ТЕХНИЧЕСКИЕ НАУКИ

THE PERFORMANCE EVALUATION OF HIGH RESOLUTION DOA ESTIMATION ALGORITHMS IN SONAR SYSTEMS

Nguyen Ngoc Dong
Ph-D, Le Quy Don Technical University, Vietnam Republic
Nguyen Trung Thanh
Ph-D, Le Quy Don Technical University, Vietnam Republic
Phan Nhat Giang
Ph-D, Le Quy Don Technical University, Vietnam Republic

ABSTRACT

The angular resolution in direction finding systems can be improved by applying phase array antenna and advanced signal processing algorithms. There have been super high angular resolution algorithms which ultilize phase array antenna and can locate several signals simultaneously. Among the algorithms have been investigated recently, the Barlett, Capon, Thermal Noise, Borgiotti-Lagunas, Music, EV, Min-Nor, Espirit and Root-Music algorithms can produce super high angular resolution but do not require the increase in the antenna size. This paper evaluates the performances of those DOA estimation algorithms.

Keywords: doa, estimation, resolution, signal processing, performance.

Introduction

The first and also primary stage of sonar signal processing consists of: the detection of signals received by antenna, the estimation of direction of arrival (DOA), the estimation of signal power characteristic, and the recovery of signal with minimum distortion so that the signal can be identified afterward.

In passive sonar systems, signals come from the targets themselves. They are noise from the target motion, they could be noise generated from propellers, noise from other activities of machine and crew on the ship, dynamical noise generated by water movement around the ship, or even by sonar systems on the ship, to name a few. Those acoustic signals propagate on water, but suffer from great loss due to the propagation environment. As a result, the signals at the input of sonar receivers are normally very weak. At the same time, there are always strong clutter sources in the sea environment, such as those from sea waves, wind, fishes and a large number of ships on the sea. The most difficult tasks in the sonar signal processing, therefore, are the detection of signals and the parameter estimation of weak signals on the strong clutter background. The detection of those signals requires the long time of accumulation and the accurate DOA estimation needs high resolution algorithms.

The DOA estimation in the passive sonar systems is even more important. This is because simple passive sonar systems by themselves are not capable of measuring range. Therefore, the accurate DOA estimation is the key to solve all other tasks of passive sonar systems.

In this paper, several DOA estimation algorithms are evaluated in terms of performance. Those algorithms are high resolution and can be applied in passive sonar systems. The remainder of this paper is organized as follows: section II reviews of the algorithms for DOA estimation. Simulation results to compare the performances of those algorithms in MATLAB are presented in section III and IV, and the conclusion is given in Section V.

A review DOA estimation algorithms

The accurate DOA estimation in passive radar plays a crucial role in the sonar signal processing. If the accurate DOA estimation can be achieved, we can then use the triangular method to locate the target and measure the range.

Most of DOA estimation algorithms are based on the search for the maximum in the pseudospectrum of the signal which corresponds to the DOA. There have been many DOA estimation algorithms in the past literature, which can be classified into 3 following categories:

+ Group 1: algorithms based on the location of local maximum of signal pseudospectrum $P(\theta)$, in which θ is the DOA of signal. This category consists of classical algorithms for beamforming such as the Barlett (CL-BEAMFORMER), and Capon, Thermal Noise (TN), Borgiotti-Lagunas algorithms [1, 2, 3]. Those algorithms use the correlation matrix$\boldsymbol{R_{xx}}$of the input signals.

The classical algorithm for beamforming can be described as:

$$P_{CL\_BEAMFORMER}(\theta) = \frac{a^H(\theta)\hat{R}_{xx}a(\theta)}{a^H(\theta)a(\theta)} \quad (1)$$

The Capon algorithm can be described as:

$$P_{CAPON}(\theta) = \frac{1}{a^H(\theta)\hat{R}_{xx}^{-1}a(\theta)} \quad (2)$$

The Thermal Noise algorithm can be described as:

$$P_{TN}(\theta) = \frac{1}{a^H(\theta)\hat{R}_{xx}^{-2}a(\theta)} \quad (3)$$

The Borgiotti-Lagunas algorithm can be described as:

$$P_{BL}(\theta) = \frac{a^H(\theta)\hat{R}_{xx}^{-1}a(\theta)}{a^H(\theta)\hat{R}_{xx}^{-2}a(\theta)} \quad (4)$$

In all equations (1) to (4),$P(\theta)$ is the pseudospectrum function, $a(\theta)$ is the steering vector, and $a^H(\theta)$ is the conjugate transpose vector of the steering vector.

