Long-Time Signal Nonlinear Integration with Arbitrary Complex Envelope

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Abstract: ***The migration of echo envelop and the complex underwater acoustic environment are challenging issues in long-time signal integration. In previous studies of long-time coherent integration, researchers usually constructed multi-pulse echo model with linear frequency modulation (LFM) signal to deduce perfect analytical formula, it has no generality when other sonar waveforms are used. Aiming to solve the problems, a nonlinear pulse integration method with arbitrary complex envelope form is discussed in this paper. The nonlinear procedure is to utilize multiply operation instead of add operation to accumulate the power of the received signals in various returns from the detected target moving with a uniform velocity. And a general expression of the integration output of the signal with arbitrary waveform envelope is given in the form of wideband ambiguity function.***

Keywords: multiplication-based integration, arbitrary envelope, impulsive noise, underwater target detection, pulse integration

1. Introduction

The detection of low observable underwater target from complex marine environment is of great concern for multitudes of sonar applications such as diver detection, fish finding, offshore oil exploration, marine navigation and harbor surveillance. Conventional detection methods usually compare the output of the matched filter to a predefined or adaptive detection threshold to declare the finding of target and estimate the time delay of the received echo signal to locate the target. Due to the complicated marine environment and relatively weak reflectivity of the underwater target, the challenge lies in detecting signal with low input signal-to-noise ratio (SNR) and estimates its time of arrival in the presence of adverse background noise.

An efficient way to obtain an increased SNR gain is the integration among different pulses [1], named pulse integration (PI). Based on addition operation, conventional PI methods add signals received in different pulse period along the slow time [2]-[8]. To simplify the analysis, noise background is modeled as additive white Gaussian noise (AWGN) in these methods. It is reasonable for most cases, but not for some other certain cases. When the background noise show an impulsive character, the performance of the AWGN based PI methods will degrade seriously.

Theoretically speaking, according to the fundamental property of additive operation, addition-based PI may alleviate the influence of strong interference by prolong the integration time. However, increased integration time would destroy the correlation between the received pulses in one CPI, especially in underwater acoustic applications. Recently, a multiplication-based pulse integration method has been proposed in [9] to detect underwater target in impulsive noise environment. However, the detecting waveform used in this paper is linear frequency modulation (LFM) signal. It is well known that a wide variety of signal waveforms are also used by modern sonar. Whether the formulas and corresponding instructive conclusions deduced by LFM can be generalized to other sonar waveforms is still a question to be resolved. Motivated by the previous researches, we proposed a generalized nonlinear pulse integration (GNLPI) method with arbitrary complex envelope to detect underwater weak target in impulsive noise environment. In this method, we assume the transmitted signal is of arbitrary envelope and derived a general expression of the integration output. The contributions of this paper are as follows:

- We use a general signal expression to deduce the final non-linear integration result.
- We give the general expression of the multiplier's output in the form of wideband ambiguity function for arbitrary signal.

The remainder of this paper is organized as follows. In section 2, the signal and noise model under consideration is established. In section 3, generalized nonlinear integration method for detecting static and moving targets from strong impulsive noise is presented. In section 4, we present our conclusions.

2. Signal and Noise Model

2.1. Signal Model

Consider a sonar system sends out signal $s(t)$ to detect underwater target. Ignoring the underwater multipath propagation, the received signal can be viewed as the sum of Q time delayed, amplitude attenuated, and Doppler scaled replicas of $s(t)$, which is

$$x(t)=\sum_{q=1}^{Q}A_q s\left[\alpha_q(t-\tau_q)\right]+n(t) \qquad (1)$$

where Q is the number of the targets that exist in the scene, A_q, α_q, τ_q are the fluctuating amplitude, Doppler scale, and round trip delay of the q^{th} target, respectively, $n(t)$ is the background noise and is uncorrelated with the transmitted signal. The Doppler scale α_q and the round trip delay τ_q satisfy

$$\alpha_q=\frac{c-v_q}{c+v_q}$$

$$\tau_q = \frac{2R_{q,0}}{c - v_q}$$

where c is the sound velocity in water, v_q and $R_{q,0}$ are the velocity and initial range of the q th target. Define v_q is positive (negative) when the target is moving closer (far away) from the sonar.

