Performance evaluation of acoustic signals for underwater applications in high-frequency range

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Received 19 October 2014; revised 13 December 2014

Performance evaluation of high frequency (20-24 kHz) underwater acoustic waveforms such as CW, LFM and HFM was carried out theoretically in the presence of white Gaussian noise, multipath and Doppler. Measured sound speed profiles off Indian coast were used in ray based models Bellhop and VirTEX to mimic the environment with multipath and Doppler. The source signals were convolved with channel impulse response function to predict the received signal. Correlation between the transmitted and received signal was used to evaluate the performance of waveforms. Performance evaluation studies have revealed that LFM and HFM have better resistance to additive white Gaussian noise than CW. Similarly multipath has affected CW the most while HFM and LFM are resistant to it. The Doppler imposed by the source/receiver motion has very little effect on HFM followed by LFM and CW. It was also found that both LFM and HFM have shown greater resistance to Doppler when the receiver is close to the surface.

[Keywords: CW, LFM, HFM, multipath, Doppler, underwater acoustic channel]

Introduction

Acoustic waves provide best means of exploration in seawater as the use of electromagnetic waves is not suitable. Electromagnetic waves get attenuated within the top ten meters as the seawater is a good conductor. Underwater acoustic signals are a restricted variety of signals chosen for their capacity to carry the information sought by the end user in specific applications like detection and localization of a target, communication etc. Acoustic waves travel almost unimpeded in water (particularly at low frequencies) due to its high density. Hence underwater devices such as active sonars or communication systems use acoustic waves for achieving their intended tasks. These devices use various acoustic waveforms like Continuous Wave (CW), Linear Frequency Modulation (LFM), Hyperbolic Frequency Modulation (HFM) etc., to detect and classify a target or to communicate with one another. The intended task is achieved based on received signal’s information. When an underwater device transmits a signal, it undergoes morphological changes due to various environmental factors. These factors include variation of sound speed with depth causing changes in refractive index, presence of ocean boundaries causing multipath and scattering effects, high temporal and spatial variability of ocean environment causing fading of signal, presence of different types of sediments at the bottom boundary causing different attenuations etc.

In addition to the reasons outlined above, additive noise originated from human as well as other activities results in very low Signal to Noise Ratios (SNR) in underwater. Therefore, it is of utmost importance to study the impact of low SNR, multipath and Doppler on the signal behavior before the actual system is designed. This will enable for designing better systems but also brings out clearly the limitations of such systems.

Several studies were undertaken globally to understand and characterize the signal behavior commensurate with the acoustic channel
characteristics\(^1\sim9\). These studies have revealed that CW is better suited for resolving the Doppler, LFM and HFM have exhibited resistance to both multipath and Doppler. However, most of these studies either have assumed iso-velocity conditions or using a climatological sound speed profiles (Levitus Climatology Atlas). In addition, the depth dependency of signal behavior was not addressed adequately. Further, similar studies in the Indian seas/coasts are scanty.

Therefore, this paper attempts to evaluate the performance of various waveforms using the measured sound speed profiles and sediment types in Indian seas at high frequencies. Although several factors influencing the underwater acoustic propagation were listed above this paper mainly concentrates on signal’s performance under low SNR, influence of multipath and Doppler.

The approach of the paper is following, section 2 explains commonly used signals in underwater applications, section 3 brings out the details of channel modeling followed by the evaluation of signal performance in various channel scenarios in section 4 and concluding remarks in section 5.

Commonly used signals in underwater applications

**CW signal**

CW signals are pure cosine waves with constant frequency of a finite duration with usually constant amplitude. A CW pulse (narrow band pulses) is the most commonly used the underwater acoustics signal since it is well suited to narrow band transducers. The major limiting factor of CW signal is its very poor spectral content; this limits the usage of the same for advanced processing to characterize targets. Furthermore, it requires relatively high input SNR\(^1\). A continuous cosine signal can be defined mathematically by a time-varying function of

\[
x(t) = A \cos(2\pi f_0 t)
\]

where, \(A\) is amplitude, \(t\) is time, \(f_0\) is cyclic frequency in cycles per unit time.