+ Group 2: algorithms based on the decomposition the correlation matrix into the eigenvalues and eigenvectors.

In this category, there are algorithms such as MUSIC, EV, MIN-NOR [4, 5].

The MUSIC algorithm can be described as:

$$P_{MUSIC}(\theta) = \frac{1}{a^H(\theta)Q_nQ_n^Ha(\theta)} \quad (5)$$

The MIN-NOR algorithm can be described as:

$$P_{MIN-NOR}(\theta) = \frac{1}{\left|a^H(\theta)\begin{bmatrix}1\\ \hat{g}\end{bmatrix}\right|} \quad (6)$$

The EV algorithm can be described as:

$$P_{EV}(\theta) = \frac{1}{\sum_{i=p+1}^{N}\frac{1}{\lambda_i}\left|a^H(\theta)Q_n\right|^2} \quad (7)$$

In all equations (5) to (7): $Q_n$is the noise subspaces, Q_n^H is the conjugate transpose matrix of the noise subspaces; $g = \begin{bmatrix}1\\ \hat{g}\end{bmatrix}$is the minimum norm vector is defined as the vector lying in the noise subspace whose first element is one having minimum norm; $\lambda_i$is the eigenvalues of the correlation matrix

+Group 3: algorithms based on the analysis and decomposition the correlation matrix into signal and noise subspaces**.** Signal and noise subspaces are used in DOA estimation algorithms such as ROOT-MUSIC, ESPIRIT [6,7]. Those algorithms based on the roots of algebraic polynomial.

The ROOT-MUSIC algorithm based on the roots of polynomial:

$$D(z) = \sum_{l=-N+1}^{N-1} C_l z^l \quad (8)$$

Where:$\boldsymbol{C_l}$is the sum of the elements in l-th diagonal of the matrix$C = Q_nQ_n^H$ and$z = e^{-jkd\sin\theta}$.

The DOA can then be estimated by the formula:

$$\theta_i = sin^{-1}\left(\frac{arg(z_i)}{kd}\right) \quad (9)$$

Where z_i is the root of the polynomial $D(z)$ and satisfies condition $|z_i| = 1$; $k = \frac{\omega}{c}$, with ω is the angular frequency of the signal, and c is the speed of signal in water; d is the element spacing of phase array antenna

On the other hand, the ESPIRIT algorithm divides array antenna into two sub-arrays. The space in between the two sub-arrays must be equal the element spacing of the array antenna.

If $a_1(\theta)$ and $a_2(\theta)$ are the two vector pointing to the source of signal from the two sub-arrays then $a_1(\theta) = a_2(\theta)\Phi$. If $Q_{s1}$and $Q_{s2}$are the two subspaces of signal corresponding to the two sub-arrays then there always exists only one matrix T which satisfies: $Q_{s1} = a_1(\theta)T; Q_{s2} = a_2(\theta)T$.

We can then determine matrix Φ by the following mathematical relation:

$$(Q_{s1}^HQ_{s1})^{-1}Q_{s1}^HQ_{s2} = (Q_{s1}^HQ_{s1})^{-1}Q_{s1}^HT^{-1}\Phi T = T^{-1}\Phi T \quad (10)$$

The DOA is then can be estimated by the following equation:

$$\theta_i = sin^{-1}\left(\frac{arg(\lambda_i)}{kd}\right) \quad (11)$$

In that: $\lambda_i$is the eigenvalues of the diagonal matrix Φwhich is generated from signals from 2 sub-arrays and also called rotational invariance.

The performance of the above algorithms depends on parameters such as: SNR, the number of antenna elements, and the length of the signal. In the next section, we will evaluate the performance of the above algorithms in different scenarios corresponding to different input parameters.

