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DECEPTION JAMMING SUPPRESSION FOR RADAR

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ABSTRACT

The problem of deception jamming suppression for a radar system and an effective spatial polarization filter strategy is outlined based on the spatial and polarization parameter joint estimates. It can make the false target filtered effectively and the desired target remained with an improved signal-to-jammer-noise ratio. In this scheme, the tri-linear decomposition model is first employed to obtain paired 2D direction of arrive and polarization parameter joint estimates of the target and jammer. Then a spatial-polarization oblique projection filter operator based on the joint estimates is constructed and utilized to project the received mixed return of radar onto to the target echo sub-linear space so as to suppress the jamming. This method is applicable on joint estimates of the target and jammer. Specific procedure of separation of main lobe and side lobe are demonstrated. However the detection probability is less in optimizing the waveform covariance matrix. An iterative algorithm is proposed to optimize the waveform covariance matrix (WCM) for maximizing the worst-case output signal-jammer-noise-ratio (SJNR) over the convex uncertainty set such that the worst-case detection performance of MIMO OFDM-STAP can be maximized By exploiting the diagonal loading (DL) method, each iteration step in the proposed algorithm can be reformulated as a semi-definite programming (SDP) problem, which can be solved very efficiently.

I. INTRODUCTION:

The development and application of military radar has become the focus of the two sides locked in battle. We can say that confrontations using radar have not been stopped since the day it was put to military use, and is becoming more intense. Active radar electromagnetic radiation leads to a direct attack from anti-radiation weapons and from electronic jamming, and radar detects the targets depending on the reflection of electromagnetic waves, which has led to the emergence of electromagnetic stealth technology, enabling the absorption and reflection of waves. Electronic Countermeasures (ECM) are “actions taken to prevent or reduce the enemy’s effective use of the electromagnetic spectrum”. Any intentional electronic attempt to confuse radar operation is generally referred as an ECM technique [1]. In radar applications its main objectives are to deny or to falsify information (detection, measurement, discrimination, and classification data) that the radar tries to obtain. ECM is primarily based on jamming: both noise jamming and deception jamming. Modern ECM systems are designed to cope with different types of radars, and they have to operate in a dense threat environment that requires computer control of the system. The back scattered returns of radar always suffer from false targets repeated by an ECM facility equipped with a Digital Radio Frequency Memory (DRFM). The false target jamming not only causes some false alarms but also raises the threshold of constant false alarm rate detector, which could severely degrade the detection performance of radar system [2].

Electronic Counter-Countermeasures (ECCM) are “actions taken to ensure friendly use of the electromagnetic spectrum against electronic warfare.” Their main objective is to eliminate or reduce the efficiency of the enemy’s ECM. Pulse diversity is considered as the most effective ECCM scheme against the DRFM repeat-type jammer [2]. Antenna-related ECCM are ECCM techniques based on the properties of antenna systems to reduce the effectiveness of ECM. Space selection based on antenna directivity and polarization selection based on the polarization properties of electromagnetic waves are the main ECCM strategies of discrimination the useful signals and interference. The main techniques for antenna-related ECCM based on spatial selection are coverage and scan control, reduction of main-beam width, reduction of side-lobe level, and employing of adaptive antennas.

The first group of methods based on antenna pattern and scan control may include blanking or turning of the receiver while the radar is observing the part of space containing a jammer, using multiple-beam configuration to detect a target by a beam not afflicted by jammers, random scanning to prevent deception jammers from synchronizing with the antenna scan rate, and other relevant measures. Reduction of beam width increases the angular resolution and is a valuable feature of any radar operating in a dense ECM environment. It should be kept in mind, however, that the reduction of beam width, for a given aperture size, results in increasing the side-lobe level that worsens a radar’s anti-jamming capability, so the reasonable compromise should be found in specifying the antenna radiation pattern.

The main side-lobe-related techniques are usage of low and ultralow side-lobe antennas, side-lobe blanking (SLB) and side-lobe cancellation (SLC). The generalization of SLC techniques in combination with adaptive processing technique is the concept of adaptive arrays. This technique is very promising as it is based on advanced methods of digital beam-forming and digital signal processing and permits super resolution capabilities that can be very useful for ECCM.