Denote the bandwidth of the transmitted signal as B, and the pulse width of $s(t)$ as T_s. When the transmitted signal is narrowband, i.e., the following condition [1],

$$2v_q T_s / c << 1/B$$

or

$$BT_s << \frac{c}{2v_q}$$

is satisfied, the Doppler effect can be simplified as the frequency shift. Thus, the received signal can be expressed as

$$x(t) = \sum_{q=1}^{Q} A_q s(t-\tau_q) e^{j2\pi f_{d,q} t} + n(t) \qquad (2)$$

where $f_{d,q}$ is the Doppler frequency and is approximated as

$$f_{d,q} \approx \frac{2v_q}{c} f_0$$

Commonly, the narrowband signal model is accurately enough for radar applications. But due to the low propagation velocity of sound in water, the narrowband model is no longer applicable for sonar systems. Thus, signal model in (1), which can not only describe narrowband signal but also wideband signal, is used in our paper.

Transmit the source signal as a pulse periodically, and denote T_p as the pulse repetition interval (PRI). Then, (1) can be rewritten into

$$x(t_k, t_m) = \sum_{q=1}^{Q} A_{q,m} s[\alpha_q (t_k - \tau_q(t_m))] + n(t_k) \qquad (3)$$

where the subscript q and m denotes the q th target and the m th pulse, respectively, $t_m = mT_p$ is the slow time, $m = 0,1,\cdots,M-1$, M denotes the number of transmitted pulses, $t_k = t - t_m$ is the fast time, $A_{q,m}$ is the fluctuating amplitude, $\tau_q(t_m) = 2R_q(t_m)/(c - v_q)$ is the round trip delay, $R_q(t_m)$ is the instantaneous range that satisfies

$$R_q(t_m) = R_{q,0} + v_q t_m \qquad (4)$$

The transmitted pulse has a finite duration, i.e., $T_s < T_p$.

Consider the q th target, the compressed signal at the output of matched filter is expressed as

$$\begin{aligned} & x_{q,mf}(t_k, t_m) \\ &= A_{q,m} \int s[\alpha_q(\tau - \tau_q(t_m))] \cdot s^*[-(t_k - \tau)] d\tau \\ &+ \int n(\tau) \cdot s^*[-(t_k - \tau)] d\tau \end{aligned} \qquad (5)$$

where * denote the conjugate operation. The impulse response of the matched filter is designed as the conjugated time-reversal of the transmitted signal $h(t) = s^*(-t)$.

Note that the wideband cross-ambiguity function (WCAF) of the transmitted signal $s(t)$ and the received signal $x(t)$ is defined as

$$\chi_{xs}(\tau, \alpha) = \int x(t) s^*[\alpha(t-\tau)] dt \qquad (6)$$

where τ and α are the time lag and Doppler scale variables respectively. Then, (5) can be written as

$$x_{q,mf}(t_k, t_m) = \frac{A_{q,m}}{\alpha_q} \chi_{ss}\left(\alpha_q(t_k - \tau_q(t_m)), \frac{1}{\alpha_q}\right) + \chi_{ns}(t_k, 1) \qquad (7)$$

where, $\chi_{ss}(\tau, \alpha)$ is the wideband auto-ambiguity function (WAAF) of $s(t)$ which is defined as

$$\chi_{ss}(\tau, \alpha) = \int s(t) s^*[\alpha(t-\tau)] dt \qquad (8)$$

$\chi_{ns}(\tau, \alpha)$ is the WCAF of $n(t)$ and $s(t)$, i.e.,

$$\chi_{ns}(\tau, \alpha) = \int n(t) s^*[\alpha(t-\tau)] dt \qquad (9)$$

It is well known that the WAAF attains the maximum of its absolute value at $(\tau, \alpha) = (0,1)$, i.e.,

$$|\chi_{ss}(\tau, \alpha)| \le |\chi_{ss}(0,1)| \qquad (10)$$

According to (7) and (10), it can be easily seen that $x_{q,mf}(t_k, t_m)$ will reach the maxima when $t_k = \tau_q(t_m)$ and $\alpha_q = 1$. However, $\alpha_q = 1$ means the q th target is static ($v_q = 0$). If the target is moving ($\alpha_q \ne 1$), due to the influence of the Doppler effect, the value of the first term in (7) may descend, which could cause sharp decline in the performance of the matched filter.

