Progress In Electromagnetics Research, *PIER 22, 181–195, 1999*

PATTERN NULLING BY ITERATIVE PHASE PERTURBATION

M. J. Mismar

Electrical Engineering Department
University of Jordan
Amman, Jordan

T. H. Ismail

Electrical Engineering Department
Al-Ahliyya Amman University
Amman, Jordan

1. INTRODUCTION

The considerable interest in phase-only control of the element weights of array antennas to suppress interference reflects the growth in importance of both phase arrays and adaptive processing. As adaptive nulling with full amplitude and phase control is rather expensive, considering the cost of the phase shifters and variable attenuators, the idea of the phase-only control [1, 2] and amplitude-only [3, 4] control were proposed. Since in a phased array the required controls are normally incorporated, phase-only perturbations of the antenna elements is of particular interest in pattern nulling. However, the general phase-only implementation involves numerical complexity in solving the phase adjustments, except for the case of small phase perturbations in which the problem can be linearized [5–7]. A consequence of the small phase assumption is that imposing two symmetrical nulls in the pattern with respect to the main beam is impossible [6].

Also, considering large arrays with full phase-only nulling, the array performance will be subjected to degradation due to the phase shifter quantization errors [8]. Thus, the full phase-only nulling method presents a problem for large arrays because of the potentially significant high cost of high-resolution phase shifters. The use of partial control for synthesizing low-sidelobe array patterns will lead to a significant reduction in the number of variable attenuators and phase shifters as compared to the full control implementation [8–10]. By partially controlling the antenna elements to suppress prescribed sectors in jammers direction, the phase perturbations of the phase shifters will be relatively large which contradicts the small phase perturbations assumption.

The problem of the array pattern synthesis with wideband interference suppression using phase-only control is of practical interest [11, 12]. The suppression of an interfering wideband signal can be achieved by means of arranging for a suppressed sector in the array pattern to coincide with the angular location of incidence of the interference signal. In general, multiple wideband interference suppression using phase-only control yields large phase perturbations. The large phase perturbations is a nonlinear problem and cannot be solved analytically. However, numerical solutions can be obtained by using nonlinear programming techniques [2].

In this paper a pattern synthesis with multiple wideband interference suppression using phase-only control is presented. The nonlinear constraints of phase perturbation are solved using an iterative procedure with linear programming to calculate a new phase set of the controlled elements. The linear programming method is used to restrict the magnitudes of the phase perturbations to be less than small value in every iteration. The full phase-only control is accomplished as well as the partial control of the edge element phases. The computer simulation results show that the partial control using the edge elements is very efficient for the large size antennas compared to the full phase-only control.

2. FULL PHASE-ONLY CONTROL FORMULATION

Consider a linear array of N isotropic equispaced elements with a_n is the nth element normalized current excitation and d_n is the nth element position with respect to the center of the array (the wavenumber is included in d_n). Denoting the angular direction $u = \sin(\theta)$, (θ is the scanning angle from broadside), then the initial pattern can be expressed as

$$F_0(u) = \boldsymbol{\Psi}_0^T \mathbf{S}(u) \tag{1}$$

where

$$\boldsymbol{\Psi}_0 = \left[e^{j\phi_1}, e^{j\phi_2}, e^{j\phi_3}, \ldots, e^{j\phi_N}\right]^T \tag{2}$$

$$\mathbf{S}(u) = \left[a_1 e^{jd_1 u}, a_2 e^{jd_2 u}, \ldots, a_N e^{jd_N u}\right]^T \tag{3}$$

are the initial phase vector and the weighted steering vector, respectively, and T is the transpose operator.

