



Weight Matrix-Based Least Mean Square Algorithm for Target Detection in Passive Radars

Venu Dunde, Koteswara Rao NV

Abstract Ambiguity function analysis is the most expensive process for target detection in passive radars. The computational cost is attributed to the extensive range-Doppler field required to evaluate the cross-correlation function. Some tools like fast Fourier transform or batching algorithm are employed to partially reduce the computational effort. In this paper a different generalization of least mean square algorithm is utilized for target detection. The basic idea is to employ the properties of the computed weight matrix to extract target coordinates. The algorithm performance is investigated by computer simulation using some practical simulated FM stereo signal. The results reveal the lower computational complexity of the presented procedure compared to existing methods..

Keywords : Least mean square, Passive radar, Target detection, Weight matrix..

I. INTRODUCTION

By exploiting available transmitters as illuminators of opportunity, passive bistatic radars(PBR) have a very high chance of staying unidentified and unlocalized in space. One efficient high performance, low implementation-cost waveform exploited by PBRs is the commercial FM radio frequency ranging from 88 to 108 MHz band[1]. For evaluation of the range-Doppler coordinates a cross correlation function (CCF) of the surveillance and reference signals is exploited. However, target's peaks are masked by the side lobes of direct signal and clutter echoes due to their much higher power. Different clutter cancellation techniques are suggested in the literature[2–4]. One simple pure block scheme is the extensive cancellation algorithm (ECA)[3].In this case, limited bins of clutter Doppler shifts are included in the pre-constructed clutter space which leads to an increased complexity. Bathes version of ECA is experimentally inspected for clutter attenuation of slow moving targets in[5].In contrast to pure block algorithms, the recursive least square (LSR) and least mean square (LMS) algorithms are

iterative methods applicable of cancelling non-stationary clutters[2].The FBLMS scheme is a fast Fourier block version of LMS which dominates LMS in terms of cost. It is shown in [6]that FBLMS provides faster convergence, shorter processing time and more qualified cross ambiguity function (CAF) for DVB-T passive radars. After cleaning the received signal from disturbances, the costly CCF analysis is performed in an extensive range -Doppler field to detect targets. The target detection capability of FM radio and HDTV is investigated in [7] in terms of range, Doppler resolution and peak side-lobe level ratio. Also, different aspects of AF is compared for FM and DVB-T signals in[8].Since the computed CAF matrix contains important data of limited targets, it has an ideal sparse structure. Hence, multiple studies have employed the compressed sensing technique to reduce the complexity required for solving CAF problem[9]. Furthermore, CAF is analyzed by employing other techniques like correlation FFT, direct FFT, and batches algorithm (BA)in [10,11]. Although LMS scheme is exploited for disturbance cancellation in the literature, a target detection weight matrix-based LMS algorithm is innovated in this paper and it is demonstrated that this matrix contains valuable information revealing targets range-Doppler. The new approach dominates the conventional CCF analysis in terms of computational cost.

II. SIGNAL MODELING AND DETECTION FUNDAMENTALS

Reference and surveillance signals are collected in dedicated channels in a PBR. Assume that the reference channel receives an acceptable copy of the direct signal. Then, they are modeled as:

$$S_{ref}[n] = A_{ref} \cdot d[n] + n_{ref}[n], \quad n = -R, \dots, N - 1 \quad (1)$$

$$S_{surv}[n] = A_{surv} \cdot d[n] + \sum_{i=1}^{N_c} c_i \cdot \exp(2j\pi n p_{c_i} / N) \cdot d[n - l_{c_i}] + \sum_{i=1}^{N_t} a_i \exp(2j\pi n p_{t_i} / N) d[n - l_{t_i}] + n_{surv}[n], \quad n = 0, \dots, N - 1 \quad (2)$$

in discrete domain, where d is the complex envelope of the direct signal as a fragment of a FM signal, A_{ref} and A_{surv} are complex amplitudes and n_{ref} and n_{surv} are the thermal noises of the reference and surveillance antennas.