Taking Doppler effect into consideration, we use matched filter bank, that is

$$h(t, \alpha) = s^*(-\alpha t) \qquad (11)$$

where the discrete parameter α is defined as

$$\alpha \in \{\alpha_{\min}, \alpha_{\min} + \Delta\alpha, \cdots, \alpha_{\max} - \Delta\alpha, \alpha_{\max}\}$$

in which $(\alpha_{\min}, \alpha_{\max})$ and $\Delta\alpha$ are the minimum, maximum possible value, and the searching precision of Doppler scale α, respectively. To guarantee the detection performance, the selection of $(\alpha_{\min}, \alpha_{\max})$ should satisfy that

$$\alpha_{\min} < \alpha_q < \alpha_{\max}, \quad q = 1,2,\cdots,Q$$

and $\Delta\alpha$ should be small enough to distinguish different targets but not too small in case of the high correlation between two adjacent bins. A slight mismatching is acceptable since the performance of the matched filter bank would not degrade too much if the transmitted signal is carefully chosen such that the WAAF of the transmitted signal has a good energy concentration property on the 2D delay-Doppler plane. Then, (7) is transformed into

$$x_{q,mf}(t_k, t_m) = \frac{A_{q,m}}{\alpha_q} \chi_{ss}\left(\alpha_q(t_k - \tau_q(t_m)), 1\right) + \chi_{ns}(t_k, \alpha_q) \qquad (12)$$

The maximum value of the first term in (12) appears at $t_k = \tau_q(t_m)$ and $\alpha = \alpha_q$.

2.2. Noise Model

In this paper, we assume that the background noise is uncorrelated with the interested signal. This assumption holds true in many practical applications and is also widely assumed in underwater signal processing [10]. The case in which the noise and signal are mutually correlated or coherent is beyond the scope of this paper.

2.2.1 White Gaussian Noise

When the background noise is modeled as WGN, which is uncorrelated with the transmitted signal $s(t)$, the second term in (12) will vanish. Thus, we obtain

$$x_{q,mf}(t_k,t_m)=\frac{A_{q,m}}{\alpha_q}\chi_{ss}\left(\alpha_q(t_k-\tau_q(t_m)),1\right) \quad (13)$$

The total output of the matched filter bank is then expressed as

$$x_{mf}(t_k,t_m)=\sum_{q=1}^{Q}\frac{A_{q,m}}{\alpha_q}\chi_{ss}\left(\alpha_q(t_k-\tau_q(t_m)),1\right) \quad (14)$$

Now, we can easily see that $|x_{mf}(t_k,t_m)|$ will have Q peaks at $(t_k,\alpha)=(\tau_q(t_m),\alpha_q)$ for each t_m. Therefore, the delay and Doppler scale of the K targets can be estimated from the locations of the K peaks, and the fluctuating amplitudes relative to the targets' reflective sonar cross section (SCS) can also be approximated by the amplitudes of these peaks.

2.2.2 Impulsive Noise

As described in many papers, background noise always shows an impulsive character in underwater acoustics [11]-[13]. Some of them modeled the impulsive noise as α -stable process, e.g. [14] adopts the symmetric α -stable ($S\alpha S$) distribution with zero-location as the impulsive noise model, whose characteristic function is expressed as

$$\varphi(\omega)=\exp(-\gamma^{\alpha}|\omega|^{\alpha})$$

where $0<\alpha\le 2$ is called the characteristic exponent that describes the tail of the distribution, and $\gamma>0$ is the scale. When $\alpha=2$, the α -stable distribution reduces to the Gaussian distribution and γ^2 is similar to the variance of the Gaussian distribution. When $\alpha<2$, α -stable noise shows heavy tails and hence is impulsive. The smaller the value of α, the more impulsive the noise is.