A fully controlled array for interference suppression means that every phase of the array elements is individually controlled to suppress the sector levels of the array pattern in the prescribed directions of interference. This can be achieved by forcing the perturbed pattern levels at the interference directions to be much below the level of the pattern in the sidelobe region direction while maintaining the main beam directed towards the desired signal. Using the full phases of the current excitations of the antenna, the new pattern with the suppressed prescribed sectors, $F(u)$, should be expressed as

$$F(u) = \boldsymbol{\Psi}^T \mathbf{S}(u) \tag{4}$$

where

$$\boldsymbol{\Psi} = \left[e^{j\psi_1}, e^{j\psi_2}, e^{j\psi_3}, \ldots, e^{j\psi_N}\right]^T \tag{5}$$

is a vector containing the element's phase perturbations. In this work we consider the general case where the element's phases could be large. To find the solution of large element phases, we will suggest an iterative procedure to find Ψ for a given initial element phases Ψ_0. Let the perturbed pattern at the kth iteration to be expressed as

$$F_k(u) = \boldsymbol{\Psi}_k^T \mathbf{S}(u) \tag{6}$$

where Ψ_k denotes the phase vector at the kth iteration,

$$\boldsymbol{\Psi}_k = \left[e^{j\psi_1^k}, e^{j\psi_2^k}, e^{j\psi_3^k}, \ldots, e^{j\psi_N^k}\right]^T \tag{7}$$

We wish to proceed from the initial point to other point such that $F_k(u)$ approximates the perturbed pattern better as the number of iteration index k increases. To establish the iterative procedure, let the nth element phase of the kth iteration to be expressed as

$$\psi_n^k = \psi_n^{k-1} + \beta_n^k \quad \text{with} \quad \beta_n^k \ll 1 \tag{8}$$

where β_n^k is the nth elements phase increment of the kth iteration. Assuming the phases increments to be very small, the perturbed pattern can be approximated by the first two terms of Taylor expansion. Thus, equation (6) in the kth iteration can be written as

$$F_k(u) = \sum_{n=1}^{N} a_n e^{j\psi_n^{k-1}} e^{jd_n u} + j \sum_{n=1}^{N} \beta_n^k a_n e^{j\psi_n^{k-1}} e^{jd_n u} \tag{9}$$

A practical approach to suppress I interfering signals is by forcing the maximum perturbed pattern level at the interference directions to be less than small quantity while maintaining the main beam and the sidelobe region as close as possible to the initial pattern. Let $\delta_i(u)$ denote a certain error function in the ith suppressed sector and $\delta_0(u)$ denote the error in the mainbeam and sidelobe regions, then the approximated perturbed pattern in every iteration should be expressed as,

$$F_k(u) = \begin{cases} F_0(u) + \delta_0^k(u) & u \in R_0 \\ \delta_i^k(u) & u \in R_i \quad i = 1, 2, \ldots, I \end{cases} \tag{10}$$

where R_0 represents the angular region of the mainbeam and the sidelobe regions and R_i represents the ith angular sector of the ith interference with lower and upper angular bounds (u_{li}, u_{ui}). Therefore, equation (9) can be written as,

$$j \sum_{n=1}^{N} \beta_n^k a_n e^{j\psi_n^{k-1}} e^{jd_n u} - \delta^k(u) = \begin{cases} -\displaystyle\sum_{n=1}^{N} a_n e^{j\psi_n^{k-1}} e^{jd_n u} + F_0(u) & u \in R_0 \\ -\displaystyle\sum_{n=1}^{N} a_n e^{j\psi_n^{k-1}} e^{jd_n u} & u \in R_i \quad i = 1, 2, \ldots, I \end{cases} \tag{11}$$

The small error function $\delta^k(u)$ can be expressed as

$$\delta^k(u) = \omega_i \delta_i^k(u) \qquad u \in (-1, 1) \tag{12}$$

and ω_i is a weight factor that enables the designer to choose the relative size of the error function in the mainbeam and the sidelobe region, R_0, and in the suppressed sectors, R_i. Equation (11) can be expressed in matrix notation as

$$\mathbf{a}_k(u)\mathbf{x}_k = b_k(u) \tag{13}$$

where

$$\mathbf{a}_k(u) = \left[ja_1 e^{j\psi_1^{k-1}} e^{jd_1 u}, ja_2 e^{j\psi_2^{k-1}} e^{jd_2 u}, \ldots, ja_N e^{j\psi_N^{k-1}} e^{jd_N u}, -\omega_i\right] \tag{14}$$

$$\mathbf{x}_k = \left[\beta_1^k, \beta_2^k, \ldots, \beta_N^k, \delta_i^k(u)\right]^T \tag{15}$$

$$b_k(u) = \begin{cases} -\boldsymbol{\Psi}_{k-1}^T \mathbf{S}(u) + F_0(u) & u \in R_0 \\ -\boldsymbol{\Psi}_{k-1}^T \mathbf{S}(u) & u \in R_i \quad i = 1, 2, \ldots, I \end{cases} \tag{16}$$

