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MUSIC for the User Receiver of the GEO Satellite Communication System

Luis Germán Aponte Reyes+, Shen Shi Tuan, Tan Zhan Zhong

School of Electronic and Information Engineering, Beijing University of Aeronautics and Astronautics, Beijing 100191, China

Abstract. Owing to the increasing demand of the high-speed fixed satellite service (FSS), the jamming from other satellite networks could be more severe. Commonly, the user receiver of the geostationary earth orbit (GEO) satellite communication system has no capability to detect and cancel the jammers. The objective of this document is to study the implementation of the Multiple Signal Classification (MUSIC) algorithm as a tool to improve the anti-jamming performance of a GEO satellite communication system. To approach this objective, the paper introduces the main characteristics and requirements of the FSS and the GEO satellite communication system. The antenna of the user receiver is a square array (SA) of isotropic elements, which we subsequently divided into square sub-arrays (SSAs) to finally utilize the output signals of these SSAs to implement the MUSIC algorithm. A simulation system was designed to introduce two jammers at the user receiver from different directions of arrival (DOAs). We verified the output signal-jammer-plus noise ratio (SJNR) and the results show that MUSIC cannot be used to cancel the jammers but it can be useful in detecting the number and DOAs of the jammers.

Keywords: Anti-jamming, Communication Satellite, Antennas Array, MUSIC.

1. Introduction

The increasing demand of commercial high-speed services is constantly promoting the creation of new GEO communications satellite systems [5]. The coordination between these new satellite networks could be ineffective, and the interference from satellites could become a serious problem for the user receivers. These jammers are generally non-intentional, but additionally, multiples evidence also shows that user receivers of commercial GEO satellite communication systems have been intentionally jammed [4]. In both cases, the commercial antennas used by user receivers of GEO-FSS, do not have the capability to identify the DOAs of the jammers.

One useful algorithm for the detection and canceling jammers is MUSIC [3], but normally it is not used in commercial GEO satellite communication systems.

Under this background, this paper studies the MUSIC implementation at the user receiver to improve the anti-jamming capability of a GEO satellite communication system.

Our approach is based on a ka band GEO-FSS (*28GHz* uplink and *19GHz* downlink) to create an interference environment at the antenna of the user receiver. The receiver antenna is a SA of *3600* isotropic elements equally spaced one-half wavelength ($\lambda/2$) apart. This number of elements produces a directional radiation pattern with maximum power gain of *38.3dBi* at the direction of arrival (DOA) of the useful signal. We assumed that this antenna meets all the requirements of the system. The downlink power flux density (FD_{dw}) at the user receiver is $-120.1dBW/m^2$, the received power of the useful signal (P_u) is *-128.8dBW*, the noise power at the user receiver (P_n) is *-138.1dBW*, and the output signal-to-noise ratio (SNR) at the user receiver is *9.3dB*. This SNR is the minimum requirement of the system, so it is the SJNR. An assumed

+ Corresponding author. Tel.: + 86 13488642469.
E-mail address: luis_aponte80@hotmail.com.

jammer with power flux density equal to $-90dBW/m^2$, concentrated in a direction (θ_j, ϕ_j) close to the DOA of the useful signal, will reduce SJNR from $9.3dB$ to $\approx -30dB$, which causes the interruption of the FSS.

2. The MUSIC implementation

In order to implement MUSIC at the user receiver side (Figure 1), we propose to divide the SA into *25* SSAs. Accordingly, the SA is controlled by weights connected to the SSAs outputs.

A spherical coordinate system is used to represent the DOAs of the incoming signals (useful signal and jammers). The origin of the coordinate system is located at a corner of the SA; the z axis is oriented to the satellite. The incoming signals angles $\theta \in [0, 90°]$ are measured from the z axis, and angles $\phi \in [0, 360°]$ are measured from the x axis. The useful signal arrives from $\theta = 0°$, thus, any ϕ can be considered. The jammers will arrive at the SA from DOAs (θ_j, ϕ_j).

