Adaptive Antenna Utilizing Power Inversion and Linearly Constrained Minimum Variance Algorithms

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Abstract: This paper presents a new algorithm based on the power inversion (PI) and the linearly constrained minimum variance (LCMV). This algorithm is capable of adjusting the weights of the antenna array in real time to respond to and improve the global positioning system (GPS) received signals coming from the desired directions and at the same time to highly suppress the jammers coming from the other directions. The simulation is performed for fixed and moving jammers. It indicates that this structure can give deeper nulls, more than 115 dB depths for fixed jammers and more than 94 dB depths for moving jammers.

Key words: adaptive antenna; power inversion algorithm; LCMV; GPS; anti-jamming

一种利用功率反演和线性约束最小方差算法的自适应天线. E. A. MOHAMED,**谈展中**. **中国航空学报(英文版)**, 2005, 18(2):153-160.

摘　要 介绍了一种新的基于功率反演和线性约束最小方差的算法,以高度抑制 GPS **接收机的干扰信号。这种结构通过提调整天线阵列的权值,实时地接收并改变来自各方向的** GPS **信号,同时对不同方向的干扰信号有高的抑制比。对固定和移动的干扰都做了仿真,仿真表明这种结构有很深的零点,对固定干扰信号的抑制比可达到** 115 dB,**对移动干扰信号的抑制比可达到** 94 dB。

关键词:**自适应天线;功率反演**(PI);**线性约束最小方差**(LCMV);GPS;**抗干扰**

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Nowadays, the global positioning system (GPS) receiver is widely used in many civilian and military applications. Interferences from the radar systems and other devices affect the civilian use, and otherwise the intentionally used jammers affect the military use. So increasing the protection against intentional and unintentional interferences is required. GPS signal which reaches the receiver is below the thermal noise power by about 30 dB. Although the GPS uses DSSS technique, it is vulnerable to high power jammers like CW, FM, pulse, and noise. Adaptive antenna is suitable to be used to cancel these types of jammers, and it utilizes the technique of cancellation based on determining the jammer directions like MUSIC algorithm Ref. [1] or PI Ref. [2]. The main purpose of adaptive antenna is to reduce the jammer signals up to a level so that the spread spectrum mechanism can extract the signals. This paper will introduce a new method based on PI and LCMV algorithms for jammer suppression. PI serves as a preprocessor to detect blindly the direction of the jammer and then LCMV constrains this direction to highly suppress the jammer. In addition, it can control the null depth for the jammer as well as controlling the gain for the useful signal.

1 Power Inversion Algorithm

PI algorithm is first introduced by Refs. [3-5] and discussed in detailed in Ref. [2]. PI algorithm is suitable when the signal to interference ratio is very low. Exactly the same situation will happen when GPS receiver is interfered by jammer signals. This algorithm is a modified version of the LMS algorithm. In LMS the optimum weight is given as

$$\boldsymbol{w}_0 = \boldsymbol{R}^{-1}\boldsymbol{r}_{\boldsymbol{X}d} \tag{1}$$

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$$\boldsymbol{R} = E[\boldsymbol{X}(t)\boldsymbol{X}^{\mathrm{H}}(t)] \tag{2}$$

$$\boldsymbol{r}_{\boldsymbol{X}d} = E[\boldsymbol{X}(t)d^{*}(t)] \tag{3}$$

$$y(t) = \boldsymbol{X}(t)^{\mathrm{H}}\boldsymbol{w} \tag{4}$$

$$\boldsymbol{X}(t) = [x_1(t) \quad x_2(t) \quad \cdots \quad x_M(t)]^{\mathrm{T}} \tag{5}$$

$$\boldsymbol{X}(t) = \sum_{i=1}^{q}\boldsymbol{\alpha}_{\mathrm{u}i}u_i(t) + \sum_{k=1}^{L}\boldsymbol{\alpha}_{\mathrm{J}k}J_k(t) + \boldsymbol{N}(t) \tag{6}$$

$$\boldsymbol{\alpha}_{\mathrm{u}i} = \left[1 \quad \exp\left[-\mathrm{j}\left(\frac{2\pi l\sin\theta_{\mathrm{u}i}}{\lambda}\right)\right] \quad \cdots \quad \exp\left[-\mathrm{j}\left(\frac{2\pi(M-1)l\sin\theta_{\mathrm{u}i}}{\lambda}\right)\right]\right]^{\mathrm{T}} \tag{7}$$

