[UCI]I804:27005-200000003704

Master's Thesis
석사 학위논문

# An IMU-based MUSIC algorithm for GPS receivers under jamming attack

Inhwan Lee(이 인 환 李 仁 煥)

Department of
Information and Communication Engineering

DGIST

2018

Master's Thesis
석사 학위논문

# An IMU-based MUSIC algorithm for GPS receivers under jamming attack

Inhwan Lee(이 인 환 李 仁 煥)

Department of
Information and Communication Engineering

DGIST

2018

# An IMU-based MUSIC algorithm for GPS receivers under jamming attack

Advisor: Professor Jihwan Choi
Co-advisor: Professor Jonghyun Kim

By

Inhwan Lee
Department of Information and Communication Engineering
DGIST

A thesis submitted to the faculty of DGIST in partial fulfillment of the requirements for the degree of Master of Science in the Department of Information and Communication Engineering. The study was conducted in accordance with Code of Research Ethics[1]

12. 29. 2017

Approved by

Professor Jihwan Choi (signature)
(Advisor)

Professor Jonghyun Kim (signature)
(Co-Advisor)

[1] Declaration of Ethical Conduct in Research: I, as a graduate student of DGIST, hereby declare that I have not committed any acts that may damage the credibility of my research. These include, but are not limited to: falsification, thesis written by someone else, distortion of research findings or plagiarism. I affirm that my thesis contains honest conclusions based on my own careful research under the guidance of my thesis advisor.

# An IMU-based MUSIC algorithm for GPS receivers under jamming attack

Inhwan Lee

Accepted in partial fulfillment of the requirements for the degree of Master of Science.

11. 23. 2017

| | |
|---|---|
| Head of Committee | ______________(signature)___ |
| | Prof. Jihwan Choi |
| Committee Member | ______________(signature)___ |
| | Prof. Jonghyun Kim |
| Committee Member | ______________(signature)___ |
| | Prof. Kyungjoon Park |

MS/IC
201622016

이 인 환. Inhwan Lee. Thesis Title. Department of Information and Communication Engineering. 2018. 22p. Advisors Prof. Jihwan Choi, Co-Advisors Prof. Jonghyun Kim

ABSTRACT

UAV navigation system using Global Positioning System (GPS) is very vulnerable due to malicious attacks such as jamming and spoofing. The GPS receiver receives the electromagnetic waves from more than 24 satellites outside the atmosphere and determines its position. However, since GPS signals are received from satellites 20,000 kilometers away, the power of the signal is very weak.

One of the most effective way to eliminate malicious interference signals is to use an array antenna in GPS receiver. Capon and Multiple Signal Classification (MUSIC) algorithms are commonly used to estimate the direction of the incident signal, i.e., direction of arrival (DOA) estimation algorithm. The MUSIC algorithm is superior to the DOA estimation, but resolution between the desired signal and adjacent signals is low and the computational complexity is high. Therefore, in this paper, we can localize the candidate angle of the MUSIC algorithm by using the angular velocity and acceleration measurement of the inertial measurement unit (IMU), and accurately estimate the DOA and reduce the complexity.

Keywords: GPS, navigation, MUSIC algorithm, DOA estimation, UAV, IMU

Abstract ············ i
List of contents ············ ii
List of figures ············ iii

I. Introduction ············ 1
1.1 Motivation ············ 1
1.2 Objective of the thesis ············ 2

II. Background ············ 4
2.1 Global positioning system ············ 4
2.2 Array antenna ············ 5
2.2.1 Uniform linear array antenna (ULA) ············ 5
2.2.2 Uniform circular array antenna (UCA) ············ 5
2.3 MUSIC algorithm ············ 7

III. Problem of MUSIC ············ 10
3.1 Limitation of MUSIC ············ 10
3.2 Complexity of MUSIC ············ 10
3.3 Vulnerability to Jamming ············ 11

IV. Solution and Result ············ 15

V. Conclusion ············ 19

References ············ 20

# List of Figures

Fig. 1: Vulnerability of GPS receiver and its frequency. ······ 3

Fig. 2: Geometric arrangement for 6 receivers. ······ 6

Fig. 3: Geometric arrangement for 10 receivers. ······ 7

Fig. 4: spatial spectrum where each signal is correctly separated. ······ 11

Fig. 5: Distorted spatial spectrum by jamming signal. ······ 12

Fig. 6: spatial spectrum where each signal is correctly separated. ······ 12

Fig. 7: Distorted spatial spectrum by jamming signal. ······ 13

Fig. 8: The contour of the spatial spectrum and the actual DOA of the received signal. ······ 13

Fig. 9: The contour of the spatial spectrum and the actual DOA of the received signal and the jamming signal. ······ 14

Fig. 10: The proposed MUSIC algorithm reduces the search candidate angle. ······ 15

Fig. 11: RMSE of the average error of the pure MUSIC algorithm and proposed algorithm according to JSR ······ 17

Fig. 12: RMSE for the number of antennas at JSR 30dB ······ 17

Fig. 13: Spatial spectrum of GPS receiver after moving ······ 18

# List of table

Table 1: The number of candidate angles required to classify the signals ········································ 16

# I. INTRODUCTION

## 1.1 Motivation

The information technology of the military is rapidly progressing for efficient operation of next generation electric equipment and attack and defense of information technology. Especially, next generation UAV technology for the development of air force is becoming more important for realization of real time location positioning technology. GPS jamming and disturbance signal countermeasure technology is required because misleading location information caused by GPS jamming and disturbance attack may lead to collision of aircraft or disabling location based equipment, which may also cause huge national loss. Therefore, the introduction of improved interference cancellation technology is necessary for the smooth development of the next generation navigation system. Since the UAV's GPS receiver is vulnerable to noise and interference, we aimed to eliminate the interference of the receiver by using an array antenna to eliminate the interference.

Unmanned aerial vehicles (UAVs), referred to as drone or remotely piloted aircraft (RPA), are manipulated remotely without the aid of a pilot on board. Initially developed for military use, it has been extended to civilian applications [1]. Drones are not only used for hobby and recreational activities, but also for commercial use. As the commercialization of UAVs has been activated in recent years, the market size of domestic UAVs is increasing. It can be used in various fields such as aerial photographing, precision agriculture, remote monitoring, and delivery. Already, global companies like Google, Facebook and Amazon are already investing heavily in drones.