Simulation results

In this section, MATLAB is used to evaluate the performance of the CL-BEAMFORMER, Capon, Thermal Noise, Borgiotti-Lagunas, MUSIC, EV, MIN-NOR,ROOT-MUSIC and ESPIRIT algorithms.

The simulation scenario is set up as the following: the number of target is known and smaller than the number of elements in the phase array; noise introduced into the simulation is the White Gaussian Noise; the phase array antenna is linear and the element spacing is d. Other parameters in the simulation are: SNR, number of snapshot K, and number of phase array element L.

In the simulation, there are 4 narrowband signals with the same power with the angle of arrival are -20, -10, 0 and 10 degrees, respectively. The noise in the simulation is the White Gaussian Noise.

Figure 1 shows the simulation results when $SNR = -10$dB, $K = 100$, $d = \lambda/2$. The results demonstrate the dependence of DOA estimation algorithms on the number of phase array antenna elements

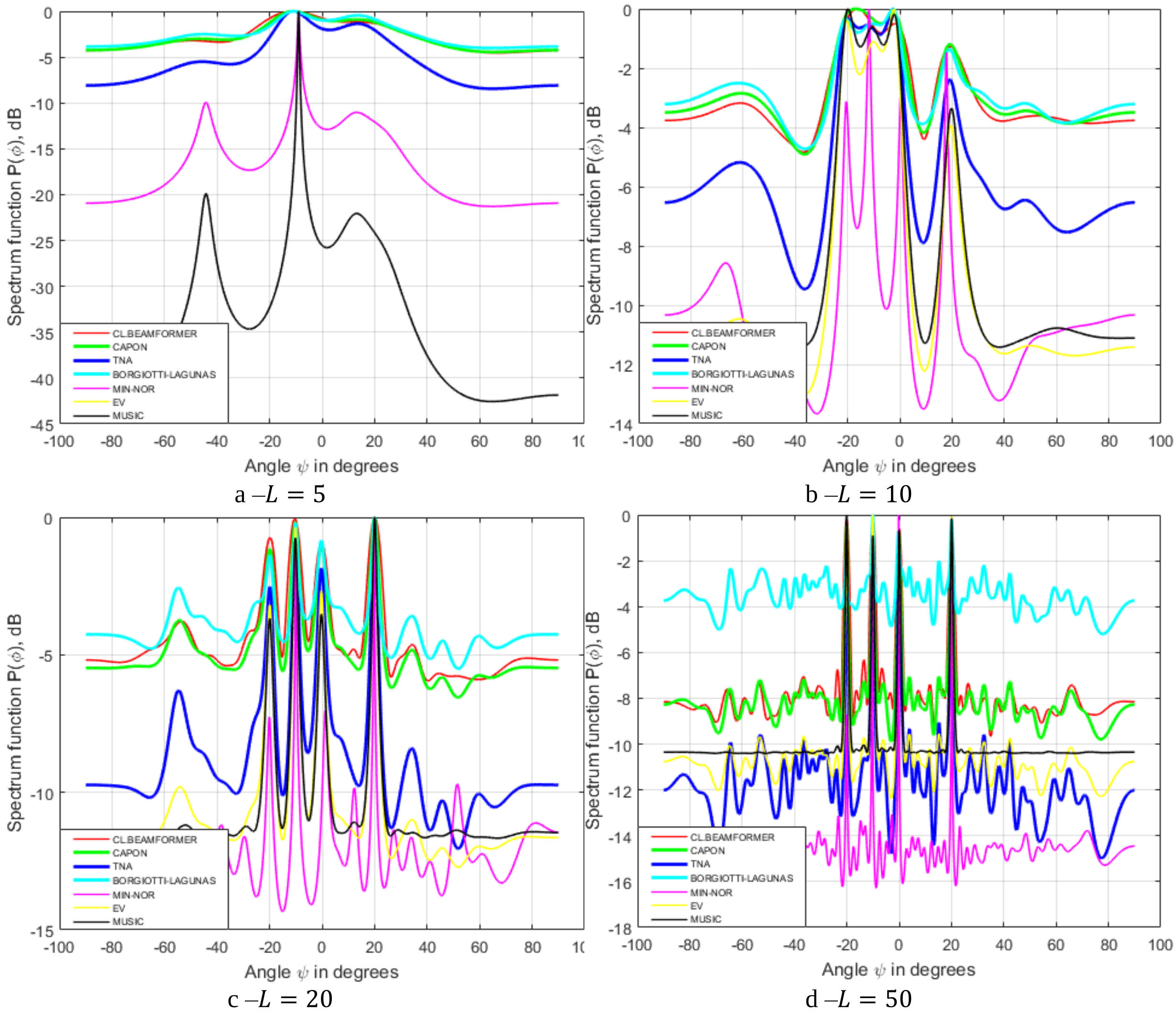


Figure 1.The dependence of DOA estimation algorithms on the number of phase array antenna elements

From the results in Figure 1, several conclusions can be drawn as follows:

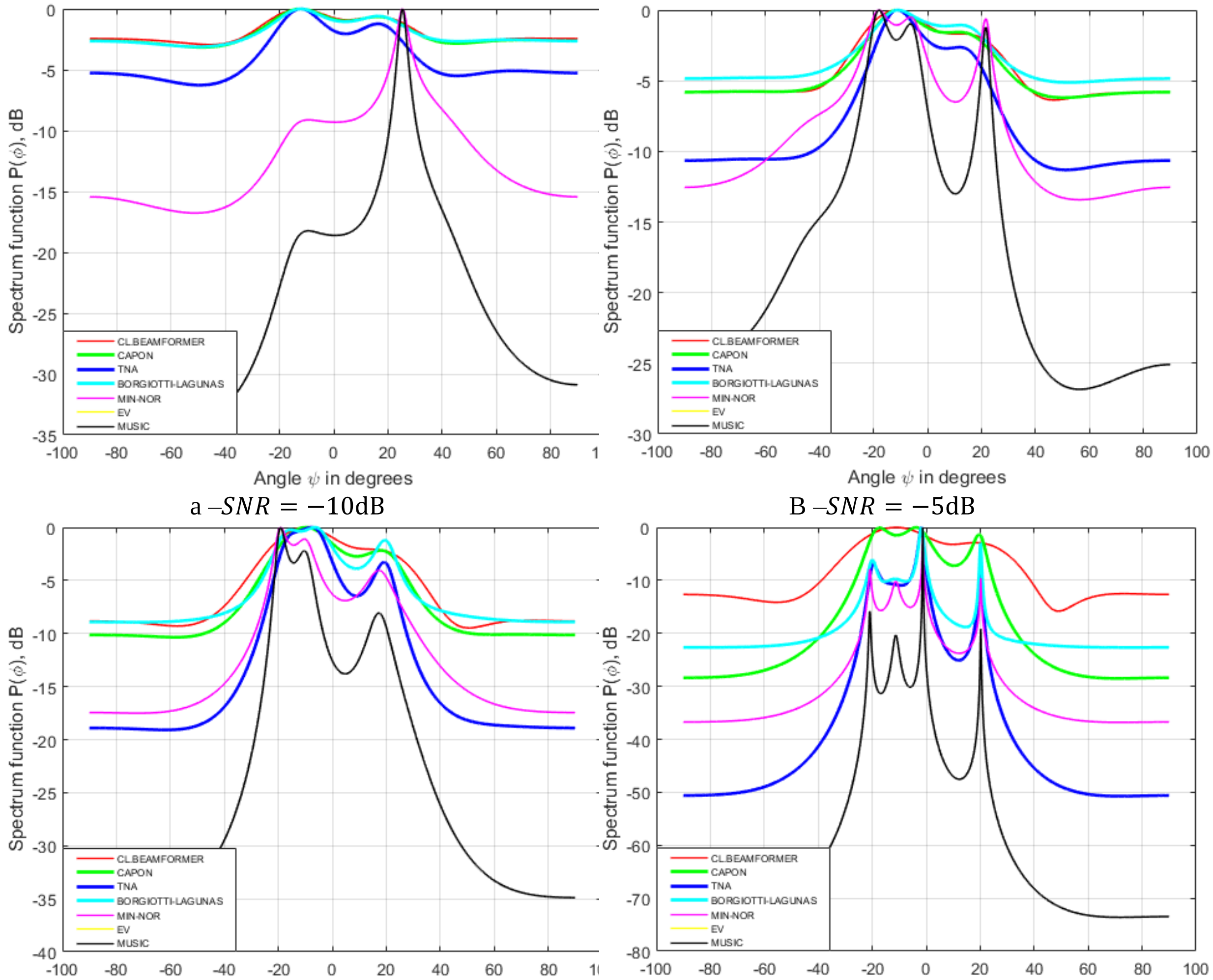
+ If the number of phase array antenna elements is small (L = 5), the accuracy of most of the algorithms is low and they can only locate up to 3 signals.