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Furthermore, c_i, p_{c_i}, l_{c_i} are complex amplitude, Doppler shift and delay of the i -th clutter from N_c clutters and a_i, p_{t_i}, l_{t_i} are complex amplitude, Doppler shift and delay of i -th target from N_t targets. The detection process in passive radars is based on the evaluation of a delay-Doppler CCF of the surveillance and reference signals as:

$$x(l, p) = \sum_{n=1}^N S_{surv}[n] \cdot S_{ref}^*[n-l] \cdot \exp(-2j\pi np/N) \quad (3)$$

$0 \leq l \leq l_{max}, p_{min} \leq p \leq p_{max}$

where, $*$ denotes conjugate, l_{max} is maximum delay bin, p_{min} and p_{max} are minimum and maximum Doppler bins. An extensive Doppler-range map is typically required to cover the desired region. Therefore, evaluation of (3) takes a high computational burden. The simplest way to observe (3) is considering it as a FFT of $S_{surv}[n]$ and $S_{ref}^*[n-l]$, resulting in $N_t(N + N \log_2 N)$ required complex products. Another observation is to compute the CCF between $S_{ref}[n]$ and a Doppler-shifted version of $S_{surv}[n]$ which needs $2N \log_2 N + N_f(N + N \log_2 N)$ products, [10,11].

A. Target detection employing LMS approach

The main idea of this paper is to employ the LMS method as an efficient target detection tool. To this end first, denote a target signal as:

$$S_{targ}[n] = A_t \cdot \exp(2j\pi np_t/N) \cdot S_{ref}[n - l_t] \quad (4)$$

$n = 0, \dots, N - 1,$

where, A_t, p_t and l_t are respectively target's amplitude, Doppler and delay. Also, define the cost and error functions as:

$$\begin{aligned} cost(n) &= |e(n)|^2 \\ e[n] &= S_{clean}[n] - W^*(n)S_r^T(n) \end{aligned} \quad (5)$$

$n = 0, \dots, N - 1,$

where, S_{clean} is the clean signal, and $W(n)$ and $S_r(n)$ are denoted as:

$$\begin{aligned} W(n) &= [w_{M_1}(n) \quad w_{M_1+1}(n) \quad \dots \quad w_{M_2-1}(n)], \\ S_r(n) &= (S_{ref}[n - M_1] \quad \dots \quad S_{ref}[n - M_2 + 1]), \end{aligned} \quad (6)$$

$n = 0, \dots, N - 1,$ (7)

where, M_1 and M_2 define the target range interval. By Applying the LMS technique, a weight sequence is sought such that the difference between the clean signal and a linear combination of M_1 to M_2 previous samples of S_{ref} is minimized. In other words, the length of the filter is $M_2 - M_1$, while the filter starts from M_1 -th delayed sample. A target generator space is also defined using M_1 -th to M_2 -th delayed replicas of S_{ref} as the columns of:

$$\begin{aligned} H_t &= [S_c(M_1) \quad \dots \quad S_c(M_2 - 1)] \\ S_c(n) &= (S_{ref}[-n] \quad \dots \quad S_{ref}[N - 1 - n])^T, \end{aligned} \quad (8)$$

for $n = M_1, \dots, M_2 - 1$. An important point is that $S_r(n)$ in (7) constructs the row space of target generator matrix H_t . The LMS algorithm is implemented by employing the rule,

$W(n) = W(n - 1) + \mu S_r(n - 1) e^*(n - 1) / 2,$ (9) where μ is the convergence factor. Then, rows of the following $N \times (M_2 - M_1)$ weight matrix are updated in sequence,

$$W_t = \begin{bmatrix} w_{M_1}(0) & \dots & w_{M_2-1}(0) \\ \vdots & \ddots & \vdots \\ w_{M_1}(N - 1) & \dots & w_{M_2-1}(N - 1) \end{bmatrix} \quad (10)$$

Consider the target signal (4) with a range and Doppler l_t and p_t . Since the l_t -th delayed replica of S_{ref} is $(l_t - M_1 + 1)$ -th column of H_t , the element-wise product of $(l_t - M_1 + 1)$ -th column of W_t and $(l_t - M_1 + 1)$ -th column of H_t reproduces the target signal only if $W_t(n, l_t - M_1 + 1) = A_t \cdot \exp(2j\pi np_t/N), n = 0, \dots, N - 1$ (11)

holds. Then, the target signal is evaluated as the element-wise product of $(l_t - M_1 + 1)$ -th column of W_t and $(l_t - M_1 + 1)$ -th column of H_t . Since limited number of targets are available, the computed weight matrix has sparse properties. The sparsity of this matrix is also mentioned in [12]. Columns of W_t with nontrivial average of its entries indicate the targets range bins. This can be simply checked by plotting the average of each column of W_t as $[\sum_{i=1}^N W_t(i, n)]/N, n = 1, \dots, M_2 - M_1.$ (12)

The corresponding target Doppler can be approximated by setting two sides of (11) equal in phase for $n = N - 1$ as: $p_t \approx [\angle W_t(N, l_t - M_1 + 1)]/[2\pi(N - 1)/N].$ (13)

The last step value of the weight vector (in last row of W_t) is employed in (13), for a more precise approximation. Plotting a small fragment of 2D-CCF for computed delay l_t while sweeping the Doppler in $[p_t - s, p_t + s]$, reveals the exact target Doppler.

