Multi-channel NLMS-based sea clutter cancellation in passive bistatic radar

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Abstract: Sea clutter suppression is critical in the detection of low-velocity targets using a passive bistatic radar. The residual sea clutter may become high when the normalized least-mean-square (NLMS) algorithm with a small step size is used for this purpose. While a large step size can be used to reduce the residual sea clutter, it yields a widened filter notch, and thereby, causes significant target signal energy loss. A multi-channel NLMS algorithm is proposed to solve this problem, and its effectiveness is verified by simulation and real radar data analysis.

Keywords: passive bistatic radar (PBR), sea clutter cancellation, multi-channel normalized least-mean-square (MCNLMS), adaptive filter

Classification: Microwave and millimeter wave devices, circuits, and systems

References

[1] J. E. Palmer, H. A. Harms, S. J. Searle and L. M. Davis: IEEE Trans. Signal Process. 61 (2013) 2116. DOI:10.1109/TSP.2012.2236324
[2] C. J. Baker, H. D. Grifths and I. Papoutsis: IEE Proc., Radar Sonar Navig. 152 (2005) 160. DOI:10.1049/ip-rsn:20045083
[3] A. Lauri, F. Colone, R. Cardinali, C. Bongioanni and P. Lombardo: IEEE Aerospace Conference (2007) 1. DOI:10.1109/AERO.2007.353068
[4] F. Colone, D. W. O’Hagan, P. Lombardo and C. J. Baker: IEEE Trans. Aerosp. Electron. Syst. 45 (2009) 698. DOI:10.1109/TAES.2009.5089551
[5] C. R. Berger, B. Demissie, J. Heckenbach, P. Willett and S. Zhou: IEEE J. Sel. Topics Signal Process. 4 (2010) 226. DOI:10.1109/JSTSP.2009.2038977
[6] S. Panagopoulos and J. J. Soraghan: IEEE Trans. Geosci. Remote Sens. 42 (2004) 1355. DOI:10.1109/TGRS.2004.827259
[7] K. Kulpa: Int. Radar Symp. (2013) 1.
[8] B. Widrow and S. D. Steams: Adaptive Signal Processing (Prentice-Hall, Englewood Cliffs, New Jersey, 1985) 55.
[9] S. Haykin: Adaptive Filter Theory, ed. E. Palik (Prentice-Hall, Englewood Cliffs, New Jersey, 2002) 4th ed. 547.
[10] J. R. Glover: IEEE Trans. Acoust. Speech Signal Process. 25 (1977) 484. DOI:10.1109/TASSP.1977.1162997
1 Introduction

Passive bistatic radar (PBR) exploits non-cooperative illuminators of opportunity as transmitters to perform target detection and localization [1]. Due to its capabilities of low-cost operation and covert surveillance, PBR has attracted considerable and increasing interests in recent years. Because the sidelobes of the ambiguity function of PBR usually have a time-varying structure and exist at a level not greatly lower than that of the peak [2, 3, 4, 5], this can lead to: 1) The direct signal interference (DSI), which is received by the sidelobe of the surveillance antenna and significantly stronger than the clutter echo, masks target echo signals, 2) The strong clutter echoes masks target echo signals. In particular, when sea-surface targets are detected, the spread Doppler spectrum of sea clutter makes the task of detecting low-velocity targets a very challenging problem [6, 7]. In addition, to perform clutter suppression before matched filtering, the signal bandwidth is significantly larger than the Doppler frequencies, making conventional filtering structures unapplicable. A commonly used adaptive interference cancellation algorithm in PBR is the normalized least-mean-square (NLMS) algorithm [8], which, in essence, is a single-channel high-pass filter that can suppress DSI and multipath clutter with low Doppler frequencies. For sea clutter with spread Doppler spectrum, the NLMS algorithm with a small step size, which forms a narrow notch with sharp notch edges in the frequency response (Doppler frequency response), usually results in a high sea clutter residues and a high false-alarm rate. When a large step size is used, on the other hand, the filter notch is widened to effectively suppress the DSI and spread sea clutter, but at the same time, the slant filter notch edges can incur an undesirable loss of the target signal energy (especially for low-velocity targets). To solve this problem, we propose a multi-channel NLMS (MCNLMS) algorithm, which is derived by exploiting multiple NLMS filtering channels and adopting a small step size in each channel. Essentially, multiple reference channels are formed by modulating the original reference signal with the Doppler frequencies of sea clutter, among which the zero-Doppler channel is mainly used to cancel DSI and zero frequency clutter, whereas other channels are used to cancel the sea clutter with non-zero frequencies. Additionally, in each filter channel, a small step size is used to obtain a sharp filter notch edge, so that each filter channel can form a narrow notch with sharp edges. A wide notch with sharp edges of the multiple filter channels is then formed by superposition of multiple adjacent channels. In addition to its ability of DSI and sea clutter suppression, MCNLMS has the advantage of protecting the slow target signal energy. Simulation and experimental results verify the effectiveness of the proposed MCNLMS algorithm.