$$\boldsymbol{\alpha}_{\mathrm{J}k} = \left[1 \quad \exp\left[-\mathrm{j}\left(\frac{2\pi l\sin\theta_{\mathrm{J}k}}{\lambda}\right)\right] \quad \cdots \quad \exp\left[-\mathrm{j}\left(\frac{2\pi(M-1)l\sin\theta_{\mathrm{J}k}}{\lambda}\right)\right]\right]^{\mathrm{T}} \tag{8}$$

$$\boldsymbol{N}(t) = [n_1(t) \quad n_2(t) \quad n_3(t) \quad \cdots \quad n_M(t)]^{\mathrm{T}} \tag{9}$$

where $q + L < M$; M the number of the antenna elements as shown in Fig.1; q the number of useful signals; L the number of jammer signals; $u(t)$ the useful signal; $\boldsymbol{\alpha}_{\mathrm{u}i}$ the steering vector associated to the useful signal; $\boldsymbol{\alpha}_{\mathrm{J}i}$ the steering vector associated to the jammer signal; $d(t)$ the reference signal; $\boldsymbol{X}(t)$ is $M\times 1$ vector representing the antenna array received signal; $\boldsymbol{N}(t)$ is $M \times 1$ vector consisting of an independent Gaussian noise including channel noise, receiver noise and antenna elements noise; $\boldsymbol{R}$ is $M\times M$ autocorrelation matrix of the antenna array received signal; $\boldsymbol{r}_{\boldsymbol{X}d}$ is $M \times 1$ vector representing the cross correlation between the antenna array received signal and the reference signal; θ_{u} the useful signal direction; θ_{J} the jammer signal direction; l the distance between each two antenna elements.

The feedback loop of the adaptive weight is not shown in Fig.1. It consists of an ideal integrator of transfer function β/s.

From Eq.(3) and Eq.(1) it can be seen that the optimum weight equals zero when there is no reference signal.

To prevent the weight from reaching zero in the absence of the reference signal, Fig.2 is modified version of Fig.1 to meet the power inversion criterion. These modifications are accomplished in two steps:

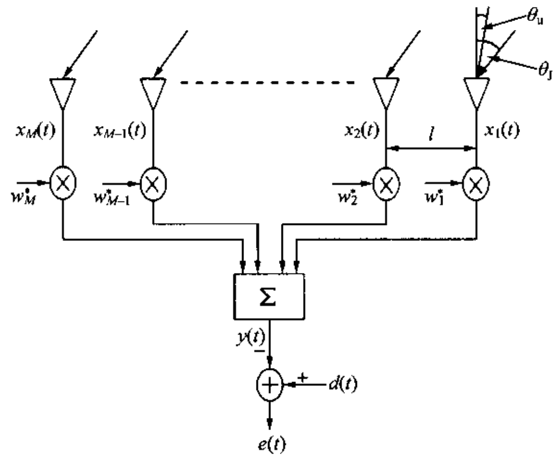


Fig.1 Adaptive antenna structure

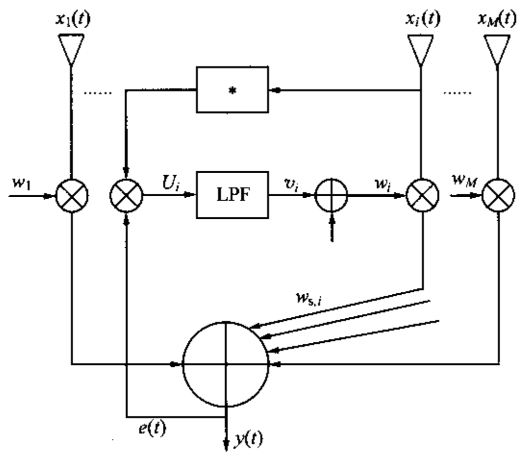


Fig.2 Feedback loop of the power inversion with low pass filter transfer function $\frac{\beta}{\tau s+1}$

(1) Replacing the ideal integrator by a low pass filter of transfer function $\beta/(\tau s + 1)$, where τ is the time constant of the low pass filter.

(2) Adding an offset weight after the low pass filter and removing the reference signal $d(t)$, so $e(t)$ becomes equal to $y(t)$.

