

# Fast M-sequence Transform for Quasi-Backscatter Sonar in Fisheries and Zooplankton Survey Applications

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## Abstract

*Existing acoustic systems commonly used in fisheries and zooplankton surveys are based on pulsed perturbation technique. This work applies binary Maximum-Length Sequences (MLS) as periodic perturbation signals for Sonar systems. Using MLS of pseudo-random nature, much higher signal-to-noise ratio (SNR), while keeping a similar spatial resolution as that using pulsed perturbation can be obtained. A fast algorithm, exploiting the Fast Hadamard Transform, is implemented for an efficient post-processing of target responses. After a brief introduction of MLS fundamentals and a fast M-sequence-based algorithm, this paper will discuss preliminary experimental results conducted in underwater environment using an experimental model.*

## 1. Introduction

Applications of acoustic techniques to marine biological surveys provide a potential means to sample the ocean efficiently and study the ecosystem dynamics non-invasively [1]. Much progress has been made and reported in zooplankton and fisheries acoustics over the past few decades [2]-[4]. The existing acoustic systems commonly used in fisheries and zooplankton surveys are based on pulsed perturbation technique. Such perturbation technique will suffer from poor signal-to-noise ratio (SNR) for long survey ranges without high intensity sounding. High intensity sounding has been found not environment-friendly. It may have dramatically negative impact on ocean ecosystem. Recently, maximum-length sequences (MLS) have also been applied in ocean

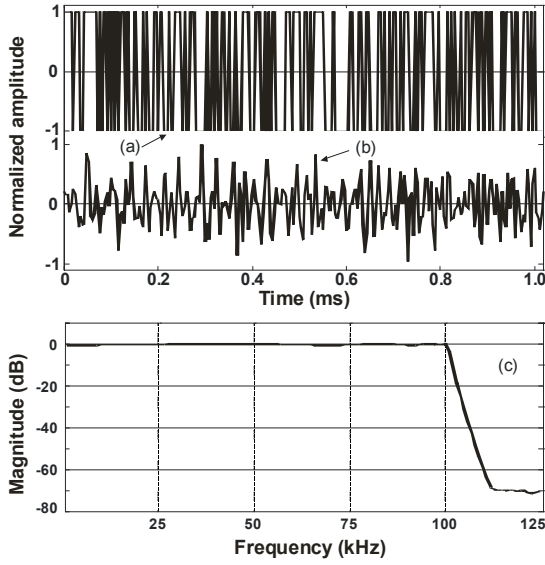
acoustic tomography [5], but merely used for transmission mode. In this paper we discuss the potential applications of binary MLS in sonar systems to ocean fisheries and zooplankton survey. Binary periodic MLS possess a number of number-theory properties which make them very attractive in various applications of science and engineering fields. Among them, low peak factor and excellent auto-correlation characteristics will be exploited in the work [7]. In exploiting their attractive properties, transmitter and receiver devices of the sonar system were arranged separately, but closely together facing target (detecting) direction, in so-called quasi-backscattering mode. In Sec. 2, we will introduce fundamentals of binary MLS and MLS-based algorithm for post-processing underwater target responses. Section 3 will discuss implementation issues and preliminary experiments conducted in water tank with simulated targets. Concludes are given in Sec. 4.

## 2. Fast Maximum-Length Sequence Transform

An  $n$ -stage linear shift-register can generate binary periodical sequences of maximal period length of  $L = 2^n - 1$  [8]. These sequences are referred to as maximal-length sequences (MLS),  $n$  is said to be the degree of the sequences. MLS possess a number of important properties [8] that make them widely useful in broad scientific and engineering fields. In relation to the current application, note that the *auto-correlation function* of MLS is a two-valued function [9] with

$$\phi(i) = \frac{L+1}{L} \delta(i) - \frac{1}{L}; \quad 0 \leq i < L. \quad (1)$$

