



## Observation and modeling approach in acoustic propagation in the shallow waters of southwest Bay of Bengal

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The primary focus of the work was to estimate propagation loss and provide a quantitative estimate in transmission loss using sound propagation modeling in shallow waters of south west Bay of Bengal and also to validate the results with field measurements. KRAKEN normal mode sound propagation for a range independent environment in the frequency range of 850-1050 Hz was used for the simulation. The water depth was taken as 20 m. Transmission loss is estimated at four different ranges for a source at 10 m depth by using the essential acoustic input parameters. To validate results obtained through modeling, an experiment was conducted to measure transmission loss directly in an environment that closely matched with the model. The results of transmission loss estimated using the model was compared with the field measurements at short ranges.

[**Keywords:** Kraken, Shallow water, Sound propagation, Transmission loss]

### Introduction

Shallow water acoustic propagation primarily depends on geometry of wave guide, sound speed profiles, frequency of interest, source position, water column depth, surface disturbances (wind, waves and roughness) and bottom characteristics<sup>1-3</sup>. Sound propagation modeling approaches give an idea about how acoustic environment influences sound propagation and help to effectively utilize acoustic devices at that location<sup>2</sup>.

Various modeling and measurement approaches in shallow water acoustic transmission and reception were conducted in different parts of the World's Ocean. Such studies were focused on different objectives such as communication<sup>4-6</sup>, acoustic tomography<sup>7-9</sup>, internal wave influence on sound transmission<sup>10-13</sup>, source localization<sup>14-16</sup>, etc.

Shallow waters around India have been modeled using different acoustic propagation models such as normal mode, ray, parabolic equation etc. But limited field observations have been conducted in shallow waters of both west and east coast of India. Among all the reported sound propagation model approaches most of them were conducted along the off west coast of India. The following reference details can provide a brief history of conducted sound propagation studies over Indian waters. Murty & Kumar<sup>17</sup> revealed the influence

of bottom sediment characteristics on shallow water sound propagation. Ray theory approach in a range-independent scenario was conducted by Balasubramanian with arbitrary sound speed profiles<sup>18</sup>. Vijayakumar & Ajaikumar<sup>19</sup> described an idea of frequency influence on sound propagation in shallow waters. Another oceanographic influence called upwelling and down welling on acoustic propagation was derived by Hareesh Kumar & Radhakrishnan<sup>20</sup>. Further Hareesh Kumar and team<sup>21</sup> have also analyzed the role of low frequency internal waves in transmission loss variability using modeling approaches. Sanjana<sup>22</sup> has conducted a study to understand influence of environmental parameters on acoustic propagation in very shallow water. A recent study has revealed the influence of seasonal variability of sound speed profile on the acoustic propagation in shallow waters of south east Arabian Sea<sup>2</sup>. Studies on acoustic ray parameters computations and seasonal variability in sound propagation were conducted in the shallow to deeper waters of western Bay of Bengal<sup>23,24</sup>. But very few propagation studies have been carried out strictly in the shallow waters of western Bay of Bengal such as propagation in the surface duct<sup>25</sup> and impact of internal waves on sound propagation<sup>26,27</sup>.

All modeling approaches incorporated relevant oceanographic and acoustic environmental parameters

to produce best possible results but in most of the cases derived output was not validated with field observations. Limited acoustic transmission and reception field experiments are conducted in Indian waters and many of them were conducted only in deep waters<sup>28,29</sup> and only a few number of acoustic field experiments are conducted in Indian shallow waters.

An implemented parabolic equation model was validated using the transmission loss measurement off Cochin by Balasubramanian & Radhakrishnan<sup>30</sup>. Another acoustic experiment was conducted to understand the influence of internal waves on acoustic propagation in shallow waters of Arabian Sea<sup>31</sup>. But no acoustic transmission loss measurement experiments towards validating sound propagation models are conducted in the shallow waters of Bay of Bengal.

This study is an attempt to validate a sound propagation model for transmission loss estimate at shallow waters of Bay of Bengal through an acoustic transmission experiment. In this work, KRAKEN normal mode sound propagation model<sup>32</sup> was used and applied to shallow waters off Chennai. Model has

been successful in explaining many shallow water preoperational phenomena. This approach is well suitable for shallow water sound propagation study<sup>33</sup>. One of the advantages is no need to calculate mode functions in all intermediate ranges between source and receiver<sup>32</sup>. KRAKEN also hold the following features such as stable eigen function calculation even with multiple ducts, calculation of leaky modes, free, rigid and homogeneous half space options for boundary conditions, high accuracy via extrapolation, ability to handle multi layered environment<sup>32</sup>, etc.

An acoustic transmission and reception experiment was also conducted at the same location. Model results reveal the features of sound propagation in the study area. Finally a comparative study of transmission loss has been carried out between model and measurement approaches.

