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Performance Analysis of Mode Switching Scheme for Reduction of Phase Distortion in GPS Anti-jamming Equipment Based on STAP Algorithm

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ABSTRACT

A method that applies space-time adaptive signal processing (STAP) algorithm based on an array antenna consisting of multiple antenna elements has been known to be effective to remove wide-band jamming signals in GPS receivers. However, the occurrence of phase distortion in navigation signals has been a problem when navigation signals, from which jamming signals are removed using STAP, are supplied to global positioning system (GPS) receivers. This paper verified the navigation performance degradation as a result of phase distortion. To mitigate this phenomenon, this paper proposes a mode switching scheme, in which a bypass mode is adopted to make the best use of the tracking performance of receivers without performing signal processing when jamming signals are not present or weak, and a STAP mode is employed when jamming signals exceed the threshold value. In this paper, the mode switching scheme is proposed for two environments: when receivers are stationary, and when receivers are moving. This paper confirmed that the performance of position error improved because phase distortion could be excluded due to STAP if the bypass mode was adopted under a condition where the jamming signal power level was below the threshold value in an environment where receivers were stationary. However, this paper also observed that the navigation failed due to the instability of tracking performance of receivers due to phase distortion that occurred at the switching time, although the number of switching could be reduced dramatically by proposing a dual threshold scheme of on- and off-thresholds that switched a mode due to the array antenna characteristics of varying gains according to the jamming signal incident direction in an environment where receivers were moving. The analysis results verified that running the STAP algorithm at all times is more efficient than the mode switching, in terms of maintaining stable navigation and ensuring position error performance, to remove jamming signals in an environment where receivers were moving.

Keywords: STAP, anti-jamming, phase distortion, mode switching, AJE

1. INTRODUCTION

The global positioning system (GPS) is a well-known system that accurately estimates the position of a target on the ground using satellites. Originally, the GPS was a system developed by the US Pentagon for the military purpose to measure target positions on earth around 1970s (Kaplan & Hegarty 2006). In particular, with the need of military modernization and advancement, types of military equipment using satellite navigation systems

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are increasing. Positioning signals transmitted from GPS satellites that run at an altitude of about 20,000 km are sent to GPS receivers located on the ground through the atmosphere. GPS receivers employ the direct sequence spread spectrum as the physical layer, which has the processing gain according to a code length to improve a weak signal power. However, since the processing gain of GPS L1 C/A (coarse/acquisition) signals, which are used mainly by GPS receivers, according to a code length is just 30 dB, marginal jamming power is just about 14.5 dB even without intentional interference signals (Yoo & Kim 2013). Thus, if jamming signals are present in the GPS signal band, it may give a fatal impact on GPS performance, and cause a significant risk due to the lack of marginal jamming power in the case of GPS receivers that employ the GPS L1 C/A code.

Although jamming signal types and classification criteria vary, they can be classified into the following two types based on the criteria of jamming signal bandwidth: narrow-band jamming signals, which are characterized by continuous wave (CW) jamming signals of 1 Hz bandwidth, and wide-band jamming signals, which have additive white Gaussian noise (AWGN) jamming signals. Narrow-band jamming signals can be dealt with by removing specific frequencies such as simple notch filters, and are relatively easy to counteract compared to wide-band signals, thus having a small effect on reception of GPS receivers (Jung et al. 2017). This paper considers the operation environment where wide-band jamming signals are present, which is relatively difficult to deal with. Although the presence of jamming signals is not normal, the environment where jammers are present can be divided into the following two categories, according to a travel condition of platform mounted with GPS receivers: stationary environment where stationary platforms are operated, and dynamic environment where moving platforms are operated. The stationary environment considers conditions where a constant power level of jamming signal is received according to a distance, assuming that a fixed jammer is transmitted at the maximum power. The dynamic environment considers moving conditions of platform with GPS receivers under the same jammer operation condition with that of the stationary environment (Jung et al. 2018). In addition, since a platform mounted with GPS receivers is traveled in the dynamic environment, the incident direction of jamming signals may change and the incident angular velocity is generated depending on the incident angle of jamming signals, unlike that of the stationary environment.

It is most effective to remove jamming signals using anti-jamming signal processing based on space-time adaptive signal processing (STAP), which is discussed in this paper, that employs multiple channel signals in an array antenna consisting of multiple antenna elements to remove wide-band jamming signals (Kim 2013). This paper adopted a method that attenuated jamming signal powers through digital beam control by processing signals received at antenna elements in an array antenna using the STAP algorithm to remove jamming signals. Although widely used STAP techniques may guarantee effective performances to maintain satellite navigations by normally delivering GPS satellite signals whose jamming signal powers are attenuated through digital beam control to GPS receivers, a time-variance signal distortion occurs at the code/carrier phase extracted from GPS receivers inter-operating after anti-jamming signals are processed (Round 2004). Since the phase distortion that occurred due to STAP algorithm cannot satisfy the preferred phase error results for precise GPS receivers that employ the code/carrier phase correction to increase accuracy and precision, studies on signal processing of adaptive digital beam control have also been conducted to estimate and correct the bias errors generated due to phase distortion (Church & Gupta 2009, Xu et al. 2018). However, because techniques used in those studies require precise synchronization between code/carrier phases of signals received at multiple antennas and a close connection with satellite signal correlators in GPS receivers, additional equipment for precise phase correction is needed when fabricating anti-jamming equipment (AJE), and the selection of GPS receivers is limited, which are drawbacks.

