A Template Matching Method of Wideband Sonar Detection

J Y Chen, X P Zhong and X Z Feng

College of Mechatronics Engineering and Automation National Univ. of Defense Technology ChangSha, HuNan, China

E-mail: kdcjy@sina.com

Abstract. Advances in computer memory, computation speed, and transducer bandwidth have made possible, higher Time-Bandwidth product (TB) transmit signals and will bring out higher resolutions. In this paper a new method is proposed to estimation Doppler velocity base on correlation analysis and mode matching in wideband condition instead of wideband matched filter. Paper use mode-matching principle to search appropriate scaled factor matrix. Simulation showing this method has well restrains noise capability and perfect calculation stability; the amount of compute can be decreased greatly by scaled factor matrix computed in advance.

1. Introduction

The processing of transmitting a known signal into an environment and listening for its reflections is referred to generally as Range Doppler-detection. It is usually known under the more specific names sonar, radar, medical ultrasound, sodar, non-destructive evaluation, etc. Advances in computer memory, computation speed, and transducer bandwidth have made possible (and will continue to make possible) higher Time-Bandwidth product (TB) transmit signals and therefore higher resolutions. Higher Time-Bandwidth product signals are desirable in sonar because they afford higher resolution and better probability of detection under correlated noise. Radar, sonar, and remote sensing applications require detection and estimation of random signals that have propagated over stochastic multipath channels and have been scattered from distributed or multihighlight objects. If the distributed target is in relative motion in respect to the transmitter and receiver, the echo is spread in delay and Doppler for narrowband systems and delay and time scale for wideband systems. Several papers have been written by Weiss showing how wideband processing can be implemented as a wavelet transform [1,2]. Jin et. al. have also shown this [3]. Altes has derived a set of signal transforms which leaves the wideband ambiguity function unchanged [4].

2. Wideband sonar signal processing model

If the transmitter emits the signal \( f(t) \), consider the target moving rules can be represent as function \( R(t) \), thus the receive echo is

\[
r(t) = f[t - \tau(t)]
\]

(1)

Where \( \tau(t) \) is time-varying propagation delay that satisfies [5]. We suppose \( \tau_0 \) is the center delay time of receive echo signal, we use Taylor series to expend \( r(t) \) around \( \tau_0 \), yields

\[
R(t) = r\left(\frac{\tau_0}{2}\right) + \tau_0 \left( t - \frac{1}{2} \tau_0 \right) + \frac{1}{2} \alpha_0 \left( t - \frac{1}{2} \tau_0 \right)^2 + \cdots
\]

(3)
Where \( v_0 \) is target velocity, \( a_0 \) is target acceleration. We use Taylor series to expand \( \tau(t) \) around \( \tau_0 \), yields

\[
\tau(t) = \tau_0 + \beta(t - \tau_0) + \alpha(t - \tau_0)^2
\]

(4)

It can be proved that

\[
\beta = \frac{2v_0}{c + v_0}, \quad \alpha = \frac{c^2 a_0}{(c + v_0)^2}
\]

(5)

So the receive signal can write as

\[
r(t) = f[K(t)(t - \tau_0)]
\]

(6)

Where

\[
K(t) = 1 - \beta - \alpha(t - \tau_0)
\]

(7)

Assuming the target acceleration is zero, then we can define scaled factor \( s \) as

\[
s = \frac{c - v_0}{c + v_0}
\]

(8)

The receive echo can be represent

\[
r(t) = f[s(t - \tau_0)]
\]

(9)

Assuming \( \omega_d \) is Doppler shift, then if \( v_0 << c \), the \( s \) can be yields

\[
s = 1 - \frac{2v_0}{c}, \quad \omega_d = -\frac{2v_0}{c} \omega_c
\]

(10)

The received echo from the elementary caterer can be simplified and approximated by

\[
r(t) = f(t - \tau_0) e^{i\omega_d(t - \tau_0)}
\]

(11)

In this Condition, Model the reflection from a moving target as it imparts a frequency shift to the reflected signal, this is called narrowband processing. The processing model is the narrowband model for signal reflection. The signal has been delayed by \( \tau_0 \) and shifted in frequency by an amount \( \omega_d \).

The following Condition is called the narrowband condition

\[
TW << \frac{c}{2|v_0|}
\]

(12)

When the velocity of the target is very high, or when the time-bandwidth product of the signal is very large, the amount by which a signal shrinks or stretches in duration (called time dilation) becomes significant. A reflection model that includes time dilation is called wideband processing.

3. Matched filter processing

In classical narrowband matched filter processing, the received time series is correlated with hypothesized Doppler shifted and delayed replicas of the transmitted signal. In order to detect the range and velocity of an object, the received signal must be correlated with hypothesized scaled and time shifted versions of the transmitted signal. The maximum of the magnitude of this narrowband correlation will correspond to the velocity and displacement of the object. But In wideband condition, narrowband matched filter is invalid completely [7]. Figure 1 gives the narrowband matched filter output in narrowband condition where target velocity is 10m/s. Figure 2 gives the Narrowband matched filter output in wideband condition at same target velocity.

So we should use wideband matched filter in wideband condition. Analogously, for wideband matched filter processing, the wideband received time series is correlated with replicas of the transmitted signal that are delayed and dilated (time-scaled) by hypothesized amounts. It can be represented as [6]

\[
WC(s, \tau) = \int r(t) \sqrt{|s|} f^*[s(t - \tau)] dt
\]

(13)
This wideband matched filter output is the maximum likelihood (ML) sense optimum detection statistic for detection of point targets in white gauss noise [7]. But we can see the amount of compute of direct wideband matched filter is huge.