Global positioning systems (GPSs) are mainly used in UAVs, and GPSs are usually used with inertial measurement unit (IMUs) because GPS is vulnerable to noise and interference [2]. If the interference of GPS receivers can be eliminated, the performance of navigation can be improved and UAV integrated control is possible. An array antenna is a suitable candidate for the interference cancellation of the GPS receiver, and the interference of the receiver can be effectively eliminated by using the antenna array processing technique. And the null steering and beam forming technique can control the propagation direction [3]. Therefore, we try to remove the interference from the array antenna to receive the GPS signal.

## 1.2 Objective of the thesis

GPS receiver is very vulnerable to malicious attacks such as jamming and spoofing [4]. One of the most effective way to eliminate malicious interference signals is to use an array antenna in GPS receiver. Capon [5] and Multiple Signal Classification (MUSIC) [6] algorithms are commonly used to estimate the angle of incidence of the signal, i.e., It is direction of arrival (DOA) estimation algorithm. The MUSIC algorithm is superior to the DOA estimation, but resolving power of between desired signal and adjacent signals is low and the calculation amount is large. Therefore, using with the angular velocity and acceleration measurement values of the IMU of the UAV can be expected to accurately estimate the DOA and decrease the complexity. In this paper, we analyze the effect of jamming signal through DOA estimation algorithm in a GPS receiver array antenna under simulated environment. Figure 1 shows a graphical representation of the vulnerability of GPS receivers. GPS receivers are highly susceptible to environmental influences such as weather effects and are easily exposed to jamming effects. Also, it is less frequent than the above two factors but spoofing attack is very vulnerable and fatal because it is possible to be intercepted by spoofer [7].

Also, the amount of computation becomes a problem when using the MUSIC algorithm. Therefore, in this paper, we propose a method to localize candidate angles using measured values of IMU sensor.

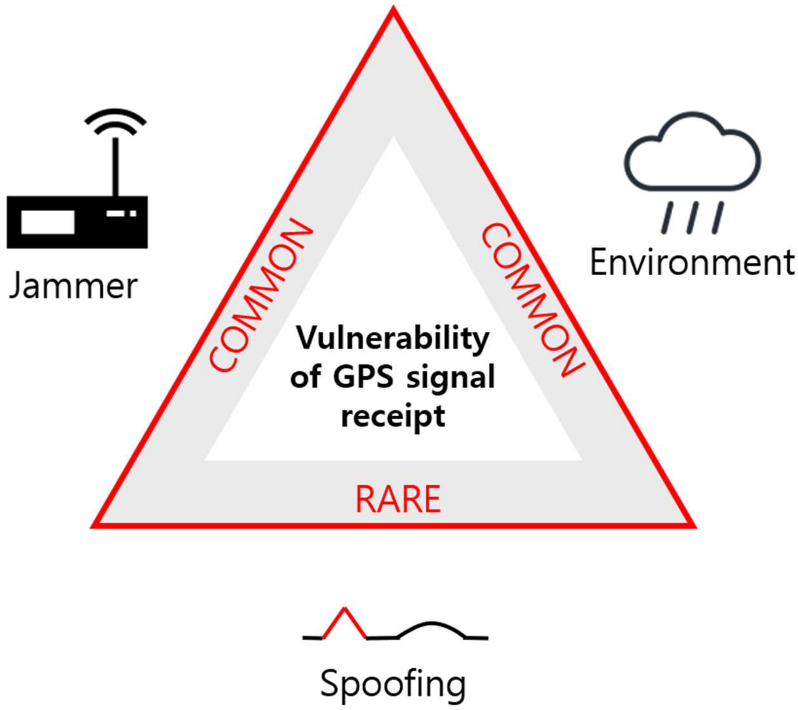


**Figure 1. Vulnerability of gps receiver and its frequency**

# II. BACKGROUND

## 2.1 Global positioning system

Global positioning system (GPS) is satellite-based navigation system operated by the United States for military purposes. But later it was allowed for civilian use. The GPS receiver receives the electromagnetic wave from more than 24 satellites outside the atmosphere and determines position by measuring time difference between receipt of signals. However, since GPS signals transmitted from satellite over 20,000 km away, the power is very weak [8], [9].

In order to determine the three dimensional position of the receiver $\mathrm{P_r(x_r, y_r, z_r)}$ three satellites are needed, and one satellite is needed to compensate for time offset because receiver clock has a bias error. Since the signal propagates at the speed of light, $c$, from the satellite, the distance to the satellite can be measured by sending time information. This measure is called a pseudo-range $\rho$. When the actual distance is $d$, and satellite system time is $t^s$, receiver system is $t = t^s + \delta$, pseudorange as follows.

$$\rho = d + c \cdot \delta. \tag{1}$$

Therefore, assuming that there are four satellites, where $j$ ranges from 1 to 4 and references the satellites. the location of the GPS receiver can be expressed as:

$$\rho_1 = \sqrt{(x_1 - x_r)^2 + (y_1 - y_r)^2 + (z_1 - z_r)^2} + c \cdot \delta \tag{2}$$

$$\rho_2 = \sqrt{(x_2 - x_r)^2 + (y_2 - y_r)^2 + (z_2 - z_r)^2} + c \cdot \delta \tag{3}$$

$$\rho_3 = \sqrt{(x_3 - x_r)^2 + (y_3 - y_r)^2 + (z_3 - z_r)^2} + c \cdot \delta \tag{4}$$

$$\rho_4 = \sqrt{(x_4 - x_r)^2 + (y_4 - y_r)^2 + (z_4 - z_r)^2} + c \cdot \delta \tag{5}$$

Where $x_j, y_j,$ and $z_j$ denote the $j$the satellite's position in three dimensions. The set of equations can be solved for the unknown $x_j, y_j, z_j$ and $\delta$ by numerical method such as a least-mean-square approach or Newton's method [4], [9].

## 2.2 Array antenna

### 2.2.1 Uniform linear array antenna (ULA)

The uniform linear array (ULA) antennas have an array structure arranged at equal intervals on a straight line. It has one of the simplest and regular geometrical structure and therefore has several advantages. ULA can apply algorithms such as Minimum-Norm and Root-MUSIC [10] that can estimate the incident angle of arrival with very few calculations without searching for the spatial spectrum formed by the incident signal. Since the antenna elements are arranged at regular intervals The spatial covariance matrix of the array antenna output has a form of diagonal-constant matrix, so that the covariance matrix can be more accurately estimated. However, the ULA antennas cannot estimate both the azimuth angle and the elevation angle.