The optimum weight is given according to Ref.[2] as follows:

$$\boldsymbol{w} = \boldsymbol{w}_{\mathrm{s}} - \boldsymbol{v} \tag{10}$$

where

$\boldsymbol{v} = [v_1 \quad v_2 \quad \cdots \quad v_i \quad \cdots \quad v_M]^{\mathrm{T}}$ represents the output of the low pass filters from all the M channels.

$\boldsymbol{w}_{\mathrm{s}} = [w_{\mathrm{s},1} \quad w_{\mathrm{s},2} \quad \cdots \quad w_{\mathrm{s},i} \quad \cdots \quad w_{\mathrm{s},M}]^{\mathrm{T}}$ is the offset weight.

$$\boldsymbol{U} = \beta \boldsymbol{X}^*(t)\boldsymbol{X}^{\mathrm{T}}(t)\boldsymbol{w} = \tau \frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}t} + \boldsymbol{v} = \boldsymbol{w} - \tau \frac{\mathrm{d}\boldsymbol{w}}{\mathrm{d}t} - \boldsymbol{w}_{\mathrm{s}} \quad (11)$$

Thus

$$\tau \frac{\mathrm{d}\boldsymbol{w}}{\mathrm{d}t} + \boldsymbol{w}_{\mathrm{s}} = \boldsymbol{w} - \beta \boldsymbol{X}^*(t)\boldsymbol{X}^{\mathrm{T}}(t)\boldsymbol{w} \quad (12)$$

At $t \to \infty$

$\frac{\mathrm{d}\boldsymbol{w}}{\mathrm{d}t} = 0$, so the optimum weight can be given as

$$\boldsymbol{w}_0 = (\boldsymbol{I} - \beta \boldsymbol{X}^* \boldsymbol{X}^{\mathrm{T}})^{-1} \boldsymbol{w}_{\mathrm{s}} \quad (13)$$

For noise alone,

$$\boldsymbol{w}_0 = \frac{1}{(1 - \beta \sigma_n^2)} \boldsymbol{w}_{\mathrm{s}} \quad (14)$$

$\boldsymbol{X}(t) = [x_1(t) \quad x_2(t) \quad \cdots \quad x_1(t) \quad \cdots \quad x_M(t)]^{\mathrm{T}}$ is $M \times 1$ vector representing the antenna array received signal; $\boldsymbol{U}$ is $M \times 1$ vector representing the input voltages to the low pass filters of all the M channels; $\boldsymbol{v}$ is $M \times 1$ output voltages vector to the low pass filters of all the M channels; $\boldsymbol{w}_{\mathrm{s}}$ is $M \times 1$ vector of the offset voltages; β is the loop gain, * which appears in Fig.2 and is a conjugate operator; σ_n^2 is the variance of the thermal noise; Eq. (14) indicates that the optimum weight equals to a scaled factor of $\boldsymbol{w}_{\mathrm{s}}$ in case of noise alone.

In case of GPS receiver, it is required to receive the useful signal un-attenuated from all directions. So if $\boldsymbol{w}_{\mathrm{s}} = [1 \quad 0 \quad 0 \cdots 0]^{\mathrm{T}}$ is chosen, this will give a quiescent pattern similar to that generated by isotropic antenna.

2 PI with LCMV Structure

Consider a linear array of M uniformly spaced elements whose outputs are individually weighted and then summed to produce the beamformer output $\boldsymbol{y}(t) = \boldsymbol{X}(t)^{\mathrm{H}}\boldsymbol{w}$.

The main objective of LCMV is to minimize the mean squared output $E(|y(t)|^2)$ subjected to a set of linear constraints on the weight vector $\boldsymbol{w}$,

$$\min |y(t)|^2 = \min \boldsymbol{w}^{\mathrm{H}}\boldsymbol{R}\boldsymbol{w} \quad (15)$$

subjected to

$$\boldsymbol{C}^{\mathrm{H}}\boldsymbol{w} = \boldsymbol{f}$$

The solution to Eq. (15) is

$$\boldsymbol{w}_0 = \boldsymbol{R}^{-1}\boldsymbol{C}[\boldsymbol{C}^{\mathrm{H}}\boldsymbol{R}^{-1}\boldsymbol{C}]^{-1}\boldsymbol{f} \quad (16)$$