**Materials and Methods**

**Location characteristics**

Shallow waters of south west Bay of Bengal, off Chennai with 20 m contour parallel to the coast was considered for this study (Fig. 1a). Four stations (Tp1, Tp2, Tp3 and Tp4) were set up from where the

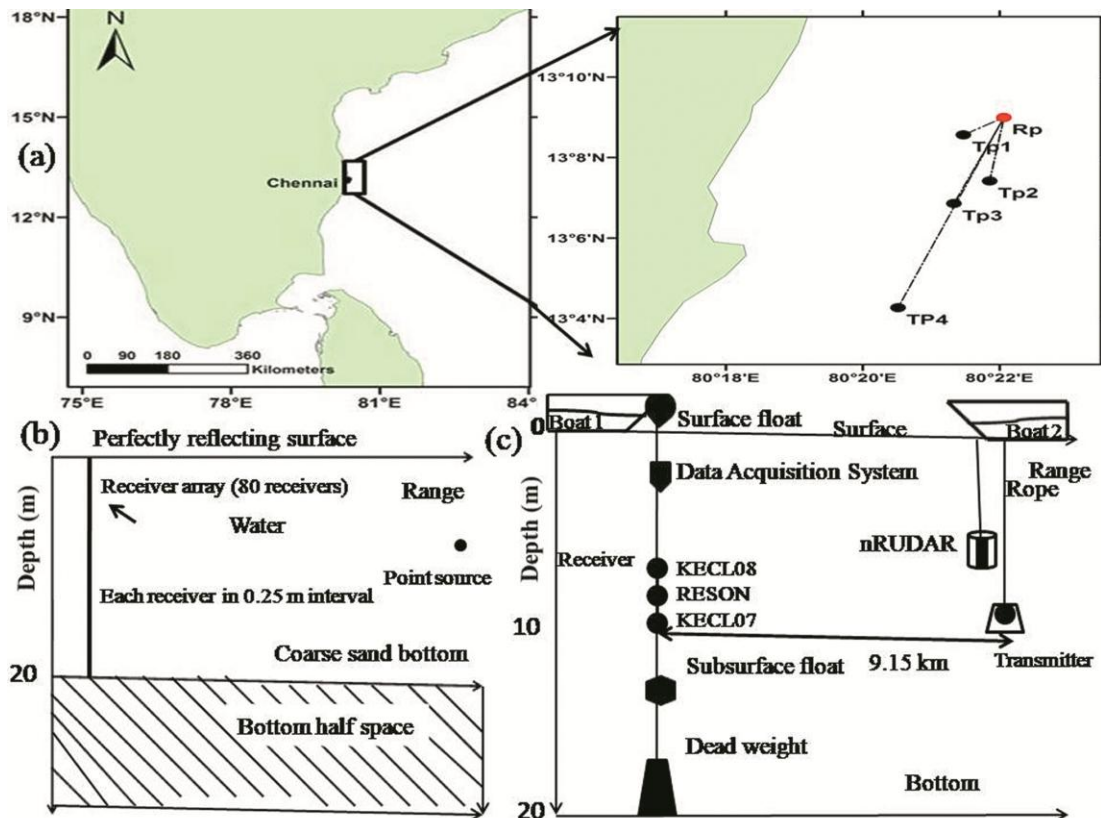


Fig. 1 — (a) Study location with transmitter (Tp1, Tp2, Tp3, Tp4) and reciver (Rp) points; (b) sound propagation model environment; and (c) tranmission and reception experiment setup in the location

acoustic transmission took place and one station located north to all the stations was fixed as a receiver point (Rp) as shown in Figure 1(a). Both transmitter and reception points were located around 5-6 km away from the coastline.

#### Methodology

As the part of modeling, a range independent KRAKEN normal mode approach is implemented for sound propagation at the location. Transmission was conducted with a sweep frequency (850-1050 Hz) signal and transmitter was placed in the mid depth of water column for all cases of transmissions. At a time, a single point source was used for propagation and then the approach was repeated for each frequencies (850, 900, 950, 1000, 1050 Hz). Model also incorporated acoustic characteristics of water column, sea surface and sea bottom to characterize the actual acoustic environment for sound propagation.

Experiment was conducted on 25 January 2017 at 6:00 AM UTC with the help of two boats in which one was used for transmission and other for reception. Ranges between transmission points Tp1, Tp2, Tp3, Tp4 and receiver point Rp were 1.3, 2.87, 4.14 and 9.15 km, respectively and the transmitters at these different ranges undergo transmission at 6:00, 7:00, 7:30 and 8:30 AM, respectively in that order. Model derived transmission loss is compared with measured transmission loss in the field experiments.

#### Oceanographic measurements and computation

Conductivity, Temperature and Depth (CTD) data was collected with CTD sensors from transmitter sides and sound speed was measured with Sound

velocity profiler (SVP) at receiver side at half an hour interval and the data is shown in Figure 2. Bottom sediments were collected with grab sampler at receiver side and from different transmitter positions. pH values were taken from Coastal Ocean Monitoring and Prediction System (COMAPS) data for calculating absorption. Sound speed was derived using Chen-Millero equation<sup>34</sup> and absorption is calculated with Francois-Garrison formula<sup>35</sup>. Density is derived from temperature, salinity and pressure measured by CTD sensors.