The steering vector of the array antenna is determined according to the array structure of the antennas. Assuming the number of $k$ identical ULA antennas, When the narrowband signal is incident on the $\theta$ direction, $i$ th antenna has a phase delay of $2\pi d(i-1)\cos\theta/\lambda$. The steering vector $\mathrm{a}(\theta)$ is expressed as equation (6).

$$\mathrm{a}(\theta) = \begin{bmatrix}1 & \mathrm{e}^{-j\boldsymbol{\kappa}d\cos\theta} \cdots & \mathrm{e}^{-j(i-1)\boldsymbol{\kappa}d\cos\theta}\end{bmatrix}^{\mathrm{T}}. \tag{6}$$

where $i = 1, 2, \ldots k$ and $d$ is the antenna spacing and $\boldsymbol{\kappa}$ is the wave number of the signal, where $\boldsymbol{\kappa} = 2\pi/\lambda$.

### 2.2.2 Uniform circular array antenna (UCA)

The uniform circular array (UCA) antenna is known to have superior beamforming capabilities over other antenna array structures [11]. The UCA places the antenna uniformly at the same distance with respect to the zero point. Assuming $k$ antennas, in order to fix the distance $d$ between the antennas, the radius $r$ is defined as follows eqation (7).

$$r = \frac{d/2}{\sin(\pi/k)} . \tag{7}$$

The location of the antenna in the plane can be written as equations (8) and (9).

$$r_{x,n} = r \ \cos\frac{2\pi(n-1)}{k} \ , \qquad n = 1, 2, \ldots \ k \tag{8}$$

$$r_{y,n} = r \ \sin\frac{2\pi(n-1)}{k}, \qquad n = 1, 2, \ldots \ k \tag{9}$$

Where $r_{x,n}$ is the x coordinate of the $n$th receiver and $r_{y,n}$ is the y coordinate of the $n$th receiver. If d = 1 and the number of antennas is set to 6 and 10, the arrangement is as shown in Fig. 2 and Fig. 3.

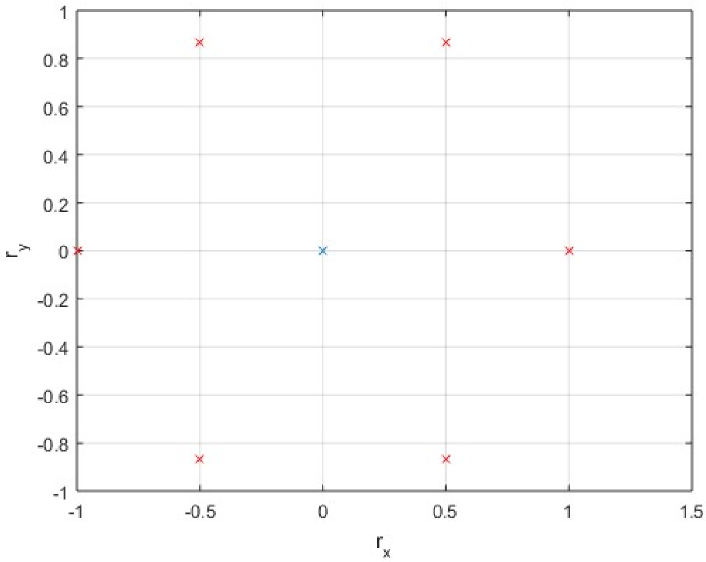


**Figure 2. Geometric arrangement for 6 receivers.**

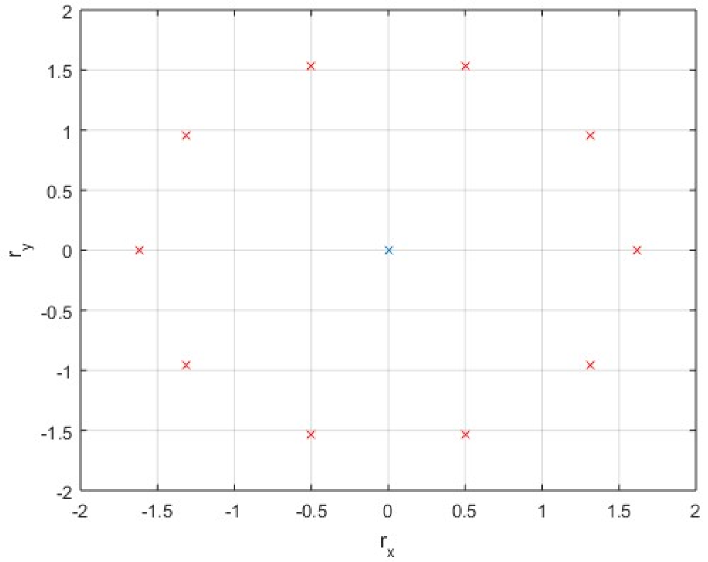


**Figure 3. Geometric arrangement for 10 receivers.**

When the narrowband signal is incident on the elevation $\theta$ and azimuth $\phi$ direction, wave number $\boldsymbol{\kappa}$ is expressed by equation (10) and the position coordinates of the antenna are expressed by the matrix of Equation (11).

$$\boldsymbol{\kappa} = \begin{bmatrix} \cos\phi_1 \cos\theta_1 & \cdots & \cos\phi_l \cos\theta_l \\ \sin\phi_1 \cos\theta_1 & \ddots & \sin\phi_l \cos\theta_l \\ \sin\theta_1 & \cdots & \sin\theta_l \end{bmatrix}. \tag{10}$$

$$R = [r_x,\, r_y,\, \mathbf{1}] \qquad r_x \in \mathbb{R}^k,\, r_y \in \mathbb{R}^k. \tag{11}$$

Then, the steering matrix can be expressed by Equation (12).

$$A = e^{-jRC} \in \mathbb{R}^{k \times l} \ . \tag{12}$$

## 2.3 MUSIC algorithm

In multiple antenna system, direction of arrival (DOA) estimation technique is used to avoid jamming signal. The purpose of DOA estimation is jammer nulling and beamforming. The various DOA estimation algorithms are Bartlett and Capon, Multiple signal classification (MUSIC) algorithm. These algorithms are spatial spectrum method. Especially, MUSIC algorithm is high resolution estimation algorithm and better than classical Bartlett and Capon DOA estimation algorithm. However, MUSIC has a weakness of substantial computation. To reduce the computational complexity uses a root-MUSIC, but there is a restriction that it can be used only in a uniform linear array (ULA).