When there is no useful or jammer signal and only uncorrelated noise exists, Eq. (16) can be written as

$$\boldsymbol{w}_{\mathrm{q}} = \boldsymbol{C}[\boldsymbol{C}^{\mathrm{H}}\boldsymbol{C}]^{-1}\boldsymbol{f} \quad (17)$$

where $\boldsymbol{w}_{\mathrm{q}}$ is the quiescent weight; $\boldsymbol{R}$ is given by Eq. (2); The total input signal to the antenna is given by Eq. (6); $\boldsymbol{C}$ is $M \times K$ matrix, and all of its columns are linearly independent; M is the number of antenna elements; K is the number of constraints; $\boldsymbol{f}$ is $K \times 1$ response vector.

Normally $K < M$. If $K = M$, this leads to that the weight vector $\boldsymbol{w}$ can be determined only by the constraints and no degrees of freedom are available to data adaptation. If $K > M$, this means that there is no enough weights satisfying the constraints. If it is required to constrain the known directions of the useful and the intentionally jammer signals to be within certain values, the LCMV minimize the total output power subjected to maintain the directions of the useful and the intentionally jammer signals to be within the required values.

So if any jammer signals come from the unknown directions the LCMV will assign new nulls to it Refs. [6,7-8].

The constraint part of Eq. (15) can be written as

$$[\boldsymbol{C}_{\mathrm{u}}^{\mathrm{H}} \quad \boldsymbol{C}_{\mathrm{J}}^{\mathrm{H}}]\boldsymbol{w} = [f_{\mathrm{u}1} \quad f_{\mathrm{u}2} \quad \cdots \quad f_{\mathrm{u}q} \quad f_{\mathrm{J}1} \quad f_{\mathrm{J}2} \quad \cdots \quad f_{\mathrm{J}(K-q)}]^{\mathrm{T}} \quad (18)$$

where $\boldsymbol{C}_{\mathrm{u}} = [\boldsymbol{u}(\theta_1) \quad \boldsymbol{u}(\theta_2) \quad \cdots \quad \boldsymbol{u}(\theta_q)]$ is $M \times q$ matrix representing the useful signals vectors.

where

$$\boldsymbol{u}(\theta_i) = u_i(t)\boldsymbol{\alpha}_{\mathrm{u}i}, i = 1, 2, \ldots, q \quad (19)$$

$\boldsymbol{C}_{\mathrm{J}} = [\boldsymbol{J}(\theta_{q+1}) \quad \boldsymbol{J}(\theta_{q+2}) \quad \cdots \quad \boldsymbol{J}(\theta_K)]$ is the $M \times (K - q)$ matrix representing the jammer signals vectors which is come from the known intentionally jammer directions.

The jammer signals' vectors can be written as

$$\boldsymbol{J}(\theta_k) = J_k(t)\boldsymbol{\alpha}_{\mathrm{J}k}, k = q + 1, q + 2, \ldots, K \quad (20)$$

If it is required to widen the region around the angle, it is required to correspond to the jammer coming from θ_{q+i} direction, $i = 1, 2, \ldots, K - q$. The constraint matrix and the response vector can be written as follows

$$C_J = [J(\theta_{q+1}) \quad \cdots \quad J(\theta_{q+i} - \Delta\theta) \quad J(\theta_{q+i}) \quad J(\theta_{q+i} + \Delta\theta) \quad \cdots \quad J(\theta_K)]$$

$$f = [f_{u1} \quad \cdots \quad f_{uq} \quad f_{J1} \quad \cdots \quad f_{Ji} \quad \cdots \quad f_{J(K-q)}]^T$$

LCMV can not assign deep nulls to the jammer directions if they are not known in advance. Also the shape of the antenna power pattern will not give exact information about the directions of the jammers. From the discussion in Section 2, PI has a quiescent pattern as an isotropic source, so it can give exact jammer directions but the depths of the nulls are very low.