This paper proposed a mode switching scheme as a method to solve phase distortion that may occur due to STAP, without additional precise correction equipment. In the mode switching scheme, a bypass mode is run without performing STAP algorithm under conditions where jamming signal power level is not present or weak by using the tracking performance of GPS receivers, and a STAP mode is used if jamming signal level exceeds the threshold condition. This paper also conducted a performance analysis in accordance with operating conditions of GPS receivers. The main characteristics of the mode switching scheme is that the scheme increases navigation performance by means of maintaining navigations even in jamming signal-applied environments through the best use of the signal tracking performance of receivers, as well as by means of excluding phase distortion due to STAP by operating the bypass mode until detecting high jamming signal powers whose position error is high. The navigation performance using the mode switching scheme in an environment where receivers were stationary was analyzed after constructing a differential GPS (DGPS) environment that can exclude external error factors. The analysis results verified that if a jamming signal-to-noise ratio (JNR) was set to the threshold value until high performance was achieved in terms of the position error criterion, better navigation performance could be ensured when operating the bypass mode than when operating the STAP mode. However, the received signal powers vary according to an incident angle of jamming signals even under the same jamming signal transmitting power in a dynamic environment where an incident angular velocity of jamming signal occurs due to the movement of receiver-installed platform. Moreover, a receive gain deviation in array antenna is relatively larger than that of single antenna, resulting in frequent switching occurrences when jamming signal powers around the threshold value are received (Kim et al. 2013). If mode switching occurs frequently due to the receive gain deviation of array antenna as the received powers of jamming signals are present around the threshold value in a dynamic environment, navigation signal tracking becomes unstable at GPS receivers, and thus navigation may not be possible. To solve this problem, a dual threshold was set to have on-threshold which enters the STAP mode, and off-threshold that exits to the bypass mode. The idea of this setting was to place a difference between on- and off-thresholds to reduce the number of mode switching occurrences dramatically according to changes in jamming signal incident angular velocity that occurred in a dynamic environment. The effect of reducing mode switching occurrences was confirmed through the performance test analysis. Although the number of mode switching occurrences was reduced using the proposed method, navigation signal tracking performance became unstable due to phase distortion at the time of mode switching occurrence in the GPS receiver, which was inter-operated with the AJE via radio frequency (RF) signals, resulting in navigation failure due to the temporary loss of satellite tracking. This paper verified that when the STAP mode was operated at all times under the same dynamic condition where the receiver was moving, the position error performance was degraded compared to that under the stationary condition due to phase distortion, but stable navigation could be performed. Accordingly, this result confirmed that navigation performance was better when running the STAP algorithm at all times than applying the mode switching scheme in a dynamic environment.

This paper is organized as follows. Chapter 2 compares and analyzes navigation performance results that are degraded due to phase distortion when the array antenna-based AJE that performs STAP, which is considered in this paper, when inter-operating with a GPS receiver. In Chapter 3, the performance of GPS receivers in a stationary environment where the proposed mode switching scheme is applied is analyzed. In Chapter 4, a dual threshold scheme, which is to solve the problem that occurs in a dynamic environment, is explained. The operation method of AJE based on STAP algorithm is proposed through a navigation performance analysis of receivers. Chapter 5 summarizes the performance analysis results, and proposes research direction to fundamentally mitigate the phase distortion phenomenon.

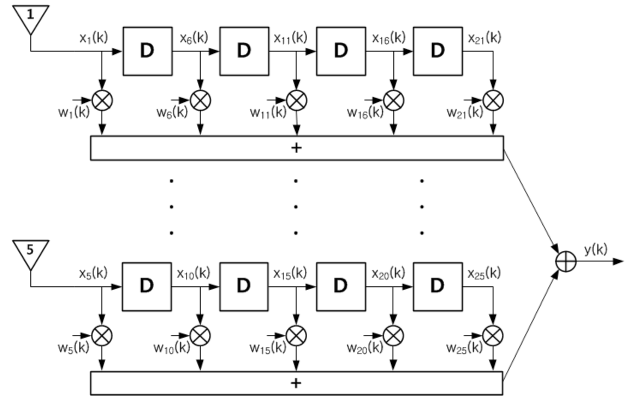

Fig. 1. Implemented STAP structure for 5-element array antenna.

2. GPS ANTI-JAMMING EQUIPMENT BASED ON STAP ALGORITHM AND PHASE DISTORTION EFFECT

Various techniques for anti-jamming signal processing that are used to remove hostile jamming or interference signals have been studied. Among them, STAP algorithm that processes multiple channel signals simultaneously using array antennas has been known to be the most effective and involve low implementation difficulties. The STAP algorithm applied in this paper is capable of not only removing all signals received from a specific direction through spatial domain filtering but also performing time domain filtering simultaneously, thereby removing specific frequency components as well. This paper applied a STAP algorithm, in which signals received through the array antenna consisting of five antenna elements are configured via a tab with five different delay times, and the structure of the algorithm is shown in Fig. 1.