The MUSIC algorithm is used to separate multiple signals. Signal separation is performed using the property that the signal subspaces and the noise subspaces are orthogonal.

All the subspace based methods are based on the eigenvector decomposition of the covariance matrix. The input signal at the receiver can be expressed as equation (13).

$$X(t) = As(t) + N(t). \tag{13}$$

Where $A$ is the steering matrix, $s(t)$ is the signal waveform, and $N(t)$ is the additive noise. Then, the covariance matrix of the input signal is expressed by equation (14).

$$R_{xx} \cong E[X(t)X^H(t)]. \tag{14}$$

The eigenvalue decomposition of the covariance matrix of the signal is shown in equation (15).

$$R_{xx}e_i = e_i\lambda_i \ (i = 1,2,\dots,k). \tag{15}$$

Where $e_i$ is eigenvector and $\lambda_i$ is eigenvalue. In the MUSIC algorithm, the number of antennas must be greater than the number of signals in order to classify the signal. Since the signal eigenvalue is generally larger than the noise eigenvalue, it can be written as equation (16). This property can be used to separate the signal and noise.

$$\lambda_1 \geq \lambda_2 \geq \ \dots \ \geq \lambda_l \ \geq \lambda_{l+1} = \ \lambda_{l+2} = \cdots = \lambda_k. \tag{16}$$

Thus, the first one is the eigenvalue of the signal and the remaining k-l are the eigenvalues of the noise. Therefore the previous number of $l$ is the signal eigenvectors and the remaining number of $(\mathrm{k} - l)$ is the noise eigenvector. The noise vector can be written as equation (17).

$$\mathrm{V_n} = [\mathrm{e_{l+1}} \dots \mathrm{e_k}] \in \ \mathbb{R}^{\mathrm{k \times (k-l)}}. \tag{17}$$

Since the signal's DOA is not known in the receiver, all candidate angles are input to the steering vector and expressed as in Eq. (18).

$$a^H(\theta, \phi) V_n V_n^H a(\theta, \phi). \tag{18}$$

Since subspace of the received signal and the noise are independent of each other, equation (18) has a value of zero when the candidate angle is equal to the actual angle. We can write the inverse of equation (18), apply the normalization, and write the spatial spectrum function of the MUSIC algorithm as shown in Eq. (19).

$$P_{music}(\theta,\ \phi) = \frac{a^H(\theta,\phi)\, a(\theta,\phi)}{a^H(\theta,\phi) V_n V_n^H a(\theta,\phi)}. \tag{19}$$

# III. Problem of MUSIC

## 3.1 Limitation of MUSIC

The MUSIC algorithm is used to separate multiple received signals. This is suitable for separating legitimate received signals from malicious attack signals (e.g., jamming signals, spoofing signals). The MUSIC algorithm performs eigenvalue decomposition of the covariance matrix of the received signal to signal subspace matrices and some noise subspace matrices. Then, signal separation is performed using the property that the signal subspace and the noise subspace are orthogonal. However, when jamming and spoofing attacks are performed, the signal components are not independent and their resolution is degraded.

## 3.2 Complexity of MUSIC

The MUSIC algorithm estimates the signal's DOA using the property that the eigenvectors of the noise subspace and the steering vectors are orthogonal to each other. Therefore, the MUSIC algorithm necessarily compares the steering vector for all candidate angles with the eigenvector of the noise subspace. Especially, in the MUSIC algorithm of UCA antenna considering both the azimuth and elevation angles, a very large amount of computation is required. The steering vector for the candidate angle is shown in equation (20).

$$a(\phi_n, \theta_n) = e^{-jR\boldsymbol{\kappa}(\phi_n, \theta_n)}. \tag{20}$$

Therefore, in order to estimate the DOA of the signal, all the candidate angles should be substituted into equation (21) to compare their sizes. For precise angle comparisons, the number of candidate angles to be assigned is enormously increased.

$$a(\phi_n, \theta_n)^H V_n V_n^H a(\phi_n, \theta_n). \tag{20}$$

## 3.3 Vulnerability to Jamming

The MUSIC algorithm estimates a large eigenvalue as the eigenvalue of the signal by eigenvalue decomposition of the input covariance matrix of the signal. However, since the magnitude of eigenvalues of a malicious signal cannot be compared with the magnitude of the eigenvalues of a desired signal, the MUSIC algorithm cannot estimate correctly. Figure 4 shows that the signal is spatially separated by the MUSIC algorithm when the signal is incident at the azimuth angles of -40, -10, 10, 24, and 50 in the ULA. And figure 5 shows that if jamming signal is mixed in environment like figure 4, it cannot make a correct estimation.