2 Signal model

Fig. 1 shows the PBR scenario for the detection of sea-surface targets. The reference antenna receives the direct signal from the transmitter, whereas the surveillance antenna receives the echo signal of targets together with the interference signal which is mainly composed of DSI and multipath (sea clutter) signals. So the echo signal can be modeled as
where $s(t)$ is the complex envelope of the direct signal, and $\alpha_p$, $\theta_p$, $\tau_p$ are the amplitude, phase shift and time delay of the $p$th multipath, respectively. Specifically, the component corresponding to $p = 0$, i.e., $\alpha_0 e^{j\theta_0} s(t) e^{-j2\pi f_{da} t}$ represents the direct signal, $\alpha_m$, $\theta_m$, $\tau_m$, and $f_{da}$ are the amplitude, phase shift, time delay and Doppler of the $m$th target, respectively, and $P$ and $M$ are the number of stationary multipaths and targets. The third term in (1) is the sea clutter term, where $f_i$ is the Doppler frequency of the $i$th sea clutter channel which is aroused by sea wave, $\alpha_{i,j}(t)$, $\theta_{i,j}(t)$ and $\tau_{i,j}$ are the amplitude, phase shift and time delay of the $j$th multipath at $i$th sea clutter channel, respectively, and $I$ and $J_i$ are the number of sea clutter channel and multipath at $i$th sea clutter channel, respectively. In addition, $n_{\text{echo}}(t)$ is the noise in the surveillance channel. The reference signal is given by

$$u(t) = A s(t) + n_{\text{ref}}(t),$$

where $A$ is the amplitude of the direct signal, and $n_{\text{ref}}(t)$ is thermal noise in reference channel. Because the direct interference, stationary multipaths and sea clutter are much stronger than the target signal, they must be suppressed effectively so as to achieve effective target detection. The interference terms can be separately expressed as

$$d_r(t) = \sum_{p=0}^{P} \alpha_p e^{j\theta_p} s(t - \tau_p)$$

and

$$s_{r}(t) = \sum_{i=1}^{I} \sum_{j=1}^{J_i} \alpha_{i,j} e^{j\theta_{i,j}} s(t - \tau_{i,j}) e^{-j2\pi f_{i} t},$$

where $d_r(t)$ represents direct and stationary multipaths, and $s_{r}(t)$ represents non-stationary multipaths (sea clutter), which has a wide Doppler spectrum and can be modeled as the frequency modulated version of the direct signal. Generally, $d_r(t)$
can be canceled by using the traditional single-channel adaptive filters (such as NLMS, RLS and Wiener), but \( s_r(t) \) cannot be suppressed effectively, especially when low-velocity targets are to be detected.