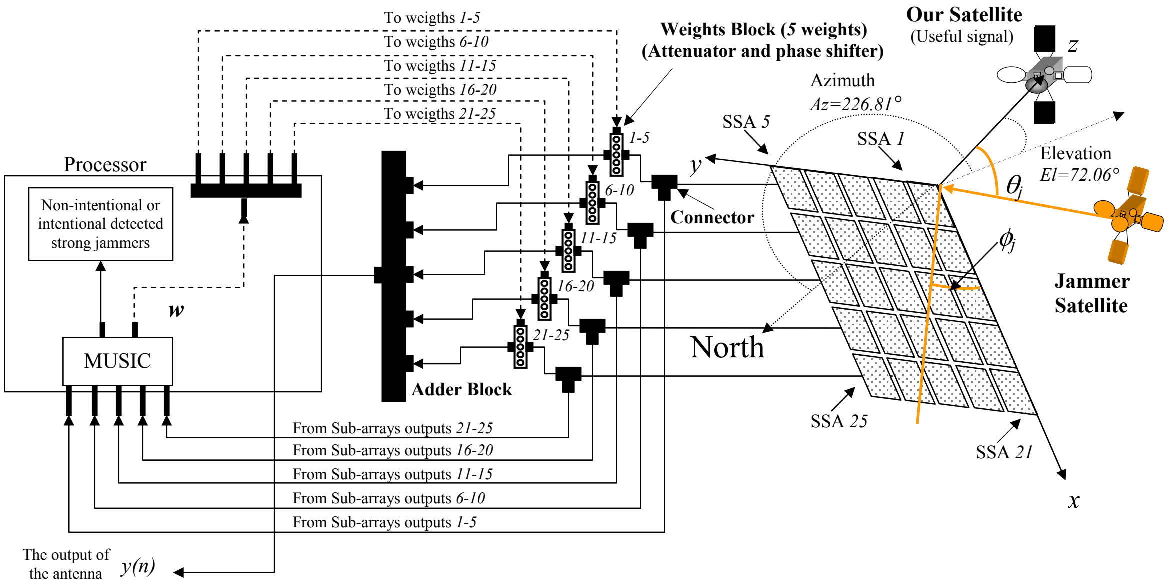

Fig. 1: MUSIC Implementation at the User Receiver

The measured signals at the *25* SSAs outputs are represented by

$$\boldsymbol{x}(n) = s(n) f_{sub} [e^{j\xi_1(\theta,\phi)} \quad e^{j\xi_2(\theta,\phi)} \quad \cdots \quad e^{j\xi_{25}(\theta,\phi)}]^T \tag{1}$$

where $s(n)$ is a sample of the incoming signal from angle (θ,ϕ) measured at time n; f_{sub} is the field pattern of any square sub-array (SSA); and $\xi_\rho(\theta,\phi)$ is a spatial phase due to the location of the ρ^{th} SSA $(1 \le \rho \le 25)$ inside of the SA.

The weights connected to the *25* SSAs outputs are given by

$$\boldsymbol{w} = [w_1 \quad w_2 \quad \cdots \quad w_{25}]^T \tag{2}$$

Thus, the output of the antenna is given by,

$$y(n) = \boldsymbol{w}^H \boldsymbol{x}(n) \tag{3}$$

The useful signal and strong jammers will arrive from different DOAs (θ_i, ϕ_i) to the SA, so considering that there are d incoming signals in total, a vector of incoming signals could be defined by

$$\boldsymbol{s}(n) = [s_1(n) \quad s_2(n) \quad \cdots \quad s_d(n)]^T \tag{4}$$

where the index n indicates the n^{th} sampling instant.