The above approximation problem can be solved using linear programming since the constraints equations are linear in terms of the coefficients set β_n^k as given in equation (13). Discretizing equation (13) at a sufficient number of points, $\{u_m, m = 1, 2, \ldots, M\}$, the following set of linear equations can be written as

$$\mathbf{A}_k \mathbf{x}_k = \mathbf{B}_k \tag{17}$$

where the mth row of the matrix $\mathbf{A}_k$ is given as

$$\begin{aligned} \mathbf{a}_k(u_m) = \Big[& ja_1 e^{j\psi_1^{k-1}} e^{jd_1 u_m},\ ja_2 e^{j\psi_2^{k-1}} e^{jd_2 u_m}, \\ & \ldots,\ ja_N e^{j\psi_N^{k-1}} e^{jd_N u_m},\ -\omega_i \Big] \end{aligned} \tag{18}$$

and the mth element of the vector $\mathbf{B}$

$$b_k(u_m) = \begin{cases} -\boldsymbol{\Psi}_{k-1}^T \mathbf{S}(u_m) + F_0(u_m) & u_m \in R_0 \\ -\boldsymbol{\Psi}_{k-1}^T \mathbf{S}(u_m) & u_m \in R_i \quad i = 1, 2, \ldots, I \end{cases} \tag{19}$$

In practical problems, it is required to minimize the maximum deviation error, $\delta^k_{\max}$, of the error function $\delta^k_i(u)$. Therefore, the linear programming approximation problem can be stated as
minimize

$$g_k = \left[\beta^k_1 \beta^k_2 \ldots \beta^k_N \delta^k_{\max}\right] * \begin{bmatrix} 0 \\ \cdot \\ \cdot \\ 0 \\ 1 \end{bmatrix} \tag{20}$$

subject to

$$Re\left\{\mathbf{A}_k \mathbf{x}_k\right\} = Re\left\{\mathbf{B}_k\right\} \tag{21}$$

$$Im\left\{\mathbf{A}_k \mathbf{x}_k\right\} = Im\left\{\mathbf{B}_k\right\} \tag{22}$$

$$\beta^k_n - \phi^k_{\max} \leq 0 \qquad \text{for } n = 1, 2, \ldots, N \tag{23}$$

$$-\beta^k_n - \phi^k_{\max} \leq 0 \qquad \text{for } n = 1, 2, \ldots, N \tag{24}$$

where $\phi^k_{\max}$ is the maximum phase of the kth iteration. The iteration procedure can be stated as follows:

1. Initialization:
   - Set $k = 0$, the initial phase column vector $\boldsymbol{\Psi}_0 = [11 \ldots 1]$, and $\delta^k_{\max} =$ any large value.
   - Set the maximum phase bound $\phi^1_{\max}$, the ith relative deviation error, ω_i, and the number of discretized points M for equation (13).
2. Set $k = k + 1$. Calculate the matrix $\mathbf{A}_k$ and the vector $\mathbf{B}_k$ according to equation (18) and (19).
3. Calculate β^k_n and $\delta^k_{\max}$ using the linear programming equations (20)–(24) and update the element phases according to equation (8).
4. If $\delta^k_{\max} < \delta^{k-1}_{\max}$ go to step 2;
   else set $\delta^k_{\max} = \delta^{k-1}_{\max}$ and $\beta^k_m = \beta^{k-1}_m$.
5. Stop.