#### Temperature and sound speed

At the transmitter side, temperature was almost uniform at vertical profile with a range of 26.45-26.7 °C and sound speed is slightly upward refracting in nature with a range of 1533.5-1534.5 m/s (Fig. 2). Similarly, temperature at receiver side experience small variability with a range of 26.4-26.6 °C and sound speed was slightly upward refracting in nature with a range of 1533.5-1535.5 m/s.

Temporal (receiver side) and spatial (transmitter side) variability of temperature and sound speed at the study location was very small (Fig. 1). Propagation model approaches were tested with transmitter side acoustic parameters (Stn 1 - Stn 4 in Fig. 2b) for all transmission ranges in a range independent acoustic environment.

#### Model description

KRAKEN normal mode sound propagation model is used to simulate the array response to the acoustic point sources for frequencies 850-1050 Hz. In this approach, sound is propagated as normal mode. Mode

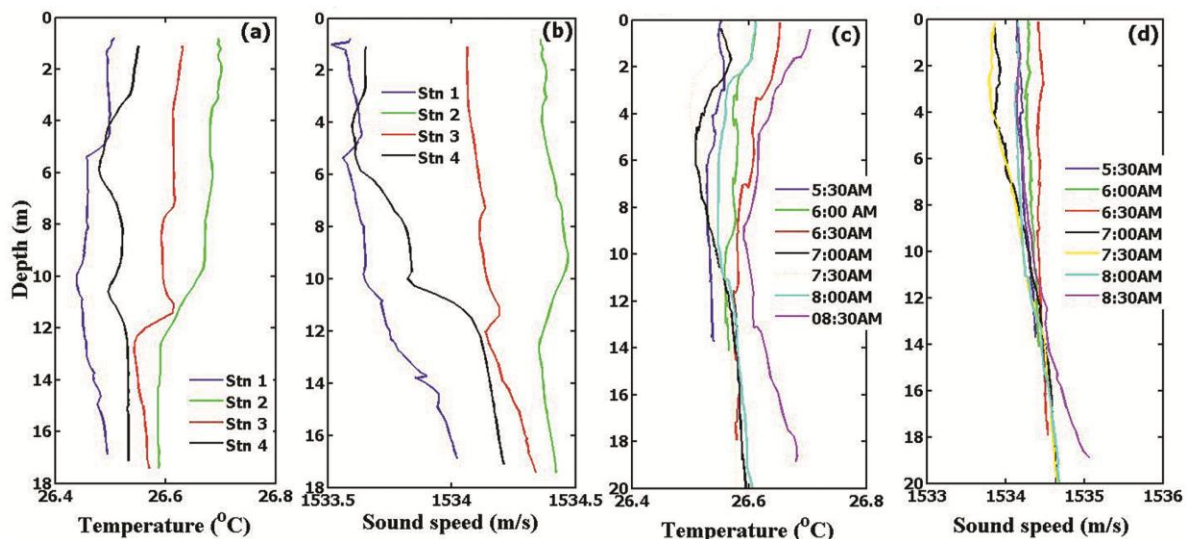


Fig. 2 — Spatial and temporal variability of temperature and sound speed profiles; (a), (b) for different transmission stations; and (c), (d) for receiver station, respectively

formation and propagation depends on the acoustic characteristics of location such as sound speed profile, water column depth, transmitting source position and frequency of source used. Propagation is also influenced by absorption of source in the water column, sea surface condition and bottom sediment features of the location. Here the approach is treated as range independent manner where the variability of parameters with range was neglected.

A diagram of model environment is also shown in the Figure 1(b). Ocean surface is considered as a perfectly reflecting pressure release boundary and the bottom is treated as an acousto-elastic half space. Major input acoustic parameters, sound speed, absorption and density were incorporated to the model. The sediment sample collected from the location was dominated by coarse sand so considered with corresponding compressional sound speed<sup>36</sup> 1700 m/s and it was matched with previous measurements from study location<sup>37</sup>.

As the part of modeling, acoustic environment is characterized in two dimensions with range and depth with a water column and half space sea bed (Fig. 1b). Receiver arrays were placed every 1 m for all considered ranges of transmission.

Each receiver array contained 80 receivers and each receiver in that array was arranged at an interval of 0.25 m. Array spacing is considered as  $\lambda/2n$  criteria ( $n = 1, 2, 3, 4\dots$ ); where,  $\lambda$  is wave length. For obtaining better features in transmission loss, array spacing is specifically used as  $\lambda/6$  where  $\lambda$  is defined with sound speed 1500 m/s and frequency 1000 Hz.

A schematic diagram of KRAKEN model is shown in Figure 3(a). File env contains information about source, receiver, water column depth, sound speed, density, absorption, acoustic features of bottom sediment etc. Field file holds the details about range of transmission, receiver positions etc. Print file (prt) is an intermediate output file which provides the complete information about all input parameters that have been taken by the model. Batch files are the core of the model and support to derive output files. Output files mode and shd consist of generated normal modes and derived acoustic pressure in the receivers, respectively.