4. Correlation analysis and mode matching method

In a sonar system, a known signal $f(n)$ is transmitted into a channel and reflected by scatterers and received as $r(n)$

$$r(n) = Af(n) + v(n), \ n = 0,1...L-1$$

(14)

Where $L$ is the length of samples, $v(n)$ is white gauss noise, noise covariance is $\sigma^2$. The auto-correlation function of receive signal can be represented as

$$R_r(m,s) = A^2 R_f(m,s) + L \delta(m) \sigma^2$$

(15)

Where $R_r(m,s)$ is the auto-correlation function of receive signal $r(n)$, $R_f(m,s)$ is the auto-correlation function of transmit signal $f(n)$. Multiply two side of (14) by $R_r(m,s)$ and sum by $m$, yields

$$\sum_{m=0}^{L-1} A^2 R_f(m,s) R_f^*(m,s) + \sum_{m=0}^{L-1} L \delta(m) \sigma^2 R_f^*(m,s) = \sum_{m=0}^{L-1} R_r(m,s) R_r^*(m,s)$$

(16)

When $m$ equal zero, equation (15) yields

$$A^2 R_f(0,s) + L \sigma^2 = R_r(0,s)$$

(17)

So we can derives the estimate linearity equation group of magnitude of signal and variation of noise

$$\begin{bmatrix}
\sum_{m=0}^{L-1} |R_f(m,s)|^2 \\
R_r(0,s)
\end{bmatrix}
\begin{bmatrix}
A^2 \\
\sigma^2
\end{bmatrix}
= \begin{bmatrix}
\sum_{m=0}^{L-1} R_r(m,s) R_r^*(m,s) \\
R_r(0,s)
\end{bmatrix} = \beta$$

(18)

Therefore we define linearity equation group coefficient matrix as scaled factor matrix $\Delta(s)$.

$$\Delta(s) = \begin{bmatrix}
\sum_{m=0}^{L-1} |R_f(m,s)|^2 \\
R_r(0,s)
\end{bmatrix}
\begin{bmatrix}
A^2 \\
\sigma^2
\end{bmatrix}$$

(19)

The Estimation of signal energy $A^2$ and noise covariance $\sigma^2$ can be represent as

$$\begin{bmatrix}
\hat{A}^2 \\
\hat{\sigma}^2
\end{bmatrix} = [\Delta(s)]^{-1} \beta$$

(20)

Then the union estimate error defined as

$$E(s) = \sum_{m=0}^{L-1} |R_r(m)|^2 - \hat{A}^2 \beta^*_1 - L \hat{\sigma}^2 \beta^*_2$$

(21)
We can see estimate error is dependent on scaled factor, where scaled factor is the amount of signal shrinks or stretches by target velocity. To minimized estimate error, we use mode-matching principle to search appropriate scaled factor matrix. When estimate error comes to minimum, the corresponding scaled factor is the actual scaled factor; corresponding velocity is actual target velocity. Simulation showing this method has well restrains noise capability and perfect calculation stability; the amount of compute can be decreased greatly by scaled factor matrix computed in advance.

We use matlab simulate the Correlation analysis and mode matching method. In this case we use direct spread spectrum signal as transmit signal, where carrier frequency is 30KHz, code frequency is 10KHz, code type is m sequence, and code length is 511. We assume target velocity is 15m/s, environment noise is white guess noise, the ratio of signal to noise(SNR) is –10dB. Figure 3 gives the result of using scaled matrix to search target velocity, X-coordinate represent search velocity, Y-coordinate represent estimate error $E$.

![Figure 3. Result of using scaled matrix to search target velocity.](image)

Simulation showing this method has well restrains noise capability and perfect calculation stability; the amount of compute can be decreased greatly by scaled factor matrix computed in advance. From equation (20) we can deduce the mean of $\hat{A}^2$ and $\hat{\sigma}^2$:

$$ E[\hat{A}^2] = \sum_{m=-L}^{L} \frac{E\{ R_x(m) R_x^*(m) \} - E\{ R_x(0) \} E\{ R_x(0) \}}{\sum_{m=-L}^{L} |R_x(m)|^2} $$

$$ E[\hat{\sigma}^2] = -\sum_{m=-L}^{L} \frac{E\{ R_x(m) R_x^*(m) \} - E\{ R_x(0) \} \sum_{m=-L}^{L} |R_x(m)|^2}{L \sum_{m=-L}^{L} |R_x(m)|^2} $$

To simplify the mean of $\hat{A}^2$ and $\hat{\sigma}^2$, we should deduce the expression of $E\{ R_x(m) \}$, from equation (15) we can get this result as

$$ E[\hat{A}^2] = A^2 R_x(m) + L\delta(m) \sigma^2 $$

then we can get the sample express of $\hat{A}^2$ and $\hat{\sigma}^2$

$$ \begin{align*}
E[\hat{A}^2] &= A^2 \\
E[\hat{\sigma}^2] &= \sigma^2
\end{align*} $$

Equation (25) indicate the estimation of signal energy $A^2$ and noise covariance $\sigma^2$ about equation (20) is a none-deflection estimation.
5. Conclusion
In this paper, we propose a new method which estimation Doppler velocity base on correlation analysis and mode matching in wideband condition instead of wideband matched filter. through calculate the mean of signal energy $A^2$ and noise covariance $\sigma^2$ estimation, we find based correlation analysis, this estimation is none-deflection. We use mode-matching principle to search appropriate scaled factor matrix. Simulation showing this method has well restrains noise capability and perfect calculation stability; the amount of compute can be decreased greatly by scaled factor matrix computed in advance.

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