Effects on the Positioning Accuracy of a GPS Receiver with Array Antenna and Time Delay Compensation for Precise Anti-Jamming

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As more GPS receivers are used in navigation systems to obtain precise position information, concerns about GPS jamming vulnerability are growing. The most effective way to overcome this jamming weakness is to use an array antenna that consists of many antenna elements and RF channels. However, an array antenna causes two side effects: a nulling pattern and a time delay error in positioning performance. We analyze the effects on the positioning accuracy of a GPS receiver equipped with a precise time-delay-compensated array antenna to overcome jamming situations. We present an analysis of the theoretical gain pattern of a 4-array antenna and experimental verification of GPS signal attenuation by obtaining a satellite’s CN0 value in the near jamming direction. We show the results of the time delay measurement in the array antenna system using two independent methods and present a new baseband linear interpolation algorithm that is evaluated as having a 0.95 ns RMS error after compensating for the invariant RF time delays. Finally, using the realistic gain pattern and time-delay-compensation results, we assess the position error of the GPS receiver and show the possibility of attaining a precise navigation system in jamming environments.

Key Words: GPS, Array Antenna, Time Delay, Anti-jamming

Nomenclature

- \( w \): weight vector of array antenna
- \( R \): covariance matrix of array antenna
- \( N \): number of antenna elements
- \( \alpha \): diagonal loading value
- \( T \): time interval between samples (s)
- \( \tau_D \): time delay to be compensated (s)
- \( f_s \): sampling frequency (Hz)
- \( \sigma_{\text{range}} \): range error of GPS receiver itself (m)
- \( o \): optimal weight vector

1. Introduction

Global positioning system (GPS) receivers are widely used in navigation and surveying areas because they provide accurate position, velocity and time information at low-cost. However, there are growing concerns about the jamming vulnerability of GPS receivers. In fact, there have been many jamming incidents, like the intentional GPS jamming operations by hostile forces and illegal personnel privacy devices (PPDs) that result in disrupting normal operation of ground-based augmentation system (GBASs) at airports. The jamming signals can severely degrade the accuracy and integrity of navigation systems that use GPS.

The most effective method to overcome GPS jamming vulnerability is to use an adaptive array antenna that has the capability of utilizing a nullifying or beamforming algorithm in a certain direction. However, using an array antenna for a GPS receiver can deteriorate position accuracy performance. One effect is the loss of some of the GPS satellite’s signals in the close jamming direction. This effect is inevitable for realizing an anti-jamming function using an array antenna, which creates a nullified area of signal attenuation. However, previous papers have not analyzed the theoretical gain patterns in order to understand the GPS signal loss. Numerically simulated gain patterns have been obtained.

Another side effect is the array antenna bias induced by the antenna signal combination: the RF front-end time delay and anti-jamming algorithms. Previous papers analyzed and proposed mitigation algorithms for this array antenna bias. One of the algorithms used very complex array antenna manifold data obtained by measuring the gain and phase information from all directions. Some papers have proposed anti-jamming signal-processing algorithms to prevent a bias of range measurement. However, most of the papers analyzed the accuracy of the GPS receiver range and phase measurement without considering the RF time delay in the array antenna system. It is also very difficult to implement a calibration algorithm of the array antenna bias by utilizing the manifold data or a reference RF signal.

In this paper, we focus on a position error minimization method with a new measuring and compensating algorithm for RF time delays. We also obtain the synthesized gain pattern of the array antenna, including the element patterns measured, and analyze the effect on GPS receiver positioning accuracy in jamming environments.
2. GPS Array Antenna Characteristics

2.1. Anti-jamming algorithm

A typical GPS array antenna schematic for anti-jamming is shown in Fig. 1. GPS satellite and jammer signals are collected by antenna element 1 to N, and then converted to low-frequency signals by a RF down-converter. After digital sampling using an analogue-to-digital converter (ADC), the signals are processed using an anti-jamming algorithm, such as a nullifying or beamforming algorithm in a field-programmable gate array (FPGA).

The array antenna system generates the final output by multiplying the number of input signals by a weight vector \( w \) and adding them together. The input value \( x \) measured at the in-phase and quadrature-phase channel of an array antenna is defined as a complex number vector of Eq. (1),

\[
x = [x_1 \ x_2 \ \cdots \ x_N]^T
\]

where \( N \) is the number of elements of the array antenna.

Because the output of the array antenna is \( f(w) = w^Hx \), the expected value of the output power can be expressed as Eq. (2),

\[
\text{Output power} = E[w^Hx^2] = w^HRw
\]

where \( E[\cdot] \) represents the expectation value, \( R = E[xx^H] \) is the covariance matrix of the array antenna input, and \( ^H \) represents the conjugate transpose. Using the variables defined above, the constrained optimization problem can be expressed as Eq. (3),

\[
\min_w w^HRw \ \text{subject to} \ Cw = c
\]

where \( C \) represents the constraint matrix, and \( c \) represents the constraining column vector. In this expression, it is important that \( C \) and \( c \) can have any value and the interference cancellation performance depends on those values.

