ACOUSTIC COMMUNICATIONS IN SHALLOW WATERS

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The shallow water channel is an environment which is of particular interest to many research workers. An underwater acoustic channel is characterized as a multipath channel. Severe signal degradation can occur in such a channel due to multipath effects and the refractive properties of the channel, which may include multiple interactions with the sea bottom and sea surface. Time-varying multipath propagation is one of the major factors that limit acoustic communication performance in shallow water.

In this paper the results of an analysis of broadband shallow water acoustic signal was shown. Linear FM pulses were chosen as the main transmit signal for numerical experiments. The transmitted signal goes through multiple paths in order to reach the receiver. The numerical simulations were performed using the broadband normal mode model. This software channel simulator is capable of simulating the effect of the shallow water propagation channel on an input broadband acoustic signal and can be used for simulations of sound propagation through both a time- and range-varing propagation channel. The received signals were all matched filtered revealing the multipath arrival structure.

INTRODUCTION

Acoustic communications in shallow water had been a difficult problem due to the channel characteristics of the underwater acoustic channel. For long range underwater acoustic communications the main problem encountered is the presence of multipath propagation caused by reflection and scattering of the transmitted signals at the bottom and the surface.

Reflections from channel boundaries and diverse objects dominate the multipath structure. The transmitted signal can go through multiple paths in order to reach the receiver. These multiple paths can cause significant time spread in received signal. Each path has can possibly have multiple surface interactions causing additional frequency spreading due to motion of the water. Shallow water propagation is very sensitive to changes in the geometrical parameters like water depth, source-receiver range or bottom slope leading to variations in the impulse response of the underwater acoustic sound channel. Normal mode approaches have been widely used in underwater acoustics and are derived from an integral representation of the wave equation. When propagation is described in terms of normal modes, changed in the environment translate into energy transfer between modes. In this paper the numerical simulations were performed using the Prosim broadband normal mode model working in Matlab environment [8].

1. BROADBAND NORMAL MODE MODEL

The Prosim can be used for simulations of broadband sound propagation through both a time- and range-varying propagation channel. The broadband model is based on a model called ORCA. ORCA is based on a layered normal mode approach assuming that the inverse of the sound speed squared varies linearly with depth in each layer. This software project is mainly intended for shallow water applications. The software consists of oceanographic and acoustic models which perform specific tasks to describe the complexity of the real ocean. The combination of several models can be a unique tool for predicting underwater acoustic systems performances, such as communication systems for which channel stability and fading are major problems. In this paper the acoustic part of package was used. This package consists of a broadband normal mode code for calculating the received signals in the time domain and this signals can be matched filtered in the case of FM transmissions.

The normal mode solution involves solving a one-dimensional equation. Normal modes are normally thought of principally in the context of range-independent problems, but they can be extended in various ways to both range-dependent problems and fully three-dimensional problems. In this paper range-independent problem is considered. Figure 1 shows the model of the range-independent environment [6].

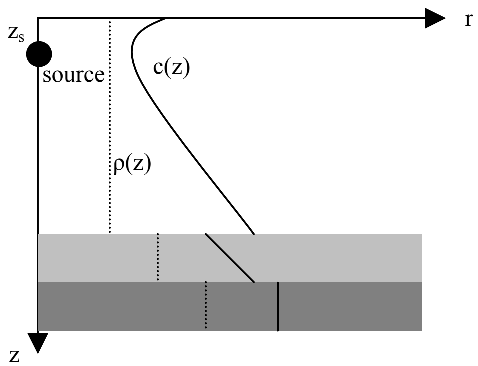

Fig.1 Model of the range-independent environment

The acoustic wave equation has the following form:

$$\nabla \cdot \left(\frac{1}{\rho} \nabla P \right) - \frac{1}{\rho c^2(z)} P_{tt} = -s(t) \frac{\delta(z - z_s)\delta(r)}{2\pi r} \tag{1}$$

where P(r,z,t) is the acoustic pressure, s(t) is the point source, ρ(z) is the density and c(z) is the sound speed.