### 3 MCNLMS algorithm

Conventional single-channel NLMS adaptive cancellation algorithm for PBR requires one reference signal, which can be only used to cancel interference at zero frequency, i.e., DSI and stationary multipaths. In order to cancel non-zero frequency interference reflected by fluctuant sea wave, multiple reference signals are needed. Toward this end, we propose the MCNLMS filter whose structure is illustrated in Fig. 2, where the multiple reference signals are formed by modulating the original reference signal with the Doppler frequencies of clutter. The MCNLMS filter consists of \( K \) parallel channels with a length-\( M \) filter in each channel, yielding the total dimension to be \( KM \). The modulation filter bank generate \( K - 1 \) frequency shifted replicates of \( u_1(n) \), expressed as \( u_i(n) = u_1(n)e^{j2\pi f_i/n_s} \), \( i = 2, 3, \ldots, K \), where \( u_1(n) \) is the original reference channel input vector, \( f_s \) is the baseband sampling frequency. Denote \( u_i(n) = [u_i(n), u_i(n-1), \ldots, u_i(n-M+1)]^T \) as the input vector of the \( i \)th channel at time \( n \), and \( w_i(n) = [w_i(n), w_i(n-1), \ldots, w_i(n-M+1)]^T \) as the corresponding weight vector, and the superscript \( T \) denotes transposition. In addition, \( d(n) \) is the desired response of surveillance channel signal and \( \hat{d}(n) = \sum_{i=1}^{K} w_i^H(n)u_i(n) \) is its estimated value, respectively, the superscript \( H \) denotes the conjugate transpose. \( e(n) = d(n) - \hat{d}(n) \) denotes the estimation error.

The mathematical description of proposed MCNLMS algorithm is as follows. Stacking the input signal vectors \( u_i(n) \) for all the \( K \) channels yields the following matrix

\[
U(n) = [u_1(n), u_2(n), \ldots, u_K(n)]
\]  
\[
= [u_1(n)e^{j2\pi f_1/n_s}, u_1(n)e^{j2\pi f_2/n_s}, \ldots, u_1(n)e^{j2\pi f_K/n_s}]^T.
\]  

(4)

The corresponding weight coefficient matrix is denoted as

![Fig. 2. Structure of the multi-channel adaptive filter.](image-url)
\[ W(n) = [w_1(n), w_2(n), \ldots, w_K(n)]. \]  

Based on the principle of minimum disturbance [9], the design criterion of the MCNLMS algorithm is a constrained optimization problem that minimizes the Euclidean norm of \( \Delta w_i(n+1) = w_i(n+1) - w_i(n) \) subject to the following constraint:

\[ d(n) = \sum_{i=1}^{K} w_i^H(n+1)u_i(n), \]  

where \( w_i(n+1) \) is the updated weight vector of the \( i \)th channel. To solve the above constrained optimization problem, the cost function based on the method of Lagrange multipliers [9] is given by

\[ J(n) = \|w_i(n+1) - w_i(n)\|^2 + \text{Re}\left\{ \lambda \left[ d(n) - \sum_{i=1}^{K} w_i^H(n+1)u_i(n) \right] \right\}, \]  

where \( \lambda \) is the complex Lagrange multiplier, superscript * denotes the complex conjugate, and \( \text{Re}\{\cdot\} \) denotes the real part operator. By setting the partial derivative of \( J(n) \) in Eq. (7) with respect to \( w_i(n+1) \) to zero, we obtain the optimum weight vector as

\[ w_i(n+1) = w_i(n) + \frac{1}{2} \lambda^* u_i(n). \]  

Substituting Eq. (8) into Eq. (6) yields

\[ \lambda = 2 \left[ d(n) - \sum_{i=1}^{K} w_i^H(n)u_i(n) \right] \left[ \sum_{i=1}^{K} \|u_i(n)\|^2 \right]^{-1}. \]  

Note that \( d(n) - \sum_{i=1}^{K} w_i^H(n)u_i(n) \) in the above equation is the error signal \( e(n) \). Thus, by substituting Eq. (9) into Eq. (8) and introducing a step size factor, the updated equation of the MCNLMS algorithm becomes

\[ w_i(n+1) = w_i(n) + \frac{\mu_i}{\sigma + \sum_{i=1}^{K} \|u_i(n)\|^2} u_i(n)e^*(n), \]  

where \( \mu_i \) is the step size of the \( i \)th channel and \( \sigma \) is a small positive value to avoid overflow.