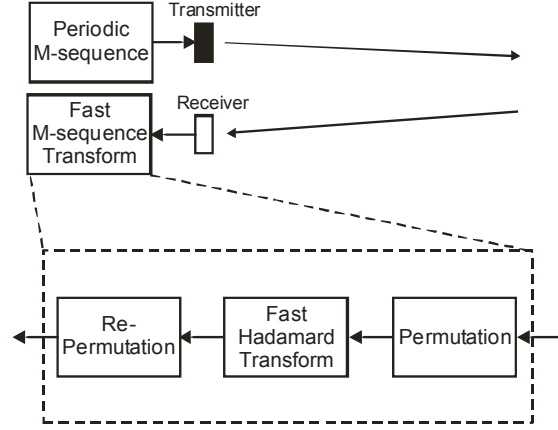
In this section we restrict our discussion to the digital



**Figure 1.** Waveforms of a maximum-length sequence (MLS) with a period length of 255 points, generated at a sampling frequency of 250 kHz. (a) MLS in its bipolar form. (b) Waveform of low-pass filtered MLS. The limit frequency of the low-pass filter is 100kHz. (c) Normalized magnitude spectrum of the low-pass filtered MLS in (b).

domain. From its auto-correlation function, it can be readily deduced that its power spectral density function is of a broadband nature and covers the entire frequency range except for the zero-frequency. Fig. 1 (a) illustrates one period waveform of the bipolar MLS with a degree of 8 ( $n = 8$ ) generated at a sampling frequency of 250 kHz. In underwater acoustics backscattering applications, bipolar MLS are generated periodically. When periodical MLS are sent through a low- or band-pass filter, the waveform of the filtered MLS will become noise-like as shown in Fig 1 (b). Due to the flat power spectrum of the original MLS the waveform in Fig 1 (b) assumes a magnitude spectrum similar to that of the low-pass filter as shown in Fig 1 (c). MLS possess highly similar random properties as random noise, but they are periodically deterministic and have a strict time structure within its period. Therefore, they are known as pseudorandom noise in the relevant literature [8].

Due to their broadband, pseudorandom nature, MLS are one of the signal classes suitable for quasi-backscattering sonar. From the acoustic excitation to the



**Figure 2.** Flow diagram for obtaining impulse response of an underwater system under test using the Fast M-sequence Transform. The system under test is excited by a periodic M-sequence. The system response to the M-sequence is M-sequence-transformed directly in time domain into the impulse response. The Fast M-sequence Transform is pursued in terms of adopting the Fast Hadamard Transform.

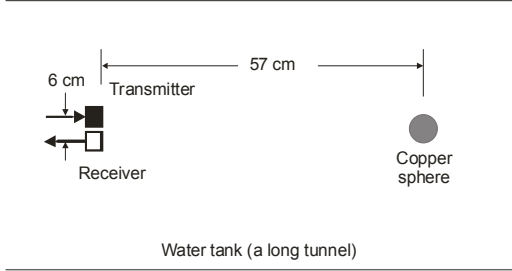
target response at the receiver sensor, it can be treated to a certain extent as a time-invariant system under test (SUT) possessing an impulse response  $h(i)$ . Using a periodic bipolar MLS  $\{m_i\}$  as the input signal of the underwater SUT, one period of its output signal  $\{s_i\}$  is the receiver response to the acoustic MLS excitation, received after the SUT arrives at its steady state. Taking Eq. (1) [9] into consideration, the normalized periodic cross-correlation function between  $\{m_i\}$  and  $\{s_i\}$  results predominantly in the impulse response of the SUT [6]:

$$\mathbf{h} \approx \frac{1}{L+1} \mathbf{M} \cdot \mathbf{s} \quad (2)$$

where  $\mathbf{h} = [h_0, h_1, \dots, h_{L-1}]^T$  and  $\mathbf{s} = [s_0, s_1, \dots, s_{L-1}]^T$  are column vectors of  $L$  elements,  $\mathbf{M}$  is a square matrix of  $L \times L$  in dimension, its row elements consist of the used MLS. In the relevant literature Eq. (2) is referred to as *M-sequences transform* [11]. Matrix  $\mathbf{M}$  is permutationally similar to Hadamard matrix [10][11]:

$$\mathbf{M} = \mathbf{P}_2 \mathbf{H} \mathbf{P}_1 \quad (3)$$

where  $\mathbf{H}$  is a Sylvester-type Hadamard matrix.  $\mathbf{P}_1$  and  $\mathbf{P}_2$  denote permutation and re-permutation matrix. Equation (3) implies an efficient algorithm for performing the M-sequences transform by adopting the fast Hadamard transform [10][11]. A computation of the fast

