Military Technical College,
Kobry El-Kobbah,
Cairo, Egypt

9th International Conference
On Aerospace Sciences &
Aviation Technology

A NOVEL ADAPTIVE SPACE - TIME TECHNIQUE OF FILTERING FOR INTERFERENCE SUPPRESSION IN PHASED ARRAY AIRBORNE RADAR SYSTEMS

Ghouz H.H. M.*, Kamal S. M.*, Hanafy A. A.*, and Salem I. A.*

ABSTRACT

This work introduces a novel adaptive technique of filtering for solving the problem of interference suppression in phased array airborne radar systems. In this adaptive process, effects of the interference are suppressed (or minimized) according to a specific set of controlling parameters. This includes the target doppler shift and the interference spatial distributions. The proposed technique is referred to as adaptive space-time filter. Performance of our novel adaptive filter is investigated, evaluated, and compared to the known adaptive filter proposed by H. Ghouz in 1990 [1]. Results of simulation indicate that with adequate filter's complexity, excellent improvement in the signal-to-interference-plus-noise ratio is obtained at the filter's output. In addition, our filter has two main advantages over the one reported in [1]. First, our filter is simple and easy to implement. Second, a minimum total computational time of the adaptation process is required. This includes estimation of the interference space-time covariance matrix and updating the filter's weights as well as the required processing time. Finally, the presented filter is a robust solution to the problem of interference challenging the airborne radar systems, in particular, the strong reflection from the ground clutter sources.

KEY WORDS

Adaptive space-time filtering, Interference suppression, Clutter suppression, signal-to-interference -plus -noise ratio, Improvement factor.

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* Egyptian Armed Forces.

I. INTRODUCTION

Ground based radars separate returned signals from moving targets and clutter by exploiting the Doppler frequency shift in the return signals due to the motion of the target. This is typically much larger than the Doppler shift impressed on the clutter returns due to any clutter motion. For pulsed radars, the Doppler shift manifests as a pulse- to- pulse phase shift in the returned signals from the target, which may be distinguished from the relatively small pulse -to- pulse phase shift induced by the motion of each clutter scatterer [2].

In a look down airborne radars, on the other hand, target signals often have to compete with strong ground clutter returns. Owing to the platform motion, the spread in Doppler of the clutter return can be significant, and clutter suppression becomes a problematical phenomena to cancelled. A one-dimensional temporal filtering technique (e.g., conventional MTI (moving target indication)), can only successfully achieve sufficient rejection over the full clutter bandwidth at the returns from slow moving targets. Since there is interdependence between clutter Doppler and clutter angular location, significantly better performance can be achieved with two-dimensional filters, which utilize both spatial frequency and temporal frequency characteristics to discriminate targets from clutter. The two-dimensional filtering approach, often referred to as space - time processing, has been the subject of considerable research interest over the past two decades [3].

The use of an adaptive space - time processing (ASTP) technique for the simultaneous rejection of both jamming and clutter has previously been considered by Brennan, Mallet and Reed [4,5]. Adaptive weights are chosen to maximize the output signal to interference - plus - noise ratio, but it is shown [4] that for Gaussian interference (cluter, thermal noise and jamming) optimal ASTP maximizes the probability of detection. A large number of papers have been published on the topic of ASTP for clutter rejection [1,6-8]. Also, many literatures have been published on the ASTP topic, e.g.[9,10]. The advantages to be gained through the use of a fully optimal ASTP technique, as proposed [4], rather than one- dimensional clutter filtering approaches are clearly shown by Klemm [6]. Unfortunately, the computational burden of the fully optimal approach is high, and for this reason a number of suboptimal ASTP methods have been proposed, e.g. [7].

This paper is organized as follows. Section (II) presents the concept and configuration of the novel adaptive space-time filter (ASTF). Target and interference models are depicted in section (III-A). In section (III-B) interference space-time covariance matrix (M_{ST}) is presented. Performance measures are depicted in section (III-C). Simulation assumptions and results are presented in section (IV). Finally, section (V) summarizes the main concluding points.