$$X(k)=\left[x_1(k),x_2(k),x_3(k),\ldots,x_{25}(k)\right]^T$$
$$W(k)=\left[w_1(k),w_2(k),w_3(k),\ldots,w_{25}(k)\right]^T \quad (1)$$

$$y(k)=W(k)^T X(k)=X(k)^T W(k) \quad (2)$$

Eqs. (1) and (2) perform constraint against strong interference signals in a manner that smaller gain is set in the direction of interference signal by minimizing the signal power received at output $y(k)$ by applying the STAP algorithm when five tap delays are present in an array antenna consisting of five elements. The input signal vector $X(k)$ and weight vector $W(k)$ are presented in Eq. (1), where T means a transpose matrix transformation. The output signal $y(k)$ where interference signals are removed can be represented as in Eq. (2) via $X(k)$ and $W(k)$. In this paper, constrained least mean squares algorithm, in which a constraint was applied, was employed to calculate the optimal $W(k)$ for the elimination of interference signals, and can be expressed by Eq. (3) (Frost 1972). The optimal $W(k)$, which minimizes the received signal power at vector Q, which is $W(0)$—the initial value of $W(k)$, and satisfies the constraint $C_T W = F$, is calculated. The steering matrix C that sets up the constraint, and coefficient F of 5-tab low path filter are presented in Eq. (4). In Eq. (3), μ means a step size, which is a value that determines an amount of movement in the direction of optimal $W(k)$ value, and helps stable convergence according to the input power. $W(k)$ value is updated every hour, and converged to the optimal $W(k)$ value over a sufficient time.

$$\begin{gathered} W(0) = Q \\ W(k+1) = P\left[W(k) - \mu y(k) X(k)\right] + Q \\ Q \triangleq C\left(C^T C\right)^{-1} F \\ P \triangleq I - C\left(C^T C\right)^{-1} C^T \\ C^T W = F \end{gathered} \tag{3}$$

$$C = \begin{bmatrix} 1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0 \end{bmatrix}, F = \begin{bmatrix} 0.2 \\ 0.2 \\ 0.2 \\ 0.2 \\ 0.2 \end{bmatrix} \tag{4}$$

This paper performs a simulation of jamming signal removal by creating a simulator where model-based design method was applied to verify the performance of the STAP algorithm. As shown in Fig. 2, simulations were performed to enter wide-band jamming signals into the STAP algorithm, considering the environment where jamming signals inputted to the 5-element array antenna are present, thereby verifying that the inputted jamming signals could be eliminated up to the digital noise level. The advantage of the model-based design method is that logic can be implemented using the simulator that performed the simulation. The logic implemented under the same condition with that of the simulator was mounted in the AJE by using the model-based design. The AJE consists of

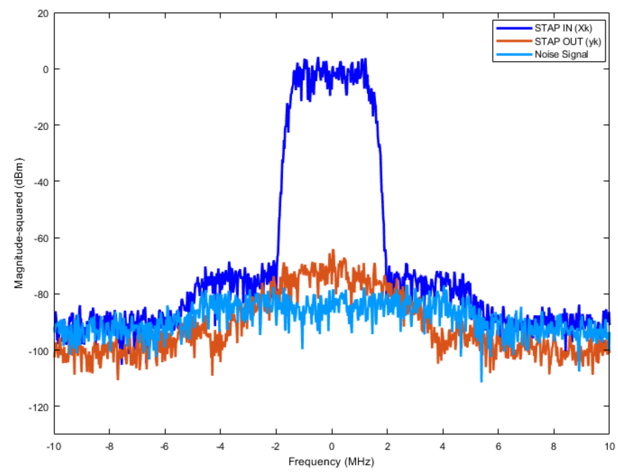

Fig. 2. Simulated jamming signal input and suppressed output by STAP based on model based design.

RF down-conversion unit that receives and converts multi-channel jamming signals and navigation signals from an array antenna into digital signals, signal processing unit that performs STAP algorithm using the inputted multi-channel digital signals, which are then converted to intermediate frequency (IF) signals where jamming signals are removed, RF up-conversion unit that converts the inputted IF signals into RF signals, which are located in the navigation signal band, and power unit that converts the external direct current (DC) voltage into required DC voltage level. The logic that performs the STAP algorithm is mounted and run inside the AJE.

The AJE, in which the STAP logic is mounted, removes jamming signals by forming a null of jamming signals through the computation with weight by channel, where both navigation and jamming signals are inputted via 5-element array antenna, and thus code/carrier phase distortion can occur in relation to navigation signals GPS receivers track (Round 2004). The navigation performance degradation caused due to phase distortion could be verified through tests with precision receivers. The tests were conducted by selecting a GPS receiver inter-operated with NovAtel OEM615 that could achieve high accuracy and precision when performing DGPS. For carrier correction without external error factors such as tropospheric, ionospheric, satellite clock and orbital error components, a reference station that could generate real-time DGPS messages was installed and operated to analyze the performance degradation due to phase distortion. Table 1 shows the test environment for DGPS message transmission. The DGPS message of GPS L1 C/A signals generated at the operating reference station was created in RTCM v2.3 format, and delivered to the GPS receiver

Table 1. DGPS test parameters and values for verification of phase distortion on GPS receivers.

Parameters	Values
GPS signal	L1 C/A
DGPS transfer medium	RS232 Cable
DGPS message type	RTCM v2.3
DGPS message logs	1, 3, 18/19
DGPS message interval (sec)	1

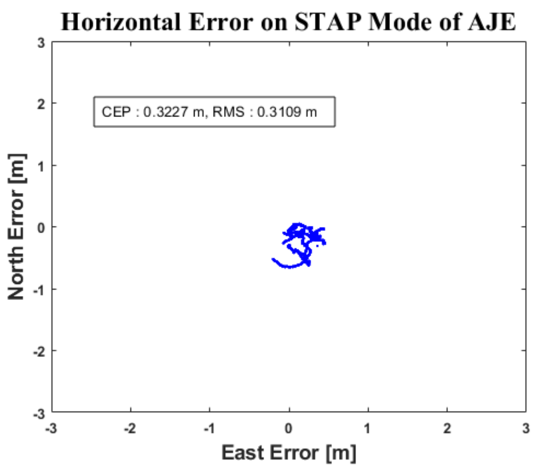

Fig. 3. Horizontal error on STAP mode of AJE.