Assuming that source time series has the form:

$$s(t) = e^{-i\omega t} \quad (2)$$

then P(r,z,t) has the form:

$$P(r,z,t) = p(r,z)e^{-i\omega t} \quad (3)$$

and we can write the following Helmholtz equation:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial p}{\partial r}\right) + \rho(z)\frac{\partial}{\partial z}\left(\frac{1}{\rho(z)}\frac{\partial p}{\partial z}\right) + \frac{\omega^2}{c^2(z)}p = \frac{-\delta(z-z_s)\delta(r)}{2\pi r} \quad (4)$$

After separating variables, i.e. substitution p(r,z)=Z(z)R(r) (with the source removed) equation (4) becomes:

$$\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial R}{\partial r}\right)\right] + \left[\rho(z)\frac{\partial}{\partial z}\left(\frac{1}{\rho(z)}\frac{\partial Z}{\partial z}\right) + \frac{\omega^2}{c^2(z)}p\right] = 0 \quad (5)$$

Equation (5) leads to the modal equation after denoting this separation constant by k^2:

$$\rho(z)\frac{d}{dz}\left(\frac{1}{\rho(z)}\frac{dZ(z)}{dz}\right) + \left(\frac{\omega^2}{c^2(z)} - k^2\right)Z(z) = 0 \quad (6)$$

$$Z(0) = 0$$

$$\frac{dZ}{dz}(D) = 0$$

The modal equation has an infinite number of solutions which are characterized by a mode shape function $Z_m(z)$ and a horizontal propagation constant k_m. The function $Z_m(z)$ is an eigenfunction and k_m or k^2_m is an eigenvalue. Finally the pressure can be writing as a sum of the normal modes:

$$p(r,z) \approx \frac{i}{\rho(z_s)\sqrt{8\pi r}} e^{\frac{-i\pi}{4}} \sum_{m=1}^{\infty} Z_m(z_s) Z_m(z) \frac{e^{ik_m r}}{\sqrt{k_m}} \quad (7)$$

The Prosim propagation model is able to approximate a source beam with a Gaussian shape, constant for all the frequencies, decomposing it as a sum of the normal modes each multiplied by the appropriate shading coefficient. The beam is parameterized by the aperture and tilt. The Prosim broadband normal mode model is in more detail described in [5,6].

2. PULSE COMPRESSION TECHNIQUES

Chirp pluses were used in these numerical experiments. Chirp is the nickname of Linear Frequency Modulation (LFM). It is a wideband and long duration frequency sweep. It is a noise-like signal. The differences between a chirp and a white noise signal are primarily the phase changes in chirp is linear, the phase change of a noise signal is random. A frequency band of chirp signal is limited whereas a noise signal's frequency band is unlimited ("white"). The chirp signal can be write in the following form in the time domain:

$$\begin{cases} A_0 \cos 2\pi\left(f_0 t + \frac{B}{2T} t^2 \right) & |t| \leq \frac{T}{2} \\ 0 & |t| > \frac{T}{2} \end{cases} \tag{8}$$

where T is the time duration of signal, f_0 is the center frequency and B is the bandwidth of signal. Spectrum of the signal after compression is given by:

$$Y(f) = H_N(f) \cdot H_O(f) \tag{9}$$

where Y(f) is the spectrum of the signal after compression, $H_N(f)$ is the spectrum of the received signal and H_O is the spectrum of the compression system. Signal y(t) in the time domain has the form:

$$y(t) = \int_{-\infty}^{\infty} H_N(f) H_O(f) e^{j\omega t} df \tag{10}$$

In case of matched filtering:

$$H_O(f) = H_N^*(f)$$

thus: (11)

$$y(t) = \int_{-\infty}^{\infty} H_N(f) H_N^*(f) e^{j2\pi f t} df \approx \frac{\sin(\pi B f_0 t)}{\pi B f_0 t} e^{j2\pi f_0 t} \tag{12}$$

Through matched filtering of the received signal with a transmit replica the pulse compression is obtained.