Polarization selection takes advantage of electromagnetic wave polarization features for discrimination of useful signals at the interference background. In [3], an interference polarization suppression method for the main-lobe jamming was presented, which was based on the spatial polarization characteristics of a single polarized antenna. Though these polarization filters can cancel the deception jamming to a certain extent, the polarization filters do not concern the spacial feature and target’s polarization, the phase and amplitude of target would vary after filtering. Especially, the target echo and jamming would be all filtered in some cases [4]. The loss of polarization filter degrades the ECCM performance. It is considered that the desired target and deception jammer have different spatial and polarizational parameters in the spacial-polarizational joint domain, which can be adopted by Pulsed Doppler (PD) radar equipped with a polarization sensitive array (PSA) and Multiple-Input Multiple-Output (MIMO) radar equipped with a PSA receiver to suppress the deception jamming effectively.

A particularly critical issue for MIMO radar is the waveform optimization, which has received considerable attention recently. The optimization problems require the specification of parameters, e.g., the target location, etc. As a sequence, the optimized waveforms depend on these pre-assigned values. In practice, these parameters are estimated with errors, and hence they are uncertain. The resultant accuracy of parameter estimation is sensitive to these uncertainties in parameters. It means that the optimized waveforms based on a certain parameter estimate can give a very low performance of parameter estimation for another reasonable estimate.

Focusing on this issue, following the min-max approach, the problem of robust waveform design is considered to attempt to systematically alleviate the sensitivity of the detection performance of the MIMO Orthogonal

Frequency Division Multiplexing (OFDM) radar based Space-Time Adaptive Processing (STAP) to the estimation errors in the initial parameter estimates by explicitly incorporating the parameter uncertainty model in the optimization problem. Because maximization of the output SINR is tantamount to maximization of the detection performance in the case of Gaussian noise [5], here the waveform covariance matrix (WCM) is optimized to maximize the worst-case output SINR of MIMO-OFDM STAP over the convex uncertainty set such that the worst-case detection performance can be maximized. To solve the resultant complicated nonlinear optimization problem, an iterative algorithm is proposed to optimize the WCM for maximizing the worst-case output signal interference-noise ratio (SINR) over the convex uncertainty set such that the worst-case detection performance of MIMO-STAP can be maximized. By exploiting the diagonal loading (DL) method, each iteration step in the proposed algorithm can be reformulated as a semi-definite programming (SDP) problem, which can be solved very efficiently.

The rest of this paper is organized as follows: The parameter estimation method is derived in Section II. In Section III, the robust waveform optimization problem to improve the worst-case detection performance is constructed.

In Section IV, simulation results are presented to verify the performance of our proposed method, whereas the conclusions are shown in Section V.

II. PARAMETER ESTIMATION METHOD

For the tri-linear model, tri-linear alternating least squares (TALS) algorithm is often employed as the common data detection method [6–7]. The fundamental idea of TALS is to update one of the slice matrices $X = [X_1, X_2, \dots\dots, X_U]$, $Y = [Y_1, Y_2]^T$, or $Z = [Z_1, Z_2, Z_3, \dots., Z_L]^T$each time using least squares (LS). The updating method can be described to update the remaining matrices with the previously obtained estimates until convergence of the LS cost function. TALS algorithm in our scheme is discussed as follows. The LS fitting of X satisfies

$$f_X = \min_{P,A,S} \left\| \begin{bmatrix} X_1 \\ X_2 \\ \cdot \\ \cdot \\ X_U \end{bmatrix} - \begin{bmatrix} PD_1(A) \\ PD_2(A) \\ \cdot \\ \cdot \\ PD_U(A) \end{bmatrix} S^T \right\|_F \quad (1)$$

and the LS update for S^T is

$$\hat{S}^T = \begin{bmatrix} \hat{P}D_1(\hat{A}) \\ \hat{P}D_2(\hat{A}) \\ \cdot \\ \cdot \\ \hat{P}D_U(\hat{A}) \end{bmatrix} + \begin{bmatrix} \tilde{X}_1 \\ \tilde{X}_2 \\ \cdot \\ \cdot \\ \tilde{X}_U \end{bmatrix} \quad (2)$$

