Performance Analysis of Reference Channel Equalization Using the Constant Modulus Algorithm in an FM-based PCL system

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ABSTRACT
A frequency-modulation (FM)-based passive coherent location (PCL) system is a passive radar system for detecting a target using commercial FM broadcasting signals. A cross-correlation function between the direct-path signal propagating line-of-sight of the FM transmitter and the receiver, and the target echo signal, can be derived to detect the target. When clutter is received on the reference channel, the target detection probability can be reduced. In order to improve the detection performance, the direct-path signal on the reference channel should be essentially recovered. In this paper, we apply the constant modulus algorithm (CMA) to remove the clutter received on the reference channel and analyze the amount of removed clutter by simulation. Furthermore, we show that the reference channel equalization plays a very important role in removing ghost targets in the cross-correlation function.

CCS Concepts
• Passive coherent location → Reference channel equalization • Adaptive filter → Constant modulus algorithm.

Keywords
Radar; Passive coherent location; Clutter cancellation; Adaptive filter; Channel equalization

1. INTRODUCTION
An FM-based PCL system tracks the position and velocity of a target by using commercial FM broadcasting signals received by a passive radar. This system simultaneously operates the reference channel and surveillance channel. The reference channel is operated to obtain a direct-path signal propagating in the shortest path between the transmitter and receiver, and the surveillance channel is operated to obtain the target echo signal. The position and the velocity of the target can be estimated from the information on the differences of time delay and the Doppler frequency between the direct-path signal and the target echo signal. This information can be estimated by deriving a cross-correlation function between the reference channel and the surveillance channel.

However, the surveillance channel receives not only the target echo signal but also the interference signals, such as direct-path signal and clutter [1]. Since these interference signals are received on the surveillance channel with higher power than that of the target echo signal, it may yield a masking effect that the target echo signal is concealed by interferences [2]. In order to overcome the masking effect and to detect the target echo signal, the interference signals should be removed from the surveillance channel. For this purpose, the adaptive filter techniques, such as least mean square (LMS), recursive least squares (RLS) [3] and extensive cancellation algorithm (ECA) are proposed as the interference cancellation schemes [1].

In order to apply the interference cancellation technique, it is essential to secure the reference channel because the reference channel is used to remove the interferences in the surveillance channel. These interference signals received on the reference channel may cause an unintended peak value in the result of the cross-correlation function. Since this kind of peak value may increase the false alarm rate, it is important to acquire only a clean direct-path signal from the reference channel. Therefore, the CMA-based reference channel equalization technique has been applied to remove the interference signals included in the reference channel [4]. In this paper, when the clutter is received on the reference channel, we show that the clutter and the interference signals can be removed by using the CMA. Based on the theoretical analysis, we present the exact value of the clutter suppression and show that the ghost target caused by the interference signals in the reference channel is removed.

2. REFERENCE CHANNEL EQUALIZATION [4, 5]
Since the FM signal has a constant amplitude, the clutter removal methods in the reference channel based on the constant modulus algorithm have been proposed [4, 5]. To remove the interference signal contained in the reference channel, an adaptive filter with a tap weight vector can be used to equalize the reference channel.

The output of the adaptive filter can be written as [5]

\[
y[k] = \sum_{m=0}^{M-1} w_m[k] x_{\text{ref}}[k-m] = \mathbf{w}^T[k] \mathbf{x}[k],
\]

(1)

\[
\mathbf{w}[k] = [w_0[k], w_1[k], \cdots, w_{M-1}[k]]^T,
\]

(2)

\[
\mathbf{x}[k] = [x_{\text{ref}}[k], x_{\text{ref}}[k-1], \cdots, x_{\text{ref}}[k-M]]^T,
\]

(3)

where \( M \) denotes the tap size of the filter, \( \mathbf{w}[k] \) is the tap weight vector to be applied on the reference channel at \( k \) th time instant, and \( \mathbf{x}[k] \) is the tapped reference channel signal at the \( k \) th time instant. The weight vector can be derived by an error signal that minimizes a specific cost function and by updating the weight vector to minimize the error signal.
The weight vector $\mathbf{w}[k]$ is updated as

$$
\mathbf{w}[k + 1] = \mathbf{w}[k] - \mu \mathbf{e}[k] \mathbf{x}[k],
$$

(4)

$$
\mathbf{e}[k] = \mathbf{y}[k] - \mathbf{y}[k],
$$

(5)

where $\mu$ is the step size that controls the convergence speed and the asymptotic mean squared error (MSE), and $\mathbf{e}[k]$ is error signal.

3. ANALYSIS OF REMAINING CLUTTER

The reference channel with the clutter can be modeled as

$$
s_{\text{ref}}(t) = A_d s(t) + A_c s(t - t_c) + n(t),
$$

(6)

where $s(t)$ is the direct-path signal, $A_d$ is the amplitude of direct-path signal, $A_c$ is the amplitude of clutter, $t_c$ is the time delay of clutter, and $n(t)$ is the white noise process.