+ If the number of phase array antenna elements increases, the accuracy of all algorithms increases and all 4 signals can be locate. Among those algorithms, the ones in Group 2 produce sharper peaks in the direction of signals while produce lower spectrum in the direction of noise, making the DOA estimation more accurate.

+ Among those algorithms, the MUSIC produces the highest level of accuracy.

The relationship between DOA estimation and the SNR

Figure 2 shows the simulation results when $L = 5, K = 100, d = \lambda/2$. The results demonstrate the dependence of DOA estimation algorithms on the SNR when the number of phase array antenna elements is not high.



a –$SNR = -10$dB B –$SNR = -5$dB

c –$SNR = 0$dB d –$SNR = 20$dB

Figure 2.The dependence of DOA estimation algorithms on the SNR

From the results in Figure 2, several conclusions can be drawn as follows:

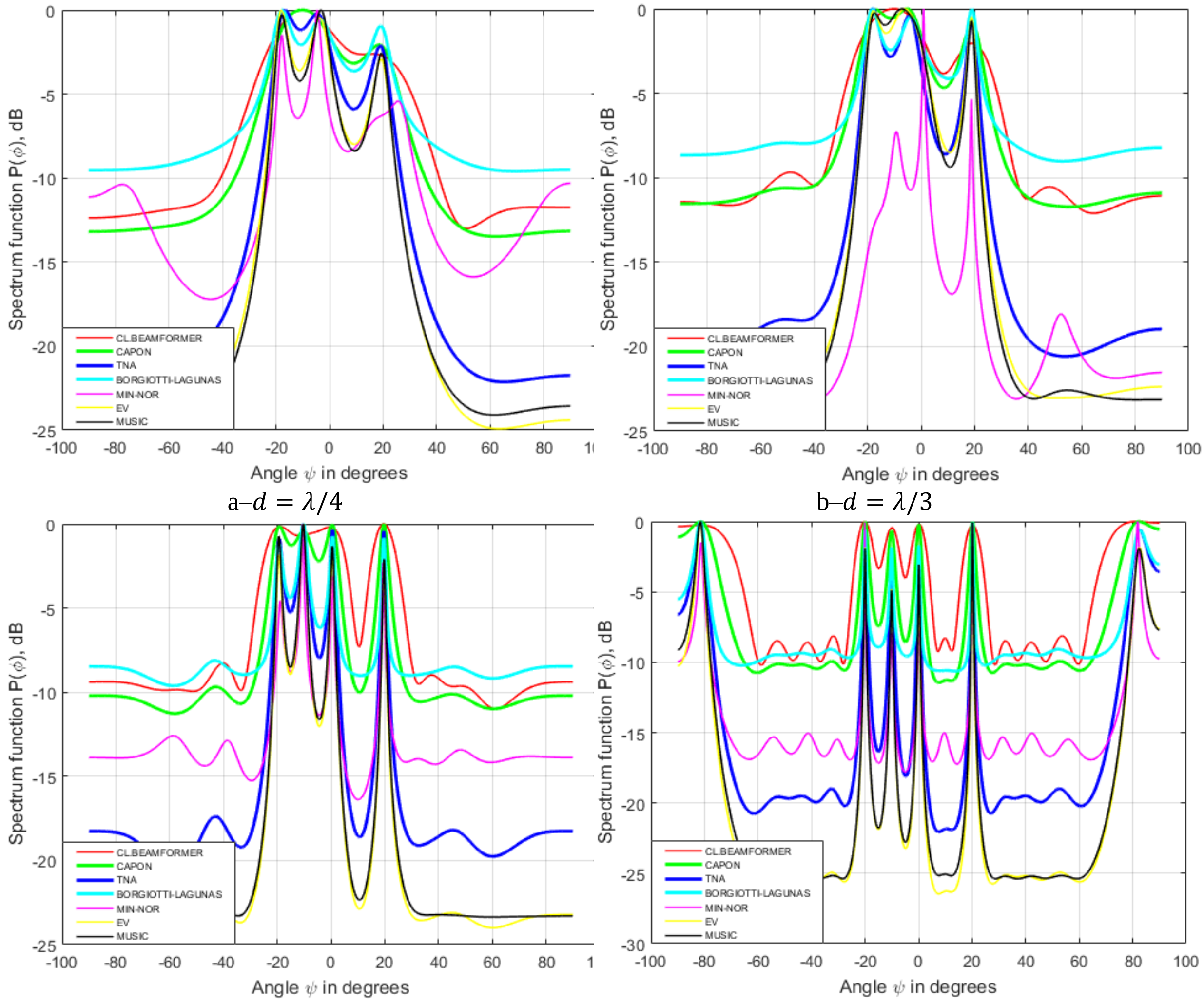
+ If other parameters remain the same, the increase in SNR will lead to the narrower peaks in the spectrum, making the DOA of the signal more clearly visible. As the result, the DOA estimation is more accurate.

