

Robust Detection of Underwater Targets Using a Nonlinear Energy Tracker

Minho Cheong and Yong-Hwan Lee
School of Electrical Engineering, Seoul National University
Kwanak P. O. Box 34, Seoul 151-744, Korea
E-mail: ylee@snu.ac.kr

Abstract-- Conventional detection methods estimate the Doppler characteristics of the underwater target by processing the received signal in the frequency domain, such as the use of the discrete Fourier transform and filter bank structures. In this paper, we propose a robust scheme for estimation of the Doppler characteristics of the underwater target by employing nonlinear processes. Since the proposed method is processed in the time domain, it can significantly reduce the computational complexity. The proposed scheme can also be used for estimation of the velocity and distance of the target. The performance of the proposed scheme is analyzed and verified by computer simulation.

I. INTRODUCTION

The use of sonar systems has been widely applied to detection of underwater targets [1]. In an active towed array sonar system (A-TASS), the frequency characteristics of the received signal can be obtained by using continuous wave (CW) or linear frequency modulation (LFM) sonar as an active sonar source [2]. In these sonar systems, the information on the underwater moving target can be extracted from the Doppler characteristics of the received signal. To estimate the Doppler characteristics of the target, the received signal is usually converted into the frequency domain using a conventional method such as the discrete Fourier transform (DFT) and filter bank structures [2,3]. But the use of these conventional methods may geometrically increase the computational complexity to enhance the resolution in the frequency domain.

In this paper, we consider detection of underwater moving targets by employing a simple nonlinear tracker processed in the time domain, significantly reducing the computational complexity compared to the conventional methods. We employ a nonlinear energy tracker called Teager algorithm [4,5] to estimate the Doppler characteristics of the target. The Teager tracker needs the use of a small memory, making it enable to provide fast adaptation to time-varying characteristics. Since the underwater target detector is usually operating in very harsh noise environment, the output of the Teager tracker can be severely corrupted by non-Gaussian noise. The output of the Teager tracker is further processed

using a nonlinear filter to provide performance robust to harsh channel condition.

In Section II, we describe the proposed scheme with brief discussion of conventional detection methods. The performance of the proposed detection scheme is analyzed and verified by computer simulation in underwater environment which is approximately modeled by a ray tracing method in Section III. Finally, concluding remarks are summarized in Section IV.

II. PROPOSED DOPPLER DETECTION METHODS

Assume that an underwater target is moving with radial velocity v_T . When a CW sonar is used, which is widely employed in the A-TASS [1]. The Doppler shift due to the movement can be represented by

$$f_D = f_0 \frac{v_T}{v_s} \quad (1)$$

where f_0 is the transmit sonar frequency and v_s is the underwater velocity of the sonar signal. For example, an underwater target with velocity 30 Knots can make a Doppler shift of up to 60 Hz when a 6 kHz CW sonar is applied [2].

The sonar spectrum is broadened due to the effect of scattering and Doppler shift under the water. The spectral ambiguity function $\phi(n, f)$ of the underwater Doppler spread can be defined by [2]

$$\phi(n, f) = \frac{\left| \sin \left(\frac{\pi \delta (N - |n - n_0|)}{f_s} \right) \right|^2}{\left| \sin \left(\frac{\pi \delta_0}{f} \right) \right|} \quad (2)$$

where the value δ making $\phi(n, f)$ maximum is called the average Doppler shift of the target.

The Doppler characteristics of the received signal can be obtained by detecting the peak in the frequency domain in conventional Doppler detection schemes. As a result, it may be required to have very fine spectral resolution enough to detect the Doppler frequency of the target.

The use of a filter bank structure has been widely applied to the CW sonar detection system [2,3], where the center frequency of each filter is different. Thus, the Doppler shift of the target can be estimated by detecting the center frequency

of the filter with the maximum output. However, it may not be easy to implement these filters so as to have an acceptable performance with limited complexity. The filter bank structure can be easily replaced with the use of the DFT method [3]. It can avoid the difficulty to design non-overlapping filters between the frequency bins. The DFT scheme can be realized using the fast Fourier transform (FFT) operation, but its computational complexity increases geometrically as the frequency resolution linearly increases. This problem can be alleviated by processing the signal in the time domain.

Assume that a tone signal $s(t)$

$$s(t) = A \cos(2\pi f_d t + \theta) \quad (3)$$

is sampled at a rate of $f_s = \frac{1}{T_s}$. When the sampled signal $s[k]$ at time $t = kT_s$ is applied to the Teager energy tracker whose output is given by [4,5]

$$T[k] = s^2[k] - s[k+1]s[k-1], \quad (4)$$

the output of the Teager tracker is

$$T[k] = A^2 \sin^2(2\pi f_d) \quad (5)$$

where $f_d = \frac{f_r}{f_s}$. That is, the output of the Teager energy tracker depends upon the ratio of the tone frequency to the sampling frequency, regardless of the phase θ of the signal.