**LFM signal**

LFM signal is also called chirp signal which is widely used in radar, sonar and underwater communications. LFM is a type of frequency modulation where the signal sweeps linearly from one frequency to another frequency. LFM signal created by concatenating small sequences each with a frequency higher than the previous. LFM signal can be created from original equation for cosine signal is given by \(x(t) = A \cos(2\pi f(t) t + \phi)\). Here Instantaneous phase given by \((2\pi f(t) t + \phi)\), changes linearly with time. If we make the phase as quadratic then the sinusoid equation is no longer constant. This equation’s frequency changes linearly with time\(^2\). LFM signal can be expressed as:

\[
x(t) = A \cos(2\pi f(t) t + \phi)
\]

where, \(f(t) = \frac{k t}{2} + f_{\text{min}}\)

\(k\) is signal slope: \(k = (f_{\text{max}} - f_{\text{min}})/T\)

\(f_{\text{min}}\) is starting frequency, \(f_{\text{max}}\) is end frequency and \(T\) is pulse length.

**HFM signal characteristics**

HFM is a type of frequency modulation where the signal sweeps hyperbolically from one frequency to another frequency. HFM signal can be created by concatenating small sequences each with a frequency higher than the previous. HFM signal is a logarithmic representation of LFM signal. It is used in active acoustic systems. HFM signal can be expressed as\(^9\)

\[
x(t) = \cos \left[ 2\pi \frac{\ln(k t + \frac{1}{f_{\text{min}}})}{k} \right]
\]

where, \(k\) is the signal slope and is given by \(k = (f_{\text{min}} - f_{\text{max}})/(T * f_{\text{min}} * f_{\text{max}})\). \(f_{\text{min}}\) is starting frequency, \(f_{\text{max}}\) is end frequency.

Channel modelling

As the performance of a chosen waveform depends on Channel Impulse Response (CIR) function, the same is required to be modeled first for evaluating system’s performance. Although there are several theories to model the channel, the most popular ones are Ray theory, Normal Mode theory and directly integrating the acoustic wave
equation between the wave numbers of interest. The models developed thus far based on normal mode and direct wave integration techniques are computationally very expensive for the frequency range (> 20 kHz) of interest in the current studies. Ray theory based models are very easy to implement, accurate, fast and explains the underlying physics very well. Therefore, the authors have adopted ray theory based models to mimic the acoustic environment in the current studies. Ray tracing involves integrating an Eikonal equations that describes the ray’s trajectory. These equations are governed by given initial conditions in order to trace the path of a ray as it propagates away from the source. The amplitude of a ray is determined by the cross-section of the ray tube bounded by adjacent rays. The main drawback associated with ray tracing is the existence of shadow zones, which are zones through which no rays pass, resulting in a pressure field of zero everywhere within them. In actuality, there is always some diffraction of sound into the areas given as shadow zones in ray tracing, resulting in a discrepancy between the exact solution and that predicted by ray tracing methods. In order to overcome this limitation of ray method, a Gaussian-beam based model was developed. Gaussian-beam based methods provide a substantial improvement over ray methods but they are not sufficiently accurate at low frequencies. Generally, ray theory cannot be used when the water depth is less than 20 times the acoustic wavelengths of interest. In the current study, frequency of interest is ranging from 20 kHz to 24 kHz and the measured sound speeds for both deep and shallow water cases were ranging from a minimum of 1490 m/s to a maximum of 1540 m/s.

Accordingly, the wave numbers under consideration would vary from 62.3 mm to 77 mm whereas the ocean depths considered herein are 500 m and 60 m which are more than 20 times of wavelengths. Therefore ray theory is valid in the current case and a Gaussian-beam based model Bellhop developed by Michael B Porter has been used in the study. The Bellhop model is a part of Acoustic Toolbox available to download at (http://oalib.hlsresearch.com/modes/acoustictoolbox/at.zip). Lack of geo-acoustic information between the source and receiver (distance is 1 km) has forced the authors to contend with only the range independent model rather than using range dependent models.

Two different sound speed profiles measured in Indian waters one in deep (Fig. 1a) and the other in shallow (Fig. 1b) waters along with their sediment properties listed in Table I are used for estimating the CIR function of respective channels. Performance evaluation of various waveforms is done using measured sound speed profiles rather than Levitus climatological profiles to ensure more realistic simulations.