B. Weak target detection

The mostly applied procedure in the literature for weak target detection, is the clean technique [13]. In this technique, a complex amplitude is computed for the strong signal as a partial correlation between the received signal and estimated normalized strong echo. A new procedure is innovated in this section for weak target detection. After evaluation of strong target's range and Doppler from (12) and (13), a real amplitude A_t as in (4) is still required to precisely reconstruct the target signal. Rewrite S_{targ} in (4) as

$$\begin{aligned} S_{targ} &= A_t S_{targ} \\ S_{targ}[n] &= \exp(2j\pi np_t/N) S_{ref}[n - l_t] \end{aligned} \quad (14)$$

$n = 0, \dots, N - 1.$

The main idea is based on minimization of the similarity between $S_{clean} - A_t S_{targ}$ and S_{targ} at the known range and Doppler as:

$$\min_{A_t} F(A_t)$$

$$F(A_t) = \left| \sum [(S_{clean} - A_t s_{target}) \cdot s_{target}^*] \right|_{l_t, p_t}$$

(15) Define $(\sum S_{clean} s_{target}^*)|_{l_t, p_t} = x_1 + y_1 j$ and $(\sum s_{target} s_{target}^*)|_{l_t, p_t} = x_2 + y_2 j$. Then, by setting $\partial F(A_t) / \partial A_t$ equal to zero, the amplitude is computed as $A_t = -(x_1 x_2 + y_1 y_2) / |s_{target} s_{target}^*|^2$.

III. RESULTS AND DISCUSSION

To evaluate the presented processing scheme, an FM signal (88 to 108 MHz) is exploited as the waveform source of opportunity[1]. A scenario of clutters and targets is defined in Tab. Error! Reference source not found.. The diverse interval assumed for clutter Doppler shifts represents a more realistic scenario. The ECA scheme requires a high computational cost to cancel the clutters in such a scenario, while assuming a pre-knowledge of Doppler shifts is irrational. In comparison, the only drawback of LMS is the slightly slow convergence speed which leads to a misalignment at the beginning steps and an inefficient disturbance cancellation. To overcome the initial convergence error, the filter is repeated for the initial p steps, while the initial weight value is set equal to the computed last step (i.e. N -th step) weight vector. In this scenario, a repeat of LMS for $p = 4 * 10^3$ initial steps which is $1/25$ of the total steps $N = 10^5$, covers the initial mismatch acceptably. Number of complex products of the improved-LMS is then $(N + p)(2M + 1)$, $M = M_2 - M_1$ which is still much lower than $(NK^2 + K^3)$ complex products required in ECA scheme[3]. Note that K is the column dimension of the augmented matrix H_c which contains the Doppler shifted replicas of its columns. Nine Doppler shifts along with the zero Doppler of direct signal result in $K = 10M$. The clutter attenuation (CA), which is the power ratio of input and output signals of the filter, as well as the number of complex products are tabulated for three algorithms LMS, improved-LMS and ECA at Tab. 1. The improved-LMS clutter attenuation is closely tracking ECA, while much lower cost is maintained. Next, the weight matrix-based target detection algorithm presented in Section 2, is

Clutters	#1	#2	#3	#4	#5	#6	#7	#8	#9	
Delay(ms)	0.05	0.1	0.15	0.2	0.25	0.07	0.17	0.22	0.13	
Doppler(Hz)	4	3	2	1	-1	-2	-3	-4	-5	
CNR	40	30	20	10	5	27	18	8	5	
Targets	#1	#2	#3							
Delay(ms)	0.3	0.5	0.6							
Doppler(Hz)	-50	100	50							
SNR	4	2	-10							

implemented on the clean signal. After construction of the weight matrix W_t , average of its columns is plotted from (12) as in Fig. 1. Two targets ranges are observable at $l_{t1} = 60$ and $l_{t2} = 100$ which correspond to delays 0.3ms and 0.5ms. A similar phenomenon to side lobe effect is observed at the neighbor bins. The corresponding Doppler shifts are evaluated from (13) at $p_{t1} = -52$ and $p_{t2} = 96$. The precise Doppler shifts -50 and 100 are then computed by plotting a 2D-CCF

fragment for l_{ti} and $p_t \in [p_{ti} - s, p_{ti} + s]$, $i = 1, 2$ where $s = 10$ is assumed, (Fig. 2). The weak target cancellation algorithm is exploited to cancel two stronger targets. Then, the weak target range is ascertained at $l_{t3} = 120$ (Fig. 3) and its corresponding Doppler is evaluated roughly at $p_{t3} = 28$. A larger guaranteeing sweeping parameter $s = 25$ is chosen to plot the 2D-CCF fragment as in Fig. 3 and the precise Doppler is eventually evaluated at $p_{t2} = 50$.