However, unlike most statistical models, α -stable distributions do not have closed-form probability density function, except for a few known cases. They are commonly described by the characteristic function [15]. To simplify the problem, and to illustrate the impulsive characteristics of the ambient noise at the meantime, background noise $n(t)$ is modeled as the sum of a Gaussian noise component $n_G(t)$ and an impulsive noise $n_I(t)$, which is

$$n(t)=n_G(t)+n_I(t) \quad (15)$$

The impulsive component $n_I(t)$ is modeled as a train of Dirac delta functions occurring at random times $\tilde{\tau}_{i,m}$ and with random amplitude $a_{i,m}$, which is expressed as

$$n_I(t)=\sum_{i=0}^{+\infty}a_{i,m}\delta(t-\tilde{\tau}_{i,m}) \quad (16)$$

In (16), $a_{i,m}$ has a relatively larger value than the target echo, $\tilde{\tau}_{i,m}$ are assumed to be Poisson distributed, and the indice m denotes the m^{th} pulse period. Accordingly, the second term in (12) is in the form of

$$\chi_{ns}(t_k,\alpha_q)=\sum_{i=0}^{+\infty}a_{i,m}h(\alpha_q,t_k-\tilde{\tau}_{i,m}) \quad (17)$$

Equation (16) is a train of Doppler scaled and time delayed matched filter response. Considering its relatively large amplitude a_i, when interfered by impulsive noise, the second part of (12) cannot be ignored as that in Gaussian noise. Hence, the matched filter response for impulsive interference can be falsely detected as a target

3. Generalized Nonlinear Pulse Integration Method

Conventional pulse integration method, coherent and non-coherent, performs addition operation to the signals received in one CPI over the slow time. The integration gain is proportional to the number of the pulse that being integrated. Pulse integration is now widely accepted as one of the best methods for improving the signal-to-noise ratio of target detection. However, the addition based pulse integration would perform poor when interfered with impulsive noise.

In this section, we present GNLPI to detect static targets and targets moving with uniformed velocity under impulsive noise environment with arbitrary waveform.

3.1 GNLPI for Static Targets

If targets in the scene are static, which means $v_q=0$, $\alpha_q=1$, $f_{q,d}=0$, and $\tau_{q,m}$ is a constant that irrelevant to the slow time t_m, (12) can be simplified as

$$x_{q,mf}(t_k,t_m)=A_{q,m}R_{ss}(t_k-\tau_q)+R_{ns}(t_k) \quad (18)$$

where τ_q is a constant relative to the initial range of the q^{th} target, $R_{ss}(\tau)=\chi_{ss}(\tau,1)$ is the autocorrelation function of $s(t)$, and $R_{ns}(\tau)=\chi_{ns}(\tau,1)$ is the cross correlation function of $s(t)$ and $n(t)$.

The total output of the matching filter bank is expressed as

$$x_{mf}(t_k,m)=\sum_{q=1}^{Q}A_{q,m}R_{ss}(t_k-\tau_q)+R_{ns}(t_k) \quad (19)$$

where $R_{ns}(t_k)=0$ when the background noise is Gaussian distributed, and $R_{ns}(t_k)=\sum_{i=0}^{+\infty}a_{i,m}h(t_k-\tilde{\tau}_{i,m})$ if the background noise is impulsive. Then, the matched filter bank output $x_{mf}(t_k,m)$ is put into a multiplier which computes the product of the M successive pulses over the slow time, as follows:

$$Y=\prod_{m=0}^{M-1}x_{mf}(t_k,m) \quad (20)$$

Then, the output of the multiplier Y is compared to a threshold T determined by the expected distribution of the noise and the target false alarm to decide whether the signal represents a target or not:

$$Y \underset{H_0}{\overset{H_1}{\gtrless}} T, \tag{21}$$

where H_1 denotes the hypothesis that the target is in the scene, while H_0 means that the target is not present in the range bin under consideration.

Because of the random occurrence of the impulsive noise, the possibility for the existence of impulses in different pulse periods at the same position is very small. Therefore, the impulsive noise component of (20) is nearly zero. If there were M impulsive interference occurred at the same position for the M consecutive integrated pulses, that is $\tilde{\tau}_{i,1} = \tilde{\tau}_{i,2} = \cdots = \tilde{\tau}_{i,M}$ for a particular i, the multiplication of the impulsive noise would exceed the threshold and be detected as a target, which is almost impossible in practice.