3. NUMERICAL EXPERIMENT

In these numerical experiments a Hanning weighted chirps of bandwidth 2 kHz and center frequency of 6 kHz with pulse duration of 500 ms was transmitted. The maximum source level was 200 dB ref. 1µPa at 1m (Fig.2).

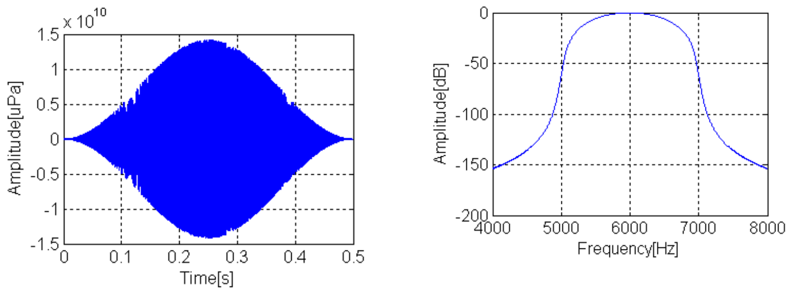

Fig.2 Transmitted chirp pulse in the time and frequency domain

Pulse compression was achieved through the use of the matched filter. The received signals were correlated with a chirp replica of the transmit waveform. The matched filtered data was used in order to examine the arrival time structure of the multipath.

The numerical experiments were repeated at ranges of 3, 6 and 9 km and with source depth of either 30 m. The receivers were set at water depths of 30, 50, 70 and 90 m respectively. Figure 3 shows the model of tested underwater acoustic channel and figure 4 shows sound speed profile for this channel. The range-independent calculations were performed.

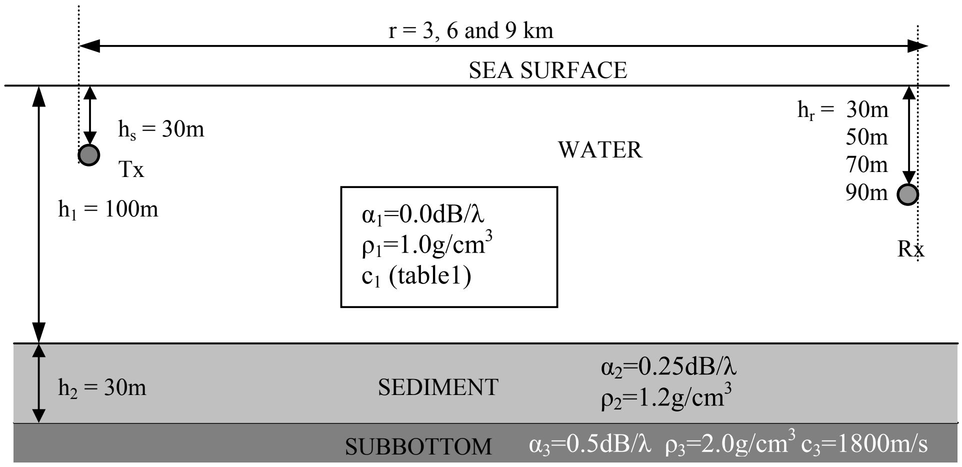

Fig.3 The model of shallow water hydroacoustic channel

The area of model is 100m in depth. The normal mode model assumes the bottom to consist of single sediment overlying a homogenous sub-bottom. The thickness of sediment layer is 30m. The sediment parameters were set: sound speed linearly increasing from 1580 to 1620m/s, attenuation constant 0.25dB/λ and relative density 1.2 (relative to 1g/cm^3, i.e. relative to the water value). In numerical experiment there is a homogenous sub-bottom with sound speed, relative density and attenuation of 1800m/s, 2.0 and 0.5dB/λ, respectively. Table 1 shows the value of sound speed profile for tested shallow water hydroacoustic channel.