+ The EV and MUSIC algorithms produce the highest level of accuracy in DOA estimation. Their performances are comparable.

+ The decrease in SNR will lead to the decrease in the performance of the algorithms. However, there is still a need to improve performance of DOA algorithms in the conditions where SNR is small, especially in sonar where such condition is common.

The relationship between DOA estimation and the array element spacing

Figure 3 shows the simulation results when $L = 10$, $K = 100$, $SNR = 0$. The results demonstrate the dependence of DOA estimation algorithms on the space between elements of the phase array antenna.



a–$d = \lambda/4$ b–$d = \lambda/3$

c–$d = \lambda/2$ d–$d = 1{,}5\lambda/2$

Figure 3.The dependence of DOA estimation algorithms on the space between elements of the phase array antenna.

From the results in Figure 3, several conclusions can be drawn as follows:

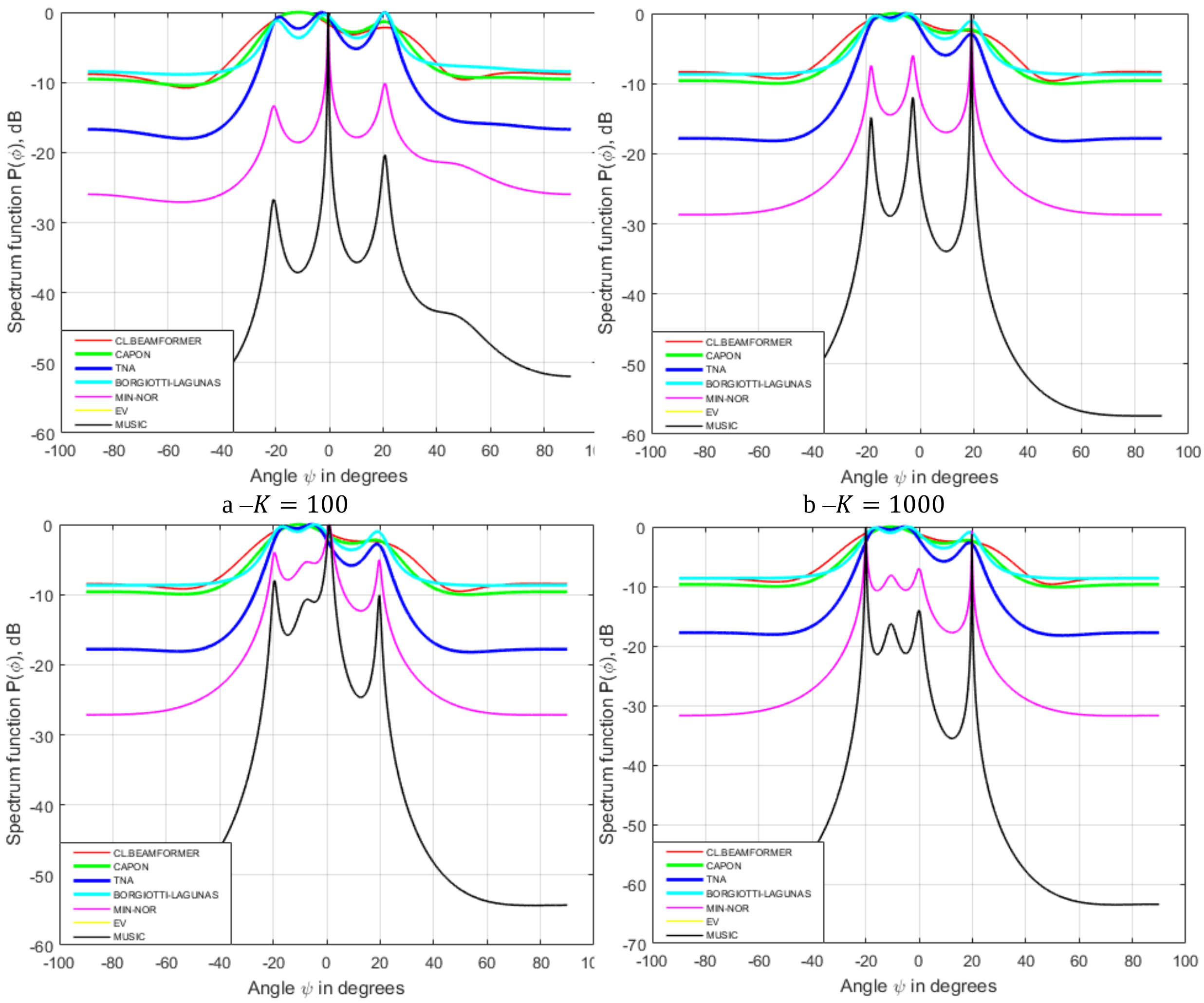
+ If other parameters remain the same and d is smaller than half of the wave length, the increase in d will lead to the narrower peaks in the spectrum, making the DOA estimation more accurate.

+ If d is greater than half of the wave length, there will be more than one solution for the DOA estimation.

+ In order to increase the accuracy in DOA estimation algorithms it is possible that we increase d, but not greater than half of the wave length. It is best practice to choose d equal to half of the wave length.

The relationship between DOA estimation and the number of snapshots