where $\hat{P}$ and $\hat{A}$ stand for the estimated matrices of P and A, $\tilde{X}_m$ $(m = 1,2, \dots, U)$ is the obtained vector in the last iteration. Similarly, the LS updates for A^T and P^T are

$$\hat{A}^T = \begin{bmatrix} \hat{S}D_1(\hat{P}) \\ \hat{S}D_2(\hat{P}) \end{bmatrix} + \begin{bmatrix} \tilde{Y}_1 \\ \tilde{Y}_2 \end{bmatrix} \quad (3)$$

$$\tilde{P}^T = \begin{bmatrix} \tilde{A}D_1(\tilde{S}) \\ \tilde{A}D_2(\tilde{S}) \\ \cdot \\ \cdot \\ \tilde{A}D_L(\tilde{S}) \end{bmatrix} + \begin{bmatrix} \tilde{Z}_1 \\ \tilde{Z}_2 \\ \cdot \\ \cdot \\ \tilde{Z}_L \end{bmatrix} \quad (4)$$

where $\tilde{S}$ denotes the estimated matrix of S, $\tilde{Y}_p$ (p = 1, 2) and $\tilde{Z}_l$ (l = 1, 2, …, L) are the previously obtained estimates.

It is noted that TALS algorithm is prone to implement and guarantee to converge, but also suffers from slow convergence. As a modified method, COMFAC algorithm is proposed to speed up the LS fitting of TALS. First, COMFAC compresses the high dimensional three-way data into the subspaces defined by the three bases P, A, and S. Then the PARAFAC model is fitted in the compressed space. Finally, the solution followed with a few TALS steps is recovered to the original space. The estimated direction matrices $\tilde{P}$, $\tilde{A}$ and $\tilde{S}$ can be utilized to estimate the 2D DOA and polarization parameters. For the i^{th} return the spatial direction vector of sub-linear array A_n (n = 1, 2, …, N) is

$$a_n(\theta_i, \varphi_i) = q_i^{n-1}[1\ p_i\ \dots\ p_i^{M-1}]^T \quad (5)$$

With the logarithm transformation ln(·) and imaginary part extraction transformation imag(·), the above formula can be further substituted as

$$g_n = -imag(\ln(a_n(\theta_i, \varphi_i))) \quad (6)$$
$$= [(n-1)v + \mu, \dots, (n-1)v + (M-1)\mu]^T$$

where $\mu = \xi \sin\theta_i \cos\varphi_i$ $v = \xi \sin\theta_i \sin\varphi_i$, $\xi = 2\pi d/\lambda$ .We define

$$Q_2 = \begin{bmatrix} 1 & 0 \\ 1 & 1 \\ \cdot & \cdot \\ \cdot & \cdot \\ 1 & (M-1) \end{bmatrix}, C_2 = \begin{bmatrix} v \\ \mu \end{bmatrix}$$

then g_2 can be expressed as

$$g_2 = Q_2 C_2 \quad (7)$$

Primarily, the estimated direction vector $\tilde{a}(\theta_i, \varphi_i)$, that is, the i^{th} column of estimated direction matrix $\tilde{A}$, is normalized to the referential phase center so as to avoid phase ambiguity. Then we extract the rows of $\tilde{A}$ followed with normalization from M+1 to 2M as matrix $\tilde{A}_2$ and obtain vector $\hat{g}_2$ with the transformation (8). After that let $\tilde{\mu}$, $\tilde{v}$ be the estimates of μ and v, and the vector C_2 can be estimated further by LS as

$$\tilde{C}_2 = \begin{bmatrix} \tilde{v} \\ \tilde{\mu} \end{bmatrix} = (Q_2^T Q_2)^{-1} Q_2^T \tilde{g}_2 \quad (8)$$

Finally, the elevation and azimuth can be paired automatically through the following formulas

$$\tilde{\theta}_i = \sin^{-1}(\sqrt{\tilde{\mu}^2 + \tilde{v}^2}/\xi) \quad (9) \qquad \varphi_i = \tan^{-1}(\tilde{v}/\tilde{\mu}) \quad (10)$$