II. A NOVEL ADAPTIVE SPACE-TIME FILTER: CONCEPT AND CONFIGURATION

The proposed adaptive space-time filter (ASTF) as depicted in Fig.1 is composed of four main units. These include phased array antenna unit, down frequency conversion and amplification unit, adaptive signal processing unit, and integrator unit. The intercepted radio frequency (RF) signal from each sensor is converted into the intermediate frequency (IF) signal. This can be performed through a down frequency conversion and amplification unit, where the signal is subjected to band pass amplifications. The IF output from each sensor is applied to two separate channels, inphase and quadrature phase (I&Q) channels. Each channel is composed of multiplier and low pass filter to extract the complex envelope of the signal. The low frequency analog signal from each channel is applied to adaptive signal processing unit, where it is converted into digital samples and weighted by an adjustable weight. The weights of "I&Q" channels are controlled according to the interference-noise field and the target doppler shift through an adaptive processing unit. This unit includes a processor that estimates the space-times covariance matrix ($\hat{M}_{ST}$) of the interference-noise field from "k_1" independent observation vectors, and computes the inverse of the estimated matrix ($\hat{M}^{-1}_{ST}$) using the Direct Matrix Inversion algorithm (DMI),[11,12]. The inverted matrix is multiplied with the cross correlation signal vector ($\underline{X}_S$) to yield an estimate of the optimum weight vector of the channel filter,[4,13]

$$\hat{W} = \hat{M}^{-1}_{ST} \cdot \underline{X}_S. \tag{1}$$

The output from the filter's channels is subjected to three sum operations. The first sum operation is performed on all I-channels to get the total inphase output. The total qudrature output is obtained by performing second sum operation on all Q-channels. Finally, these outputs are added coherently to form the final output of the filter's channels. This output is applied to an ideal integrator unit with unity coefficients to yield the final filter's output.

The main objective of the ASTF is to suppress adaptively the interference in either side-lobe or main-lobe to get a sufficient output signal-to-interference –plus-noise ratio ($SINR_o$) for detection of the intercepted target. In fact, this filter has two degrees of freedom. These are the target doppler shift (time domain filtering) and the interference spatial-distribution (spatial-domain filtering) to suppress (or minimize) the interference power in an adaptive manner. This means that the ASTF is always matched to the desired signal vector, and consequently, its output SINR is currently maximized.

III. PROBLEM FORMULATION

I. Target and Interference Models

The complex envelope of the target signal at k^{th} element can be represented as follow [1]

$$S_k(t_1) = A(t_1).e^{j(2\pi F_{ds}.t_1)}.e^{j((2\pi kd/\lambda).(\sin(\theta_s))} \quad k=1,2,3,\ldots,N, \tag{2}$$

where, $A(t_1)$ denotes the input signal level at each I or Q channel for time instant t_1,

F_{ds} denotes the target Doppler frequency, λ denotes the wave length of the incident wave, d denotes the spacing between the sensors, and θ_s denotes the direction of the target signal.

Let, $2\pi F_{ds}\, t_1$=Ks (t_1), and $_s$=0.0,then Eqn. (2) becomes,

$$S_k(t_1) = A(t_1).e^{jK_s(t_1)}, \quad k=1,2,3,.....,N, \qquad (3)$$

where, $Ks(t_1)$, denotes the normalizes target doppler frequency at the time instant $t_1 = 1/T_r$, and it is given by

$$Ks = F_{ds} / F_r \in [0,1] \qquad (4)$$

A clutter source is assumed to be Gaussian distributed process, represented by a scatterer which has certain statistical parameters. The considered parameters are the standard deviation (σ) and the mean (μ) of its complex envelope return as reported in [1]. The clutter complex envelope at k^{th} element, at time instant t_1 is expressed as

$$C_k(t_1) = \sum_{i=1}^{N_c} c_i(t_1).\exp(j(2\pi kd/\lambda)\sin(\theta_i) + \psi_i(t_1)), \quad k=1,2,3,..,N, \qquad (5)$$