Dealing with GPS signals, the satellite and the user directions are known, then the useful signal directions are exactly known, but the jammer signals directions are unknown. Hence to deal with the above problem, the proposed structure in Fig.3 is used and based on three steps:

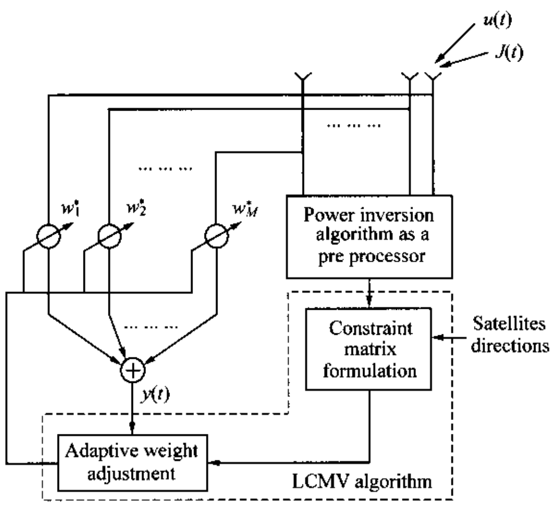


Fig.3 PI with LCMV (PI _ LCMV) structure as jammer suppression for GPS receiver anti jamming

(1) Use PI as a preprocessor to detect the jammer signals directions.

(2) Construct the constraint matrix C which contains both the useful and the jammer signals directions.

(3) Using LCMV to deal with the useful signals and the jammers from known directions.

For adaptively calculating the weight vector, the Lagrange multiplier is used to change the constrained Eq. (15) to unconstrained one, then,

$$Q = w^H R w + \lambda^H (C^H w - f) + (w^H C - f^H)\lambda \tag{21}$$

Minimizing the output power means taking the gradient of Eq. (21) with respect to w^H and equating the result by zero.

$$\frac{\partial Q}{\partial w^H} = 2Rw + 2C\lambda = 0 \tag{22}$$

where λ is $K \times 1$ vector.

Utilizing the steepest descent technique to iteratively update the weight vector,

$$w(k+1) = w(k) - \mu \frac{\partial Q}{\partial w^H} \tag{23}$$

Using both Eq. (22) and $f = C^H w(k+1)$ which is the constraint part of Eq. (15) in Eq. (23), λ can be obtained as

$$\lambda = \frac{1}{\mu}[[C^H C]^{-1} C^T (I - \mu R) w(k) - [C^H C]^{-1} f] \tag{24}$$

Using Eq. (24) in Eq. (23)

$$w(k+1) = Aw(k) - \mu A R w(k) + w_q = A(I - \mu R) w(k) + w_q \tag{25}$$

$A = [I - C[C^H C]^{-1} C^H]$ is the projecting matrix which projects $(I - \mu R) w(k)$ to the $(M-K)$-dimensional subspace Ω. This subspace passes through the origin and parallel to the $(M-K)$-dimensional weight vector hyperplane Π. The orthogonal matrix A will cancel any component perpendicular to Ω.

$w_q = C[C^H C]^{-1} f$ is found in the K-dimensional constraint subspace which is the span of the constraint vector and orthogonal to Π. w_q is the shortest vector terminating to Π.

Considering the instantaneous value of the autocorrelation matrix so that $R = XX^H$, Eq. (25) can take the form

$$w(k+1) = A(w(k) - \mu X(k) y(k)) + w_q \tag{26}$$

$$y(k) = w^H(k) X(k).$$

It is clear that Eq. (26) represents the LMS algorithm if A and w_q are eliminated. Eq. (26) can be represented geometrically Ref. [9] in Fig.4. w_q is represented by OB. It also can be given by GF which is parallel to OB. OP represents the weight vector at iteration k. PD represents the value $-\mu \boldsymbol{X}(k) y(k)$. $\boldsymbol{w}(k)-\mu \boldsymbol{X}(k) y(k)$ is represented by OD, which is the weight vector at iteration $k+1$ in case of LMS algorithm.

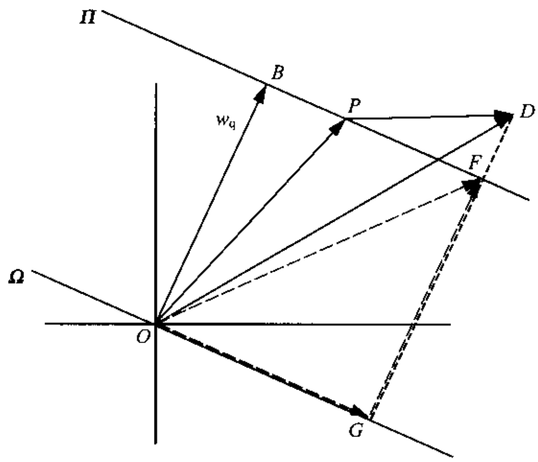


Fig.4 Operation of LCMV

According to Fig.5, $\boldsymbol{w}_{\mathrm{LMS}}(k+1)$ will not terminate to $\boldsymbol{\Pi}$. To make $\boldsymbol{w}(k+1)$ all the time satisfies the constraint condition, it must be projected on $\boldsymbol{\Omega}$ and the quiescent weight must be added to the projecting vector.