The model derived acoustic pressure can convert to Transmission loss (TL) in dB with the equation

$$TL = -20 \log|P/P_r| \quad \dots (1)$$

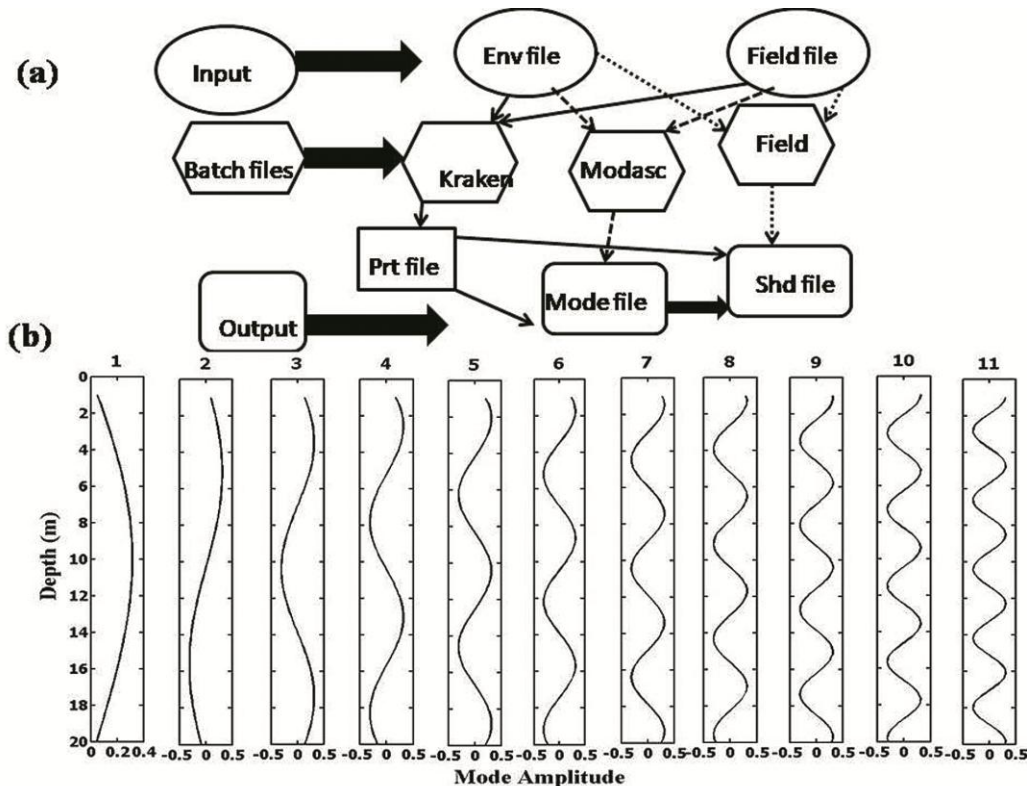


Fig. 3 — (a) Schematic diagram of implemented KRAKEN model; (b) KRKAEN computed modes for 1000 Hz mid depth source (10 m) propagation for sation 1 sound speed profile in a range independent approach

Where  $|P/P_r|$  is the a solute value of the ratio of model derived acoustic presuure to the reference pressure in water<sup>32,33</sup>.  $P_r$  = Reference pressure in water (1 micro Pascal).

#### Field transmission and reception

A schematic diagram of transmission and reception experiment is shown in Figure 1(c). Receiver system is deployed as shown in the Figure 1(c) with the help of a boat. Transmitter source is placed at the mid depth of water column with a vertically aligned rope by fixing one end in the boat (Fig. 1c) and also a digital hydrophone is placed in similar way very near to the source (with in 1 m) to measure sound pressure level.

Receiver hydrophones are placed at mid depth of water column as shown in the Figure 1(c). Two boat engines were completely off and anchored during signal transmissions. Also sea state was calm and a very weak current was observed visually in the experiment location.

#### Receiver specification

An automated subsurface noise recording system was used as receiver containing an array of 3 hydrophones; each one separated with 1 m distance was deployed at shallow waters (20 m) off Chennai (Rp is location point in Fig. 1a). Measured signals were stored in the Data Acquisition System (DAS) containing battery and sufficient storage capacity. Dead weight and sub surface float (Fig. 1c) strongly support the vertical alignment and stability of receiver system.

This receiver system was separately moored till the observation was completed (Fig. 1c). Hydrophones in the array KECL08-Keltron, RESON TC4014 and KECL07-Keltron are located at 8, 9 and 10 m depth of water column. Receiver array was specified with a sampling frequency of 10 kHz and sampling duration of 10 minutes.

Apart from the recording of transmitted signals, the experiment was also intended to study ambient noise in the location within the band of 5 kHz. Ambient noise level during non transmission period is measured with KE08 hydrophone. Automated measurements in the receiver hydrophones were repeated in each 30 minute interval. Sound speed profiles are also measured within same interval with sound velocity profiler at receiver location. Calibrated results of receiving sensitivity responses of KECL07, KECL08 and RESON TC4014 hydrophones for desired frequency ranges are tabulated in the Table 1.