4 Simulation results

With the results presented in [10], the transfer function of the MCNLMS algorithm can be approximately derived as

\[ H(f) = \prod_{i=1}^{K} \frac{e^{j2\pi f_i/f_s} - e^{j2\pi f_i/2f_s}}{e^{j2\pi f_i/f_s} - (1 - \frac{u}{2}) e^{j2\pi f_i/2f_s}}. \]  

Note that, when \( K = 1 \), Eq. (11) reduces to the transfer function of the NLMS algorithm. Therefore based on Eq. (11), we can derive the amplitude-frequency characteristics of NLMS and MCNLMS. In the following simulations, we assume \( f_s = 10 \text{ MHz}, f \in [-50 \text{ Hz}, 50 \text{ Hz}] \). Fig. 3 shows the amplitude-frequency char-
acteristics of the NLMS algorithm with a large step size and a small step size, and that of the MCNLMS algorithm with small step sizes ($\mu_1$ to $\mu_5$) at five channels ($K = 5$), respectively modulated by $f_1 = 0$ Hz, $f_2 = -2$ Hz, $f_3 = 2$ Hz, $f_4 = -4$ Hz and $f_5 = 4$ Hz. It is evident that the NLMS is a high pass filter, where a narrow notch leads to a poor interference suppression performance when the step size is small, and a wide notch leads to a severe target energy loss for slow targets when the step size is big. On the other hand, the MCNLMS filter also acts as a high pass filter, where the five narrow notches form a widened one for effective clutter suppression when five step sizes are all small. The sharp notch edges of MCNLMS filter imply enhanced clutter suppression and better signal protection, particularly for low-velocity targets. In addition, the frequency response notch of the MCNLMS filter can be widened with the increase of the step sizes.

To compare the abilities of low-velocity target signal protection and clutter suppression of the above two algorithms, we examine the signal energy loss at different frequencies versus step size. Assume that the Doppler frequency of the target is 15 Hz and the Doppler frequencies of the clutter include 0 Hz, $\pm 2$ Hz and $\pm 4$ Hz. The signal energy loss versus step size is shown in Fig. 4. For fair comparison, the step size of the two algorithms are set to have the same signal energy loss at zero frequency. Fig. 4(a) shows the signal energy loss at different frequencies versus step size by using the NLMS algorithm. Fig. 4(b) shows the signal energy loss at different frequencies versus step sizes by using MCNLMS algorithm with five channels, where the step size of zero frequency channel ($\mu_1$) is set as a variable and the step sizes of other four channels ($\mu_2$ to $\mu_5$) are all set as 0.00001. It can be concluded from the two figures that the target signal energy loss of MCNLMS is less than that of NLMS, and the clutter energy loss of the MCNLMS at $\pm 2$ Hz and $\pm 4$ Hz is more than that of NLMS. Therefore, the better performance of low-velocity target signal protection and clutter suppression can be achieved by using MCNLMS algorithm.
5 Real data verification

For the passive radar application, the time delay and Doppler profile of the target return are extracted by the cross ambiguity function (CAF), which is defined as [1]

$$\chi(\tau, \nu) = \int_0^T u(t) \cdot e(t + \tau) e^{-j2\pi\nu t} dt$$  \hspace{1cm} (12)

where $\tau$ and $\nu$ are time delay and Doppler, respectively, $u(t)$ and $e(t)$ are the reference signal and the canceled echo signal, respectively, and $T$ is the coherent integration time.