where, θ_i represents direction of the i^{th} scatterer source, c_i (.) is the clutter amplitude, and, $\psi_i(t_1)$ denotes the phase variations of the clutter return. These variations are due to the clutter motion itself and/or the platform motion. The first cause of the phase variation of the clutter source is related to its type. It is defined for weather clutter sources as $2\pi f_{dc}(t_1)$,where, $f_{dc}(t_1)$ is the scatterer doppler which changes randomly. In this work we consider $f_{dc}(t_1)$ change randomly from [0 to $0.01F_r$]. The first phase contribution is zero in case of the ground clutter sources (fixed). On the other hand, the second source of phase variation is a contribution due to two main parameters. These include the effect of the antenna beamwidth and the doppler shift of the platform. Therefore, in general, the total phase variation $\psi_i(t_1)$ is given by

$$\psi_i(t_1) = [2\pi.(F^i_{dc}(t_1) \pm F_{dA} t_1) + \Phi_{Bw}], \qquad (6)$$

where, F_{dA} is the doppler shift of the aircraft, and Φ_{Bw} is additional random phase due to the effect of the antenna motion.

The jammer complex envelope at k^{th} element at time instant t_1 is expressed as:

$$J_k(t_1) = \sum_{i=1}^{N_J} J_i(t_1).\exp(j(2\pi kd/\lambda)\sin(\theta_i) + \phi_i(t_1) + 2\pi(f^i_{dj} \pm F_{dA}).t_1), \quad k=1,2,..,N, \qquad (7)$$

where, θ_i represents direction of each jammer source, f_{dj} denotes the doppler of each jammer source, $J_i(.)$ is the amplitude of each jammer source, and ϕ_i denotes the random phase of each jammer source $[0,2\pi]$.

B. Interference Space-Time Covariance Matrix

The space-time covariance matrix of interference can be expressed analytically as

$$M_{ST}= E\{\underline{X}.\ \underline{X}^{*T}\}, \tag{8}$$

where, E {.}, denotes the mathematical expectation operator, and the data observation vector $\underline{X}$ is due to the interference only (signal is absent), and is given by

$$\underline{X} = [\underline{X}_I, \underline{X}_Q]^T, \tag{9}$$

where, $\underline{X}_I$ denotes the vector components of the inphase channel, and $\underline{X}_Q$ denotes the vector components of the quadrature channel,these vectors are given by:

$$\underline{X}_I = [x_{I1}, x_{I2}, \ldots\ldots, x_{IN}], \tag{10}$$

$$\underline{X}_Q = [x_{Q1}, x_{Q2}, \ldots.., x_{QN}], \tag{11}$$

In practice, the statistical parameters of the interference sources are not a priori known. Therefore, the covariance matrix has to be estimated. The approach considered in our work is the sample covariance, where a number of statically independent data vectors (k_1) are used for estimation procedure. The estimate of the space-time covariance matrix ($\hat{M}^{-1}_{ST}$) is given by

$$\hat{M}^{-1}_{ST} = \frac{1}{k_1} \sum_{i=1}^{k_1} X_i X_i^{*T} \tag{12}$$

The number of data vectors (k_1) is related to the rank of the matrix $\hat{M}_{ST}$ (RNK) as [11],

$$k_1 \geq 2(RNK) \tag{13}$$

C. Performance Measures

Two measures are considered to evaluate the performance of the proposed ASTF.These are output signal-to-interference-plus-noise ratio ($SINR_o$) and the Improvement factor (IMF). The $SINR_o$ at the filter's output is analytically expressed as [11]

$$SINR_o = \underline{X}_s^T M^{-1}_{ST} \underline{X}_s \tag{14}$$

Equation (11) represents the maximum value of $SINR_o$. The Improvement factor is defined as

$$IMF = SINR_o / SINR_i\ , \tag{15}$$

where, $SINR_i$ denotes the signal-to-interference-plus-noise ratio at the input of the filter's channels.