Table 1 — Receiving sensitivity response of reciever hydrophones to considered frrequencies after calibration

Frequency (Hz)	Receiving Sensitivity (dB re 1V/ $\mu$ Pa)		
	KECL07-Keltron	KECL08-Keltron	RESON TC4014
850	-176.9	-174.3	-184.4
900	-177.0	-174.0	-184.4
950	-177.1	-174.2	-184.4
1000	-177.0	-174.4	-184.3
1050	-177.0	-174.4	-184.4

#### Transmitter specification

An acoustic source is placed at mid depth (10 m) of water column (Fig. 1c) and transmitted a band of frequency 850-1050 Hz (a sweep signal) for duration of 3 minutes. A digital hydrophone, nano Remote Underwater Digital Acoustic Recorder (nRUDAR) with a sampling frequency 96 kHz is positioned near (within 1 m) to the source (Fig. 1c). Hydrophone holds a flat band of receiving sensitivity response with -158.43 dB re 1V/ $\mu$ Pa for the all desired transmitted frequencies (Flat response for all considered frequencies). During all transmissions, nRUDAR measurement is started before the transmission and was stopped after transmission to capture the complete transmitted signals. Measured sound pressure level in the nRUDAR is treated as source signal level.

After fixing receiver and transmitter in a considered transmission range, the acoustic transmission was conducted at transmitter side with band of 850-1050 Hz source. This acoustic transmission is repeated for different ranges (1.3, 2.87, 4.14, 9.15 km) with 3 minute duration. All transmissions during the experiment are carried out within the recording period of receiver hydrophones.

## Results and Discussion

#### Kraken mode generation

Propagation of normal mode along the wave guide is depend upon the incident angles on both bottom and surface associated with each mode. Shallow angle modes (lower order modes) are more sensitive to water coloumn and steeper angle modes (higher order modes) penetrates to the sea bed. Generally lower order modes are more concentrated in the lower sound speed layer and all higher order modes span the entire water column depth. This discriminination can observe where the gradient of sound speed profile is present but here sound speed profile shows almost isovelocity in nature at the location (Fig. 2). So all modes span

(Fig. 3) the entire water column depth<sup>32</sup>. In the normal mode approach, number of modes are directly proportional to the depth of water column and source frequency but inversely proportional to the sound speed<sup>33</sup>. In this case, 12 modes are computed for source frequency 1000 Hz and computed modes are shown in Figure 3(b) which are corresponding to station 1 sound speed profile (Fig. 2b). Modes for all cases were computed for desired frequency ranges (850-1050 Hz) and show an increasing trend with frequency (around 2 modes per 100 Hz) for all considered range independent sound speed profiles.

**Transmission loss**

*Model derived transmission loss*

Model generated acoustic pressure was converted to transmission loss and is expressed in Figure 4. It

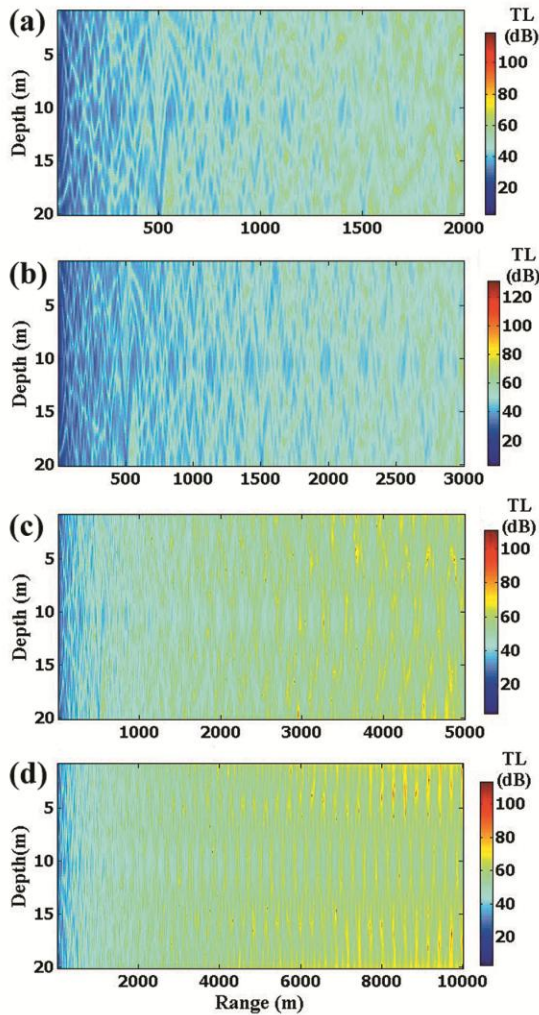


Fig. 4 — Model derived transmission loss for 1000 Hz mid depth source (10 m) for different transmitter-receiver ranges: (a) 2 km; (b) 3 km; (c) 5 km; and (d) 10 km

represent the transmission loss for 1000 Hz mid depth source for different ranges (2, 3, 5 and 10 km) similar to the ranges in the experiment part.