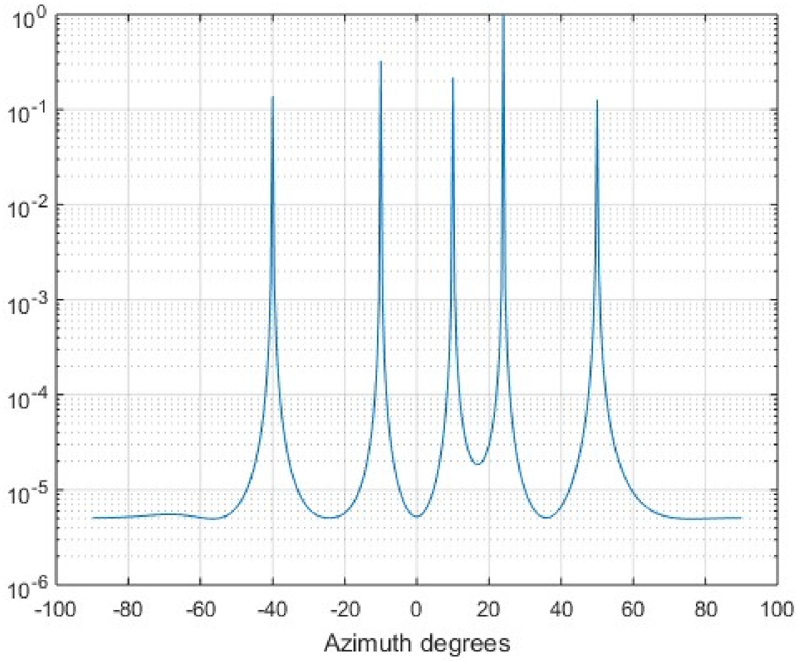


**Figure 4. spatial spectrum where each signal is correctly separated.**

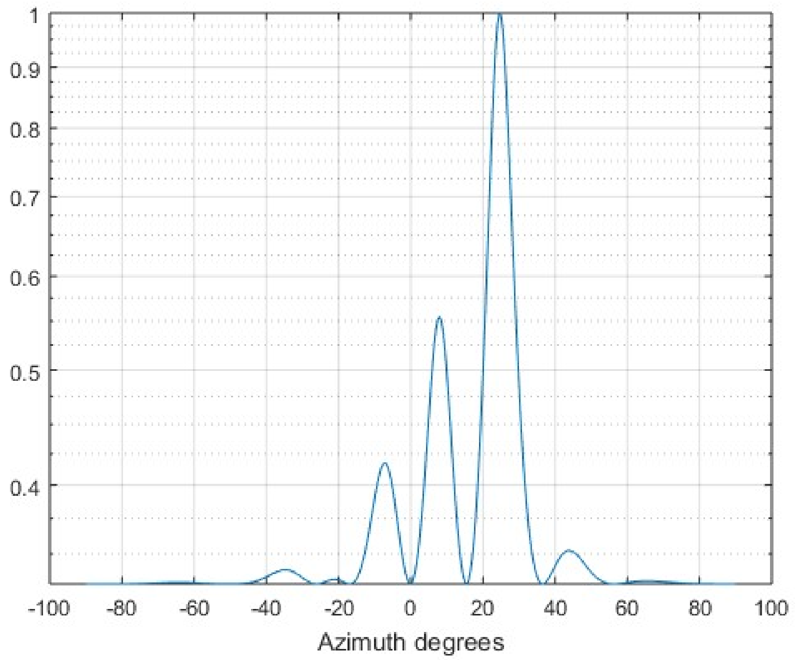


**Figure 5. Distorted spatial spectrum by jamming signal.**

Similarly, Figure 6 shows a spatial spectrum in which the received signal is properly separated from the azimuth and elevation angles. And figure 7 is distorted by the jamming effect. It just does not seem like a difference, figure 8 and figure 9 show the location of the actual GPS signals and jammers.

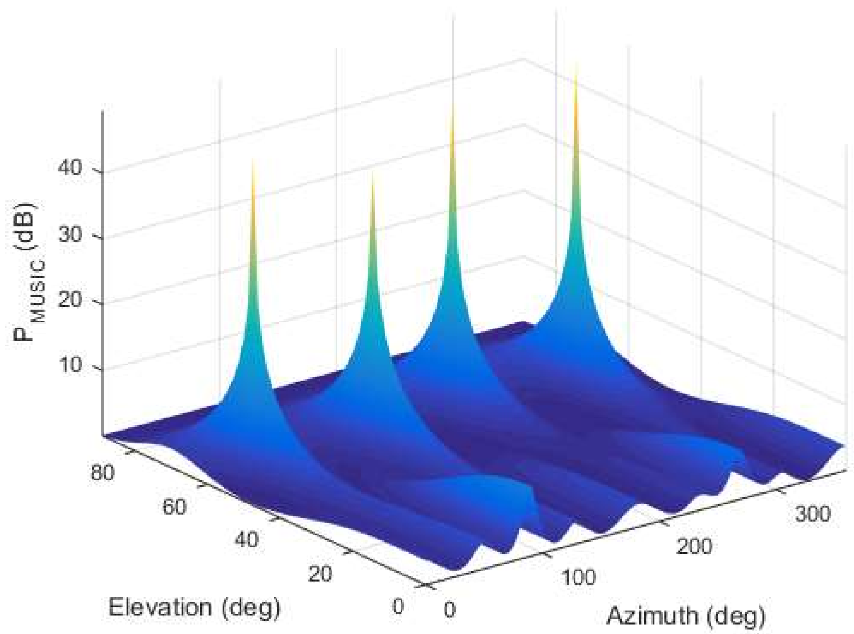


**Figure 6. spatial spectrum where each signal is correctly separated.**

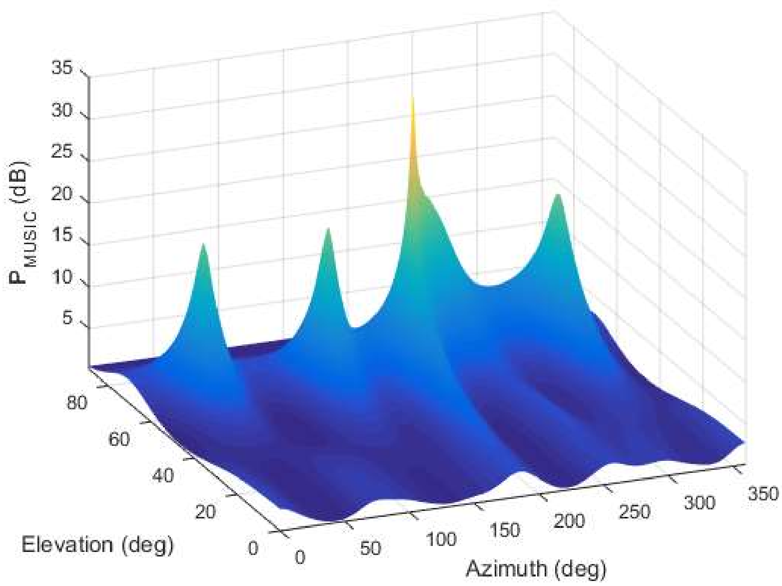


**Figure 7. Distorted spatial spectrum by jamming signal.**

In figures 8 and 9, The red star is the location of the actual GPS, and in figure 9 the blue triangle is the location of the jammer. And the rest are contour lines of the spatial spectrum. The maximum value of the spatial spectrum is the incident angle of the received signal estimated by the MUSIC algorithm.