IV. SIMULATION ASSUMPTIONS AND RESULTS

A. Simulation Assumptions

The performance of the adaptive space time filter (ASTF) is investigated and evaluated through computer simulation under different interference conditions. The estimated SINRo at the filter's output ($\hat{SINR}_O$) is given by [1]

$$\hat{SINR}_O = \frac{E\{Y_1\} - E\{Y_O\}}{Var\{Y_O\}} \tag{16}$$

where, Y_o denotes the filter output when the desired signal is absent, and Y_1 denotes the filter output when the signal desired in addition to the interference is present. The signal-to-interference - plus - noise ratio at the array input is given by:

$$SINR_i = P_s/(P_c + P_j + P_n), \tag{17}$$

Where, P_s is the average power of the signal complex envelope at ASTF input, P_n is the power of thermal gaussian noise at the input of each channel, P_c is the total clutter power (due to N_c clutter sources) at the ASTF input, and P_j is the total jamming power (due to N_j jammer sources) at the ASTF input.

In practice, the jammer source is located on the ground and represents either side lobes jammer (SLJ) or main lobe jammer (MLJ), which is considered one of three different types. These are random phase (RP), random amplitude (RA), and random phase and amplitude (RPA). In this paper the case of RPA will be considered. Two statistical models are assumed to generate the jammer signal. For the jammer phase, a uniform distribution $[0,2\pi]$ is assumed. A gaussian model with zero mean and variance equal to the complex envelope of the jammer power is assumed for the random amplitude variation [14].

B. Results

Performance of the proposed ASTF is investigated, evaluated, and compared for different interference environment including clutter, jammer, and clutter plus jammer (combined interference). For the clutter case, two clutter types are considered separately. This includes ground and weather clutter sources. In our simulation, the clutter includes five ground sources (θ^o_g=[45,5,1,-5,-45], μ_g=40 dB,

σ_g=20 dB, f_{dc}=0.0, & F_{dA} =0.6F_r) and five weather sources (θ^o_w= [45,10,1,-10,-45], μ_w=10 dB, σ_w=30 dB, f_{dc} random [0 to 0.01F_r], & F_{dA}=0.6F_r). Also, a ground jammer source with random phase and amplitude (RPA-GJ) is considered in the presented simulation. The jamming senario is represented by a fixed jammer source to jam the airborne radar from its main lobe. The parameters of the assumed jamming senario are [f_{dj}=0.0, F_{dA} =0.6, P_j=30dB, and θ_j =2°]. Also, the beamwidth of the airborne antenna is assumed to be θ_{Bw}=8°. Finally, the size of the ASTF is considered to be twenty-four sensor and four snapshots (N=24 and N_p=4). Also, k_1 is assumed to be equal to 150. The $SINR_o$ and the IMF computed, and the results are graphed as function of the normalized target doppler frequency (Ks) for different interference conditions.

Fig.2a illustrates the output $SINR_o$ versus the normalized target doppler frequency for different clutter types. The ASTF has a superior performance for weather clutter sources (curve No.2) as compared to the other clutter type (curve No.1). This is due to the fact that three ground clutter sources are located in the direction of the main lobe as compared to the one weather clutter source. In addition, the total intercepted power of the main lobe ground clutter sources is greater than that of the weather clutter. Less performance has been observed in case of mixed clutter case as shown form the figure (curve No.3). The improvement factor is also depicted in Fig.2b. In conclusion, under severe clutter conditions, a sufficient SINR for the detection circuit has been obtained at the filter output.

To give an insight about the effectiveness of the novel ASTF as an interference suppression technique, a computer program for the filter reported in [1] has been developed, and its performance is evaluated and compared to the proposed ASTF under the same clutter conditions. Results of simulation are depicted in Fig.3. As it is clear from Figs.2&3, almost on average the same performance is obtained for all considered clutter sources. It is important to note that although the performance of both filters is approximately the same, the proposed filter has the following unique advantages. First, the hardware of the proposed filter is less complex as compared to the other filter. Second, less required computation time for matrix estimation, matrix inversion, and optimum weights versus the other filter. This is due to the reduction of the rank of the space-time covariance matrix of the proposed ASTF. Finally, less required processing time (real response time) as compared to the other filter.