We consider the use of the Teager energy tracker as a pre-processor for detection of the Doppler characteristics of the received signal. A block diagram of the proposed detector is depicted in Fig. 1. It can be seen that when the decimation ratio L is equal to $\frac{1}{4f_d}$, the output of the Teager tracker is

maximized. Since the received signal has large power near the DC due to the reverberation effect, it needs to suppress the signal components near the DC after demodulation. Once the reverberated components are sufficiently removed, the additive noise term can be regarded as a major factor limiting the detection performance [2,3].

Detection of an underwater target based on the estimation of the Doppler frequency can be described as a simple hypothesis testing problem [6]. Let hypothesis H_1 be the case when there exists an underwater target moving with velocity v_r (i.e., with Doppler frequency f_d) and hypothesis H_0 be the case when no moving target exists. Then, the demodulated signal can be represented as

$$r[k] = \begin{cases} A \cos[2\pi f_d k + \theta] + v[k] & H_1 \\ v[k] & H_0 \end{cases} \quad (6)$$

where $v[k]$ represents zero-mean additive white Gaussian noise (AWGN) with variance σ_v^2 . Assume that the demodulated signal $r[k] = s[k] + v[k]$ is input to the Teager energy tracker, the output of the Teager energy tracker $T[k]$ can be represented as

$$T[k] = \begin{cases} A^2 \sin^2[2\pi f_d] + v^2[k] + A \cos[2\pi(k+1)f_d + \theta]v[k-1] \\ + A \cos[2\pi(k-1)f_d + \theta]v[k+1] \\ + 2A \cos[2\pi f_d]v[k] + v[k+1]v[k-1] & H_1 \\ v^2[k] + v[k+1]v[k-1] & H_0 \end{cases} \quad (7)$$

Since $v[k]$ is assumed as a Gaussian random variable, noise term $A \cos[2\pi f_d]v[k]$, $A \cos[2\pi(k+1)f_d + \theta]v[k-1]$ and $A \cos[2\pi(k-1)f_d + \theta]v[k+1]$ are also Gaussian, except the term $v[k+1]v[k-1]$. Since the signal-to-noise power ratio (SNR) in the water is usually very low in practice, the product of two Gaussian noise components $v[k-1]$ and $v[k+1]$ is the major noise term in the Teager tracker output. The probability density function (pdf) of the product Z of two zero-mean Gaussian random variables X and Y with the same variance σ_v^2 can be obtained by [7]

$$f_z(z) = \frac{1}{2\pi\sigma_v^2} \int_{-\infty}^{\infty} \frac{1}{|y|} e^{-\frac{1}{2\sigma_v^2} \left(\frac{z^2}{y^2} + y^2 \right)} dy \quad (8)$$

Since (8) is not representable in a closed form, we consider an approximate of (8). Numerical results indicate that $Z[k] = v[k+1]v[k-1]$ can be approximated as a Laplacian random variable with variance $2\eta^2$, i.e.,

$$f_z(z) = \frac{1}{2\eta} e^{-\frac{|z|}{\eta}} \quad (9)$$

where $2\eta^2 = \sigma_v^4$.

It is well known that the use of linear processing techniques is not effective for suppressing non-Gaussian noise [6]. We consider the use of an order statistic filter (OSF) as a nonlinear post-processor. Since the use of median filter is known to be optimum for suppression of Laplacian noise [8], we consider the use of a running median filter (RMF) with window size W for post-processing the Teager tracker output.

When the output U_i of the RMF is applied to the fixed sample size (FSS) test, the test statistic is

$$Z_N[k] = \frac{1}{N} \sum_{i=k-N+1}^k U_i = \frac{1}{N} \sum_{i=k-N+1}^k MED_w[T_i] \begin{cases} \geq \lambda_w \Rightarrow H_1 \\ < \lambda_w \Rightarrow H_0 \end{cases} \quad (10)$$

where $MED_w[\cdot]$ denotes the output of an RMF with window size W .