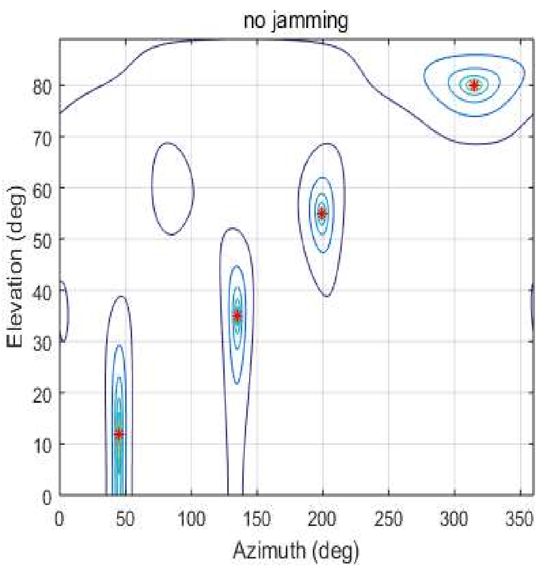


**Figure 8. The contour of the spatial spectrum and the actual DOA of the received signal (red star).**

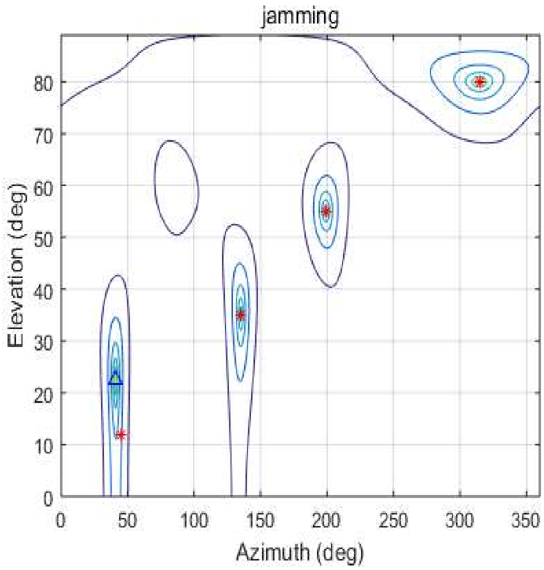


**Figure 9. The contour of the spatial spectrum and the actual DOA of the received signal (red star) and the jamming signal (blue triangle).**

# IV. Solution and Result

In the MUSIC algorithm, the amount of computation caused by the comparison between the eigenvectors and the steering vectors can be reduced by a simple method. By measuring the angular velocity and velocity of inertial sensor of UAV, it is also possible to predict the amount of change of DOA. Therefore, if the satellite signal is received correctly at first, then the DOA can be corrected through the velocity and angular velocity rate of change.

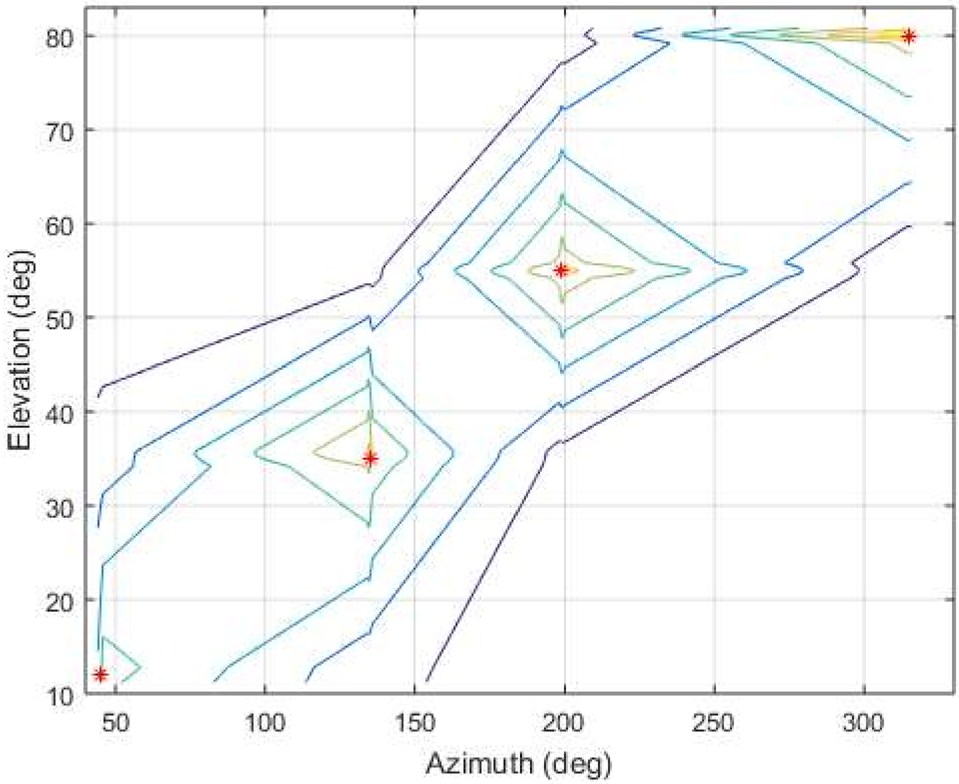


**Figure 10. The proposed MUSIC algorithm reduces the search candidate angle.**

The conventional MUSIC algorithm should compare 360 × 90 × 1/0.2 = 162,000 candidate angles using azimuth 360°, elevation angle 90° and 0.2° resolution. However, if localization is possible through the inertial sensor, it is only necessary to search around the measured value. If 4 candidate angles are set and the azimuth and elevation angle is 3 degrees with a resolution of 0.2 degrees, we can search the total candidate angles of 3 * 3 * 5 * 4 = 180, It is 1/900 of the search area of conventional

MUSIC. The spatial spectrum of the proposed algorithm is shown in figure 10. Table 1 shows the number of candidate angles required to classify the signals.