Meanwhile, with the estimated DOA $(\tilde{\theta}_i, \tilde{\varphi}_i)$, the vector $[\sin\gamma_i \exp(j\eta_i), \cos\gamma_i]^T$ can be calculated as

$$\begin{bmatrix} \tilde{\psi} \\ \tilde{\zeta} \end{bmatrix} = \begin{bmatrix} \sin\gamma_i \exp(j\eta_i) \\ \cos\gamma_i \end{bmatrix} = \begin{bmatrix} \cos\tilde{\theta}_i \cos\tilde{\varphi}_i & -\sin\tilde{\varphi}_i \\ \cos\tilde{\theta}_i \sin\tilde{\varphi}_i & \cos\tilde{\varphi}_i \end{bmatrix}^+ \tilde{P}_i \quad (11)$$

and polarization parameters can be estimated as

$\tilde{\gamma}_i = \tan^{-1}\left(\left|\frac{\tilde{\psi}}{\tilde{\zeta}}\right|\right)$ (12)

$\tilde{\eta}_i = imag\left(\ln\left(\frac{\tilde{\psi}}{\tilde{\zeta}\tan(\tilde{\gamma}_i)}\right)\right)$ (13)

III. SOLUTION TO THE OPTIMIZATION PROBLEM

It is obvious that this optimization problem contains the constant modulus constraint, and it should be a NP-hard problem. To tackle the this problem, the first constraint can be relaxed to a square constraint due to $\tilde{A}$ contains a_m^2, which can be rewritten as:

$$\max_{\Psi} \min_{\Delta R_c} \tilde{V}_t^H \left(J_{MNL} + \tilde{A}\tilde{R}_c\right)^{-1} \tilde{A}\tilde{V}_t$$

$$s.t. R_c \in \Re$$

$$a_m^2 = D_m$$

$$\sum_{m=1}^{M} a_m^2 = P \qquad \|a_m\|^2 \geq 0$$

(14)

Where $D_m = C_M^2$

Meanwhile, with $\tilde{A} \geq 0$ and $R_c \geq 0$, and hence the term $\tilde{A}R_c$ is indefinite. We now treat the inner optimization problem firstly. In order to solve it, the diagonal loading (DL) method, which has been usually used in the robust beam-forming, is employed to Ψ such that: $\bar{\Psi} = \Psi + \varepsilon J > 0$ (15)

where $\varepsilon \ll \lambda_{max}(\Psi)$, is the so-called loading factor, and $\lambda_{max}(.)$ is the largest eigenvalue of a matrix. Note that $\tilde{A} = J_L \otimes \bar{\Psi} \otimes Q^{-1} > 0$ due to $\bar{\Psi} > 0$.

$$SJNR = |\rho_t|^2 V_t^H (J + \tilde{A}R_c)^{-1} \tilde{A} V_t \quad (16)$$

By replacing $\tilde{A}$ in above with $\bar{\tilde{A}}$, we can obtain

$$(J_{MNL} + \bar{\tilde{A}}\tilde{R}_c)^{-1} \bar{\tilde{A}} = (\bar{\tilde{A}}^{-1} \tilde{R}_c)^{-1} \quad (17)$$

The inner optimization can be written as

$$\min_{\Delta R_c, t} t$$

$$s.t. \begin{bmatrix} \sigma^2 & vec(\Delta R_c) \\ vec^H(\Delta R_c) & I \end{bmatrix} \geq 0$$

$$\begin{bmatrix} t & V_t \\ V_t^H & \bar{\tilde{A}}^{-1} + \tilde{R}_c \end{bmatrix} > 0 \quad (18)$$

We consider the outer optimization problem. For obtaining the optimal solution, similar to the method for solving the inner optimization problem, the DL method is employed to $\tilde{R}_c$ such that

$$\bar{\tilde{R}}_c = \tilde{R}_c + \rho J > 0 \quad (19)$$

where $\rho \ll \lambda_{max}(R_c)$ In the following, we choose $\rho \ll \lambda_{max}(R_c)/1000$ by numerical examples. By replacing $\tilde{R}_c$ in (14) with $\bar{\tilde{R}}_c$ we can obtain

$$SJNR = |\rho_t|^2 V_t^H (J + \tilde{A}\bar{\tilde{R}}_c)^{-1} \tilde{A}\bar{\tilde{R}}_c \bar{\tilde{R}}_c^{-1} V_t \quad (20)$$