The real data were acquired using an digital television (DTV)-based PBR system at the east coast of China. Fig. 5 shows our experimental environment, where a single Yagi antenna is used for receiving the direct signal, and a double Yagi antenna is used for receiving the echo signal. The baseline length between the

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Fig. 4. Signal energy loss versus the step size: (a) Signal energy loss versus the step size of NLMS algorithm. (b) Signal energy loss versus the step sizes of MCNLMS algorithm.

Fig. 5. Experimental environment.
receiving station and the Qingdao television tower is about 3.5 Km, the range between the receiving station and the small boat is about 4.61 Km, and the velocity of the small boat is about 6 m/s. The carrier frequency and the bandwidth of the transmitted DTV signal are 746 MHz and 7.56 MHz, respectively. The real data were collected by our experimental PBR system with a baseband sampling rate of 10 MHz. For fair comparison between different algorithms, a fixed data segment of a certain data file is used for the operation of the CAF, where the coherent integration time is 0.5 s, thus the length of the data segment is 5000000, and the Doppler resolution is 2 Hz. The length of the NLMS filter is set as 1000. The cancellation gain is defined as $G_c = 10 \log_{10} [E(|d(n)|^2)/E(|e(n)|^2)]$ with $E(\cdot)$ denoting averaging, where $d(n)$ and $e(n)$ are the echo signal and the canceled echo signal, respectively. The signal-to-clutter-plus-noise ratio of the target is defined as $SCNR = 10 \log_{10}(P_t/P_j)$, where $P_t = \chi^2(\tau_t, v_t)$ and $P_j = E(\chi^2(\tau_n, v_n))$ are the measured target correlation peak power and the measured average power of clutter-plus-noise, respectively, $\tau_t$ and $v_t$ are time delay and Doppler of target, respectively, and $\tau_n$ and $v_n$ are time delays and Doppler of interference, respectively. Fig. 6 shows the CAF maps before cancellation, and no target can be detected. Fig. 7 shows the CAF maps using the NLMS algorithm with a small step size of 0.003. Fig. 7(a) shows the three-dimensional and side elevation maps of the CAF, from which we can derive the range and Doppler of the target to be 4.61 Km and $-24$ Hz, respectively, and $G_c$ to be 22.19 dB. Fig. 7(b) shows the normalized power in the Doppler dimension, where the normalized average power line (NAPI) of clutter-plus-noise, which is defined as $P_{NAPI} = 10 \log_{10}[E(\chi^2(\tau_n, v_n))/\max(\chi^2(\tau, v))]$, is $-18.61$ dB. High residual sea clutter is evident in this figure. To quantitatively analyze the residual clutter, we define the residual clutter-to-interference (clutter-plus-noise) ratio as $CIR = 10 \log_{10}(P_{rc}/P_j)$, where $P_{rc}$ is the measured maximum value of the residual clutter peak power, which is defined as $P_{rc} = 10 \log_{10}[\max(\chi^2(\tau_{rc}, v_{rc}))]$, where $\tau_{rc}$ and $v_{rc}$ are time delay and Doppler of residual clutter, respectively. The $CIR$ is $18.61$ dB (usually the minimum detectable signal-to-noise ratio (MDSNR) is about $13$ dB in PBR), which will lead to a high false alarm rate. Fig. 8 shows the CAF maps using the NLMS
algorithm with a large step size of 0.01. Fig. 8(a) shows the three-dimensional and side elevation maps of the CAF, and Fig. 8(b) shows the normalized power in the Doppler dimension, where the $G_c$ is increased to 24.06 dB and the $CIR$ is decreased to 5.23 dB, whereas the target $SCNR$ is reduced by 2.68 dB to 12.16 dB. For the MCNLMS algorithm, five channels are used and the filter length in each channel is set as 1000. The modulation frequencies used in the five channels are set as $f_1 = 0$ Hz, $f_2 = -2$ Hz, $f_3 = 2$ Hz, $f_4 = -4$ Hz and $f_5 = 4$ Hz, respectively. The step sizes of the five channels are set as $\mu_1 = 0.003$ and $\mu_{2-5} = 0.0002$. Fig. 9 shows the CAF maps using the proposed MCNLMS algorithm. Fig. 9(a) shows the three-dimensional and side elevation maps of the CAF, and Fig. 9(b) shows the normalized power in the Doppler dimension, where the $G_c$ become to 23.89 dB and the $CIR$ to 7.66 dB, meanwhile the $SCNR$ of the target is increased to 15.21 dB. It is obvious that the residual sea clutter is reduced dramatically whereas the target $SCNR$ is improved.