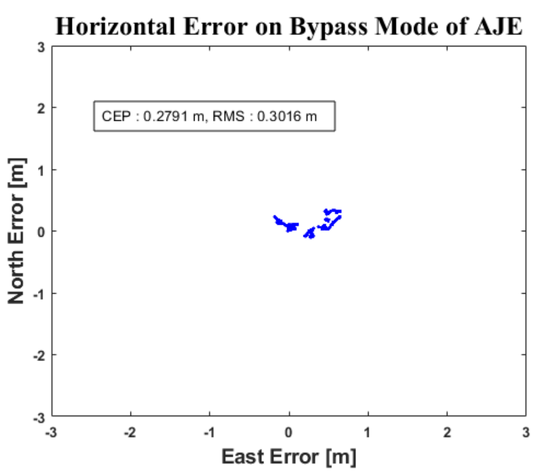

Fig. 4. Horizontal error on bypass mode of AJE.

OEM615 via wire through RS232 cables. The DGPS message log was set to transmit 1, 3, and 18/19 every second.

Figs. 3 and 4 show the navigation-performing results with signals received at the 5-element array antenna under the condition where the external jamming signals inside the GPS L1 band are not applied to the AJE inter-operated with the GPS receiver that performs real-time DGPS in the GPS L1 band after receiving DGPS messages set in Table 1. Fig. 3 shows the DGPS results of STAP-applied on signals at the GPS receiver with regard to signals inside the GPS L1 band received through the array antenna. Fig. 4 shows the DGPS results of bypass mode-run signals at the GPS receiver without performing STAP after selecting only a single reference element in the array antenna, although the AJE is run. The test results in Figs. 3 and 4 show both the circular error probability (CEP) to analyze the accuracy, and the horizontal root mean square (RMS) results to analyze the precision of one-hour navigation. When operating the STAP algorithm, CEP 0.3227 m and RMS 0.3109 m were obtained, whereas CEP 0.2791 m and RMS 0.3016 m were obtained when the bypass mode was run without using the STAP algorithm. The above test results showed that anti-jamming signal processing of signals received at the 5-element array antenna resulted in 15.6% performance degradation in CEP, compared to that when bypassing only a single reference element signal. When the array antenna-based AJE and GPS receiver were inter-operated with RF signals, navigation performance degradation in accuracy and precision was found to occur due to phase distortion of navigation signals caused by the STAP through the test results in Figs. 3 and 4.

3. MODE SWITCHING SCHEME FOR FIXED GPS RECEIVER AND PERFORMANCE ANALYSIS

The previous test results verified that navigation accuracy and precision were degraded due to phase distortion at the GPS receiver inter-operated with the AJE that employed the STAP algorithm. Since conditions where hostile jamming signals are applied are not normal, the performance of GPS receiver excluding phase distortion can be acquired by operating the bypass mode under the conditions that do not exceed the threshold value set in the AJE or where no jamming signals are present by utilizing the signal tracking performance of GPS receiver, rather than obtaining degraded navigation performance due to phase distortion by performing the STAP algorithm inside AJE for the majority of the time when GPS receivers are operated. The navigation performance of GPS receiver was analyzed by applying the mode switching scheme where the STAP algorithm was run to switch to the STAP mode if jamming signals were received and measured JNR value exceeded the set threshold when the AJE was run with the bypass mode. In addition, assuming that jamming signals are transmitted at the maximum signal power level in an environment where the platform is stationary, signals received at the array antenna are received constantly according to the gain in the receive antenna in the incident direction and the free space loss by distance. Thus, mode switching can be performed by measuring the received jamming signal power.

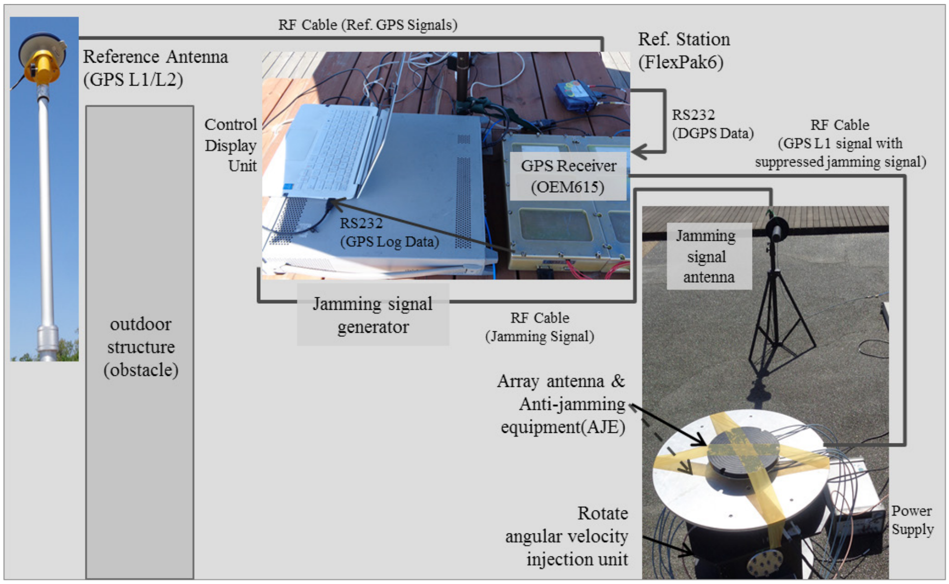

Fig. 5. AJE and supplies of outdoor test environments for fixed and moving GPS receivers.