Figure 4 shows the simulation results when$SNR = 0$, $L = 5$, $d = \lambda/2$. The results demonstrate the dependence of DOA estimation algorithms on the number of snapshots



a – $K = 100$ b – $K = 1000$

c – $K = 5000$ d – $K = 10000$

Figure 4.The dependence of DOA estimation algorithms on the number of snapshots

From the results in Figure 4, several conclusions can be drawn as follows:

+ If the number of antenna components is small and SNR is low, the increase L will not bring about high performance for all the algorithms

+ All the above algorithms can estimate the DOA of all 4 signals only if K is lager enough. In this case, for example, K must be greater than 5000, if K is smaller than 5000 then the DOA of maximum 3 signals can be estimated.

It has been shown that the performances of the ROOT-MUSIC and ESPIRIT algorithms are better than other algorithms. The two algorithms, however, require extensive computation and can only be used with linear phase array antenna. In the next section, we will compare the performances of the two algorithms in the same condition.

Performances of ROOT-MUSIC and ESPIRIT algorithms

In this section, ROOT-MUSIC and ESPIRIT algorithms are simulated in the same conditions and their performances are compared. The input parameters for simulation are:$L = 10$; $K = 100$; $d = \lambda/2$ and the angle of arrival are $\theta_1 = 10$, $\theta_2 = 20$,$\theta_3 = 30$and $\theta_4 = 60$ degrees, respectively. Both algorithms are tested with SNR of 0 dB and 20 dB, simulating an unfavorable and a favorable situation. The noise introduced in the simulations is the White Gaussian Noise.