3. PARTIAL PHASE-ONLY CONTROL FORMULATION

When the number of interfering sources are much smaller than the number of antenna elements $(I \ll N)$, a partially controlled array is preferred. A partially controlled array for interference suppression means that only part of the elements weights are controlled [8–10]. It is shown that the edge elements of a uniformly excited array are ideal for cancellation of specific sidelobes of the pattern [10, 13]. Let the first and the last P elements are used to create I wide suppressed sectors in the array pattern at the directions of the interference sources by controlling the corresponding current phases only. Then the new pattern with the suppressed prescribed sectors, $F(u)$, should be expressed as

$$F(u) = \sum_{n=1}^{P} a_n e^{j\psi_n} e^{jd_n u} + \sum_{n=P+1}^{N-P} a_n e^{j\phi_n} e^{jd_n u} + \sum_{n=N-P+1}^{N} a_n e^{j\psi_n} e^{jd_n u} \tag{25}$$

Considering the general case where the element's phases could be large and following the suggested iterative procedure to find elements' phases $\{\psi_n\}$ for a given initial element phases $\{\phi_n\}$. The perturbed pattern in the kth iteration can be expressed as

$$F_k(u) = \sum_{n=1}^{P} a_n e^{j\psi_n^k} e^{jd_n u} + \sum_{n=P+1}^{N-P} a_n e^{j\phi_n} e^{jd_n u} + \sum_{n=N-P+1}^{N} a_n e^{j\psi_n^k} e^{jd_n u} \tag{26}$$

where $\{\psi_n^k\}$ denotes the set of the phases for the first and the last P elements in the kth iteration. Let the nth element phases' of the kth iteration be expressed as

$$\psi_n^k = \psi_n^{k-1} + \beta_n^k \text{ with } \beta_n^k \ll 1,\ n = 1, \ldots, P \text{ and } n = N - P + 1, \ldots, N \tag{27}$$

where β_n^k is the nth elements phase increment in the kth iteration. Assuming the phases increments to be very small, the perturbed pattern can be approximated by the first two terms of Taylor expansion. Thus, equation (26) in the kth iteration can be written as

$$\begin{aligned} F_k(u) = &\sum_{n=1}^{P} a_n e^{j\psi_n^{k-1}} e^{jd_n u} + \sum_{n=P+1}^{N-P} a_n e^{j\phi_n} e^{jd_n u} + \sum_{n=N=P+1}^{N} a_n e^{j\psi_n^{k-1}} e^{jd_n u} \\ &+ j\sum_{n=1}^{P} \beta_n^k a_n e^{j\psi_n^{k-1}} e^{jd_n u} + j\sum_{n=N=P+1}^{N} \beta_n^k a_n e^{j\psi_n^{k-1}} e^{jd_n u} \end{aligned} \tag{28}$$

Now, with partial control, the interference suppression problem can be obtained by forcing only the pattern levels at the interference directions to be less than small quantity while controlling only the phases of the antenna edge elements. To suppress I interfering signals which covered an angular sector R, the perturbed pattern must be forced to be equal to a certain small error function $\delta_k(u)$. Therefore, equation (28) can be written as

$$F_k(u) = \delta_i^k(u) \qquad u \in R_i \quad i = 1, 2, \ldots, I \tag{29}$$

Consequently,

$$j \sum_{n=1}^{P} \beta_n^k a_n e^{j\psi_n^{k-1}} e^{jd_n u} + j \sum_{n=N-P+1}^{N} \beta_n^k a_n e^{j\psi_n^{k-1}} e^{jd_n u} - \delta^k(u) = -\boldsymbol{\Psi}_{k-1}\mathbf{S}(u) \qquad u \in R_i \quad i = 1, \ldots, I \tag{30}$$

with

$$\boldsymbol{\Psi}_{k-1} = \left[e^{j\psi_1^{k-1}}, \ldots, e^{j\psi_P^{k-1}}, e^{j\phi_{P+1}}, \ldots, e^{j\phi_{N-P}}, e^{j\psi_{N-P+1}^{k-1}}, \ldots, e^{j\psi_N^{k-1}}\right]^T \tag{31}$$

and the small error function $\delta^k(u)$ as given by equation (12). Equation (30) can be expressed in matrix notation as