The solution to this constrained optimization problem is one of the stationary points of the Lagrangian and can be obtained using a Lagrangian multiplier. Using this, the optimal weight vector \( w_o \) can be calculated as shown in Eq. (4),

\[
w_o = R^{-1}C(C^HR^{-1}C)^{-1}c
\]

The degree of freedom is \( N - 1 \) because the number of weight vector \( w_o \) elements is \( N \).

As mentioned before, the interference cancellation performance depends on the constraint condition of Eq. (3). The well-known constraint conditions are as in Eq. (5), and the corresponding optimal weight vector is as in Eq. (6),

\[
C = [1\ 0\ 0\ 0\ \cdots\ 0]^T, \ c = 1
\]

\[
w_o = R^{-1} \times [1/R_{1,1}^{-1} \ 0\ 0\ \cdots\ 0]^T
\]

The algorithm using these conditions is called a nullification algorithm and uses no constraints on the GPS satellite direction or signal. Therefore, the nullification algorithm does not require the attitude information of the array antenna or GPS satellite positioning data. This anti-jamming algorithm is very effective and easy to implement when the legacy GPS receiver is used.

2.2. Side effects of array antenna

Using an array antenna for a GPS receiver causes two side effects in positioning performance. The array antenna uses a combination of RF channels with many GPS signals instead of a pure one-channel GPS signal in order to eliminate the jamming signals, as shown in Fig. 1. Because of this property, the time delay in RF channels influences GPS receiver positioning performance due to the multipath phenomenon. \(^3\)

The position error can be increased by combining multiple GPS signals that have different time delays. This error can be minimized by reducing the relative time delays between the array antenna RF channels. This paper focuses on a position error minimization method with a measuring and compensating algorithm for time delays.

On the other hand, GPS satellite signal loss can occur due to the nullification pattern of the array antenna. The nullification pattern is needed to eliminate jamming signals that are injected into the array antenna. In particular, the signal gain loss is severe in the near region of the jammer direction, so GPS satellite signals near the jammer direction region should not be lost.

These two side effects of the array antenna directly deteriorate GPS receiver position error. Position error is determined by multiplying the range measurement error and the GPS satellite geometry, called “Position Delusion of Precision (PDOP),” as shown Eq. (7), \(^3\)

\[
\text{Position error} = \sigma_{\text{range error}} \times \text{PDOP}
\]

The difference in time delays in an array antenna is related to the range measurement error \( \sigma_{\text{range error}} \), whereas the nullification pattern in the array antenna is significantly related to the PDOP value.

3. Design of a Precise Array Antenna

3.1. Nullification pattern analysis

The directional gain pattern of a GPS array antenna can be obtained by combining the carrier phase differences between antenna elements. In this paper, we consider a four-element array antenna system, as shown in Fig. 2, and it is easy to
assess the gain pattern with this coordinate.

When the jamming signal enters the direction of azimuth $\phi$ and elevation $\theta$, the input vector from element signals 1 to 4 is as follows,

$$x = [e^{j\psi_1} e^{j\psi_2} e^{-j\psi_3} e^{-j\psi_4}]^T + n_{4\times1}$$ (8)

where,

$$\psi_1 = 2\pi \left( \frac{d}{\lambda} \right) \cos \theta \cos \phi$$ (9)

$$\psi_2 = 2\pi \left( \frac{d}{\lambda} \right) \cos \theta \sin \phi$$ (10)

$$\lambda = \text{wave length of carrier signal}$$ (11)

$$n_{4\times1} = \text{noise}$$ (12)

The antenna noise vector $n_{4\times1}$ has no correlation with the elements of the vector. Therefore, the covariance matrix of array antenna input $R$ is also calculated according to Eq. (13) after adding a term of diagonal loading $\alpha$, which is larger than 1 and corresponds to adding antenna noise power$^{13}$

$$R = \begin{pmatrix} \alpha & e^{j(\psi_1-\psi_3)} & e^{j(2\psi_3)} & e^{j(\psi_1+\psi_3)} \\ e^{j(\psi_1+\psi_3)} & \alpha & e^{j(\psi_1+\psi_3)} & e^{j(2\psi_3)} \\ e^{j(2\psi_3)} & e^{j(\psi_1+\psi_3)} & \alpha & e^{j(\psi_1-\psi_3)} \\ e^{j(\psi_1-\psi_3)} & e^{j(2\psi_3)} & e^{j(\psi_1-\psi_3)} & \alpha \end{pmatrix}$$ (13)