Performance of both proposed ASTF and the other filter is investigated, evaluated and compared for the considered jamming senario, and the results of simulation are depicted in Figs. 4a&b respectively. As it is clear from the figures, a superior performance is obtained for both filters as compared to the clutter case (curve No.1). Poor performance has been obtained for our filter as compared to the other filter (curve No.2). The difference in the obtained SINRo is about 10.0dB. To improve our filter's performance, we have to increase the number of filter channels (N) while keeping the number of integrated pulse Np. In this case, the same SINRo is obtained for both filters (curves No.3). This is due to the fact that the reduction of the rank of the space-time covariance matrix as compared to the other filter. Therefor, a trad-off between filter complexity and the required SINRo should be considered for the practical filter implementation. However, even with "32" sensor (N=32) and four pulses (N_p=4), the proposed filter is less complex and easy to implement as compared to the other filter presented in [1]. Finally; the proposed filter presents inexpensive and versatile solution to the interference problem challenging the airborne radar, in particularly, the strong return from the ground clutter.

V. CONCLUSION

A novel ASTF has been presented, analyzed, and investigated for interference suppression in phased array airborne radar systems. A set of practical cases of study including different clutter and/or jammer senario has been considered. The aim is to show the filter's capabilities for interference suppression as compared to the other known techniques. In particularly, the performance of the proposed filter is compared with the adaptive space-time filter reported in [1]. Results of simulation show that with moderate filter's complexity, an excellent improvement in the signal to interference -plus- noise ratio ($SINR_o$). Furthermore, performance of the ASTF is very sensitive to the main lobe interference type (close to the desired signal direction) despite of the angular distribution of the other interference sources. In addition, our filter's performance is nearly the same as the filter mentioned above with less hardware complexity and required processing time. Finally, our presented filter is considered as an attractive solution for detecting a ground target immersed in a severe interference background.