Defining the steering vector by,

$$\boldsymbol{a}_i = \boldsymbol{a}(\theta_i, \phi_i) = [a_{i1} \quad a_{i2} \quad \cdots \quad a_{i25}]^T \qquad 1 \le i \le d \tag{5}$$

where from Eq.1, $a_{i\rho} = f_{sub} e^{j\xi_\rho(\theta_i,\phi_i)} (1 \le \rho \le 25)$, the received signals at the *25* SSAs outputs are given by

$$\boldsymbol{x}(n) = [\boldsymbol{a}_1 \quad \boldsymbol{a}_2 \quad \cdots \quad \boldsymbol{a}_d] \boldsymbol{s}(n) + \boldsymbol{n}(n) = \boldsymbol{A}\boldsymbol{s}(n) + \boldsymbol{n}(n) \tag{6}$$

where $\boldsymbol{n}(n)$ is a noise column vector of dimension 25×1.

The dimension of the matrix $\boldsymbol{A}$ is $25\times d$. Each one of the 25 rows is considered as a vector in C^{1xd}, and each steering vector $\boldsymbol{a_i}$ belongs to the space C^{25}.

Assuming that the noise and the signals are totally de-correlated, the correlation matrix $\boldsymbol{R}_{xx}$ can be expressed by

$$\boldsymbol{R}_{xx} = E[\boldsymbol{x}(n)\boldsymbol{x}^H(n)] = \boldsymbol{A}\boldsymbol{R}_{ss}\boldsymbol{A}^H + \boldsymbol{R}_{nn} \quad (7)$$

where $\boldsymbol{R}_{ss} = E[\boldsymbol{s}(n)\boldsymbol{s}^H(n)]$ is the correlation matrix of the signals vector, and $\boldsymbol{R}_{nn} = E[\boldsymbol{n}(n)\boldsymbol{n}^H(n)]$ is the correlation matrix of the noise vector.

MUSIC algorithm is based on the eigen-decomposition of the correlation matrix $\boldsymbol{R}_{xx}$. In our case, this matrix has 25 eigenvalues ($\lambda_1, \lambda_2, \ldots, \lambda_{25} \geq 0$) and 25 eigenvectors $\boldsymbol{e}_i$ ($1 \leq i \leq 25$). There are $E=25-d$ belonging to noise sub-space and d eigenvectors belonging to signal sub-space. The E noise eigenvectors and the d signal eigenvectors are orthogonal [2]. This means, the E noise eigenvectors and the d steering vectors $\boldsymbol{a}_i$ ($1 \leq i \leq d$) of the incoming signals are orthogonal. Any one of the E noise eigenvectors is chosen to be the MUSIC weight vector $\boldsymbol{w}$. This $\boldsymbol{w}$ produces nulls at the DOAs (θ_i, ϕ_i) ($1 \leq i \leq d$) of the incoming signals. Thus, the power at the output of the antenna (P_o) will be zero as well,

$$P_o(\theta_i, \phi_i) = \boldsymbol{w}^H \boldsymbol{a}_i \boldsymbol{a}_i^H \boldsymbol{w} P_i = 0 \quad (8)$$

where $P_i = E[s_i(n)s_i^*(n)]$ is the power of the incoming signal s_i ($1 \leq i \leq d$) at the input of the antenna, and $\boldsymbol{w}^H\boldsymbol{a}_i\boldsymbol{a}_i^H\boldsymbol{w}$ is the power gain of the antenna at the DOA of the incoming signal s_i.

In our GEO satellite communication system, the useful signal and strong jammers do not belong to noise sub-space. In this situation, MUSIC will recognize both the DOA of the useful signal and the DOAs of the strong jammers. If the weight vector $\boldsymbol{w}$ given by MUSIC is used to control the SA, the jammers and the useful signal will be cancelled at the output of the antenna.

Summary of MUSIC implementation:

- Measure the received signals at the 25 SSAs outputs to form the vector $\boldsymbol{x}(n)$
- Calculate the correlation matrix $\boldsymbol{R}_{xx}$
- Calculate the E eigenvalues and eigenvectors of matrix $\boldsymbol{R}_{xx}$
- Use any one of these E eigenvectors as the weight vector $\boldsymbol{w}$.
- Use $\boldsymbol{w}$ to estimate the number of impinging signals d, and its DOAs from Eq.8.
- Get the number $d-1$ and the DOAs of the strong jammers.