Since the output of the RMF with window size W is a $(W-1)$ -dependent random process, the pdf of the output Y of the RMF for an independent and identically distributed (i.i.d.) input X is given by [8]

$$f_Y(y) = \frac{4W!}{(W-1)!(W-1)!} F_X^{\frac{W-1}{2}}(y) [1 - F_X(y)]^{\frac{W-1}{2}} f_X(y) \quad (11)$$

where $F_X(x)$ is the distribution function of random variable X . When an RMF with $W = 3$ is employed, the variance of the median output U_i of a Laplacian random variable T_i

with variance $2\eta^2$ can be approximated as $0.64\eta^2$ [9]. The mean and variance of U_i can be approximated as

$$\mu_U = \begin{cases} A^2 \sin^2(2\pi f_r) + \sigma_v^2 & ; H_1 \\ \sigma_v^2 & ; H_0 \end{cases} \quad (12)$$

$$\sigma_U^2 = \begin{cases} 1.92A^2\sigma_v^2 + 0.96\sigma_v^4 & ; H_1 \\ 0.96\sigma_v^4 & ; H_0 \end{cases} \quad (13)$$

Note that the approximate variance can be somewhat larger than the actual one due to the assumption of *i.i.d.* random variables. However, it is acceptable because it can guarantee conservative design of a detector. If N is not too small, the test statistic $Z_N[k]$ in the FSS test can also be approximated as a Gaussian random variable with mean $\mu_{z_N} = \mu_U$ and

variance $\sigma_{z_N}^2 = \frac{\sigma_U^2}{N}$. For desirable true detection probability P_D and false-alarm probability P_F , the required sample number N_w and threshold level λ_w are determined by

$$N_w = \left\lceil \frac{[\sigma_{z_{N_0}} Q^{-1}(P_F) - \sigma_{z_{N_1}} Q^{-1}(P_D)]^2}{\mu_{z_{N_1}} - \mu_{z_{N_0}}} \right\rceil \quad (14)$$

$$\lambda_w = \mu_{z_{N_0}} + \sigma_{z_{N_0}} Q^{-1}(P_F) \quad (15)$$

where $\mu_{z_{N_i}}$ and $\sigma_{z_{N_i}}$ denote the mean and standard deviation of $Z_N[k]$ under hypothesis H_i , $i=0,1$, and $Q(x)$ is the complementary error function defined as

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-t^2} dt. \quad (16)$$

Once a target is detected by (10), its Doppler frequency can be estimated by

$$\hat{f}_D = \frac{f_s}{2\pi} \sin^{-1} \left(\frac{\sqrt{Z_N[k] - \hat{\sigma}_v^2}}{\hat{A}} \right) \quad (17)$$

where \hat{A} and $\hat{\sigma}_v^2$ are the estimated amplitude A and variance σ_v^2 , respectively, which can be obtained by

$$\hat{A}^2 = 2E_1\{r^2[k]\} - 2\hat{\sigma}_v^2 \quad (18)$$

$$\hat{\sigma}_v^2 = E_0\{r^2[k]\} \quad (19)$$

where $E_i\{x\}$ denotes the expectation of x under hypothesis H_i , $i=0,1$.

The distance D between the target and the observer can also be estimated by observing the time t_{\max} corresponding to the maximum $Z_N[k]$

$$\hat{D} = \frac{v_s}{2} (t_{\max} - t_0) \quad (20)$$

where t_0 is the time required for preparation of the detection. Thus, the test statistic $Z_N[k]$ can also be used for estimation of the velocity and distance of the target.

III. PERFORMANCE EVALUATION

To verify the analytic design of the proposed detection

scheme, the detection performance of the proposed detection scheme is first evaluated with the use of a 6 kHz CW sonar in AWGN channel. Fig. 2 depicts the false alarm probability when the desired $P_D=0.5$, SNR=-10dB and $f_D=30$ Hz and the true detection probability when the desired $P_F=0.01$, SNR=-10dB and $f_D=30$ Hz. It can be seen that the proposed scheme can be analytically designed. Fig. 3 depicts the sample size required by the proposed scheme when the Teager tracker output is post-processed with the use of an RMF with $W=3$ when the desired $P_D=0.5$ and $P_F=0.01$. It can be seen that the required sample size is reduced almost by one third with the use of a simple RMF.

The performance of the proposed detection scheme is also evaluated by computer simulation using the approximate underwater model [10]. The simulation condition is summarized in Table 1. Since the block size of the conventional FFT method is 128 to get a frequency resolution of approximately 1Hz Doppler spread, the decimation ratio L is similarly set to a fixed value of 128. Fig. 4 depicts the output of the Teager tracker after the post-processing with the use of an RMF with $W=3$. It can be seen that the peak magnitude of the filtered Teager tracker output is associated with the speed and distance of the target, i.e., the Doppler shift can be estimated by measuring the peak amplitude of the trajectory with known received sonar power given in (18) and (19). The distance can also be estimated by measuring the time instant corresponding to the peak magnitude. As an example, in the case of target B, the time at the peak magnitude occurs at 2.4 seconds after the observation. Since the preparation time is 0.4 second, the estimated distance is $\hat{D}=1500$ m from (20).