By using the matrix inversion lemma [8], above equation can be rewritten as

$$SJNR = |\rho_t|^2 V_t^H \bar{\tilde{R}}_c^{-1} V_t - |\rho_t|^2 V_t^H (\bar{\tilde{R}}_c + \bar{\tilde{R}}_c \tilde{A} \bar{\tilde{R}}_c)^{-1} V_t \quad (21)$$

Note that $\bar{\bar{R}}_c + \bar{\bar{R}}_c \breve{A} \bar{\bar{R}}_c > 0$ due to $\bar{\bar{R}}_c > 0$ and $\breve{A} > 0$. As a consequence, the maximization problem in above equation can be reshaped as

$$\min_{\varphi} V_t^H (\bar{\bar{R}}_c + \bar{\bar{R}}_c \breve{A} \bar{\bar{R}}_c)^{-1} V_t$$

$$s.t.\, a_m^2 = D_m$$

$$\sum_{m=1}^{M} a_m^2 = P$$

$$\|a_m\|^2 \geq \quad (22)$$

Similar to that in the inner optimization problem, above equation can be recast as an SDP:

$$\min_{\varphi, t} t$$

$$s.t. \begin{bmatrix} t & V_t \\ V_t^H & \bar{\bar{R}}_c + \bar{\bar{R}}_c \breve{A} \bar{\bar{R}}_c \end{bmatrix} \geq 0$$

$$a_m^2 = D_m$$

$$\sum_{m=1}^{M} a_m^2 = P$$

$$\|a_m\|^2 \geq \quad (23)$$

The working flowchart of the PD radar with a PSUPA for deception jamming suppression is given in Figure 1. When the special target echo and deception jamming impinge on a PSUPA simultaneously, the radar system will primarily judge whether the repeat deception jammer exists, based on the processing result with regard to the current and previous PRI. If the deception jamming is detected, the radar system has to estimate the DOA and polarization parameters with our proposed method.

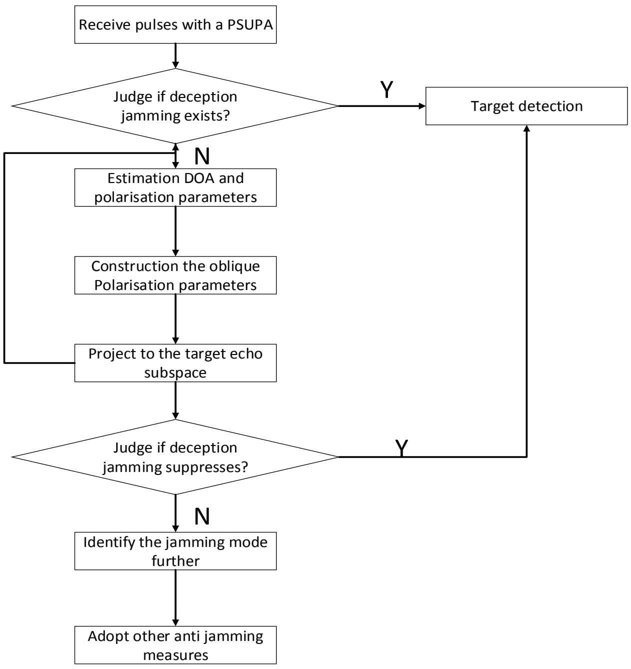

Fig. 1. Working flowchart of a PD radar for deception jamming suppression

With the estimates, the oblique projection filter operator can be constructed in the spacial-polarizational domain. It is noted that the estimated polarization parameters are also helpful to identify the true target from the deception jamming further. Finally, followed with the oblique projection, the received mixed returns of the target, deception jamming and noise are projected to the target echo subspace and the jamming is filtered effectively. If the above suppression is not effective enough and much deception jamming still remains, the jamming mode would be identified with other features further and other corresponding anti-jamming measures would be adopted.

IV. SIMULATION RESULTS

Define the relative absolute average error (RAAE) as

$$\rho_i^{RAAE} = \frac{1}{200}\sum_{j=1}^{200}\left|\frac{\tilde{\rho}_{ij}-\rho_i}{\rho_i}\right| \quad (24)$$

where ρ_i and $\tilde{\rho}_{ij}$ are the desired value and estimate for the jth Monte Carlo trial, respectively.