After the MUSIC implementation, the power of the useful signal at the output of the antenna is $P_u(\theta_u, \phi_u) = \boldsymbol{w}^H\boldsymbol{a}_u\boldsymbol{a}_u^H\boldsymbol{w}P_{u,i}$; $P_{u,i}$ is the power of the useful signal at the input of the antenna; the power of a jammer at the output of the antenna is $P_j(\theta_j, \phi_j) = \boldsymbol{w}^H\boldsymbol{a}_j\boldsymbol{a}_j^H\boldsymbol{w}P_{j,i}$; $P_{j,i}$ is the power of the jammer at the input of the antenna.

3. Simulations

3.1. Simulation System (SS)

The block diagram of the SS for the MUSIC implementation is shown in the following Figure 2.

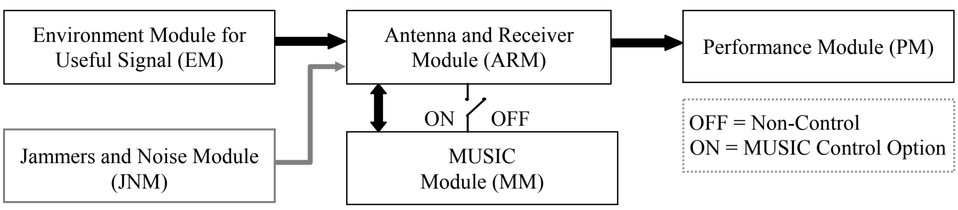

Fig. 2: MUSIC Implementation SS Blocks

The EM is used to obtain the power flux density of the useful signal at the user receiver. The JNM works: 1) to simulate thermal noise at the output of the antenna as zero-mean Gaussian noise; 2) to introduce jammers (CW_j) and (WB_j) with different DOAs. The ARM is used: 1) to simulate the power pattern of the antenna when it is non-controlled; 2) to simulate the signal at the SSAs outputs; and 3) to simulate the signal at the output of the antenna. MM is the MUSIC algorithm module. It can be connected or not (ON-OFF) to the ARM by a virtual switch. If the switch is ON, MM controls the SA by MUSIC. The resulting weights will go to the ARM, and this module simulates the power pattern of the antenna when it is controlled by MUSIC. The PM receives the output from the ARM and estimates the output SJNR.

3.2. Simulation Process (SP)

In order to evaluate the performance of the antenna before and after being controlled by the MUSIC algorithm, eight scenarios were defined as shown in Table 1.

Table 1. Scenarios for the SP

Scenario	CW_j $[dBW/m^2]$	θ	ϕ	WB_j $[dBW/m^2]$	θ	ϕ
1	*-90*	*1°*	*180°*	*-210*	*1°*	*0°*
2	*-90*	*1°*	*180°*	*-110*	*1°*	*0°*
3	*-90*	*1°*	*270°*	*-210*	*1°*	*90°*
4	*-90*	*1°*	*270°*	*-110*	*1°*	*90°*
5	*-90*	*1°*	*135°*	*-210*	*1°*	*315°*
6	*-90*	*1°*	*135°*	*-110*	*1°*	*315°*
7	*-90*	*1°*	*225°*	*-210*	*1°*	*45°*
8	*-90*	*1°*	*225°*	*-110*	*1°*	*45°*

For all the cases, it is assumed that the antenna is oriented to the satellite, so the DOA of the useful signal is (θ=$0°$, at any ϕ).

The first step in the SP is to check the influence of the jammers at the output of the antenna before MUSIC implementation. The results in Table 2 show that SJNR is under the requirement.