**Table 1. The number of candidate angles required to classify the signals.**

| | Range (deg) | | Resolution (deg) | The number of candidate angles |
|---|---|---|---|---|
| | azimuth | elevation | | |
| MUSIC | 360 | 90 | 0.2 | 162,000 |
| Proposed | 3 per peak | 3 per peak | 0.2 | 180 |

Also, the influence of jamming causes the spatial spectrum to be distorted and the accuracy to degrade. Also, the influence of jamming causes the spatial spectrum to be distorted and the accuracy to degrade. Localization yields more accurate results in a distorted spatial spectrum. Figure 11 shows the result of simulating jamming signal around GPS signal as shown in Fig. 9, and calculating RMSE of average angle error by performing JSR 100 times every 0.5dB from -20dB to 30dB. When the JSR is low, it is similar to the existing MUSIC algorithm, but when the jamming signal is added, it shows a big gap.

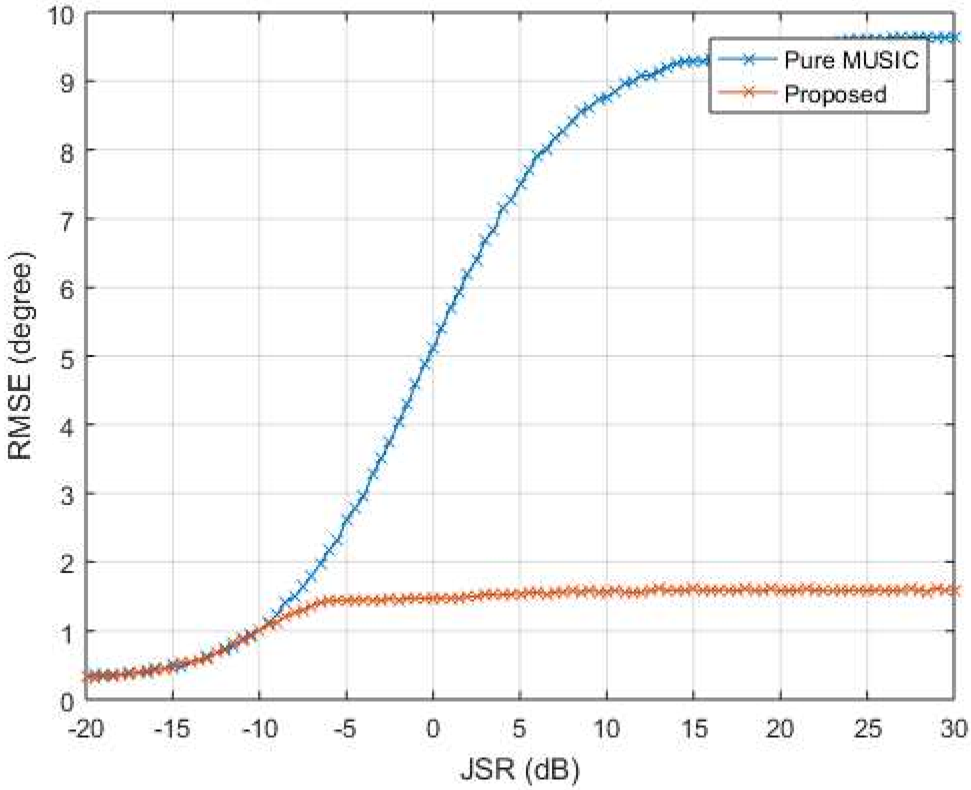


**Figure 11. RMSE of the average error of the pure MUSIC algorithm and proposed algorithm according to JSR.**

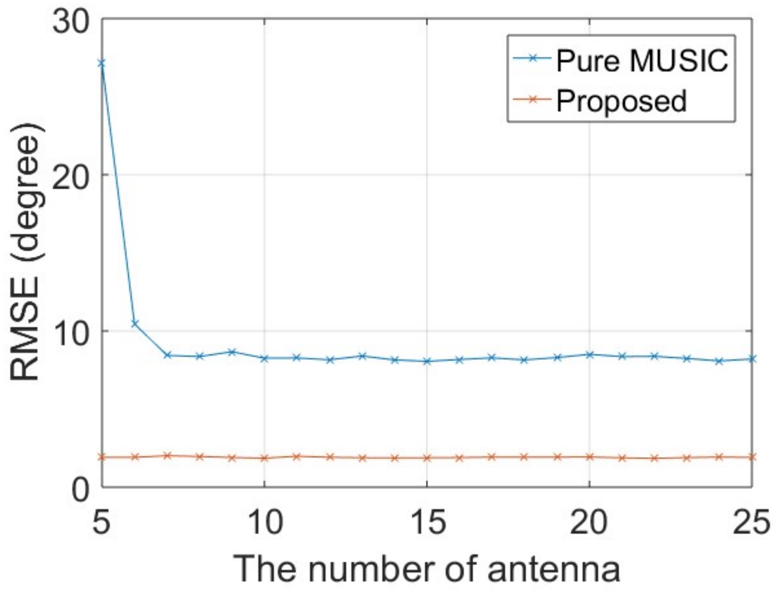


**Figure 12. RMSE for the number of antennas at JSR 30dB.**

Figure 12 shows the RMSE for the number of antennas. At least five antennas are required because an interference signal is added to the four satellite signals. In the conventional MUSIC algorithm, the smaller the number of antennas, the larger the RMSE. However, the proposed algorithm has no difference in RMSE for the number of antennas.

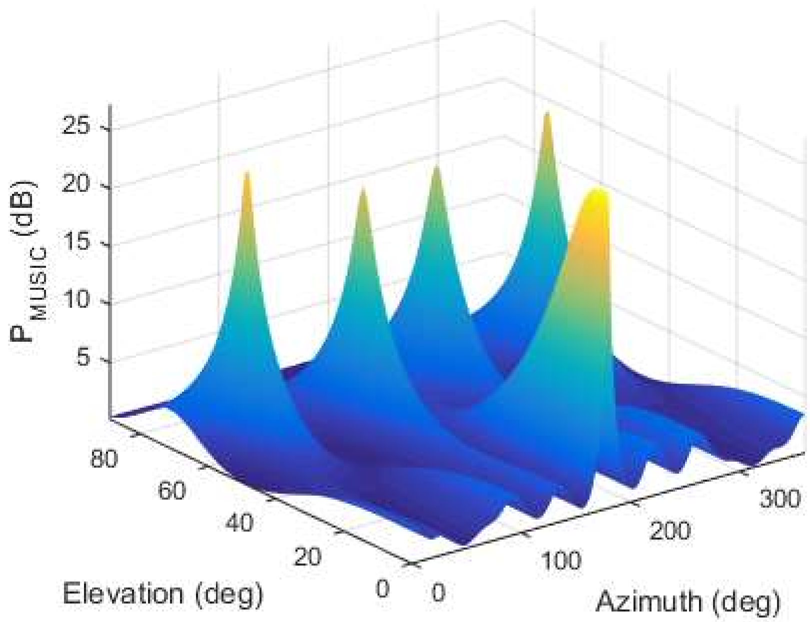


**Figure 13. Spatial spectrum of GPS receiver after moving.**

When the UAV is moving, the distance of the GPS satellite is relatively long, so the change in the angle of arrival is small. On the other hand, the distance of the radio interference signal is close to the distance of the jammer, and the DOA change is large. Using the conventional MUSIC algorithm, all five signals are determined by the receiving angle of the signal, but the jammer signal can be excluded when localized through the proposed algorithm.