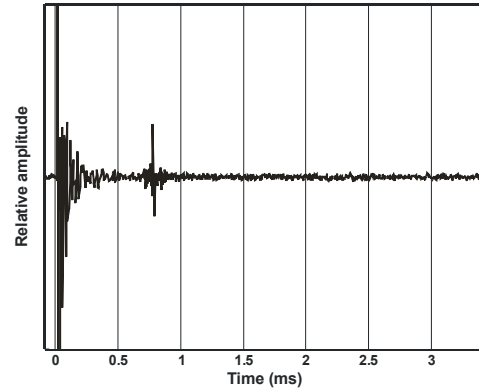


**Figure 3.** Experimental model in underwater environment. A copper sphere of 6 cm in diameter is 57 cm away from the sonar transducers. A pair of broadband transducers is arranged in quasi-backscattering mode.

Hadamard transform, which requires only  $L \times n$  additions / subtractions, is more efficient than a fast Fourier transform (FFT). Fig. 2 shows the major steps of the Fast MLS Transform (FMT) for obtaining impulse responses of the underwater backscattering SUT. Determination of the subsequent permutation matrices has been well documented in [6],[9],[11].

### 3. Experiments in a water tank

The quasi-backscattering sonar concept using MLS described in previous section has been tested in a water tank. The tank is of dimension of 1m x 1m x 20 m. A pair of broadband transducers (MSI 1-3 composite) are arranged 6 cm apart in the underwater environment, facing target direction. A copper sphere of 6 cm (Cu60) in diameter is hanging 57 cm away from the transducers in the water tank. Figure 3 shows a photo of the experimental setup. An MLS of  $2^{15} - 1$  in length is used at a sampling frequency of 200 kHz for the measurement. Purposely we reduce the gain of the amplifier by 40 dB in



**Figure 4.** Backscattering result in underwater environment. A copper sphere of 6 cm in diameter is 57 cm away from the sonar transducers. After direct strong electromagnetic coupling and spillover, a target reflection is identified at 0.76 ms.

order to prove a SNR improvement. The measurement result as shown in Fig. 4 still shows a target reflection at 0.76 ms after a strong electromagnetic coupling and ‘spillover’ impulse, corresponding to about 57 cm away. Even in the reduction of amplifier gain a satisfactory SNR can also be achieved in this experiment. The achieved SNR is similar to that using traditional pulsed sounding when a total 80dB gain would be additionally set at transmission and reception amplifiers.

### 4. Discussions

The impulse response of the backscattering by an individual target (Cu60) obtained from Eq. (2) and shown in Fig. 3 can be used to compute its target strength (TS) by [12]:

$$TS = 20 \log_{10} |r H(f) / W(f)|, \quad (4)$$

where the  $H(f)$  is the Fourier transform of the  $h(t)$ ,  $r$  is the distance between the center of the transducers to the target. The function  $W(f)$  is the Fourier transform of the autocorrelation function of M-sequence and equals to 1 for discrete signal as assumed at the beginning of this paper (Sec. 1). However, Eq. (4) can also be used for continuous signals and the corresponding  $W(f)$  would be a Sinc function defined as:

$$W(f) = \tau \left[ \frac{\sin(\omega\tau/2)}{\omega\tau/2} \right], \quad (5)$$

where  $\omega$  is the angular frequency and  $\tau$  is the pulse width (or width of one bit) of the autocorrelation function. If the targets are marine organisms such as fish or zooplankton, their target strengths can be uniquely determined [3].

## 5. Conclusions

Binary periodic maximum-length sequences (MLS) have been used for underwater quasi-backscattering sonar technique. MLS possess a number of excellent properties that make them suitable for quasi-backscattering sonar technique in achieving dramatically improved signal-to-noise ratio. The implemented measurement technique has been tested in a water tank using a simulated target to demonstrate the feasibility of the measurement concept. The measurement results in underwater environment have confirmed that MLS are suitable perturbation signals for sonar applications and a fast algorithm termed fast M-sequence transform (FMT) is efficient to process the target responses in order to yield backscatter impulse responses. The MLS and FMT technique can be used in fisheries and zooplankton survey applications.

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