Table 2. Antenna for Non-Control Option

Scenario	P_u $[dBW]$	CW_j $[dBW]$	WB_j $[dBW]$	P_n $[dBW]$	SJNR $[dB]$
1	*-128.8*	*-103.1*	*-223.1*	*-138.1*	*-25.8*
2	*-128.8*	*-103.1*	*-123.1*	*-138.1*	*-25.8*
3	*-128.8*	*-103.1*	*-223.1*	*-138.1*	*-25.8*
4	*-128.8*	*-103.1*	*-123.1*	*-138.1*	*-25.8*
5	*-128.8*	*-102.8*	*-222.8*	*-138.1*	*-26.0*
6	*-128.8*	*-102.8*	*-122.8*	*-138.1*	*-26.1*
7	*-128.8*	*-102.8*	*-222.8*	*-138.1*	*-26.0*
8	*-128.8*	*-102.8*	*-122.8*	*-138.1*	*-26.1*

Subsequently, the antenna is controlled by MUSIC (switch ON).

The MUSIC option is a function that receives the vector $\boldsymbol{x}(n)$ from ARM and calculates $\boldsymbol{R}_{xx}=E[\boldsymbol{x}(n)\boldsymbol{x}^H(n)]$, the eigenvalues ($\lambda$) of $\boldsymbol{R}_{xx}$ and its corresponding eigenvectors ($\boldsymbol{e}$). The $\boldsymbol{e}_i$ ($1 \le i \le 25$) are organized in a 25×25 matrix ($\boldsymbol{E}_m$), and the λ_i ($1 \le i \le 25$) are organized in a 25×1 vector ($\boldsymbol{E}_v$) according to the magnitude as shown in Eq.9.

$$(for\ Scenario\ 2) \qquad \boldsymbol{E}_v = [\underbrace{1.98e-6 \quad 8.15e-8 \quad 3.93e-10}_{Signal} \quad \underbrace{1.55e-14 \quad \cdots \quad 1.55e-14}_{Noise}]^T \tag{9}$$

According to Eq. 9, $\boldsymbol{E}_v$ is divided into λ_i of the signal subspace ($\boldsymbol{E}_s$) and λ_i of the noise subspace ($\boldsymbol{E}_n$). Subsequently, the $\boldsymbol{E}_s$ is obtained from $\boldsymbol{E}_m$ columns *23* to *25*, and the $\boldsymbol{E}_n$ from $\boldsymbol{E}_m$ columns *1* to *22*.

As we mentioned, any column of $\boldsymbol{E}_n$ can be selected as the MUSIC weight vector ($\boldsymbol{w}$). Our MUSIC function selects the first column of $\boldsymbol{E}_n$ (Column *1*) as the MUSIC weight vector, this is

$$(for\ Scenario\ 2) \qquad \boldsymbol{w} = [\boldsymbol{w}_1 \quad \boldsymbol{w}_2 \quad \boldsymbol{w}_3 \quad \boldsymbol{w}_4 \quad \boldsymbol{w}_5]^T \tag{10}$$

$$\boldsymbol{w}_1 = \begin{bmatrix} 0.07 - 0.14i \\ -0.09+0.29i \\ 0.02 - 0.26i \\ 0.10+0.07i \\ -0.05+0.02i \end{bmatrix}^T \quad \boldsymbol{w}_2 = \begin{bmatrix} 0.06 - 0.12i \\ -0.10+0.28i \\ 0.01 - 0.27i \\ 0.09+0.06i \\ -0.06+0.02i \end{bmatrix}^T \quad \boldsymbol{w}_3 = \begin{bmatrix} 0.06 - 0.12i \\ -0.10+0.29i \\ 0.01 - 0.26i \\ 0.08+0.07i \\ -0.06+0.03i \end{bmatrix}^T \quad \boldsymbol{w}_4 = \begin{bmatrix} 0.06 - 0.11i \\ -0.10+0.29i \\ 0.00 - 0.26i \\ 0.09+0.07i \\ -0.07+0.02i \end{bmatrix}^T \quad \boldsymbol{w}_5 = \begin{bmatrix} 0.05 - 0.10i \\ -0.11+0.30i \\ 0.01 - 0.27i \\ 0.07+0.09i \\ -0.05 \end{bmatrix}^T$$

Table 3 summarizes the performance results after the antenna being controlled by the MUSIC weight vector (Eq.10).