As brought out earlier, Bellhop model was used for estimating the CIR of both deep and shallow waters and presented in Fig. 2(a) and Fig. 2(b). The CIR was estimated for a source and receiver depths of 30 m and 50 m respectively with 1000 m distance between them. A total of 4400 rays were considered within beam taking of

<table>
<thead>
<tr>
<th>Geo-acoustic parameters</th>
<th>Deep</th>
<th>Shallow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sediment type</td>
<td>Sand</td>
<td>Silt</td>
</tr>
<tr>
<td>Compressional sound speed</td>
<td>1650 m/s</td>
<td>1575 m/s</td>
</tr>
<tr>
<td>Ratio of sediment density to seawater density ($\rho$)</td>
<td>1.9</td>
<td>1.7</td>
</tr>
<tr>
<td>Compressional attenuation ( $\alpha$ )</td>
<td>0.8 dB/ $\lambda$</td>
<td>1.0 dB/ $\lambda$</td>
</tr>
</tbody>
</table>
angle of ±30° for both deep and shallow water cases. In case of deepwater shown in Fig. 2(a) only 4 rays connected the source and receiver and the delays are of the order of 200 ms between the direct path and the bottom reflected paths. The bottom reflected paths got attenuated more than the surface reflected path. Therefore signal with lesser pulse widths are not easily affected by the multipath. However, in case of shallow waters (Fig. 2b) the scenario is very complicated because out of 4400 rays 24 rays have connected the source and receiver. The time delays between the direct path and other paths are much less than 10 ms therefore the signals are susceptible to multipath.

![Fig. 2 - Eigenray and channel impulse response of (a) deep water and (b) shallow water for a source depth of 30 m, receiver depth of 50 m and receiver range of 1 km. The red color in ray diagram indicates direct path, black is surface reflected and the blue is bottom reflected.](image)

**Performance of CW, LFM and HFM signals under various channel characteristics**

Since the aim of the paper is to characterize the signal performance under various environmental conditions like low SNRs, influence of Multipath and the effect of Doppler in both shallow and deepwaters off Indian coast. Signals were simulated using the equations 1-3 of section 2 and the same were convolved with the CIR function estimated for both shallow and deepwaters as explained in section 3 to arrive at resultant time series at a hypothetical receiver’s position. The performance evaluation of each of the said waveforms was done using the autocorrelation peak or Matched Filter (MF) output. MF is obtained by correlating a known transmitted signal with an unknown received signal to detect the presence of the known signal in the unknown signal. The MF is a good indicator of maximum achievable instantaneous signal to noise power ratio.

**Effect of low SNR on matched filter**

In order to evaluate the performance of the different waveforms in the presence of additive Gaussian white noise, signals were contaminated deliberately with white Gaussian noise. Two sets of such signals, one with an SNR of +5 dB and the other with -20 dB were generated. Each of these signals was convolved with the impulse response functions of both deep and shallow waters. The resulting matched filter output was shown in Fig. 3.

It is evident from the Fig. 3 that CW, LFM and HFM have shown strong resistance to white Gaussian Noise. However, LFM and HFM were better because of their autocorrelation characteristics. It can also be observed that at high SNRs (+5 dB), the autocorrelation peak is clearly evident. At low SNR (-20 dB), the energy in side lobes has increased significantly. However, the peak still remains. As the results remain same for both deep and shallow waters only one case is presented in the paper. It is known that the amplitude and the width of central pulse in Matched Filer (MF) output depend on the bandwidth and the pulse width of the signal. The higher the signal bandwidth, the sharper the central pulse will be and also the higher the amplitude. Therefore, in case of very low SNRs both LFM and HFM with larger pulse width and higher bandwidth will yield desirable results.

**Multipath**

Multipath propagation of signal occurs due to reflection of sound from sea surface, bottom and any objects. A signal received by receiver can be represented as sum of number of ray arrival amplitudes and their corresponding delays.

In an effort to study the impact of noise on marine mammals, a simulation model (VirTEX) based on ray theory was developed by Martin Siderius and Michael B. Porter. The model
generates a time-series of transmitted signals as heard by a marine mammal and it is capable of simulating both multipath and Doppler imposed by source/receiver motion. The algorithm uses the outputs of Bellhop ray tracing model for predicting the receiver output time series. Therefore VirTEx model was used for simulating the multipath at zero velocities of both source and receiver.

**Multipath effect in deep water and shallow waters**

A measured sound speed profile shown in Fig. 1(a) along with the respective sediment type described at table I are used for estimating the impulse response function. The sediment type found at the measurement site is silt. Multipath signal was simulated as brought out in the preceding section.

As far as the performance of LFM and HFM in deep waters is concerned, their autocorrelation peaks (Fig. 4c and Fig. 4e) are much narrower than that of CW (Fig. 4a). The peaks are well discernable with hardly any side lobes. Therefore it can be concluded safely that both LFM and HFM have shown very good resistance to multipath and hence can be very useful in deepwater environments.