$$\mathbf{a}_k(u)\mathbf{x}_k = b_k(u) \qquad u \in R_i \quad i = 1, 2, \ldots, I \tag{32}$$

where

$$\mathbf{a}_k(u) = \Big[ja_1 e^{j\psi_1^{k-1}} e^{jd_1 u}, \ldots, ja_P e^{j\psi_P^{k-1}} e^{jd_P u}, ja_{N-P+1} e^{j\psi_{N-P+1}^{k-1}} e^{jd_{N-P+1} u}, \ldots, ja_N e^{j\psi_N^{k-1}} e^{jd_N u}, -\omega_i\Big] \tag{33}$$

$$\mathbf{x}_k = \left[\beta_1^k, \beta_2^k, \ldots, \beta_P^k, \beta_{N-P+1}^k, \ldots, \beta_N^k, \delta_i^k(u)\right] \tag{34}$$

$$b_k(u) = -\boldsymbol{\Psi}_{k-1}^T \mathbf{S}(u) \qquad u \in R_i \quad i = 1, 2, \ldots, I \tag{35}$$

Evaluating the above equation at a sufficient number of points, the following set of linear equations is obtained

$$\mathbf{A}_k \mathbf{x}_k = B_k \tag{36}$$

where the mth row of the matrix $\mathbf{A}_k$ is given as

$$\mathbf{a}_k(u_m) = \Big[ja_1 e^{j\psi_1^{k-1}} e^{jd_1 u_m}, \ldots, ja_P e^{j\psi_P^{k-1}} e^{jd_P u_m}, \\ ja_{N-P+1} e^{j\psi_{N-P+1}^{k-1}} e^{jd_{N-P+1} u_m}, \ldots, ja_N e^{j\psi_N^{k-1}} e^{jd_N u_m}, -\omega_i\Big] \tag{37}$$

and the mth element of the column vector $\mathbf{B}$

$$b_k(u_m) = -\boldsymbol{\Psi}_{k-1}^T \mathbf{S}(u_m) \tag{38}$$

The above approximation problem can be solved using linear programming since the constraints equations are linear in terms of the coefficients set β_n^k as given in equations (35). As before, it is required to minimize the maximum deviation error, $\delta_{\max}^k$, of the error function $\delta_i^k(u)$. Therefore, the linear programming approximation problem can be stated as
minimize

$$g_k = \left[\beta_1^k, \beta_2^k, \ldots, \beta_P^k, \beta_{N-P+1}^k, \ldots, \beta_N^k, \delta_{\max}^k\right] * \begin{bmatrix} 0 \\ \cdot \\ \cdot \\ 0 \\ 1 \end{bmatrix} \tag{39}$$

subject to

$$Re\{\mathbf{A}_k \mathbf{x}_k\} = Re\{\mathbf{B}_k\} \tag{40}$$

$$Im\{\mathbf{A}_k \mathbf{x}_k\} = Im\{\mathbf{B}_k\} \tag{41}$$

$$\beta_n^k - \phi_{\max}^k \leq 0 \text{ for } n = 1, 2, \ldots, 2P \text{ and } n = N-P+1, \ldots, N \tag{42}$$

$$-\beta_n^k - \phi_{\max}^k \leq 0 \text{ for } n = 1, 2, \ldots, 2P \text{ and } n = N-P+1, \ldots, N \tag{43}$$

where $\phi_{\max}^k$ is the maximum phase of the kth iteration.

4. NUMERICAL EXAMPLES

To demonstrate the validity of full and partial phase-only control for multiple wide band interference suppression, several computer simulation examples were conducted and discussed. Although the derived equations are valid for arbitrary phase values, the phases are