This paper performed a navigation performance analysis according to the incident signal intensity based on the recognizable JNR in the AJE to set up the threshold that is applied to the signal processing mode switching scheme. Fig. 5 shows the test environment for the navigation performance analysis under the jamming signal-applied condition, in which 100 Hz AWGN jamming signals were applied at 0° of elevation as wide-band jamming signals. DGPS messages that were inputted to exclude external factors in the GPS receiver inter-operated with the AJE were set as the same as shown in Table 1. We set a distance between the jamming transmit antenna and the reference station antenna to perform the real-time DGPS without jamming signal effect on navigation signals received at the reference station. The reference station antenna was installed at a location where the obstacle effect could be obtained by outdoor structures between two antennas in the test. The separation distance between the jamming transmit antenna and the receive array antenna was set to be the minimum distance that satisfied the electromagnetic far field condition according to the length of transmit and receive antennas (Jung et al. 2018). In addition, for an analysis of navigation performance, navigation data logging was conducted on the test notebook, which was connected to the GPS receiver that received GPS signals from which jamming signals were removed using the AJE.

Since testing by applying different power levels of jamming signals at the same time was difficult in an outdoor environment, navigation performance analysis was conducted by adding a parameter of user equivalent range errors (UERE) along with CEP, horizontal RMS, and mean horizontal dilution of precision (HDOP) to exclude the influence according to the number of satellites and configuration in order to set a threshold. The UEREs for performance analysis were obtained through {UERE = RMS / HDOP}. Table 2 presents results of CEP, horizontal RMS, UERE, and mean HDOP according to an increase in jamming signal power level incident to the array antenna, that is, JNR. Fig. 6 depicts the CEP, horizontal RMS, and UERE values in Table 2 for a better intuitive understanding of the threshold setup criteria. The threshold in this paper was set between JNR 5 dB and 6 dB where the performances of CEP and UERE were reversed in the STAP and bypass modes for the threshold values for switching from the bypass mode to the STAP mode, as shown in the result of Fig. 6. That is, the AJE inter-operated with the GPS receiver in an environment where the platform was stationary exhibited the maximum performance in terms of position errors when switching from the bypass mode to the STAP mode once the power level of input jamming signal exceeded JNR 5 dB.

Table 2. Test performance results on STAP and bypass modes of AJE in static platform environment.

JNR	CEP [m]		RMS [m]		UERE [m]		Avg. HDOP	
[dB]	STAP	Bypass	STAP	Bypass	STAP	Bypass	STAP	Bypass
0	0.3741	0.3352	0.3510	0.2762	0.40	0.22	0.89	1.27
1	0.2402	0.3407	0.2035	0.2965	0.23	0.18	0.89	1.62
2	0.3323	0.2837	0.3003	0.2606	0.33	0.18	0.90	1.43
3	0.4895	0.2341	0.4202	0.2178	0.47	0.10	0.90	2.08
4	0.1745	0.1142	0.1745	0.1002	0.21	0.04	0.83	2.81
5	0.6007	0.2098	0.5611	0.1749	0.66	0.06	0.85	3.11
6	0.3372	1.9262	0.3156	1.6963	0.37	0.63	0.85	2.68
7	0.4489	2.3065	0.4034	2.0181	0.14	1.29	0.87	1.57

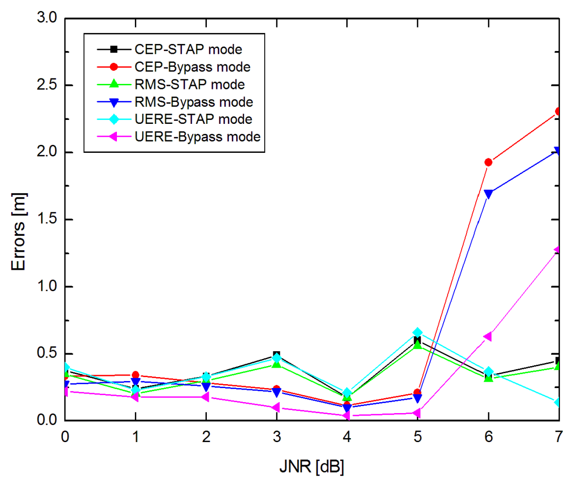

Fig. 6. Performance comparison on STAP and bypass modes of AJE in static platform environment.

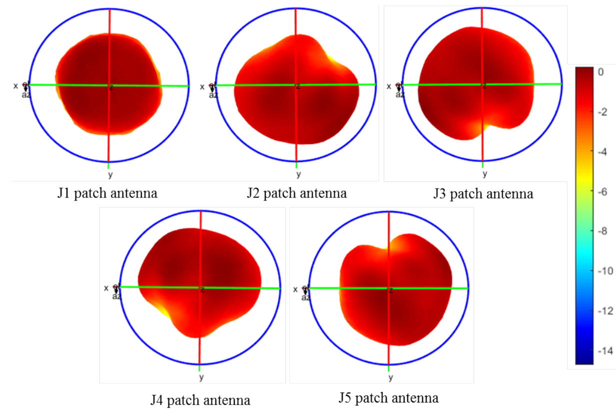

Fig. 7. Radiation patterns on xy-plane of the 5-element array antenna.