Table 3. Antenna Controlled by the MUSIC weight vector

Scenario	P_u [dBW]	CW_j [dBW]	WB_j [dBW]	P_n [dBW]	SJNR [dB]
1	*-305.9*	*-317.5*	*-285.1*	*-138.1*	*-167.8*
2	*-354.1*	*-380.7*	*-382.1*	*-138.1*	*-216.0*
3	*-305.1*	*-324.1*	*-279.2*	*-138.1*	*-167.0*
4	*-354.4*	*-378.1*	*-379.9*	*-138.1*	*-216.3*
5	*-316.0*	*-329.7*	*-291.7*	*-138.1*	*-177.9*
6	*-378.2*	*-391.3*	*-385.0*	*-138.1*	*-240.1*
7	*-302.7*	*-318.0*	*-282.1*	*-138.1*	*-164.6*
8	*-362.7*	*-386.6*	*-386.6*	*-138.1*	*-224.6*

According to Table 3, the antenna controlled by the MUSIC weight vector cannot meet SJNR requirements. This is because the useful signal does not belong to the noise sub-space, so the MUSIC weight vector is orthogonal to the DOA of the useful signal and the algorithm produces pattern nulls < *-135dBi* in this direction. Nevertheless, an important result for us is that MUSIC can be used to detect the number of jammers and its DOAs.

Figure 3 shows the detected DOAs of the jammers by using Eq.10 for scenario 2, and the power pattern of the antenna. The gain at the DOA of the useful signal is *-187dBi*, the gain at the DOA of the CW_j is *-243.7dBi* and the gain at the DOA of the WB_j is *-225.1dBi*.

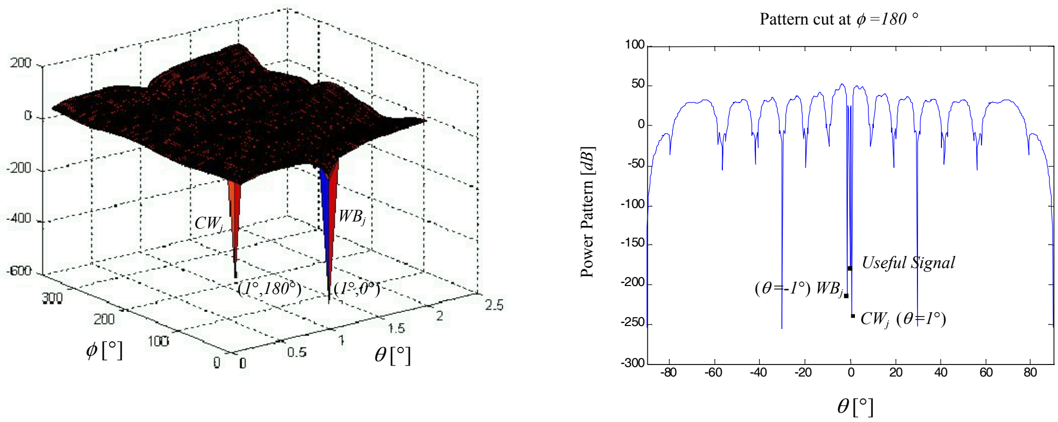

Fig. 3: MUSIC Simulations for the scenario 2. a) Detected DOAs of the strong jammers (Left).
b) Power Pattern of the Antenna Controlled by the MUSIC weight vector (Right).

4. Conclusions

This study shows that it is possible to implement MUSIC at the user receiver of the GEO satellite communication system to detect a $CW_j = -90dBW/m^2$ ($\theta = 1°$, at any ϕ) and a $WB_j = -110dBW/m^2$ ($\theta = 1°$, at any ϕ). In all the simulated scenarios, it was demonstrated that MUSIC cannot be used to mitigate those jammers because the weights control the antenna to produce nulls < *-135dB* in the DOA of the useful signal. MUSIC detected the DOAs of the strong jammers.

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