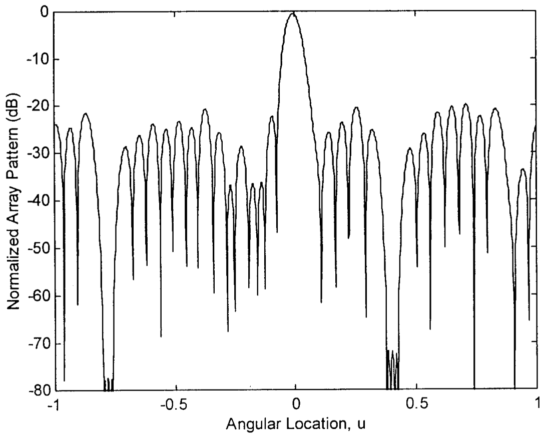

Figure 1. Perturbed pattern with two suppressed sectors imposed at $R_1 = (-0.8, -0.76)$, $R_2 = (0.38, 0.42)$ with $\omega_0 = 0.1$, $\omega_1 = 50$, and $\omega_2 = 25$.

assumed to be symmetrically odd with respect to the center of the array to reduce the number of calculations. The full phase-only control is illustrated using a 40 equispaced linear array elements of a 30-dB Chebyshev initial pattern with half wave interelement spacing. The phases of antenna elements are computed using equations (20–24). Figure 1 shows the perturbed pattern with two prescribed wide sector imposed at the angular locations $R_1 = (-0.8, -0.76)$ and $R_2 = (0.38, 0.42)$ with $\omega_0 = 0.1$, $\omega_1 = 50$ and $\omega_2 = 25$. The number of discretized points, $M = 40$, is taken as 10 points in each suppressed sector and 20 points in the mainbeam and the sidelobe regions. From Figure 1, the corresponding sector depths for the suppressed sectors are $\delta_1 = 78\,\text{dB}$ and $\delta_2 = 72.3\,\text{dB}$, respectively. And Figure 2 shows the perturbed pattern with two symmetrical wide sectors imposed at $R_1 = (-0.52, -0.48)$ and $R_2 = (0.48, 0.52)$ with $\omega_0 = 0.1$, $\omega_1 = 75$ and $\omega_2 = 75.1$. Figure 2 shows that the obtained sector depths are $\delta_i = 78\,\text{dB}$ for both symmetrical suppressed sectors. Also, the computed element phases for the Figures are given in Table 1. The above results show the ability of this technique to suppress multiple wide band interfering signals even if they are symmetrically located around the mainbeam.

On the other hand, the partial phase-only control is illustrated using a 100 equispaced linear array elements of a uniform initial pattern with half wave interelement spacing. Figure 3 shows the perturbed pat-

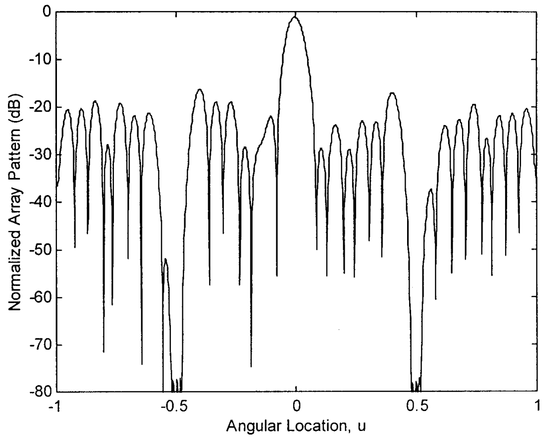

Figure 2. Perturbed pattern with two suppressed sectors imposed at $R_1 = (-0.52, -0.48)$ and $R_2 = (0.48, 0.52)$ with $\omega_0 = 0.1$, $\omega_1 = 75$, and $\omega_2 = 75.1$.

tern with two prescribed wide sectors imposed at $R_1 = (-0.52, -0.48)$ and $R_2 = (0.48, 0.52)$ with $\omega_1 = 1$ and $\omega_2 = 1.01$ while controlling only the first and the last 10 edge array elements, $(P = 10)$. The number of discretized points, $M = 20$, is taken as 10 points in each suppressed sector. From Figure 3, the corresponding sector depths are $\delta_1 = 79.7\,\text{dB}$ and $\delta_2 = 79.8\,\text{dB}$ for the suppressed sectors, respectively. Table 2 gives the computed phases of the first and the last ten elements using equations (39–43). Notice that the phases are symmetrically odd with respect to the center of the array as it was mentioned above. Although the array consists of 100 elements, only 10 controllers are required to realize the prescribed sector suppression which reduce the system complexity. Furthermore, the pattern of the partial control method is only discretized at a smaller number of points, $M = 20$, in the interference directions, and the results show the ability of this method to suppress the wide sectors while maintaining the main beam in the desired signal direction. As the controlled phases of the edge elements are used to suppress the prescribed sectors the uncontrolled coefficients of the antenna elements are used to maintain the perturbed pattern as close as possible to the initial pattern.