Model derived transmission loss is proportional with range of transmission. A narrow relatively minimum loss path is observed for all ranges at mid depth of water column, it may be due to the mid depth source position. There is no other specific duct is observed due to the very slight gradient sound speed profile and very shallow depth of water column.

*Observed transmission loss*

All transmitted signals with duration of 180 s are captured by nRUDAR digital hydrophone. nRUDAR always keep near to the transmitter (with in 1 m) for all cases of transmissions to measure source level. nRUDAR measured signal during the case of 1.3 km range of transmission is shown in the spectrogram (Fig. 5c).

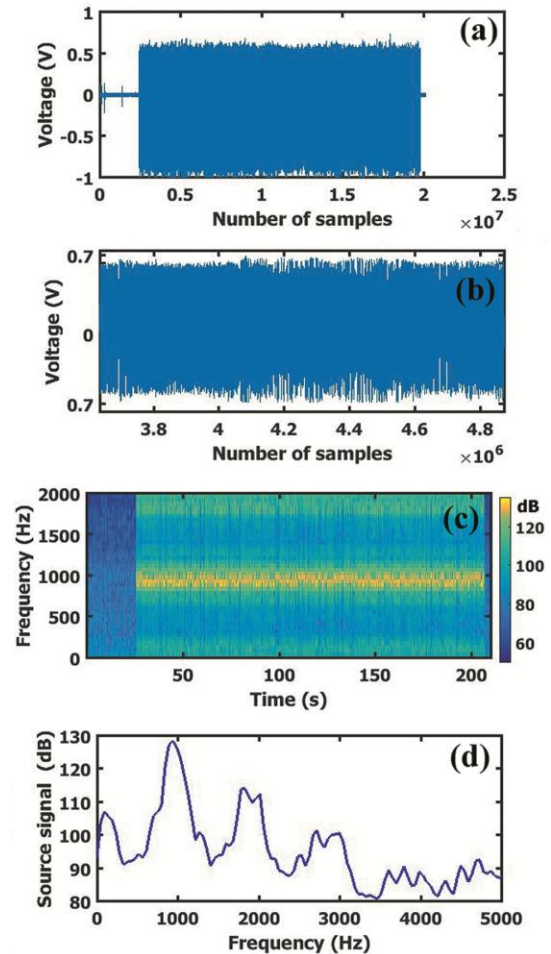


Fig. 5 — (a) Voltage; (b) off set removed and chopped signal used to calculate level of source signal; (c) Spectrogram; and (d) Power spectrum of nRUDAR hydrophone observed signal with in 1 m range of transmitter

Observed acoustic time series has been converted to frequency domain with required converting parameters through the Fourier transform and derived power spectrum was analysed in all cases of observations (Appendix S1). Power spectrum of observed signal (Fig. 5d) gives the transmitted source signal of frequency band 121.2, 128.7, 128, 125.4 and 121.3 dB re 1V/ $\mu$ Pa for 850, 900, 950, 1000 and 1050 Hz, respectively. Similar trends are observed in the nRUDAR during the other ranges of transmission (2.87, 4.14, 9.15 km).

Measured ambient noise level during non transmission period with KE08 hydrophone is shown in the Figure 6(d). Ambient noise level experienced a decreasing trend with frequency in the study location with a range of 80-60 dB re 1V/ $\mu$ Pa for all frequency range (200-5000 Hz) of observation. Also it showed a background noise level of around 76-74 dB re 1V/ $\mu$ Pa for considered frequency range (850-1050 Hz).

In the receiver side, transmitted signals in all four cases were received in all hydrophones of receiver array. Voltage and spectrogram of KE08 hydrophone signal is displayed in Figure 6(a, c) for 1.3 km range of transmission. Arrival structure of transmitted signal (Time-Pressure) shows a delay between 3 hydrophones. KE07 experience a delay of 500 micro seconds with RESON and KE08 showed a delay of 400 micro seconds with RESON (Fig. 6b).

Received sound noise levels of all hydrophones in this case are represented in Figure 6(d). Other levels for transmitted source frequencies 850, 900, 950, 1000, 1050 Hz in KE08 hydrophone are 94.30, 107.8,

109.3, 105.1 and 98.33 dB re 1V/ $\mu$ Pa, and for KE07 are 95.5, 108.8, 109.8, 106.0 and 98.59 dB and in RESON are 93.57, 107.9, 109.1, 105.2 and 97.5 dB re 1V/ $\mu$ Pa, respectively.