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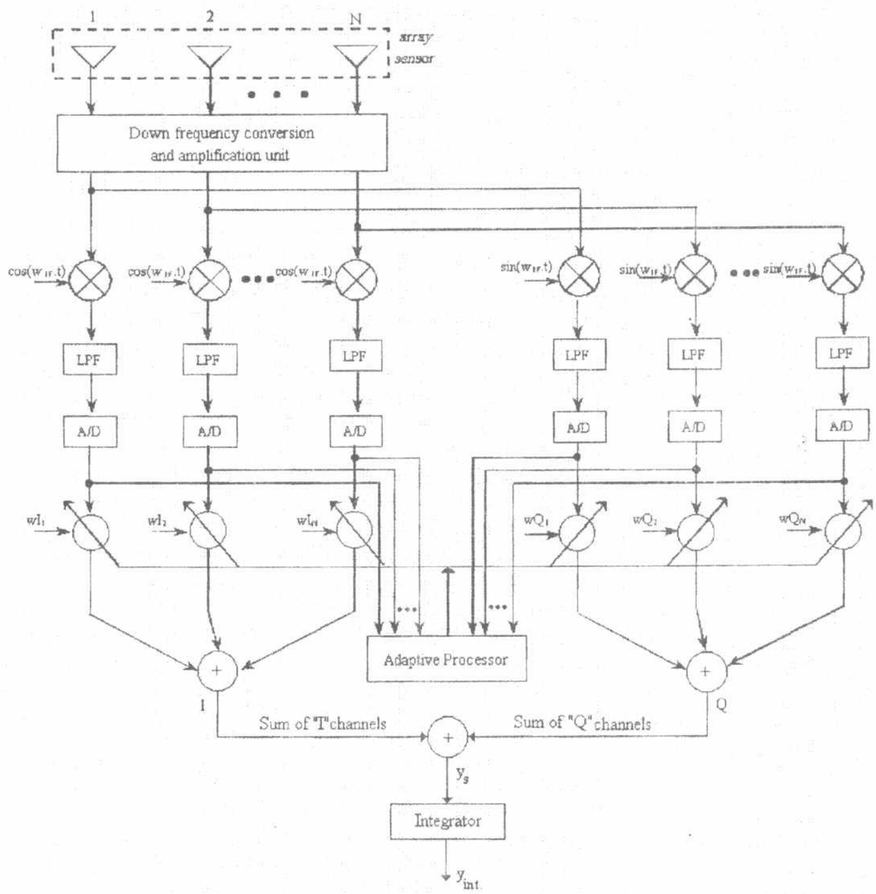
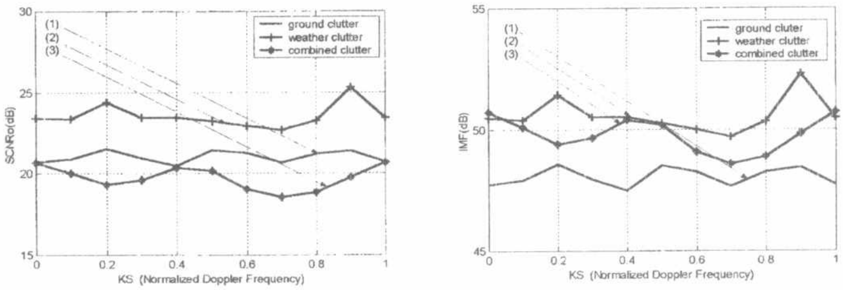
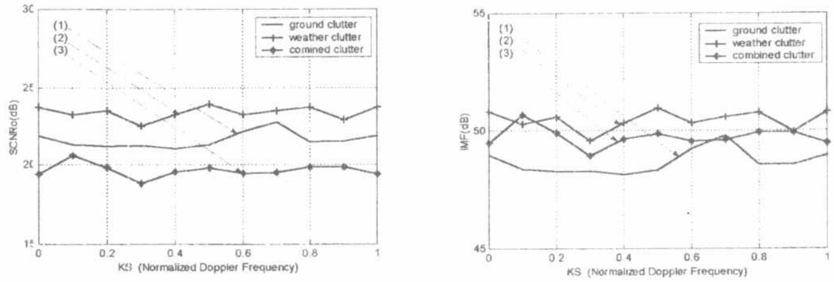


Fig.1 A novel adaptive space-time filter configuration for interference suppression.



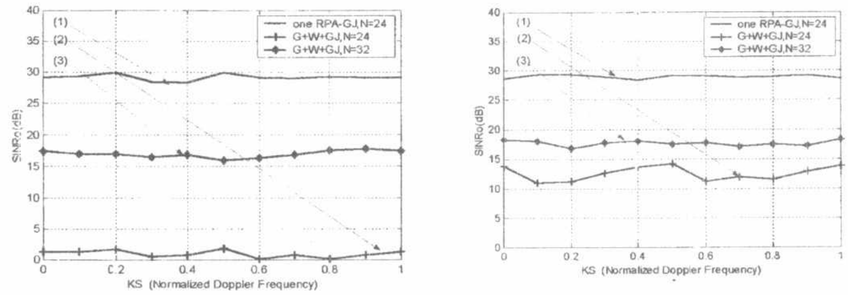
(a) (b)

Fig.2 SINRo & IMF achieved by the novel ASTF versus Ks for (1) ground clutter, (2) weather clutter, and (3) Combined clutter (1+2), (SNRi=10dB, N=24, and Np=4). (a) SINRo and (b) IMF.



(a) (b)

Fig.3 SINRo & IMF achieved by the adaptive filter proposed in [1] versus Ks for (1) ground clutter, (2) weather clutter, and (3) combined clutter (1+2), (SNRi=10dB,N=24, and Np=4).(a) SINRo and (b) IMF.



(a) (b)

Fig.4 SINRo achieved by the ASTF Versus Ks (SNRi=10dB & N_p=4) for (1) one RPA-GJ, and N=24, (2) combined interference (G+W+GJ), and N=24, and (3) the same as case (2) but with N=32. (a) by the novel ASTF, and (b) by the adaptive filter proposed in[1].