OG is represented by $\boldsymbol{A}(\boldsymbol{w}(k)-\mu \boldsymbol{X}(k) \cdot y(k))$; $OF=OG+GF$; $OF=\boldsymbol{w}(k+1)$ is given by Eq. (26) and terminates to $\boldsymbol{\Pi}$.

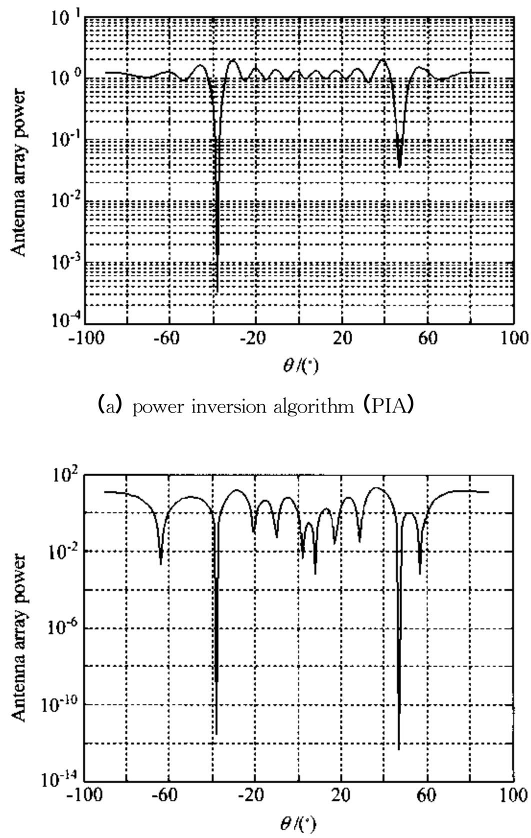
3 Simulations

Computer simulations are performed using 13 elements uniform linear arrays arranged in the y-axis with elements spaced half wave length apart. There are six useful GPS signals, each with power -165dBW coming from directions $[0° \quad 15° \quad 30° \quad 45° \quad 60° \quad -36°]$. Two jammers come from directions $[47° \quad -38°]$. The jammer coming from 47° has power -120 dBW and the other coming from $-38°$ has power -100 dBW. Simulation is performed using 200 snap shots. Five cases are simulated.

(1) The requirement is to achieve the distortionless response in the directions of the useful signals and null the jammer coming form the fixed directions. Consequently the constraint response can be given as $\boldsymbol{f}=[1 \quad 1 \quad 1 \quad 1 \quad 1 \quad 1 \quad 0 \quad 0]^{\mathrm{T}}$, and the constraint matrix takes the form

$$[u(0°) \quad u(15°) \quad u(30°) \quad u(45°) \quad u(60°) \quad u(-36°) \quad J(47°) \quad J(-38°)].$$

The power pattern levels for the desired and the jammer signals from Fig.5 are summarized in Table 1, in case of using PI algorithm alone. It is clear that the maximum difference between the highest level for the desired directions and the lowest level for the jammer directions is 36 dB. In case of PI _ LCMV, the difference between all of the desired signal directions and jammer from direction



(a) power inversion algorithm (PIA)

(b) PIA with LCMV structure (PI _ LCMV)

Fig. 5 Antenna array power patten

Table 1 PI against PI _ LCMV in case of distortionless response and nulling the jammer direction

Angle in degrees θ/(°)	Power pattern level PI/dB	PI _ LCMV/dB
0	1.06	0
15	0.7	0
30	0.5	0
45	−5.6	0
60	1.14	0
−36	−4.8	0
47	−14.7	−123.2
−38	−34.86	−115.6

47° is 123.2 dB and from direction −38°, 115.6 dB.