All other transmissions also were treated in similar way and their received source signals are displayed in Figure 7 and the corresponding transmission losses are tabulated in Table 2 with model output. Level at receiver side is subtracted from the level at transmitter side to obtain the transmission loss. Noise level

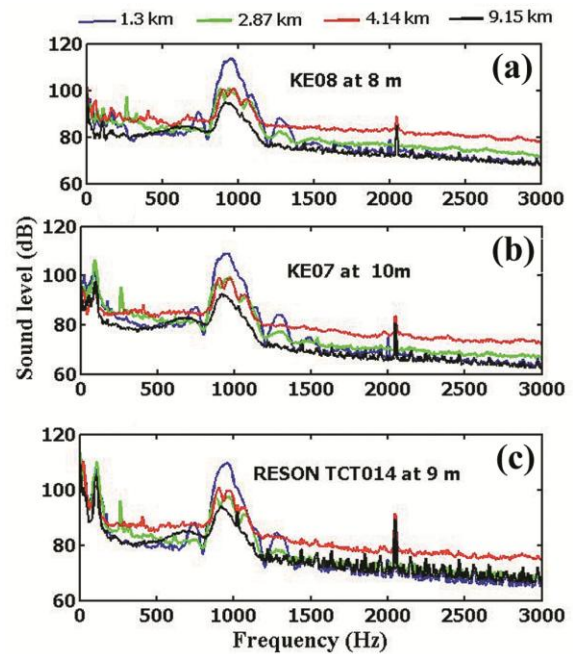


Fig. 7 — Received sound levels in (a) KE08; (b) RESON; and (c) KE07 hydrophones for source of 850-1050 Hz at different ranges

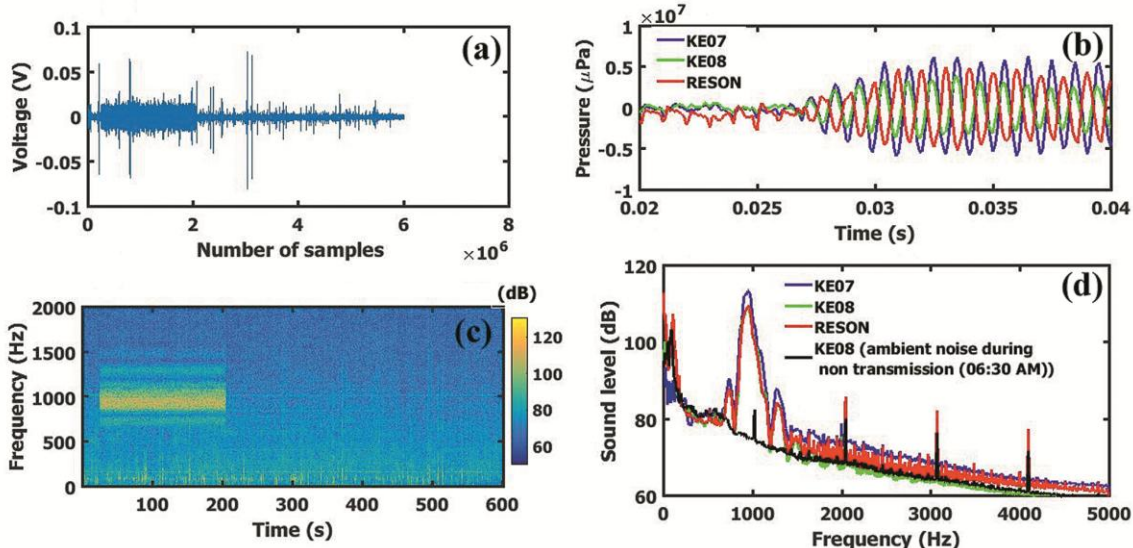


Fig. 6 — (a) Voltage; (b) Spectrogram of KE08 hydrophone; and (c) Power spectrum of observed signal for hydrophones KE08, KE07 and RESON at receiver side for a range of 1.3 km

Table 2 — Modeled and observed transmission loss (dB) for different transmission source frequencies and ranges

F (Hz)	Hydrophone at 8 m depth (KE08)							
	Observed				Model			
	1.3 km	2.87 km	4.14 km	9.15 km	1.3 km	2.87 km	4.14 km	9.15 km
850	26.9	29.73	31.03	36.78	23.0	25.4	26.5	28.7
900	20.9	32.21	31.07	37.56	23.1	26.8	28.3	30.6
950	18.7	29.37	30.4	35.73	22.1	31.5	26.8	32.5
1000	20.3	28.8	30.3	38.54	23.4	24.5	26.1	30.0
1050	22.97	29.75	30.2	37.29	25.5	28.1	29.2	29.7

F (Hz)	Hydrophone at 9 m depth (RESONTC4014)							
	Observed				Model			
	1.3 km	2.87 km	4.14 km	9.15 km	1.3 km	2.87 km	4.14 km	9.15 km
850	27.63	29.72	30.37	36.73	22.9	27.6	28.1	28.5
900	20.8	32.25	30.58	36.78	22.1	26.1	28.4	29.2
950	18.7	29.9	29.39	35.13	22.4	25.8	26.3	31.7
1000	20.3	28.84	30.04	37.88	23.8	25.5	27.4	30.8
1050	22.97	29.73	29.82	36.82	21.6	26.0	26.5	29.1

F (Hz)	Hydrophone at 10 m depth (KECL07)							
	Observed				Model			
	1.3 km	2.87 km	4.14 km	9.15 km	1.3 km	2.87 km	4.14 km	9.15 km
850	25.7	28.84	30.36	38.12	24.0	25.1	27.7	28.6
900	19.9	31.52	30.46	36.49	21.3	25.8	26.4	28.2
950	18.2	28.59	29.36	34.73	21.5	24.0	26.1	30.0
1000	19.4	28.31	28.61	37.28	22.2	24.7	25.1	28.3
1050	22.35	29.2	29.32	35.72	22.8	25.6	26.1	28.5

decreases with range and it is clearly observed in Figure 7. A difference of around 10-20 dB in level is observed between short (1.3 km) and long (9.15 km) range at mid depth of water column for considered band of frequency (Table 2).