For each simulation, a set of 1000 samples is generated which is considered as statistically sufficient. For a single set of 1000 results, two variables are produced: the mean value of error (ME), and the root mean square of the error (RMSE). These variables are taken as the quality benchmark for the two algorithms.

Table 1 and 2 show the simulation results for 2 cases, SNR=0 dB and 20 dB, respectively.

Table 1

ME AND RMSE OF ROOT-MUSIC AND ESPIRIT WHEN SNR = 0 DB

$SNR = 0$dB	ROOT-MUSIC				ESPIRIT			
	$\boldsymbol{\theta_1}$,**deg**	$\boldsymbol{\theta_2}$,**deg**	$\boldsymbol{\theta_3}$,**deg**	$\boldsymbol{\theta_4}$,**deg**	$\boldsymbol{\theta_1}$,**deg**	$\boldsymbol{\theta_2}$,**deg**	$\boldsymbol{\theta_3}$,**deg**	$\boldsymbol{\theta_4}$,**deg**
ME	-0,0861	-0,0276	0,0805	0,0382	-0,1186	-0,0899	0,0635	0,1676
RMSE	0,3066	0,4422	0,3529	0,3433	0,4344	0,5205	0,4721	0,4886

Table 2

ME AND RMSE OF ROOT-MUSIC AND ESPIRIT WHEN SNR = 20 DB

$SNR = 20$dB	ROOT-MUSIC				ESPIRIT			
	θ_1,deg	θ_2,deg	θ_3,deg	θ_4,deg	θ_1,deg	θ_2,deg	θ_3,deg	θ_4,deg
ME	0,0038	0,0039	0,0029	0,0037	0,0039	0,0051	0,0065	0,0039
RMSE	0,0283	0,0434	0,0339	0,0305	0,0376	0,0491	0,0517	0,0425

From the results in Table 1 and 2, several conclusions can be drawn as follows:

+ The increase in SNR will lead to the increase in the accuracy of the DOA estimation.

+ In this condition, the ROOT-MUSIC is better than the ESPIRIT algorithm in terms of accuracy of DOA estimation**.**

Conclusion

The paper evaluates the performances of high resolution DOA estimation algorithms in sonar systems. Simulation results show several ways to increase the accuracy of the DOA estimation, including: increase the SNR, increase the space between antenna elements, or increase number of snapshot. The results also show that the algorithms in Group 2 produce better DOA estimation than those of Group 1, but algorithms in Group 3 produce the most accurate estimation. The Group 3's algorithms, however, require complicated signal processing schemes which need longer time to calculate and they can only be applied with linear and evenly spacing phase array antenna. Therefore, depending on the DOA system's requirement, the DOA estimation algorithm should be selected accordingly.

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ОСОБЕННОСТИ РАЗРАБОТКИ ИНФОРМАЦИОННОГО ПОРТАЛА РОИЗВОДСТВЕННЫХ ПРЕДПРИЯТИЙ ОБЕСПЕЧИВАЮЩЕГО ВЫСОКУЮ ИНФОРМАЦИОННУЮ БЕЗОПАСНОСТЬ

Ахмедова Хамида Гаджиалиевна
доцент, кандидат физико-математических наук,
ФГБОУ ВО «Московский государственный университет технологий управления им. К.Г. Разумовского (ПКУ)», г. Москва
Николаева Светлана Владимировна
профессор, доктор технических наук,
ФГБОУ ВО «Московский государственный университет технологий управления им. К.Г. Разумовского (ПКУ)», г. Москва

АННОТАЦИЯ

В работе рассмотрены особенности проектирования, этапы разработки и основные требования, предъявляемые к информационному порталу. Показана необходимость проведения обязательного детального исследование предприятия, поскольку допущенные на этом этапе ошибки могут привести к значительному снижению качества портала. Описаны уровни тестирования программного продукта. Описана важность обеспечения должного уровня информационной безопасности программного продукта.

ABSTRACT

The paper discusses the design features, development stages and basic requirements for the information portal. Necessity of carrying out obligatory detailed research of the enterprise as the mistakes made at this stage can lead to considerable decrease in quality of a portal is shown. The levels of software product testing are described. The importance of ensuring the proper level of information security of the software product is described.