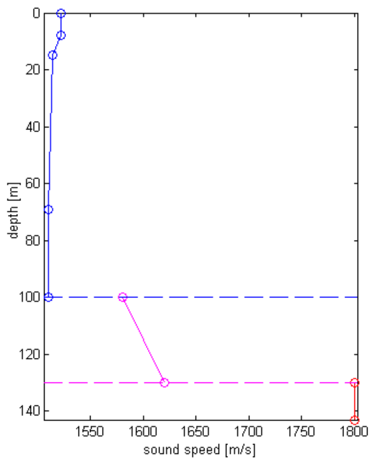

Fig.4 Sound speed profile for tested underwater acoustic channel

Tab.1 The shallow water sound speed profile

Depth [m]	Sound speed [m/s]
0	1522.1
8	1522.1
15	1514
69	1509.6
100	1509.6

Figures 5, 6 and 7 give examples of received signals at a range of 3, 6 and 9 km and depths of 30, 50, 70 and 90m, respectively. Figures 8, 9 and 10 show the received signals after matched filtering for receiver at a range of 3, 6 and 9 km and depths of 30, 50, 70 and 90m, respectively. These figures revealed the multipath arrival structures obtained in shallow water. The multiple reflection effect is obvious. The matched filtered received signals show variability in the arrival time. The observed time variability in the received signals increase with increasing range.

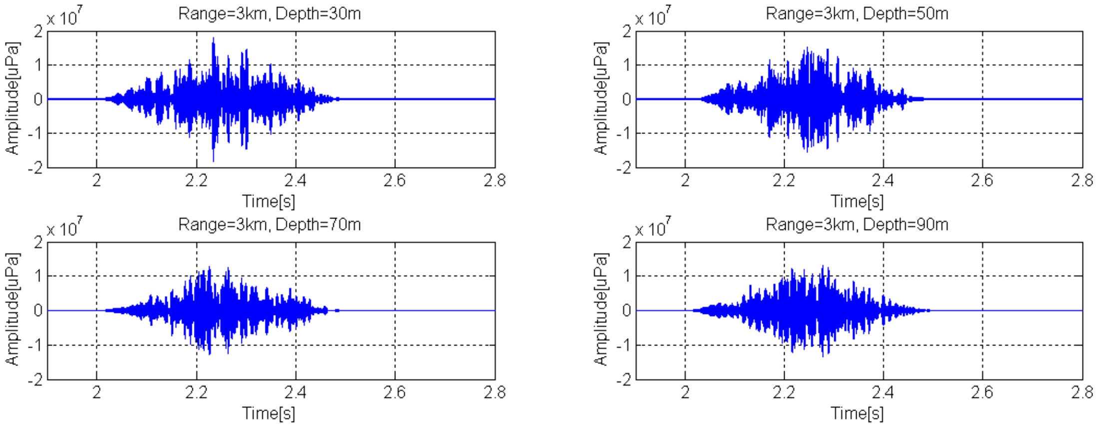

Fig.5 The received signals as calculated by BNM (Broadband Normal Modes) model for receiver at a range of 3 km and depths of 30, 50, 70 and 90m, respectively

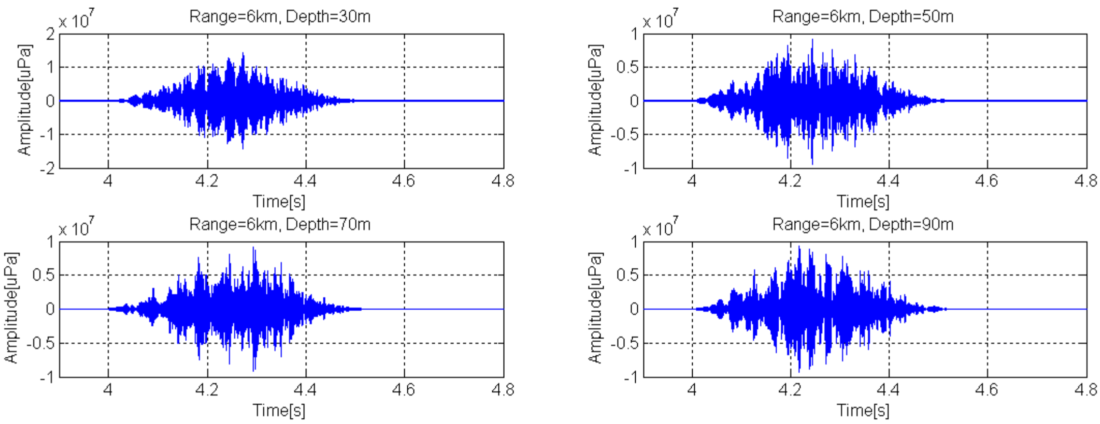

Fig.6 The received signals as calculated by BNM model for receiver at a range of 6 km and depths of 30, 50, 70 and 90m, respectively

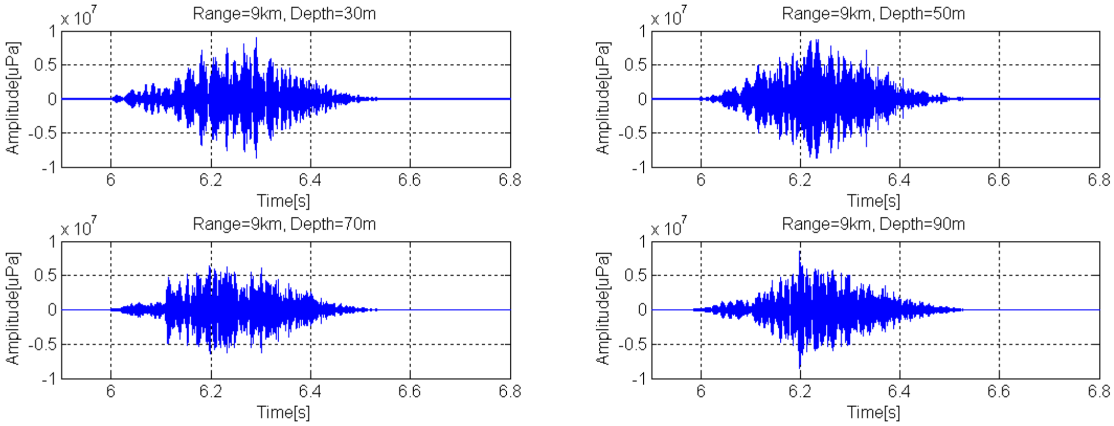

Fig.7 The received signals as calculated by BNM model for receiver at a range of 9 km and depths of 30, 50, 70 and 90m, respectively

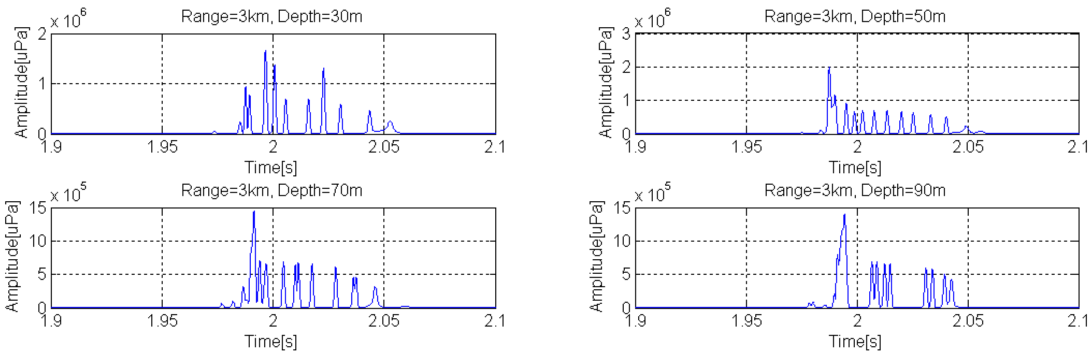

Fig.8 The received signals after matched filtering for receiver at a range of 3 km and depths of 30, 50, 70 and 90m, respectively

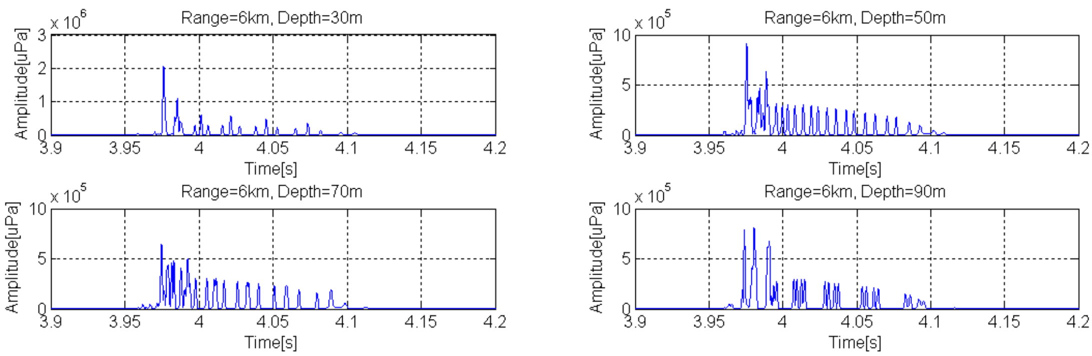

Fig.9 The received signals after matched filtering for receiver at a range of 6 km and depths of 30, 50, 70 and 90m, respectively

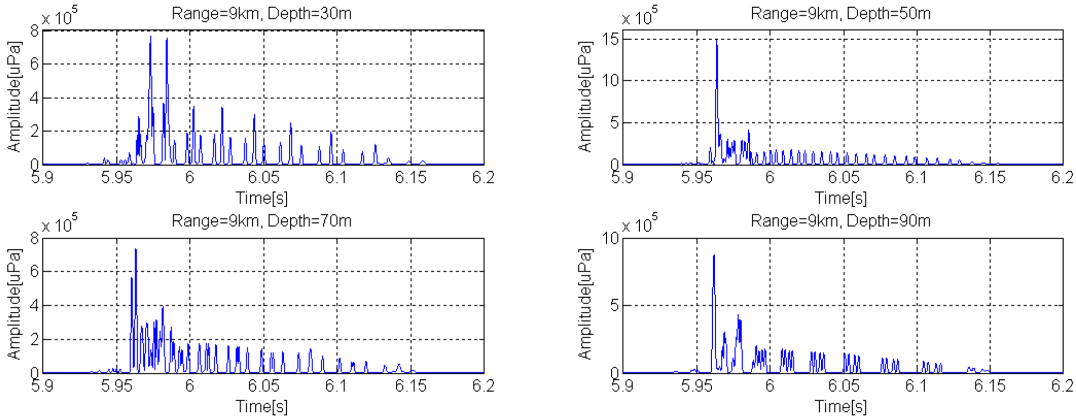

Fig.10 The received signals after matched filtering for receiver at a range of 9 km and depths of 30, 50, 70 and 90m, respectively

4. CONCLUSIONS

The paper has considered the long range shallow water hydroacoustic channel. Chirp signals have been reviewed in relation to underwater acoustic channel. The multipath effect in a shallow water channel has been discussed. The received chirp pulses were all matched filtered showing variability in arrival time and revealing the multipath structure. The results from numerical experiments clearly show temporal variability in the acoustic signals which is important pieces of information for the design of shallow water communication systems.

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