In addition, in order to show the advantages of the MCNLMS, the normalized power maps of NLMS versus the step size and MCNLMS versus channel numbers are given by using the real radar data. Fig. 10 shows the normalized power maps of the NLMS in the Doppler dimension versus step sizes. It can be concluded that the
power of residual clutter decreases with the increase of step size, but the power of target also decreases which isn’t what we want. Fig. 11 shows the normalized power maps of the MCNLMS in the Doppler dimension versus channel number. It can be seen that the power of residual clutter decreases with the increase of channel number, meanwhile the SCNR of target has a little change and remains around 15 dB, which is a satisfactory result we need. The specific values of SCNR and the CIR of the NLMS with different step sizes are illustrated in Table I. It can be concluded that the SCNR and the CIR decrease with the increase of step size, and the CIR is higher than the SCNR when the step size is smaller than 0.006, which results in a high false-alarm rate. On the other hand, when the step size exceeds 0.006, the SCNR is higher than CIR, yet may be lower than MDSNR (Assume MDSNR is 13 dB). Therefore, it is difficult to achieve a satisfactory result (high SCNR and low CIR) using the NLMS algorithm. Table II shows the SCNR and the
CIR of MCNLMS with small step sizes ($\mu_1 = 0.003$ and $\mu_2 = 0.0002$) versus the channel number. It can be concluded that CIR decreases rapidly with the increase of the channel number, which means that a low level of clutter residues (a low false-alarm) can be achieved with this approach. On the other hand, the SCNR increases at first and then slightly decreases with the increase of the channel number, which is because the energy loss of the target increases slightly with the increase of the channel number. Anyhow, it is obvious that a higher SCNR and a lower CIR can be achieved when the channel number is greater than or equal to 3. So a satisfactory performance can be achieved by using the MCNLMS.

### 6 Conclusion

A novel MCNLMS algorithm was studied in this paper. The proposed algorithm, with advantages of widened filter notch and sharp filter notch edges, is very useful for sea clutter suppression and signal protection of low-velocity targets in PBR. Its effectiveness has been demonstrated by simulation and real radar data analysis.

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**Fig. 11.** The normalized power maps of the MCNLMS in the Doppler dimension.

| Table I. CIR and SCNR of NLMS with different step sizes |
|--------------------------------------------------------|
| step size | 0.003 | 0.004 | 0.005 | 0.006 | 0.007 | 0.008 | 0.009 |
| CIR (dB) | 18.61 | 15.46 | 14.62 | 13.33 | 10.66 | 8.89  | 7.23  |
| SCNR (dB) | 14.84 | 14.44 | 14.25 | 13.25 | 12.86 | 12.43 | 12.26 |

| Table II. CIR and SCNR of MCNLMS with different numbers of channels |
|---------------------------------------------------------------------|
| number of channels | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| CIR (dB) | 18.61 | 16.56 | 12.29 | 11.14 | 7.66 | 7.53 | 7.43 |
| SCNR (dB) | 14.84 | 15.17 | 15.29 | 15.30 | 15.21 | 15.15 | 15.07 |
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