To discuss the effect of the number of controlled edge elements on the suppressed sector level with partial-control method, the 40 equispaced linear array elements of a 30-dB Chebyshev initial pattern with half

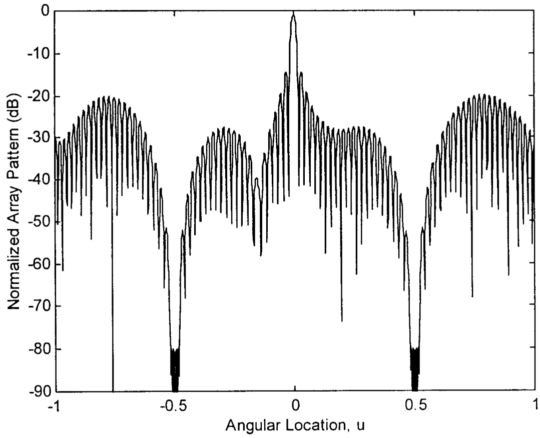

Figure 3. Perturbed pattern with two suppressed sectors imposed at $R_1 = (-0.52, -0.48)$ and $R_2 = (0.48, 0.52)$ with $\omega_0 = 0.1$, $\omega_1 = 1$, and $\omega_2 = 1.01$.

Element No.	β_n (Deg.)	
	Fig. 1	Fig. 2
1,40	± 41.6226	± 74.1593
2,39	± 31.9801	∓ 85.0603
3,38	∓ 20.0410	± 55.8476
4,37	± 58.6006	∓ 66.0368
5,36	± 82.5794	∓ 76.2894
6,35	∓ 30.6446	± 45.1371
7,34	± 22.8177	± 35.1777
8,33	∓ 11.3709	± 16.8822
9,32	± 6.7372	∓ 8.5715
10,31	± 6.9882	∓ 1.3458
11,30	± 10.5177	∓ 14.0623
12,29	± 6.6230	± 26.0699
13,28	∓ 4.6079	± 2.6778
14,27	± 0.0628	∓ 5.7901
15,26	∓ 7.4101	∓ 12.1979
16,25	± 3.1102	± 2.3777
17,24	± 3.0741	± 7.0550
18,23	± 0.3971	∓ 4.7330
19,22	± 4.0436	∓ 21.3055
20,21	∓ 8.7185	± 4.2666

Table 1. Computed element phase $\{\beta_n\}$ for Figure 1 and 2.

Element No.	β_n (Deg.)
1,100	$\pm$90.0116
2,99	$\mp$89.1207
3,98	$\pm$79.5280
4,97	$\mp$78.9170
5,96	$\mp$55.0763
6,95	$\pm$56.4949
7,94	$\mp$31.8783
8,93	$\pm$33.2656
9,92	$\pm$16.6322
10,91	$\mp$16.1241
11,90	0

Table 2. Computed phases $\{\beta_n\}$ of the first and last 10 elements for Figure 3.

P	3	4	5	6	7	8	9	10
δ_i (dB)	56	67.2	67.7	68	86.1	99.2	96.8	99.1

Table 3. Suppressed sector level, δ_i (dB), versus the number of the controlled edge elements, P, with one wide suppressed sector centered at $R_1 = (0.48, 0.52)$. The initial pattern is a 30-dB Chebyshev with $2N = 40$.

wave interelement spacing is used. Table 3 gives the suppressed sector level, δ_i (dB), versus the number of the controlled edge elements, P, with one wide suppressed sector centered at $R_1 = (0.48, 0.52)$. From the Table the suppressed sector level increases as the number of the edge elements increases. For the purpose of comparison, 85.4 dB was achieved by using the full-control method while imposing the same suppressed sector. As given by the Table, using only 7 controlled edge elements, $(P = 7)$, the level of the suppressed sector is 86.1 dB which is slightly more than the level of suppressed sector with the full-control method.