(2) The requirement is to achieve controlled response for the useful and the jammer signals. It is assumed that the jammers come form fixed directions. The response vector is

$$f = [\sqrt{10} \quad \sqrt{10} \quad \sqrt{10} \quad \sqrt{10} \quad \sqrt{10} \quad \sqrt{10} \quad 0.0001 \quad 0.0001]^{\mathrm{T}}$$

This response vector assures that the antenna must has 10 dB gain in the directions of the all the GPS useful signals. It guarantees that the null depth corresponds to directions 47° and −38° to be −80 dB. It is obvious from Fig.6 and Table 2 that the antenna power pattern achieves the constraints exactly.

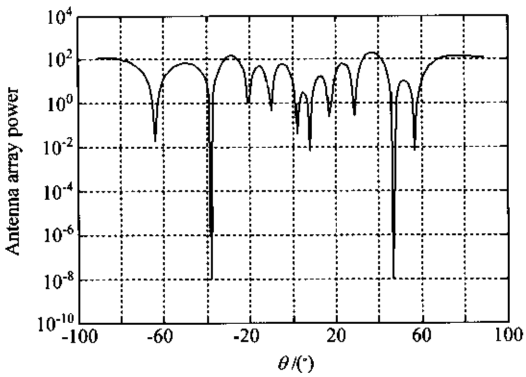


Fig.6 Antenna array power pattern PI _ LCMV structure in case of controlling the desired direction gains and the jammer direction null

Table 2 Summarizing the power patten levels of Fig.6

Angle in degrees θ/(°)	Power pattern level PI _ LCMV/dB
0	10
15	10
30	10
45	10
60	10
−36	10
47	−80
−38	−80

(3) The requirement is to achieve distortionless response in the directions of the useful signals and null the moving jammers' directions. So the constraint matrix is given as

$$[u(0°) \quad u(15°) \quad u(30°) \quad u(45°) \quad u(60°) \quad u(-36°) \quad \cdots \quad \cdots \quad J(46°) \quad J(47°) \quad J(48°) \quad J(-39°) \quad J(-38°) \quad J(-37°)]$$

and the response vector is given as

$$f = [1 \quad 1 \quad 1 \quad 1 \quad 1 \quad 1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0]^{\mathrm{T}}$$

In simulation the two jammers are carried by two airplanes 600 km distance from the antenna. Both airplanes move with one Mach speed. One degree movement by the airplane corresponds to 30.7999 s. The simulation is done within 23 s by 1.7 GHz Pentium IV computer. The constraint matrix is constructed to achieve 2° null width for both jammers to assure that the jammers' directions lie inside the null.

Fig.7 illustrates the power pattern levels for each direction given by the constraint matrix. Table 3 summarizes the power pattern levels for each direction given by the constraint matrix. It is obvious from Table 3 that the difference between all the useful signal directions and the jammer from 47° ranges between [94.67 :94.74] dB.

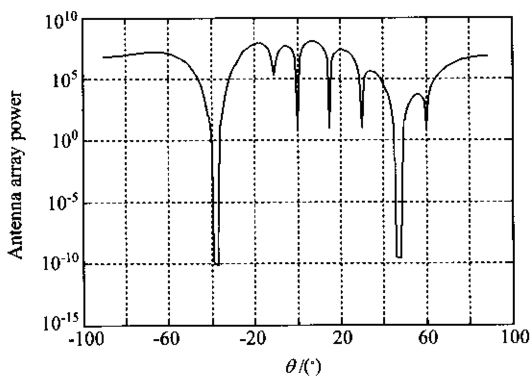


Fig.7 Antenna array power pattern in case of using PI-LCMV with two moving jammers

Table 3 Summarizing the power pattern levels of Fig.7

Angle in degrees θ/(°)	Power pattern level PI _ LCMV/dB
0	0
15	0
30	0
45	0
60	0
−36	0
46	−94.73
47	−94.67
48	−94.73
−39	−100.6
−38	−101.66
−37	−102.8

The difference between the desired signals and the jammer from −38° ranges between [100.6 : 102.8] dB. It is clear that the proposed structure achieves the constraints and highly suppresses the moving jammers. Also the suppression takes into consideration of any miss track given by the PI.