3.2 GNLPI for Moving Targets

When detecting moving targets, the output of the matched filter bank is written as

$$\begin{aligned} & x_{mf}(t_k, t_m) \\ & = \sum_{q=1}^{Q} \frac{A_{q,m}}{\alpha_q} \chi_{ss}\left(\alpha_q (t_k - \tau_q(t_m)), 1\right) + \sum_{q=1}^{Q} \chi_{ns}(t_k, \alpha_q) \end{aligned} \tag{22}$$

Plugging (17) into (22) gives (23)

$$\begin{aligned} x_{mf}(t_k, t_m) = & \sum_{q=1}^{Q} \frac{A_{q,m}}{\alpha_q} \chi_{ss}\left(\alpha_q (t_k - \tau_q(t_m)), 1\right) \\ & + \sum_{q=1}^{Q} \sum_{i=0}^{+\infty} a_{i,m} h(\alpha_q, t_k - \tilde{\tau}_{i,m}) \end{aligned} \tag{23}$$

Equation (23) shows that, the peaks of the target echo would change with the slow time after matched filtering. When the offset exceeds the range resolution, the range migration effect would occur, making the signal energy defocused. Thus, GNLPI cannot be used directly.

Keystone transform is often used to eliminate the linear range migration generated by the movement of the target [16]-[19]. Other methods like Radon-Fourier transform (RFT) also have been reported recently for the weak target detection [20]. The RFT realizes the coherent integration for the moving targets with range migration via joint searching along range and velocity direction. However, RFT needs lots of computations for the 2-D searching when the location and velocity of the target are both unknown. Furthermore, while RFT accumulates the signal energy along the direction that the envelope migrates, it is hard for our integration scheme to adopt it. Thus, we utilize Keystone to detect moving targets. Denote the transmitted pulse $s(t)$ as the combination of its envelope $u_c(t)$ and the carrier frequency component $e^{j2\pi f_0 t}$, which is

$$s(t) = u_c(t) e^{j2\pi f_0 t} \tag{24}$$

Thus, the result of performing Fourier transform on (23) over the fast time variable is expressed as

$$\begin{aligned} & Y_{mf}(f, t_m) \\ & = \sum_{q=1}^{Q} \frac{A_{q,m}}{\alpha_q^2} \left| U_c\left(\frac{f - \alpha_q f_0}{\alpha_q}\right)\right|^2 e^{-j2\pi(f - f_0)\tau_q(t_m)} e^{j2\pi f_0 \tau_q(t_m)} \\ & + \sum_{i=0}^{+\infty} a_{i,m} H(f) e^{-j2\pi f \tilde{\tau}_{i,m}} \end{aligned} \tag{25}$$

where $U_c(f)$ is the Fourier transform of $u_c(t)$. It is the first exponential term in (25) that causes the range migration. What we are interested in is when dose the interference happened, but not how it looks like after matched filtering. Therefore, in (25), the impulsive noise at the output of the matched filter bank is simplified as $\sum_{i=0}^{+\infty} a_{i,m} H(f) e^{-j2\pi f \tilde{\tau}_{i,m}}$, the influences of α_q on the matched filter output of impulse noise is not taken into consideration. Rescale the time axis for each frequency by the Keystone transform

$$t_m = \frac{f_0}{f + f_0} \tilde{t}_m \tag{26}$$

Then, we can obtain a new spectrum function

$$\begin{aligned} & Y_{mf}(f, t_m) \\ & = \sum_{q=1}^{Q} \frac{A_{q,m}}{\alpha_q^2} \left| U_c\left(\frac{f - \alpha_q f_0}{\alpha_q}\right)\right|^2 e^{j2\pi \frac{f_{d,q}}{\alpha_q} \tilde{t}_m} \\ & \times e^{-j2\pi(f + f_0)\frac{2R_{q,0}}{c - v_q}} e^{j2\pi f_0 \tau_q(t_m)} \\ & + \sum_{i=0}^{+\infty} a_{i,m} H(f) e^{-j2\pi f \tilde{\tau}_{i,m}} \end{aligned} \tag{27}$$

Note that the coupling between frequency f and slow time t_m has disappeared, which means the range migration caused by target's movement is corrected by Keystone transform. Then, the received M pulses can be integrated by multiplication as shown in (20).

4. Conclusions

In this paper, we have addressed the impulsive interference problem and various detection waveforms for the detection of underwater dim target. Considering the complex underwater conditions, background noise is modeled as the mixture of white Gaussian noise and impulsive noise. To detect underwater target from strong pulse interference with arbitrary waveform, generalized nonlinear pulse integration scheme is proposed. The detecting waveform is given in a generalized expression and the wideband ambiguity function is used to give a general expression of the integration output.

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