5. CONCLUSION

A pattern nulling for multiple wide band interference suppression using phase-only control has been presented. The large phase perturbation of the antenna elements are calculated using an iterative procedure with linear programming technique. The simplification in system complexity is achieved by assuming small phase perturbations in every iteration while updating the approximated initial pattern. The full phase-only control is accomplished as well as the partial control of the edge element phases. First, the interference suppression problem has been formulated by forcing the maximum perturbed pattern level at the interference directions to be less than a small quantity while maintaining the main beam and the sidelobe region as close as possible to the initial pattern.

Next, the interference suppression problem has been formulated by forcing only the pattern levels at the interference directions to be less than a small quantity while controlling only the phases of the antenna edge elements. The computer simulation results show that the partial control using the edge elements is very efficient for large size antennas compared to the full phase-only control. In contrast to the small phase perturbation method, this technique can impose symmetrical nulls in the perturbed pattern as a consequence of the large phases.

ACKNOWLEDGMENT

The authors thank the University of Jordan for supporting this research which Dr. Mismar was on sabbatical leave.

REFERENCES

1. Baird, D., and G. Rassweiler, "Adaptive sidelobe nulling using digitally controlled phase shifters," *IEEE Trans. on Antennas and Propagation,* Vol. 24, No. 5, 638–649, Sept. 1976.
2. Steyskal, H., R. A. Shore, and R. L. Haupt, "Methods for null control and their effects on radiation pattern," *IEEE Trans. on Antennas and Propagation,* Vol. 34, 404–409, March 1986.
3. Vu, T. B., "Method of null steering without using phase shifters," *IEE Proc. H, Microwaves, Opt. & Antennas,* Vol. 131, No. 4, 242–246, 1984.

4. Mismar, M. J., and T. Ismail, "Null steering using minimax by controlling only the currents' amplitudes," *International Journal of Electronics,* Vol. 78, 409–415, 1995.
5. Steyskal, H., "Simple method for pattern nulling by phase perturbation," *IEEE Trans. on Antennas and Propagation,* Vol. 31, 163–166, 1983.
6. Shore, R. A., "Nulling at symmetric pattern location with phase-only weight control," *IEEE Trans. on Antennas and Propagation,* Vol. 32, 530–533, May 1984.
7. Haupt R. L., "Adaptive nulling in monopulse antennas," *IEEE Trans. on Antennas and Propagation,* Vol. 36, No. 2, 202–208, Feb. 1988.
8. Chang, D., K. Ho, and C. Hung, "Partial adaptive nulling on a monopulse phased array antenna system," *IEEE Trans. on Antennas and Propagation,* Vol. 40, No. 2, 121-125, Feb. 1992.
9. Lee, T.-S., "Simultaneous nulling for monopulse array with partially adaptive weights," *IEEE Trans. on Antennas and Propagation,* Vol. 42, No. 7, 928–935, July 1994.
10. Mismar, M. J., and T. H. Ismail, "Partial control for wide band interference suppression using eigen-approach," *IEEE Trans. on Antennas and Propagation,* Vol. 46, No. 4, 600–602, April 1998.
11. Er, M. H., "Techniques for antenna array pattern synthesis with controlled broad nulls," *IEE Proc.,* Vol. 135, Pt. H. No. 6, 375–380, Dec. 1988.
12. Mismar, M. J., and T. Ismail, "Linear array pattern synthesis with multiple broad nulls using partial amplitude control," *Journal of King Saud University,* Vol. 9, [Engineering Sciences No. 2], 239–250, 1997.
13. El-Azhari, I., M. Afifi, and P. Excell, "Fast cancellation of sidelobes in the pattern of a uniformly excited array using external elements," *IEEE Trans. Antennas Propagat.,* Vol. AP-38, 1962–1965, 1990.