The signal model of the reference channel in (6) is obtained by passing the FM signal $s(t)$ through a propagation channel with the following impulse response:

$$
h(t) = A_d \delta(t) + A_c \delta(t - t_c).
$$

(7)

In order to remove the clutter, the propagation channel in (7) should be equalized. The equalization of the propagation channel can be performed by the deconvolution of the following IIR (infinite impulse response) filter:

$$
h_{\text{inverse}}(t) = \delta(t) - \alpha \delta(t - t_c) + \alpha^2 \delta(t - 2t_c) - \alpha^3 \delta(t - 3t_c) + \cdots,
$$

(8)

$$
\alpha = \frac{A_c}{A_d},
$$

(9)

where $\alpha$ is the ratio of the clutter signal amplitude to the direct-path signal amplitude. Since the amplitude of the direct-path signal is generally greater than the amplitude of the clutter, $\alpha$ is less than 1.

The amount of the clutter removal can be calculated from $\alpha$ in Equation (9). The clutter remaining on the reference channel after applying equalization can be written as

$$
s_{\text{remain}}(t) = (A_d - \alpha A_c) s(t - t_c),
$$

(10)

Since the propagation channel equalizer is an IIR filter, the induced clutter, which is defined as the remaining part of the clutter, may occur. Then, the clutter and induced clutter in the reference channel can be written in the following generalized equation:

$$
s_{\text{clutter}}(t) = \left(\alpha^{-l-1} A_d - \alpha^l A_c\right) s(t - lt_c),
$$

(11)

where $l \geq 1$.

4. SIMULATION RESULTS

The signal model of the reference channel in (6) is set to have a direct-path signal of 20 dB and a clutter of 10 dB. The clutter is set to have a time delay of 30 samples. In terms of distance, the clutter has a bistatic range of 17.4 km. The adaptive filter operates with $M = 100$ taps, and $\mu = 5 \times 10^{-5}$.

![Figure 1. Cross-correlation function of the direct-path signal and the reference channel signal before applying CMA.](image)

![Figure 2. Cross-correlation function of the direct-path signal and the reference channel after applying CMA.](image)

Figure 1 shows the result of the cross-correlation function between the direct-path signal and the reference channel before applying CMA. From this figure, we can notice the signal power of the clutter in the reference channel approximately. Figure 2 shows the result of the cross-correlation function between the direct-path signal and the reference channel after applying CMA. This result shows that the clutter of the reference channel has been removed.

<p>| Table 1. Remaining amount of the clutter and the induced clutters |
|--------------------|----------------|----------------|----------------|</p>
<table>
<thead>
<tr>
<th>Delays [Sample]</th>
<th>Clutter [dB]</th>
<th>Induced 1 [dB]</th>
<th>Induced 2 [dB]</th>
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<tr>
<td>30</td>
<td>-8.7644</td>
<td>-13.5303</td>
<td>-14.5467</td>
</tr>
<tr>
<td>60</td>
<td>-33.6063</td>
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The amount of the clutter and the induced amount are calculated in Table 1.
As shown in (1), since the weight vector of the adaptive filter acts as a channel equalizer, it can be expected that this vector will appear as in (8). Figure 3 shows the tap weight of the adaptive filter, which is similar to the values in (8).

Using the equations of (10), (11), and the tap weight vector of the CMA shown in Figure 3, we can calculate the amount of the residual clutter and the induced clutter. Table 1 shows the remaining amount of the clutter and the induced clutters in decibel. According to Table 1, the reduced clutter power is about 20 dB, and it can be seen that the clutter of -8.7644 dB remains.

Figure 4 compares the autocorrelation function before and after applying the CMA to the reference channel. Compared with the reference channel before applying CMA, the clutter located in 30 samples of reference channel after applying CMA is remarkably reduced. In addition, the induced clutter is also removed and is not visible on the autocorrelation function because it is equal to or smaller than the noise level floor.

Figure 5 shows the error of the adaptive filter. The adaptive filter updates the weight vector to minimize the error signal. Figure 5 shows that the error decreases as the iteration increases.
Figure 6 shows the cross-correlation function between the reference channel without clutter removal and the surveillance channel with the ECA. The induced clutter remains at $2\sigma_c$ due to the clutter included in the reference channel. The ghost target is generated by the coherence of the clutter in the reference channel and the target echo signal in the surveillance channel.

Figure 7 shows the cross-correlation function between the reference channel with the CMA and the ECA output signal. After removing the clutter of the reference channel, the ghost target and induced clutter are disappeared.

5. CONCLUSIONS AND FURTHER RESEARCH

Since the presence of the clutter included in the reference channel can degrade the detection performance of the target echo signal in the PCL system, it is important to obtain a clean direct-path signal in the reference channel. Thus, we removed the clutter in the reference channel by using the CMA and also confirmed the result of the clutter removal in the reference channel through the cross-correlation and the autocorrelation function. In addition, the theoretical calculation method of the amount of the clutter removal using the adaptive filter was derived. The channel equalizer is basically an IIR-type filter, however, the adaptive filter has limitation to generate the tap weight vector with infinite number of taps. Thus, the induced clutter is not completely removed at the end.

We confirmed that induced clutter and the ghost target can be deleted when the ECA and CMA are applied in the surveillance channel and the reference channel, respectively. In the zero Doppler frequency, it was confirmed that the interference was removed from the surveillance channel, however, the interference signal still remained in the vicinity of the zero Doppler frequency. We will perform further research on how to mitigate and reduce this signal near the zero Doppler frequency.

6. ACKNOWLEDGMENTS

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7. REFERENCES


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* Position can be chosen from: master student, Phd candidate, assistant professor, lecturer, senior lecture, associate professor, full professor

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