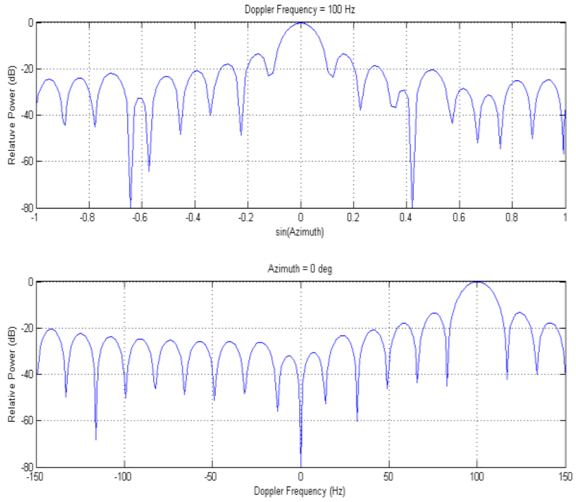

Fig. 2. Principal Cuts at Target Azimuth and Doppler

Figure 2 show the azimuth angle can be estimated even with the changes in the Doppler frequency.

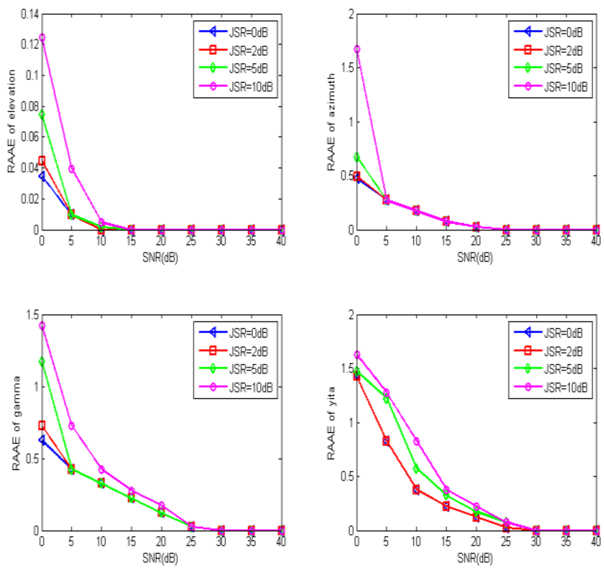

Fig. 3. RAAE curves of target's parameters estimated

Figure 3 and 4 depict the RAAE curves of DOA and polarization estimates of target echo and jamming with different SNR and JSR. From Figure, we find that the RAAE of each estimate raises slightly with the JSR increasing and decreases with the SNR climbing for a fixed JSR.

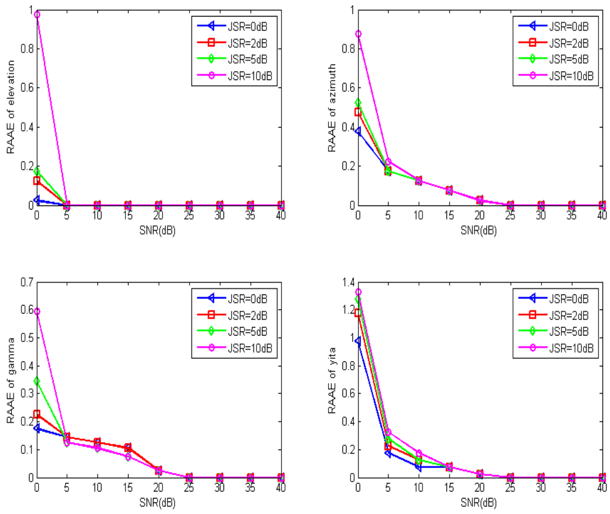

Fig. 4. RAAE curves of jammer's parameters estimated

V. CONCLUSION

In this paper, we have investigated the problem of robust waveform optimization for improving the worst-case detection performance of MIMO PSUPA based on the tri-linear decomposition model has been addressed, and a deception jamming suppression algorithm has been proposed. Experiment results demonstrate that our proposed algorithm can have desirable jamming suppressing performance which could effectively enhance the performance of radar target detection in the complicated electromagnetic environment.

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