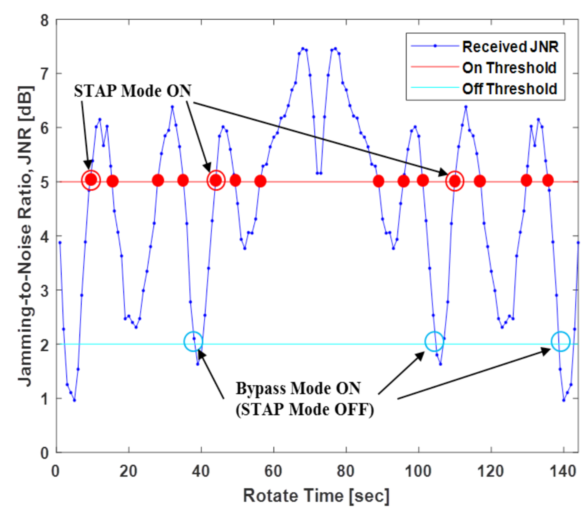

Fig. 8. Array antenna simulation results for 2-step STAP mode switching scheme.

4. MODE SWITCHING SCHEME FOR MOVING GPS RECEIVER AND PERFORMANCE ANALYSIS

The array antenna-based STAP algorithm employs an array antenna designed to 5-element array antenna housing where a number of antenna elements are basically mounted to eliminate wide-band signals. Due to the limitation of array antenna size in an operation environment that requires mounting such array antenna in a platform, a distance between antenna elements must be closer than $\lambda/2$, which is the theoretical optimal distance. As a result, a radial pattern for each antenna patch is formed in a squashed shape rather than in a hemispherical shape (Kim et al. 2013). As shown in Fig. 7, the result of the test performed by fabricating an array antenna for anti-jamming signal processing takes the same squashed shape of beam pattern as the theoretical shape. As such, a gain pattern varies for each element in the array antenna depending on the incident direction, and an incident direction differs according to the direction of mounted array antenna in an environment where the platform moves dynamically. Thus, the power of jamming signals received by the AJE continuously changes.

In an environment where a platform moves dynamically, the incident angular velocity of jamming signals varies according to the platform moving condition. To reduce the performance degradation due to phase distortion which is caused by the STAP algorithm in a dynamic environment, it is difficult to set up a jamming signal threshold as in a stationary environment. This will cause frequent switching between STAP and bypass modes as the incident angle changes when the jamming signal intensity incident to the array antenna is near the threshold. If mode switching occurs frequently, a receiver system may be unstable because phase changes in satellite signals received at receivers suddenly occur at the time of mode switching, resulting in a loss of tracking. This paper proposes a dual threshold scheme to solve this problem, in which on-threshold that makes switching to the STAP mode for the reduction of jamming signals is set higher than off-threshold that makes switching to the bypass mode to reduce the phase distortion using the receiver's tracking performance. Fig. 8 shows the simulation test results of the dual threshold scheme using the measurement data in the array antenna used in Fig. 7. Simulation tests were performed on the basis of jamming signal power incident to the array antenna at -35° of elevation when jammers

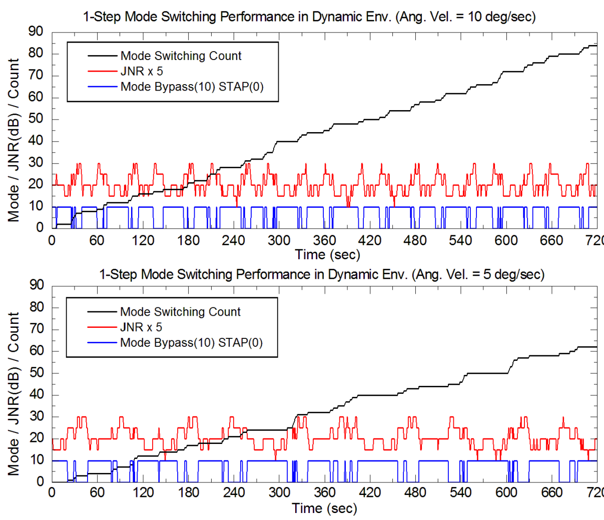

Fig. 9. Test performance results for 1-step STAP mode switching scheme in dynamic environments.

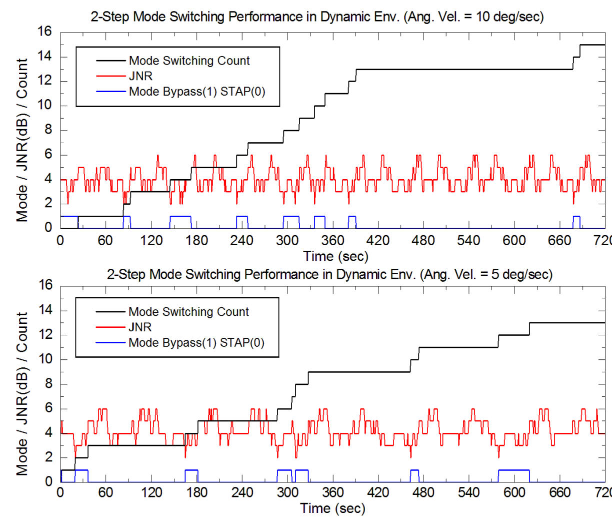

Fig. 10. Test performance results for 2-step STAP mode switching scheme in dynamic environments.