Table. 1 Comparison of three algorithms ($N = 10^5, M_1 = 50, M_2 = 130$).

Algorithm	LMS	Improved-LMS	ECA
CA(dB)	32.4884	49.6275	57.7170
Complex multiplications	16,100,000	16,744,000	6.4512 * 10 ¹⁰

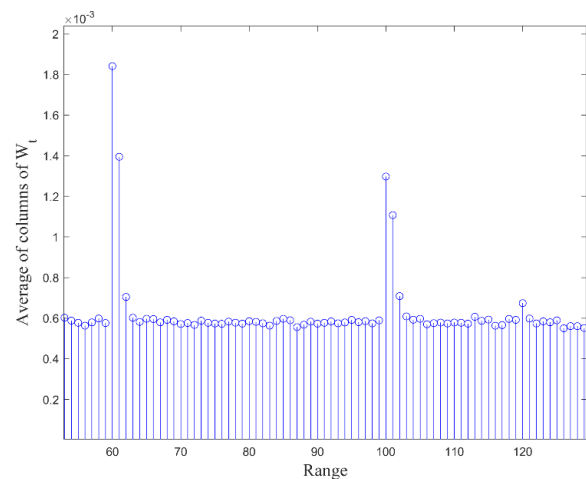


Fig.1 Target detection by plotting average of columns of the weight matrix W_t .

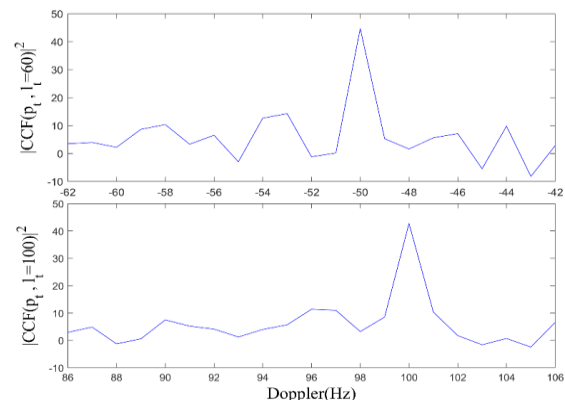


Fig.2 Strong targets Doppler evaluation.

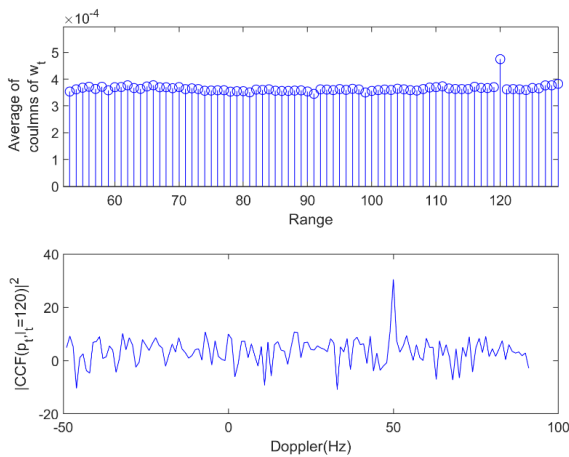


Fig.3 Weak target delay and Doppler detection.

IV. CONCLUSION

A novel target detection algorithm is presented based on the least mean square difference between the clean signal and a linear combination of delayed samples of reference signal. While the traditional AF analysis, employed for target detection, has many challenges in terms of reducing the computational cost, in the presented algorithm a considerably lower computational burden is required. The key idea is to utilize the properties of computed weight matrix in LMS algorithm for target detection. The targets ranges are detected by evaluation of the weight matrix columns which have nontrivial averages. However, targets Doppler shifts are just approximated and their precise values are computed by plotting a small fragment of 2D-CCF. Weak target detection problem is also dealt by strong target removal. To this end, the strong target amplitude is computed based on minimizing the similarity between the strong target and its difference with the clean signal at the computed Doppler and range. Furthermore, LMS response in disturbance cancellation is improved by repeating limited primary steps (improved-LMS). Then the computational effort is shown to be way lower than conventional approaches, while the clutter attenuation is improved to a much higher level. Since RLS technique is also capable of considering Doppler effects on computed weights, its target detection capability might be inspected in further investigations.

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