(4) The requirement is to achieve 10 dB gains for the useful signals and 2° null of depth −80 dB in the moving jammers' directions. The response vector that achieves the above requirements is

$$f = [\sqrt{10} \quad \sqrt{10} \quad \sqrt{10} \quad \sqrt{10} \quad \sqrt{10} \quad \sqrt{10} \quad \cdots \quad \cdots 0.0001 \quad 0.0001 \quad 0.0001 \quad 0.0001 \quad 0.0001 \quad 0.0001]^{\mathrm{T}}$$

and the constraint matrix is given as

$$[u(0°) \quad u(15°) \quad u(30°) \quad u(45°) \quad u(60°) \quad u(-36°) \quad \cdots \quad \cdots J(46°) \quad J(47°) \quad J(48°) \quad J(-39°) \quad J(-38°) \quad J(-37°)]$$

It is clear from Fig.8 and Table 4 that the proposed structure achieves the required constraints exactly.

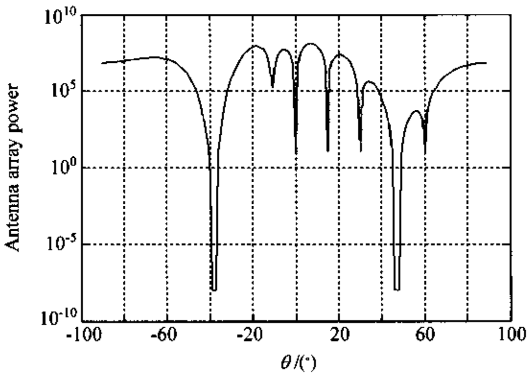


Fig.8 Antenna array power pattern in case of using PI _ LCMV with two moving jammers and controlling the desired and jammer directions

Table 4 Summarizing the power pattern levels of Fig.8

Angle in degrees θ/(°)	Power Pattern Level PI _ LCMV/dB
0	10
15	10
30	10
45	10
60	10
−36	10
46	−80
47	−80
48	−80
−39	−80
−38	−80
−37	−80

(5) This case is exactly like Case (1), but after constructing the constraints matrix a new jammer of power −110 dBW from direction −18° is illuminated. Fig.9 illustrates the behavior of the proposed structure. Table 5 indicates that a new null of depth 57 dB is generated at −18° to cancel the jammer.

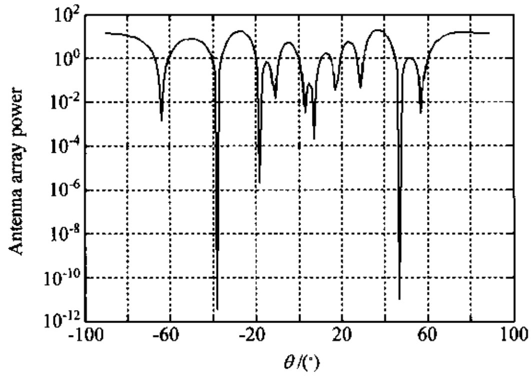


Fig.9 Antenna array power pattern in case of using PI _ LCMV when a new jammer from direction −18° is illuminated after updating the constrains matrix by PIA

Table 5 Summarizing the power patten levels of Fig.9

Angle in degrees θ/(°)	Power pattern level PI _ LCMV/dB
0	0
15	0
30	0
45	0
60	0
−36	0
47	−110
−38	−114
−18	−57

4 Conclusions

PI is one of the best methods using for GPS anti-jamming. But when the input jammer to desired signal ratio is not very high, this leads to bad output signal to noise ratio. LCMV with constraint of the jammer direction gives a very good result for jammer suppression, but in case of GPS the jammer direction is unknown. So the proposed structure utilizes the power inversion as a pre-processor to update the constraint matrix by the jammer direction. LCMV minimizes the total output power subjected to constraining both the desired and the jammer directions. The simulation takes all the possible situations into consideration like two fixed jammer, and the response vector constrains the useful signal to be unity or specific values and the jammer signals to be zeros or specific values. Two moving jammers with constraint of the useful and jammer signals take certain specified values. The effect of a new jammer appears after updating the constraints matrix by the PIA is introduced. All the simulations indicate that the proposed structure is more efficient than the power inversion alone.

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天线设计理论晦涩高深，让许多工程师望而却步，然而实际工程或实际工作中在设计天线时却很少用到这些高深晦涩的理论。实际上，我们只需要懂得最基本的天线和射频基础知识，借助于 HFSS、CST 软件或者测试仪器就可以设计出工作性能良好的各类天线。

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