Transmission loss is proportional with range but its loss rate for unit distance is higher in short ranges than at long ranges. This rate loss difference is due to higher and lower arrival angles of sound waves in short and long range respectively. Shallow angle waves can propagate long ranges than steep angle waves after reflection from bottom and surface. Most of waves are passing through the short ranges where as shallow angle waves only reach at long ranges. So all waves experience loss in short ranges but only shallow angle waves account in long ranges. This difference make the variability in rate loss in both short and long ranges.

**Comparison between model and observation**

After completing both modeling (KRAKEN) and field approaches for transmission loss in sound propagation, a comparison study has been initiated for both approaches. Figure 8 explain this validation approach for 1000 Hz mid depth source acoustic propagation. At all considered depths, transmission loss shows relatively strong agreement in short range

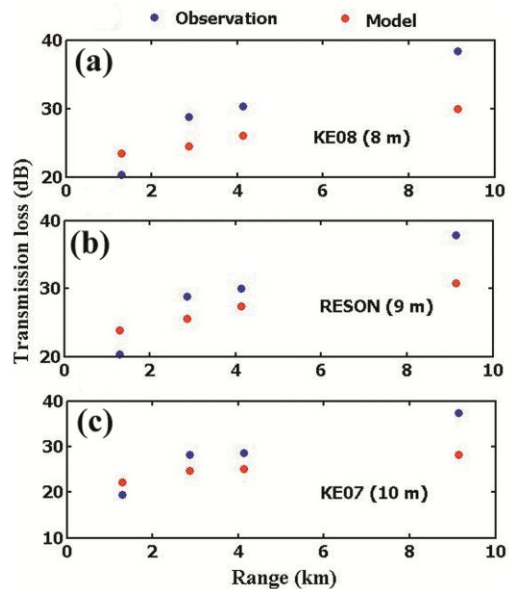


Fig. 8 — Transmission loss comparison for model and observation at different receiver depths and ranges for the transmission of 1000 Hz mid depth source

than long range between field and observation data (Fig. 8). This trend is following for all other frequencies in the band of 850-1050 Hz (Table 1). Comparison study provides a quantitative validation of transmission loss (Table 2) in both approaches.



### Limitations of the model compared with field observation

Experiment location is not exactly match with model environment. Range dependent influence in sound speed and sea floor sediment features also characterize experiment field. It also includes atmospheric and oceanographic parameters such as currents, wind etc. Such actual condition increases the complex nature of experiment location than model environment hence results the anomaly in transmission loss for both approaches. Model transmitted source frequencies at different time (separate transmission for each frequency) but the experiment transmitted sweep signal source at a time. Source level is not assigned to model point source but it is assigned to transmitter source in the observation. Model considered huge number of receivers in receiver array than in the field observations for getting high resolute features (Fig. 4) of transmission loss. Array element spacing is also different in both model and observation approaches.

### Conclusion

KRAKEN normal mode range independent approach derived transmission loss for mid depth source frequency band (850-1050 Hz) has been validated with acoustic field observation conducted in same location. Transmission loss experience better agreement for short range than long ranges between field and model data. Model always experience low transmission loss level than observation. Reason for such anomaly is due to the shortage of further actual input conditions and parameters. So the model was not able to characterize up to actual acoustic environment for such study of sound propagation. Obviously for long ranges of transmission such anomaly increases than in short ranges. But this quantitative approach in acoustic transmission experiment (observation) strongly supports the effective use of acoustic devices in that location. And also validation approach between model and observation increases the reliability and accuracy of model by giving better comparability in transmission loss with field observation. But further tuning in model and detailed consideration in experiment setup is required to get better comparison.

### Supplementary Data

Supplementary data associated with this article is available in the electronic form at [http://nopr.niscair.res.in/jinfo/ijms/IJMS\\_50\(03\)177-186\\_SupplData.pdf](http://nopr.niscair.res.in/jinfo/ijms/IJMS_50(03)177-186_SupplData.pdf)

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### Conflict of Interest

On behalf of all authors, the corresponding author K K Noufal states that there is no conflict of interest.

### Author Contributions

NKK: Conceptualization, model setup and run, data processing and analysis, participation in field experiments, and draft preparation; GL: Conceptualization, editing, review, funding acquisition and overall supervising of work; and RR: Review, editing, suggestion and guidelines to the work.

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