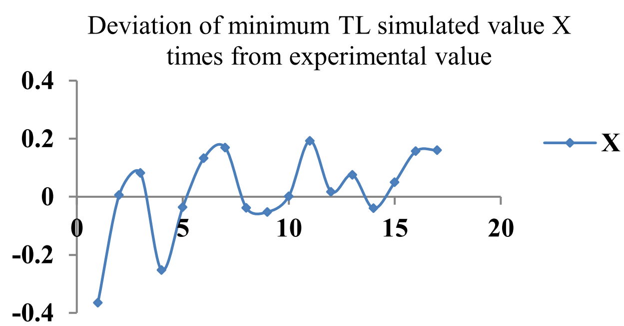

Fig.13. Deviation of simulated minimum TL from experimental minimum TL

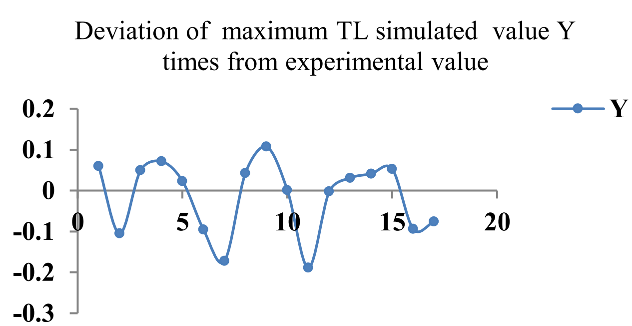

Fig.14. Deviation of simulated maximum TL from experimental maximum TL

The analysis of transmission loss due to sidewalls is simulated for placements of projectors and hydrophones at middle of width of uw tank to avoid near field effects. The choice of optimum placements will be done based on considering minimum deviation in both maximum & minimum simulated & experimental TL as shown in table IX. Combination no 3,5,8,10,12,13,14,15 where agreement between theory and experiments is fully perfect. Hence SWARA path loss model will be deemed useful for providing range and depth dependent TL analysis.

VII. CONCLUSION

The experimental results show that presence of strong absorption from sidewalls and bottom, high characteristic impedance of water & more interference among sound pressure fields reflecting from boundaries of uw tank significantly alters propagation loss of acoustic signals. Smaller dimension tank will have higher number of multipaths. Therefore, to calculate accurate propagation loss at receiver it is important to consider location specific pressure field treatments.

Plane wave theory is applied to simulate propagation loss which is a difference between effective plane wave intensities calculated at 'r' m and at 1m from acoustic source. Mean squared pressure fields recorded by projector are used to calculate sound intensity level at 'r' m & 1 m. Difference between these intensities is referred as experimental TL.

Out of 17 combinations, 8 combinations show that there is close agreement between theory and experiments. Where Combination no. 10 shows perfect agreement between theory and experimental results. Deviation of simulated TL for combination no. 3,5,8,10,12,13,14, &15 varies from -3% to 8% of experimental TL.

Whereas from remaining 9 combinations, combination no 2,6,7,9,11,16, &17 shows that simulated values of TL are -0.18 to 0.19 times experimental transmission loss. It shows that agreement between theoretical and experimental TL is within reasonable limit. Combination no. 1, and 4 simulated values are not in range of (acceptable) reasonable limits.

From the literature, We found that the following attributes may be present behind this deviation in simulated wrt experimental TL as: 1. Assumed constant theoretical source level at 1m from an acoustic source, practically source-level depends on accurately measured reverberation time 'T60' of UW tank. 2. Distribution of sound field is assumed to be uniform in the far-field, but it depends on whether hydrophone is placed in the reverberant field i.e. near to surface or at the middle of depth or near to bottom. 3. Total mean squared sound pressure fields at hydrophone are a combination of reflected sound fields from boundaries of uw tank, Segregation of respective sound filed at point of measurement is practically irresolvable using only one hydrophone. For this, we need to consider an array of hydrophones to segregate each multipath arrival and its direction at the measurement point.4. Uncertainty in measuring equipment including known projector & hydrophones.

The closed agreement between theory and experiment shows from table IV and VI. This shows that interpretation of transmission loss by SWARA mathematical model for above placements of projector and hydrophone is valid and considered physically correct.

Hence proposed SWARA path loss model can be referred as forward propagation model wherein the analysis of transmission loss for all possible placements of projector and hydrophone can be simulated in detail. This mathematical model provides specific path based and time-based analysis of multipaths which is quite useful in analyzing operational site before deployment of acoustic set-up.

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*Authors' contributions: In the current study Sangram S. More has done simulation and programming of multipath channel model for underwater acoustic communication using MATLAB and the execution of planned experiment. In the current study Dr.Prashant P. Bartakke has done concept and design of modelling of experiment for underwater acoustic communication. In the current study Dr.Monika Aggarwal has done concept and design of modelling of multipath channel for underwater acoustic communication.

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