IV. CONCLUSION

In this paper, we have proposed a new scheme for detection of underwater moving targets by employing a nonlinear energy tracker. To obtain the detection performance robust to harsh channel condition, the output of the Teager tracker is post-processed using a running order statistic filter. The detector is analytically designed using an approximate model and verified by computer simulation. The proposed scheme can also estimate the velocity and the distance simultaneously. The complexity of the proposed scheme is much smaller than that of the conventional FFT-based detection schemes.

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Table 1. Underwater simulation condition

Condition	Detail
Sampling frequency in the receiver	32 kHz
Sensor type in the transmitter	HMS
Active sonar source	CW (6.0 kHz)
Duration of a ping	3.0 seconds
Location of the transmitter	8 m depth
Sonar power	235 dB
Sensor type in the receiver	VDS
Location of the receiver	50 m depth
Volume of target	100 m length 10 m height
Wind velocity	14 Knots
Power level of background noise	53 dB
Underwater sonar velocity profile	SVP type 1A
Sea depth	100 m

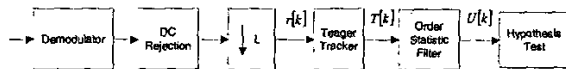


Fig. 1. The proposed detection scheme

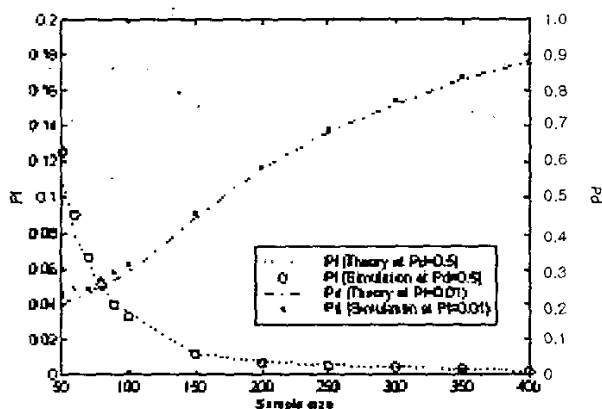


Fig. 2. Performance evaluation in a 6 kHz CW sonar AWGN condition

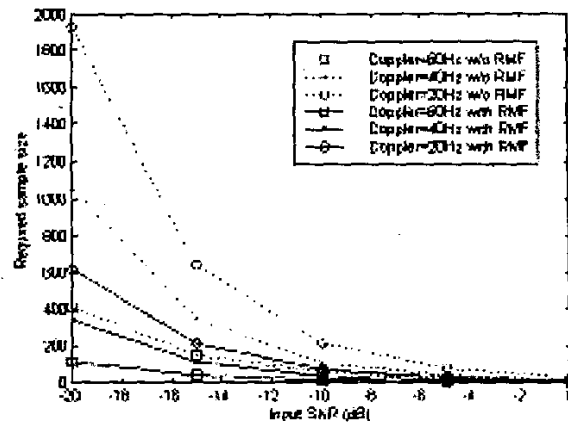
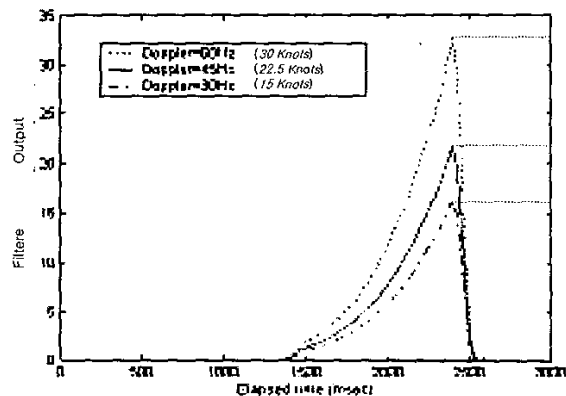
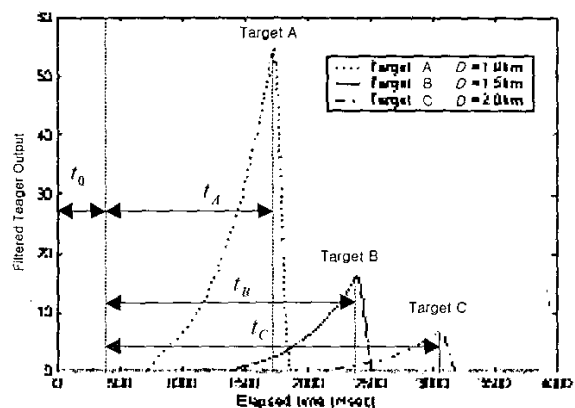


Fig. 3. Required sample size for $P_D=0.5$ and $P_F=0.01$ with and without the RMF



(a) Estimate of the velocity



(b) Estimate of the distance

Fig. 4. The RMF filtered Teager tracker output