at the GPS L1 band were generated while separating the 8 kW jammer by 50 km. The number of mode switching occurrences was simulated under the moving condition where a 720 degree turn is made each in the clockwise/counter-clockwise directions and where the incident angular velocity of jamming signals incident to the antenna was 5 deg/sec. Since the purpose of on- and off-thresholds that turn on and off the STAP mode is different in the dual threshold scheme proposed in this paper, the criteria of the two thresholds were set differently. Since the on-threshold that turns on the STAP mode should be performed when the position error at the signal processing mode in Table 2 was better than that in the bypass mode, switching is performed at JNR 5 dB. The off-threshold that turns off the STAP mode was set to JNR 2 dB, which is the condition below the mean HDOP < 2.0 in Table 2, when the satellite state becomes good for normal navigation in the bypass mode. In Fig. 8, JNR 5 dB and 2 dB, which are the on- and off-thresholds, are marked. The number of mode switching occurrences in the dual threshold condition occurs at the times in the red and blue circles, resulting in 6 times of switching. The number of mode switching occurrences under the single threshold condition occurs at the times in the red points, generating 14 times of switching. The simulation test results confirmed that when the dual threshold scheme was applied, the number of switching occurrences is dynamically reduced compared to that in the single threshold scheme.

The dual threshold scheme was implemented in the AJE for an environment where a GPS receiver-mounted platform moves, and their performances were compared with those of single threshold scheme in the same environment used in Fig. 5. The current AJE operation mode, receive JNR, and the number of mode switching occurrences were analyzed under the conditions of moving rates at 5 deg/sec and 10 deg/sec for 720 sec in total using the rotational angular velocity simulator to simulate the changes in incident angular velocity of jamming signals incident to the platform. The analysis was also conducted by logging GPS receiver navigation results under the condition where DGPS information in Table 1 was received. Figs. 9 and 10 show the data that analyze the number of mode switching occurrences according to JNR when using the single and dual threshold schemes, respectively, which are test results by running the rotational angular velocity simulator under the jamming signal-applied conditions of JNR 4 dB from jamming signals at 0° of incident elevation to the array antenna at 0° of azimuth. The operation mode of bypass and STAP modes was marked as 1 and 0, respectively. In the case of the single threshold scheme, as a large number of mode switching occurred in the test time during mode switching performance test, the operation mode was multiplied by 10, and receive JNR was multiplied by 5, which are shown in Fig. 9. When comparing Figs. 9 and 10, the number of mode switching occurrences was much larger in the single threshold scheme than in the dual threshold scheme. And the slope of the number of mode switching occurrences was steep because it frequently passed through the part whose gain pattern in the array antenna was uneven when the incident angular velocity was faster than jamming signal incident angular velocity. For the dual threshold scheme, on some cases, mode switching occurred infrequently due to the JNR value that was updated every second when the incident angular velocity of jamming signals changed at a rate of 10 deg/sec. Fig. 11 summarizes the results by comparing only the number of mode switching

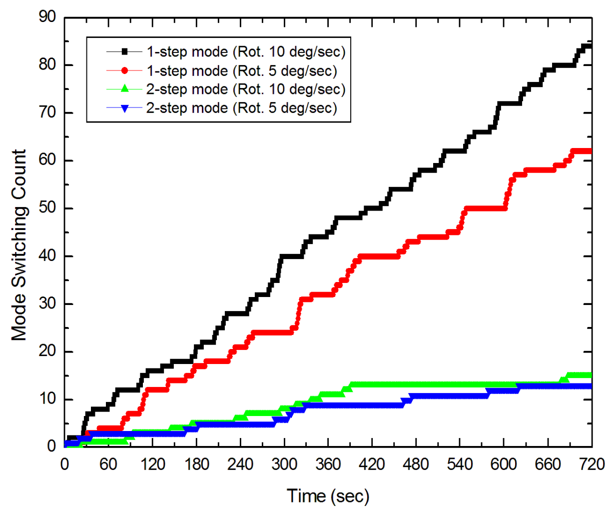

Fig. 11. Mode switching count comparison on mode switching scheme and rotation angular velocity.

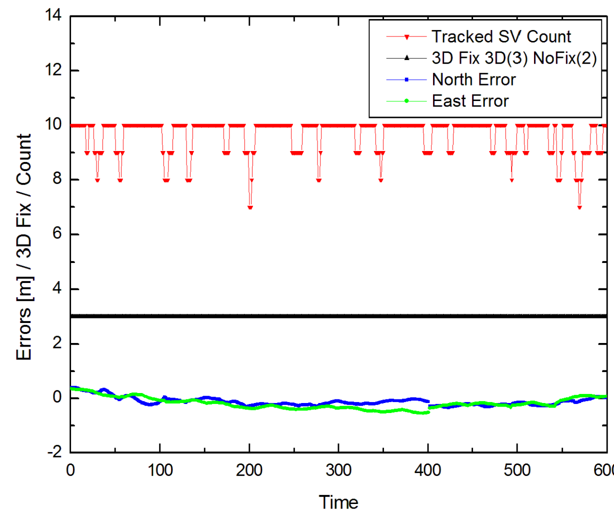

Fig. 13. Performance of STAP mode always running in 10 deg/sec rotation angular velocity.