The optimal weight vector of a nullification algorithm is Eq. (6), which is found by the inverse matrix calculation of a $4\times4$ matrix $R$. Then, the theoretical gain pattern is found using the weight vector $w_o$. The inverse matrix of $R$ is as follows,

$$R^{-1} = \frac{1}{\det(R)} \begin{pmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{pmatrix}$$ (14)

where the important elements are $a_{11}, a_{21}, a_{31}, a_{41}$ because the first column of $R^{-1}$ in Eq. (6) is related to the optimal weight vector $w_o$. The values of the elements are as follows,

$$a_{11} = \alpha^2 - 3\alpha + 2$$ (15)

$$a_{21} = (-\alpha^2 + 2\alpha - 1)e^{j(\psi_1+\psi_3)}$$ (16)

$$a_{31} = (-\alpha^2 + 2\alpha - 1)e^{j(2\psi_3)}$$ (17)

$$a_{41} = (-\alpha^2 + 2\alpha - 1)e^{j(\psi_1-\psi_3)}$$ (18)

Finally, the optimal weight vector $w_o$ is calculated as Eq. (19),

$$w_o = \left[ 1 \quad \beta e^{j(\psi_1+\psi_3)} \quad \beta e^{j(2\psi_3)} \quad \beta e^{j(\psi_1-\psi_3)} \right]^T$$ (19)

where $\beta = (\alpha^2 + 2\alpha - 1)/(\alpha^2 - 3\alpha + 2)$.

The weight vector is briefly determined by the jamming signal direction and the diagonal loading $\alpha$. But the weight vector is not simple when multiple jamming signals are present. In this case, we need the numerical calculation process. The directional gain pattern is obtained by multiplying the steering vector $\hat{P}$ with the weight vector. This gain pattern consists of exponential functions and can be utilized to predict the GPS satellite signal loss due to the side effect of the nullification algorithm. In Section 4 we verify this side effect by conducting experiments using a Controlled Reception Pattern Antenna (CRPA) simulator. One example of the gain pattern is shown in Fig. 3, with the jamming signal azimuth $\phi = 90^\circ$, elevation $\theta = 32^\circ$ and $\alpha = 1.001$. This confirms that the gain is very low in the near jamming direction.

The side effect nullification area is defined as the area that is below a certain gain value. We assume that the normal GPS signal power in the carrier-to-noise ratio ($C/N_0$) is 41.9 dB/Hz and the minimum tracking signal power is 28 dB/Hz. From this assumption, the side effect nullification area is the area below a gain of $-13.9$ dB ($-41.9$ dB/Hz $- 28$ dB/Hz)) and is expressed by the thick line in Fig. 3.

In the real array antenna, which is typically made of patch elements, there also exists the gain or phase pattern of antenna elements and gain mismatches between antenna elements, as shown in Fig. 4. Luckily, the fixed mismatches of the gain or the phase don’t affect the array antenna synthesis pattern in the near jamming direction nor nullification performance$^{14,15}$ Additionally, they are usually compensated by the calibration manifold data$^{15}$ The synthesized gain pattern of the real array antenna is determined by multiplying the weight vector and the gain patterns of antenna elements. In
Section 5, we use these gain patterns shown in Fig. 4 to acquire more realistic analysis results.

3.2. Precise time delay measurement

A GPS receiver measures the time delay from the satellite to the receiver’s antenna. The final range measurement, which is called a pseudorange, is estimated by multiplying the time delay by the speed of light. The pseudorange is used to calculate the position of the GPS receiver. From this aspect, the time delay is very important to the precise positioning of the GPS receiver. But the position error can be increased by the combined multipath effect of the array antenna time delays.

In this paper, we measured the time delay quantity of a real 4-array antenna system using two methods and propose a compensation algorithm. First, we used a RF group delay measurement device (Rohde Schwarz Inc., ZVA40). The second method utilized the high-power GPS signal of a GPS simulator (Spirent Corporation, STR4760).

The ZVA40 time delay measurement device measures the time delay in the RF front-end with a mixer component to convert the input RF frequency to a lower one. The measurement accuracy specification is about 1 ns. We obtained the time delay results of the 4-array antenna as shown in Table 1. These measurement results are reasonable considering RF component group delay.

The second time delay measurement method is to use the high-power GPS signal from the monitoring port of the GPS simulator. The GPS signal level is +70 dB higher than the normal GPS signal level of −130 dBm. Only one GPS satellite signal was generated and divided by the splitter. The four signals were entered to the anti-jamming system to get the time delay. The schematic diagram of this method is shown in Fig. 5.

Table 1. