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Mathematical Modelling of Ultrasonic System for Riverbed Identification and Classification

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***Abstract*— Knowledge of seabed/riverbed properties is required to predict mine burial, to study the effect of habitat on fisheries etc. Collection of samples of seabed/riverbed sediment and their characterizations are tedious and time consuming tasks even for a small area. The nature of seabed/riverbed will be affects on the characteristics of reflected echo. Mathematical modeling of the river bed system is designed. The modeling of the system is based on the acoustic behavior of river (water) and river bed (river bottom layer). Various types of losses in the acoustic signal at water layers are calculated using standard acoustic wave propagation equation. Using these loss parameters and other channel introduced noises, the system is mathematically modeled. Using the mathematical model, it is possible to predict the behavior of the system and reflected echoes. With the known transmitted signal parameters and created reflected echoes an algorithm is developed for extracting the required parameters like water depth and layer types. The algorithm includes acquisition of reflected echoes, removal of noise, envelope detection, and computation of echo amplitude and classification of layer type.**

Keywords*— Mathematical modelling, acoustic signal, ultrasonic transducer, envelope detection

I. INTRODUCTION

Morphological studies are quite important because of the dynamics of the coastlines and rivers. Knowledge about the properties of riverbed is essential to detect sea mine ranges, to study the effect of biological species etc. Collection of riverbed samples or seabed samples is a difficult task. For these applications there arise needs for accurate and high resolution measuring techniques which was so far unavailable. The main disadvantage of the conventional Doppler profiling technique is that the bottom 10% to 15%of the depth range is not possible to measure. Riverbed classification using non acoustic techniques badly affects the real phenomena under study.

Conventional echo sounding experiences difficulty in penetration through hard sandy sediments. Also it experiences difficulty to extract small features. Received acoustic signal may be distorted by gas in sediments.

The speed of sound in water is 1500m/s. During the propagation of the sound wave it losses some of its acoustic energy. This energy loss is called attenuation. As a sound wave is attenuated, its amplitude is reduced. While acoustic energy travels well in water, it gets interrupted by a sudden change in medium, such as rock, sand or clay. When a moving sound pulse encounters such a medium, some fraction of its energy propagates into the new material. This amount of energy depends on various factors such as material loss of the particular sediment, speed of sound within that sediment etc. The echo bounces off and is received at the transducer. The rest is scattered in all directions. The echo maintains the frequency characteristics of the source wave. The nature of seabed/riverbed will be affects on the characteristics of the reflected echo.

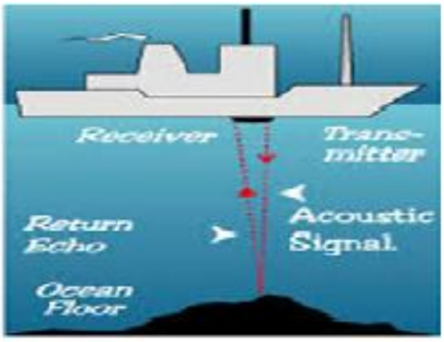

Fig. 1. Ultrasonic transducer transmitting acoustic signal and receiving corresponding reflected echo from the sea bed

The first step of riverbed type classification is signal acquisition from the riverbed. Ultrasonic transducers are used for signal acquisition from the riverbed [15]. The function of the ultrasonic transducer is to transmit acoustic signal into the water medium and receive subsequent returned echo reflected from objects or riverbed. The ultrasonic transducer operation is shown in Fig 1. Transducer possesses different modes of operation. It measures echoes one at a time at many locations.

Acoustic methods have wide applications in marine geology, hydrographic, marine engineering and fisheries to characterize the riverbed sediments. By this new acoustic method, classification of the river bed is possible.

This paper is organized as follows. Section II describes the mathematical modeling of the riverbeds. Generation of the echo incorporated by various types of transmission losses is included. Losses for riverbed types such as rock, sand, clay, mud and silt is discussed. Section III describes the envelope detection of the received echo using various methods. This section discusses the three methods 1) Envelope detection without using BPF, 2) Envelope Detection using BPF, 3) Envelope detection using Inphase-Quadrature method. Section IV presents the algorithm development for riverbed type classification and the riverbed thickness and depth calculation. Section V presents the profiling of the riverbed based on the conduction of the echo detection performed at each ping. By observing the riverbed profile we can distinguish between different types of river bed. In the Section VI we make a comparison between different envelope detection methods and the conclusions are presented.

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II. MATHEMATICAL MODELLING OF RIVERBEDS

The modeling of the system is based on the acoustic behavior of river (water) and river bed (river bottom layer). When a transmitted acoustic signal passes through water various types of losses will be happened to the signal. These losses are calculated based on the standard acoustic wave propagation equations. Also some losses will be happened to the signal at water-layer interface boundaries. These losses are calculated based on the acoustic impedance equations. Using these loss parameters and other channel introduced noises, the system is mathematically modeled using Matlab. Using the mathematical model we can predict the behavior of the system and reflected echoes for a particular transmitted signal without conducting any hardware realization and experimentation.

A. *Echo Generation*

The operating frequency range is ultrasonic frequency range. The input acoustic signal frequency is taken as33 KHz. The input signal frequency is represented as fi. The sampling frequency is taken as ten times the input acoustic signal frequency. Therefore the sampling frequency is 330 KHz. The time period of the input signal is

$$Ti = \frac{1}{33\times 10^3} = 30\mu s \tag{1}$$

Ti is the time period of the input signal. Therefore the sampling time should be 3µs.

B. *Transmission Losses*

During the transmission of the acoustic signal through the water, transmission loss occurs. Transmission loss (TL) consists of spreading and absorption losses. Spreading loss (SL) is termed as when a sound wave propagates away from the source a decrease in the level occurs uniformly in all directions. It is the major contribution of the transmission loss. Absorption loss (AL) occurs when the sound waves are absorbed by the medium (water) they encounter. The transmission loss can be represented by the following equation.

$$TL = SL + AL \tag{2}$$

where SL= 20 log (R) and AL= R× 8 dB/km. R is the distance travelled by the input acoustic signal.

Acoustic signal travels from the surface of the water body and strikes an element in the sea/river bed and get reflected back to the surface. Hence it travels twice the depth of the river. D denotes the depth. So the distance travelled by the signal is 2×D. The transmission loss in dB is

$$TL\ (dB) = 20 \log (2\times D) + 2 \times D\times 0.008\ dB/m \tag{3}$$

The transmission loss in voltage gain/loss is

$$TL = 10^{\frac{TL(dB)}{20}} \tag{4}$$

Amplitude of the received echo signal is

$$Rx\ amp = Tx\ amp \times TL \tag{5}$$

Where Tx amp represents the amplitude of the input acoustic signal. The time delay for generating echo is

$$T\ delay = \frac{2\times D}{1500} \tag{6}$$

Velocity of sound in water is 1500m/s. The take of time of the echo is

$$tof = 10 \times fi \times Tdelay \tag{7}$$

To remove different types of noises present in the channel the received echo is filtered using the BPF. Hence SNR can be improved. At different depths amplitude and duration of the received echoes are different. When the distance travelled by the acoustic signal is more amplitude of the reflected echo should become less. This is because when distance increases transmission losses also increases.

Fig. 2 shows the transmitted acoustic signal and the corresponding return echo for riverbed depth of 1m, 5m and 10m respectively. When the depth of the riverbed is more, amplitude of the reflected echoes should become less. For high riverbed depth, transmission loss will be high. Thus the strength of the echo will be less.

C. *Classifying Different Layer Types*

1) Rock: The reflection loss of acoustic signal in rock lies between 0dB to 3 dB. In terms of voltage the reflection loss in rock is

$$Rloss = 10^{\frac{Rloss(dB)}{20}} \tag{8}$$

So the amplitude of the received echo signal from the rock type river bed is

$$Rx\,rock = \frac{Tx\ amp}{TL\times IL\times Rloss} \tag{9}$$

where IL is the insertion loss of the ultrasonic transducer. The transmission loss of the acoustic signal during its propagation through the rock type river bed is

$$T\ rock = 1 \times T \tag{10}$$

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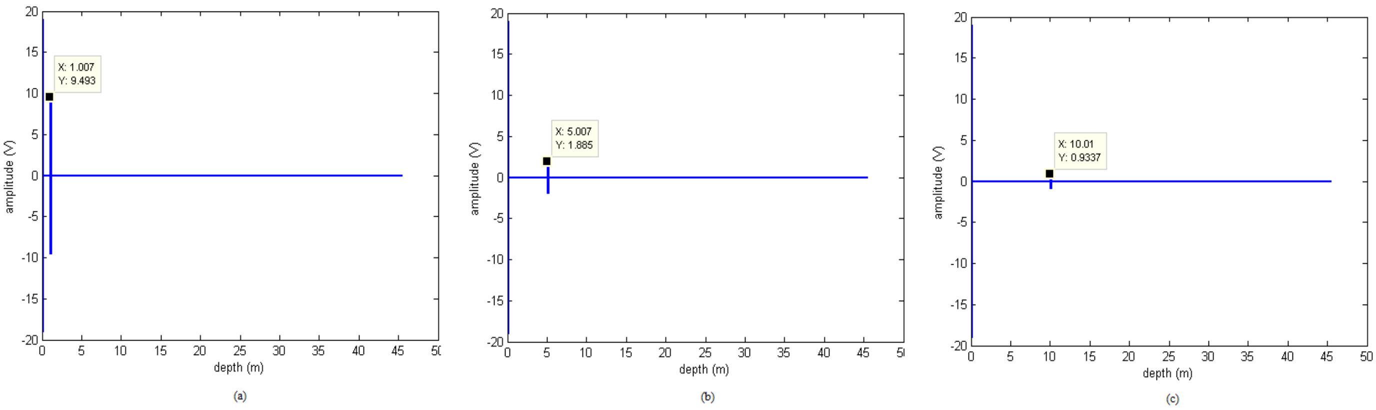

Fig. 2. Transmitted acoustic signal and the corresponding reflected echo for three riverbed depths. (a) River depth of 1m. (b) River depth of 5m. (c) River depth of 10m.

where T is the distance travelled by the acoustic signal through the riverbed i.e. the thickness of the riverbed.

1) Sand: The reflection loss of acoustic signal in sand lies between 3dB to 9 dB. In terms of voltage the reflection loss in sand is

$$Sloss = 10^{\frac{Sloss(dB)}{20}} \tag{11}$$

So the amplitude of the received echo signal from the sand type river bed is

$$Rx\ sand = \frac{Tx\ amp}{TL \times IL \times Sloss} \tag{12}$$

The transmission loss of the acoustic signal during its propagation through the sand type riverbed is

$$T\ sand = 16 \times T \tag{13}$$

2) Clay: The reflection loss of acoustic signal in clay lies between 9dB to 12dB. In terms of voltage the reflection loss in clay is

$$\text{Closs} = 10^{\frac{\text{Closs(dB)}}{20}} \tag{14}$$

So the amplitude of the received echo signal from the clay type river bed is

$$\text{Rx clay} = \frac{\text{Tx amp}}{\text{TL} \times \text{IL} \times \text{Closs}} \tag{15}$$

The transmission loss of the acoustic signal during its propagation through the clay type riverbed is

$$\text{T clay} = 2 \times \text{T} \tag{16}$$

3) Mud: The reflection loss of acoustic signal in mud lies between 12dB to 18dB. In terms of voltage the reflection loss in mud is

$$\text{Mloss} = 10^{\frac{\text{Mloss(dB)}}{20}} \tag{17}$$

So the amplitude of the received echo signal from the mud type river bed is

$$\text{Rx mud} = \frac{\text{Tx amp}}{\text{TL} \times \text{IL} \times \text{Mloss}} \tag{18}$$

The transmission loss of the acoustic signal during its propagation through the mud type riverbed is

$$\text{T mud} = 6 \times \text{T} \tag{19}$$

4) Silt: The reflection loss of acoustic signal in silt lies between 18dB to 24 dB. In terms of voltage the reflection loss in silt is

$$\text{Siltloss} = 10^{\frac{\text{Siltloss(dB)}}{20}} \tag{20}$$

So the amplitude of the received echo signal from the rock type river bed is1

$$\text{Rx silt} = \frac{\text{Tx amp}}{\text{TL} \times \text{IL} \times \text{Siltloss}} \tag{21}$$

The transmission loss of the acoustic signal during its propagation through the mud type riverbed is

$$\text{T silt} = 8 \times \text{T} \tag{22}$$

III. ENVELOPE DETECTION OF THE ECHO

For the classification of different types of river beds envelope detection of the received echo should be performed first. Envelope detection can be done via different methods. They are envelope detection without using band pass filter (BPF), envelope detection using band pass filter, envelope detection using Inphase-Quadrature (IQ) method [16].

Input acoustic signal travels from the surface of the water body and strikes an element in the sea/river bed and get reflected back to the surface. These reflected echoes are collected. Width of the echo should be greater than the product of number of cycles and half of the time period of the input signal. Otherwise it should not be treated as echo. It can be mathematically expressed as

$$\text{Echo width} > \frac{\text{Number of cycles} \times \text{Timeperiod}}{2} \qquad (23)$$

A. Envelope Detection without using BPF

The purpose of the algorithm is to detect echoes that reflected from the water-layer boundaries. By using the mathematical model developed we can create the reflected echoes for various water depths and layer types. With the known transmitted signal parameters and created reflected echoes the algorithm will be developed for extracting the required parameters like water depth and layer types. The algorithm will consist of the following blocks. Acquisition of reflected echoes (collection of reflected echoes to array), rectification of signal (to remove the negative half cycles), computation of noise threshold, computation of echo start to find the water depth, computation of echo amplitude, computation of reflection coefficient and classification of layer type from the computed reflection coefficients.

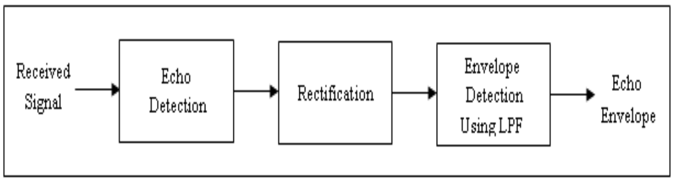

Fig. 3. Envelope detection of the echo without using BPF.

The received echo signal is mathematically represented as A sin (ωt + ϕ), where ϕ is the phase shift. A is the amplitude of the received echo signal. The full wave rectified output can be mathematically represented as the absolute value of the input. The absolute value is the positive square root of the square of the input. The full wave rectification output is

$$Y = \sqrt{A^2 \sin^2(\omega t + \phi)} \qquad (24)$$

The term $\sqrt{A^2 \sin^2(\omega t + \phi)}$ can be written as $A\sqrt{\frac{1-\cos(2\omega t + 2\phi)}{2}}$. So the above equation changes to the following equation.

$$Y = A\sqrt{\frac{1}{2} - \frac{\cos(2\omega t + 2\phi)}{2}} \qquad (25)$$

Next step is low pass filtering the echo to generate the echo envelope. By low pass filtering the above output, the high frequency component $\frac{\cos(2\omega t + 2\phi)}{2}$ is removed. Thus the LPF output i.e. the echo envelope is

$$Z = A\sqrt{\frac{1}{2}} = 0.707A \qquad (26)$$

Using this echo envelope we can calculate depth and thickness of the river/sea bed. Due to channel introduced noises and other noises the echogram is contaminated by these noises. In order to remove these noises a noise threshold is defined. By applying the noise threshold, it is possible to extract the echo signal only. The point which first crosses the threshold is taken as depth. Signal below the threshold should be excluded.

The next calculation is the peak detection of the echo. Point having maximum amplitude is taken as the peak of the echo envelope.

The second received echo signal is used for the thickness calculation. Duration and distance travelled by the second echo is calculated. From this the thickness of the riverbed can be derived. This method has a limitation. It requires a minimum signal to noise ratio (SNR) of 22 dB. Below 22 dB, depth and thickness measurement and peak detection is not possible.

B. Envelope Detection using BPF

This method is similar to the above method. An addition is that a BPF for noise removal is used in this method.

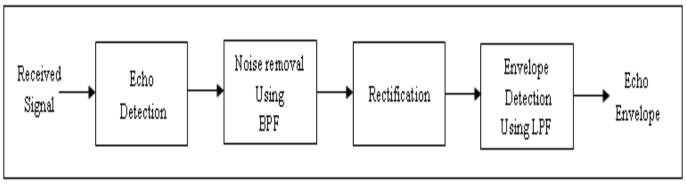

Fig. 4. Envelope detection of the echo using BPF.

The echo is detected first. The detected echo possesses different kinds of noises. Usually noises are of high transitions. They usually occur at high frequency. Before the rectification noises can be removed using the BPF which is placed before rectifier. Rectification and envelope detection is then performed to produce the echo envelope. A noise threshold is defined and depth and thickness can be calculated. Then peak detection of the echo is performed.

Limitations of the envelope detection without using BPF method can be overcome by inserting a BPF before the rectification of the echo signal. Hence the minimum required SNR reduces to 13 dB. Here the results become more accurate.

C. Envelope Detection using Inphase Quadrature Method

The envelope detection of the echo can also be done using this method.

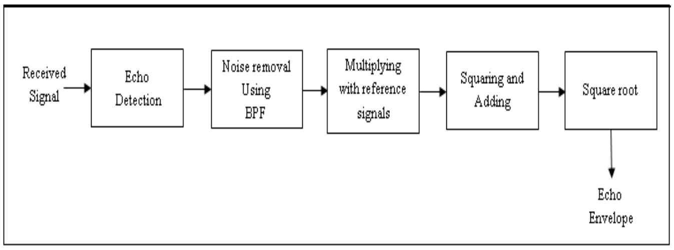

Fig. 5. Envelope detection of the echo using inphase quadrature method.

Initially the echo detection is performed. The obtained echo signal is filtered using BPF to remove the noise. Two reference signals are taken- sine wave and cosine wave. Both signals have the same frequency of the echo signal. The procedure for this method is

- Multiply the echo signal with the reference sine wave.
- Multiply the echo signal with the reference cosine wave.
- Filter both the signals using LPF.
- Sum of squares of both the low pass filtered signals is performed.
- The square root of the obtained signal is taken to get the echo envelope.

The echo signal is mathematically represented as $A\sin(\omega t + \phi)$ where ϕ is the phase shift. A is the amplitude of the received echo signal. The two reference signals can be represented as $B\sin(\omega t)$ and $C\cos(\omega t)$. Both signals have same frequency as that of echo signal. B and C represent the amplitude of sine and cosine wave respectively.

The first step is the multiplication of the echo signal with the first reference (sine) wave. It is indicated as the variable V. It can be mathematically represented as

$$V = A\sin(\omega t+\phi)\, B\sin(\omega t+\phi) \tag{27}$$

The term $A\sin(\omega t+\phi)\, B\sin(\omega t+\phi)$ can be written as $\frac{AB}{2}[\cos(\omega t+\phi-\omega t)-\cos(\omega t+\phi+\omega t)]$. So the above equation changes to the following equation.

$$V = \frac{AB}{2}[\cos(\phi)-\cos(2\omega t+\phi)] \tag{28}$$

By low pass filtering the above output, the high frequency component $\cos(2\omega t+\phi)$ is removed. Thus the LPF output X is

$$X = \frac{AB}{2}\cos(\phi) \tag{29}$$

The next step is the multiplication of the echo signal with the second reference (cosine) wave. It is indicated as the variable W. It can be mathematically represented as

$$W = A\sin(\omega t+\phi)\, C\cos(\omega t+\phi) \tag{30}$$

The term $A\sin(\omega t+\phi)\, C\cos(\omega t+\phi)$ can be written as $\frac{AC}{2}[\sin(\omega t+\phi+\omega t)+\sin(\omega t+\phi-\omega t)]$. So the above equation changes to the following equation.

$$W = \frac{AC}{2}[\sin(2\omega t+\phi)-\sin(\phi)] \tag{31}$$

Low pass filtering the above output results in the removal of the high frequency component $\sin(2\omega t+\phi)$. The LPF output Y is

$$Y = \frac{AC}{2}\sin(\phi) \tag{32}$$

Squaring and adding both the low pass filter outputs yields

$$X^2+Y^2 = \left(\frac{AB}{2}\cos\phi\right)^2+\left(\frac{AC}{2}\sin\phi\right)^2 = \left(\frac{AB}{2}\right)^2\cos^2\phi+\left(\frac{AC}{2}\right)^2\sin^2\phi \tag{33}$$

The final step is the generation of the echo envelope. The echo envelope is indicated as Z. Taking the square root of the above output gives the echo envelope. The echo envelope is

$$Z = \sqrt{X^2+Y^2} = \sqrt{\left(\frac{A}{2}\right)^2 B^2\cos^2\phi+\left(\frac{A}{2}\right)^2 C^2\sin^2\phi} \tag{34}$$

Thus the echo envelope is

$$Z = \frac{A}{2}\sqrt{B^2\cos^2\phi+C^2\sin^2\phi} \tag{35}$$

If B=C i.e. the amplitude of both the reference signals are same, the above equation becomes

$$Z = \frac{AB}{2} \tag{36}$$

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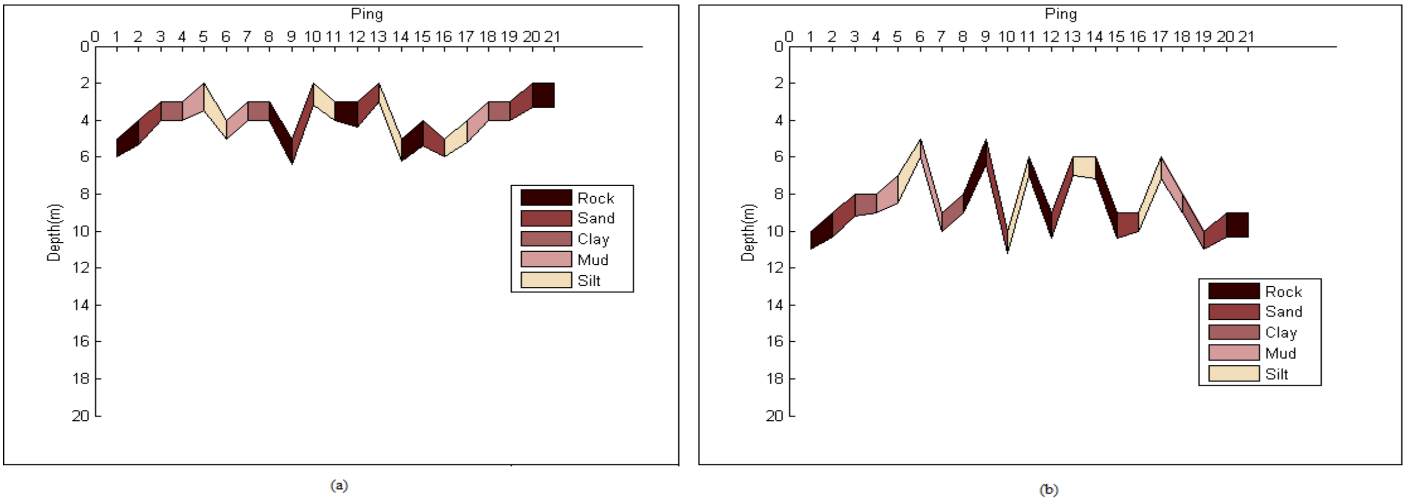

Fig. 6. Riverbed profile. (a) River depths under 5m. (b) River depths under 10m.

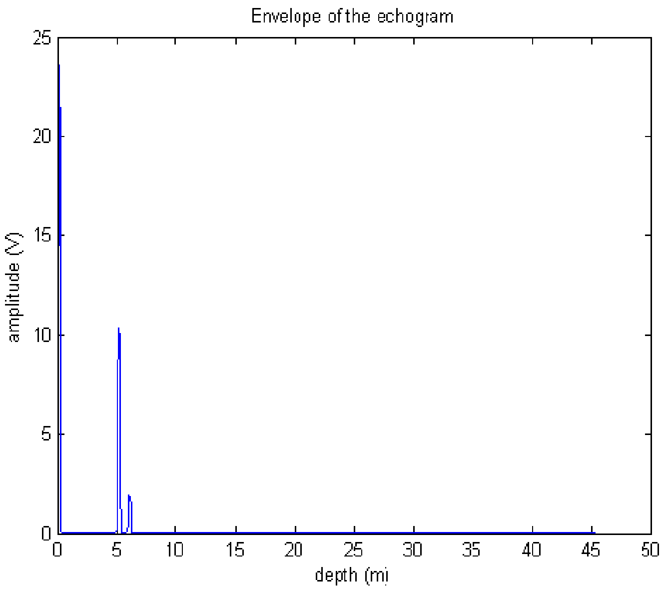

Fig. 7. Echogram Envelope.

The detected echo is represented as I_X . The detected echo is mathematically represented by the following equation.

$$I_X = \begin{cases} A\sin(\omega t + \phi) & for \quad 0 \le t \le 300\mu s \\ 0 & for \quad 300\mu s < t \le \dfrac{D}{V} \\ A\sin(\omega t + \phi) & for \quad \dfrac{D}{V} < t \le \dfrac{D}{V} + 300\mu s \\ 0 & for \quad t > \dfrac{D}{V} + 300\mu s \end{cases} \qquad (37)$$

After the envelope detection, the obtained envelope of the echo is represented as O_X . The echo envelope can be mathematically represented by the following equation.

$$R_X = \begin{cases} \dfrac{AB}{2} & for \quad 0 \le t \le 300\mu s \\ 0 & for \quad 300\mu s < t \le \dfrac{D}{V} \\ \dfrac{AB}{2} & for \quad \dfrac{D}{V} < t \le \dfrac{D}{V} + 300\mu s \\ 0 & for \quad t > \dfrac{D}{V} + 300\mu s \end{cases} \qquad (38)$$

Compared to the first method high SNR can be achieved via this envelope detection method. Here the minimum required SNR is 4dB.

IV. DEPTH AND THICKNESS CALCULATION AND RIVERBED TYPE IDENTIFICATION AND CLASSIFICATION

The echo start is computed to find out the water depth. An appropriate threshold is taken to for calculating the river depth and the algorithm is performed throughout the echo gram. The point which first crosses the threshold is taken as depth.

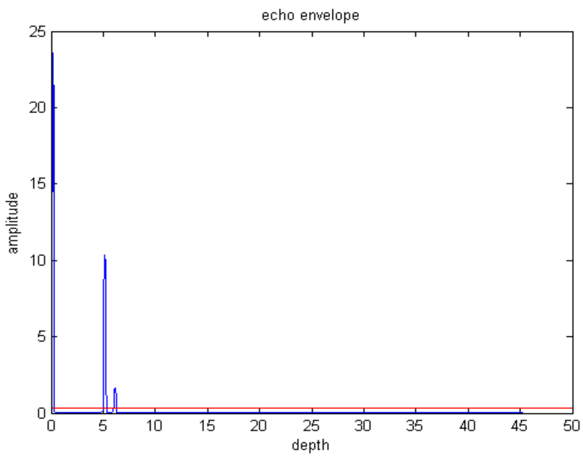

Fig. 8. Depth and riverbed thickness calculation algorithm from the echo envelope.

The reflection ratio is calculated to find out which type of riverbed is present. It is the ratio of transmitted signal amplitude and the received echo amplitude. For different types of riverbeds the reflection ratios varies.

TABLE I. REFLECTION RATIOS FOR VARIOUS TYPES OF RIVER BEDS

Sediment Types	Reflection ratio
Rock	0 to 3
Sand	3 to 9
Clay	9 to 12
Mud	12 to 18
Silt	18 to 24

The second received echo signal is used for the thickness calculation. Envelope detection of the received echogram is carried out using any of the envelope detection methods explained above. After the echo detection corresponding duration and distance travelled by the second echo is calculated. From this the thickness of the riverbed can be derived. Fig. 8 shows the algorithm for the calculation of river depth and riverbed thickness.

V. PROFILING

In the profiling of the river bed, echo detection is performed at each ping. Depth and thickness of the riverbed is calculated at each ping. Based on the obtained information profiling of the river bed can be done. Riverbed profile at various depths and riverbed thicknesses is shown in Fig. 6.

By observing the profile we can distinguish between different types of river bed.

VI. DISCUSSIONS AND CONCLUSIONS

Envelope detection using inphase quadrature method is better when compared to the other two methods.

TABLE II. MINIMUM REQUIRED SNR AT DEPTHS 1, 2, 5 AND 10 METERS FOR ENVELOPE DETECTION WITHOUT USING BPF

Depth	Minimum Required SNR
1 m	20 dB
2 m	21 dB
5 m	22 dB
10 m	23 dB

TABLE III. MINIMUM REQUIRED SNR AT DEPTHS 1, 2, 5 AND 10 METERS FOR ENVELOPE DETECTION USING BPF

Depth	Minimum Required SNR
1 m	11 dB
2 m	12 dB
5 m	13 dB
10 m	15 dB

TABLE IV. MINIMUM REQUIRED SNR AT DEPTHS 1, 2, 5 AND 10 METERS FOR ENVELOPE DETECTION USING INPHASE QUADRATURE METHOD

Depth	Minimum Required SNR
1 m	2 dB
2 m	3 dB
5 m	4 dB
10 m	5 dB

Table I-III shows that envelope detection using inphase quadrature method which gives high SNR compared to the other two methods.

The nature of seabed/riverbed will be affects on the characteristics of reflected echo. When the signal is transmitted to the bottom of the water bodies, loss occurs for each layer of water. These losses also can be calculated based on the acoustic impedance equations. By examining the characteristics of the echo it is possible to extract parameters like water depth, peak of the echo and layer types. The mathematical model produces predictions about the behavior of seabed types. This is a simple, highly effective, low cost method. Out of these systems, side scan sonar is used because of the interest in image processing.

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