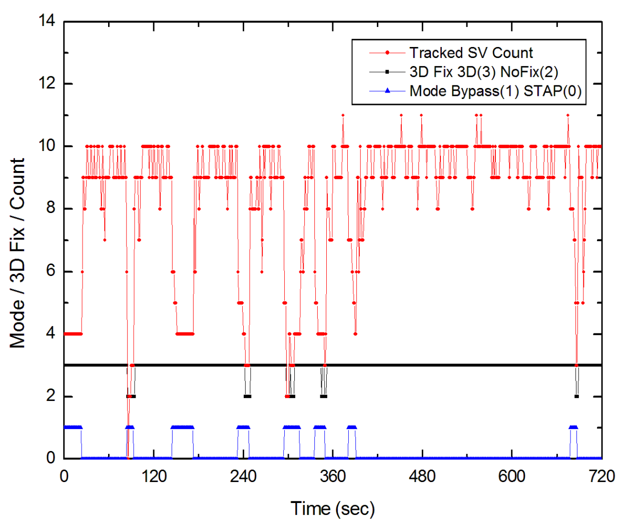

Fig. 12. Performance of mode switching scheme running in 10 deg/sec rotation angular velocity.

occurrences. As seen from the figure, the number of mode switching occurrences that made the receiver system unstable could be dramatically reduced by applying the dual threshold scheme in an environment where a receiver-mounted platform is moving.

Fig. 12 shows the GPS receiver navigation results under the dual threshold scheme-applied condition, which were analyzed along with the AJE operation mode. The figure shows the analysis of the operation mode, whether 3D fix navigation was performed, and the number of tracking satellites over time at 10 deg/sec of incident angular velocity of jamming signals in Fig. 10. The results of the analysis confirm that the loss of satellite tracking occurred frequently within a few seconds immediately after mode switching was performed. The satellite tracking loss was also found not only in the bypass mode but also during the transition into the STAP mode. This was because tracking performance became unstable due to phase distortion when GPS receivers tracked satellites at the time of mode switching. Fig. 13 shows the analysis results of operation mode, whether 3D fix navigation was performed, and north/east horizontal direction position error over time at 10 deg/sec, which is the same incident angular velocity of dynamic jamming signals as that in Fig. 12, after the AJE, that always run the STAP mode, was mounted without applying the dual threshold scheme. The horizontal position errors were analyzed, and the results were CEP 0.3327 m, RMS 0.3389 m, UERE 0.31 m, and mean HDOP 1.09. As seen from Fig. 13, even if code/carrier phase distortion occurred due to STAP when jamming signals were incident, the effect on satellite tracking performance of the receiver was smaller than that of mode switching. Thus, 3D fix navigation could continue without a tracking loss of satellites, and the position error performance was not degraded significantly compared to that of static test results. The test results shown in Figs. 12 and 13 confirm that running the STAP algorithm at all times is more efficient in terms of navigation performance than applying the mode switching scheme in a dynamic environment where AJE and GPS receiver are inter-operated.

5. CONCLUSIONS AND FUTURE WORK

This paper verified the navigation performance degradation due to phase distortion that may occur at GPS receivers inter-operated with AJE on which STAP algorithm was applied that could effectively remove wide-band jamming signals. This paper proposed a mode switching scheme, which can be used in the STAP algorithm-applied AJE to alleviate the navigation performance degradation due to phase distortion. The analysis of the test results show that position error performance could be improved when the mode switching scheme was applied in an environment where receivers were stationary. It was also found that the number of mode switching occurrences could be significantly reduced through the mode on/off dual threshold method to solve the frequent occurrences of mode switching when the power levels of incident jamming signals were near the threshold due to the gain deviation of array antenna that changed according to an incident angle in an environment where receivers were moving. However, navigation could fail due to the unstable tracking performance of navigation signals as a result of phase distortion at the time of mode switching in a precision receiver. This paper verified that when the STAP mode was operated at all times under the same dynamic condition where the receiver was moving, the position error performance was degraded compared to that under the stationary condition due to phase distortion, but stable navigation could be performed. Accordingly, this result confirmed that navigation performance was better when running the STAP algorithm at all times than applying the mode switching scheme in a dynamic environment.

Such phase distortion can be fundamentally solved by estimating bias and phase distortion for each navigation satellite, which are generated due to signal processing proposed in the aforementioned literature, and correcting and delivering the estimated values for each correlator of satellite signals inside the receiver. To implement this method, it is necessary to configure hardware that can perform the signal processing of GPS navigation signal correlator and STAP at the same time, rather than implementing a method of inter-operation using RF signals between the AJE that performs STAP considered in this paper and the precise GPS receiver. It is also necessary to apply additional precise correction equipment to perform precise correction for code/carrier phase and an additional signal processing scheme that can employ corrected phase.

AUTHOR CONTRIBUTIONS

Conceptualization, J. Jung; methodology, J. Jung; software, J. Jung and G.-J. Yang; validation, J. Jung, G.-J. Yang and S. Park; formal analysis, J. Jung and S. Park; investigation, J. Jung, G.-J. Yang, and S. Park; writing—original draft preparation, J. Jung, G.-J. Yang, and S. Park; writing—review and editing, J. Jung, H. Kang, S. Kwon, and K. J. Kim.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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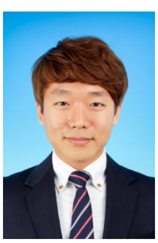

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