**Multipath effect in shallow water**

Usually, Acoustic waves travelling in shallow waters are prone to multipath and degrade the system performance, as was evident from Fig. 2(a). An acoustic signal transmitted through such shallow waters will be affected by multipath as the signal impulse response shows more surface and bottom reflected paths with very less time delays. As far as autocorrelation peaks or MF output is concerned, both LFM (Fig. 4d) and HFM (Fig. 4f) have shown good resistance to multipath capability than the CW (Fig. 4b) in shallow water also. However, number of side lobes has increased dramatically in shallow waters. Therefore, one needs to exercise caution in selecting the pulse width of a device.

**Doppler**

In addition to the performance degradation caused by the changes in environmental parameters, motion of transmitter or receiver causes either time compression or spreading of the signal which is known as Doppler Effect. The magnitude of the Doppler Effect is proportional to the ratio of the relative transmitter-receiver velocity to the speed of sound. It is well known that a Doppler sensitive waveform such as CW burst is used for estimating the target velocity. However, as shown in preceding sections CW is susceptible to multipath and additive noise. Therefore, one needs to look for alternative waveforms which can resolve Doppler reasonably well with fairly good reverberation resistant capabilities.
In the present study the authors have used VirTEX model for evaluating the performance of CW, LFM and HFM in both shallow and deep waters off Indian coast. In a set of numerical experiments, the source was assumed to be travelling with speeds ranging from 0 to 30 m/s in steps of 5 m/s while receiver is stationary. During the source transit it was transmitting CW (22 kHz) and LFM/HFM (bandwidth is 4 kHz and central frequency is 22 kHz) signals with pulse length of 30 ms (pulse length remained same for all the three signals). Such transmitted signals were received at 10, 30 and 50 m depths in shallow waters and 10, 50 and 200 m depths in deep waters. As far as source is concerned it is at a depth of 30 m and a range of 1 km in both shallow and deepwater cases.

Similar to the studies carried out in the preceding section, MF output was estimated for each case and MF peak was normalized with zero velocity’s MF peak value. This process will bring out the waveform’s ability to resist Doppler very clearly. The process was carried out for various speeds for both shallow and deep water cases. In case of deep water, it is very apparent from Fig. 5 that CW is most affected by the Doppler which why it has the better ability to resolve the Doppler than the other two waveforms.

HFM has exhibited strong resistance to Doppler. However, in shallow water case (Fig. 6) although, the performance of CW remained same, LFM and HFM has shown similar degree of resistance to Doppler with HFM being slightly more resistant than LFM.

In an effort to understand the depth dependence of MF outputs, receivers were placed at different depths like 10, 30 and 50 m depths in shallow waters and 10, 50 and 200 m depths in deep waters. Although the results did not show considerable depth dependence in deep waters LFM and HFM have shown greater resistance to Doppler when the receiver is close to the surface (Fig. 7).

LFM and HFM have behaved entirely differently in the presence of Doppler. LFM has shown moderate resistance to Doppler whereas
Conclusions

In this paper, various signals used in underwater applications were characterized using the measured sound speed profiles off Indian coast in both deep and shallow waters. Performance of waveforms such as CW, LFM and HFM were evaluated in conditions like low SNRs, presence of multipath and Doppler.

As far as the performance of different waveforms in the presence of additive white Gaussian noise is concerned, LFM and HFM have performed better than the CW. Similarly, HFM and LFM have shown greater resistance to multipath in deep waters while the CW was the worst affected among the three. However in shallow waters, the performance of HFM and LFM were not as good compared to deep waters due to large number of side lobes being present. As far as the impact of Doppler on the signal performance is concerned, CW is most affected in the presence of Doppler which why it has the better ability to resolve the Doppler than the other two waveforms. Compared to CW, both LFM and HFM have shown moderately strong resistance to Doppler. Within HFM and LFM, HFM has shown stronger resistance to Doppler in deep waters. In case of shallow waters, both LFM and HFM have shown similar degree of resistance to Doppler. Depth dependent performance of waveforms has revealed that both LFM and HFM have shown greater resistance to Doppler when the receiver is close to the sea surface.

Acknowledgement

The authors would like to thank the Director, NSTL for giving an opportunity to work in this niche area of research. The First author is particularly grateful to NSTL for having allowed him to do his Master’s thesis at the institute.

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