# V. Conclusion

In this paper, we evaluate the performance of the proposed algorithm using MUSIC algorithm, which is one of DOA estimation techniques. It is very difficult to estimate the DOA when a jamming attack is applied to the GPS receiver antenna. We can estimate the DOA from the measured values of the IMU sensor, set the candidate angle based on the estimated angle, and calculate DOA. Simulation results show that the proposed algorithm shows lower error than the conventional MUSIC algorithm and the amount of calculations also decreased.

Using conventional MUSIC algorithms, it is difficult to distinguish signals when the number of antennas is small. Therefore, if the number of antennas is small, the RMSE of the conventional MUSIC algorithm becomes large. However, it can be seen that the proposed algorithm works well with low number of antennas.

In conclusion, the reduction of the calculation amount means that the resolution of the MUSIC algorithm can be increased and the adjacent signals can be better separated. Therefore, it can be seen that, in the UAV using IMU sensor and GPS together, the proposed algorithm can be expected to improve the interference signal separation performance.

# References

[1] Watts, A. C., Vincent G. A., and Everett A. H. "Unmanned aircraft systems in remote sensing and scientific research: Classification and considerations of use." *Remote Sensing,* 4(6), 2012, pp. 1671-1692.

[2] Noureldin, Aboelmagd, et al. "Performance enhancement of MEMS-based INS/GPS integration for low-cost navigation applications." *IEEE Transactions on Vehicular Technology,* 58(3), 2009, pp. 1077-1096.

[3] Sahmoudi, M., and M. G. Amin. "Unitary cyclic MUSIC for direction finding in GPS receivers." *Sensor Array and Multichannel Processing, 2006. Fourth IEEE Workshop on,* IEEE, 2006, pp. 70-73.

[4] Tippenhauer, N. O, et al. "On the requirements for successful GPS spoofing attacks." *Proceedings of the 18th ACM conference on Computer and communications security,* ACM, 2011, pp. 75-86.

[5] Capon, J. "High-resolution frequency-wavenumber spectrum analysis." *Proceedings of the IEEE*, 57(8), 1969, pp. 1408-1418.

[6] Schmidt, R. "Multiple emitter location and signal parameter estimation*." IEEE transactions on antennas and propagation*, 34(3), 1986, pp. 276-280.

[7] Kerns, A. J., et al. "Unmanned aircraft capture and control via GPS spoofing." *Journal of Field Robotics,* 31(4), 2014, pp. 617-636.

[8]Kaplan, E., Christopher H. *Understanding GPS: principles and applications*, Artech house, 2005, 3 pages.

[9] Schüler, Torben. *On ground-based GPS tropospheric delay estimation,* Univ. der Bundeswehr München, 2001.

[10] Rao, B. D., and Hari, K. S.. "Performance analysis of root-MUSIC." *IEEE Transactions on Acoustics, Speech, and Signal Processing,* 37(12), 1989, pp. 1939-1949.

[11] Ioannides, P., and Balanis, C. A. "Uniform circular arrays for smart antennas." *IEEE Antennas and propagation magazine,* 47(4), 2005, pp. 192-206.

# 요 약 문

## MUSIC 알고리즘을 사용한 GPS 수신기에서의 재밍 영향

무인기 (UAV)에서 항법을 위해 주로 사용되는 GPS 는 날씨 환경의 영향과 재밍 또는 스푸핑의 영향에 매우 취약하다. 또한 GPS 스푸핑을 통해 무인기의 위치를 속여서 탈취가 가능하다고 알려져 있으며, 실제로 미국 무인기가 이란의 스푸핑 공격에 의해 탈취되는 사건이 일어나기도 하였다. 그리하여, 본 논문은 무인기 GPS 수신기의 간섭 영향을 알아보기 위해 배열 안테나(array antenna)를 이용해 재밍의 영향을 알아보고 대응 하고자 하였다.

본 논문에서는 4 개의 GPS 신호와 재밍 신호를 분리하기 위해 Multiple Signal classification (MUSIC) 알고리즘을 사용하였다. MUSIC 알고리즘은 신호의 입사 방향 즉, Direction of arrival (DOA) 를 추정하는 대표적인 알고리즘이다. 이 알고리즘을 사용하면 수신기에 입사되는 GPS 신호와 재밍 신호의 각도를 추정할 수 있지만, 분해능에 한계가 존재하고, 계산량이 많다는 것이 단점이다. 이 문제를 보완하기 위해 관성 센서(IMU)의 각속도 측정값을 사용하면 무인기의 이동에 따라 위성 신호의 DOA 를 좀 더 정밀하게 추정할 수 있고, MUSIC 알고리즘의 후보각을 대폭 줄일 수 있기 때문에 계산량 측면에서도 유리하다.

먼저 MUSIC 알고리즘을 통해 재밍의 영향을 알아보기 위해, 재밍 신호가 있는 환경의 공간 스펙트럼을 계산해 보았고, 관성 센서의 측정값을 사용하였을 때 재밍 신호 세기에 따른 DOA 추정 오차를 시뮬레이션을 통해 알아 보았다. 재밍과 같은 방해 전파가 수신기에 가해지면 DOA 를 추정하는 것이 매우 어렵다. 제안된 알고리즘은 관성 센서의 측정 된 값으로부터 DOA 를 추정 하는데 높은 정확도를 보였고, 계산량 또한 기존 알고리즘의 1/900 로 감소 시켰다.

핵심어: GPS, navigation, MUSIC algorithm, DOA 추정, 무인기, 관성 센서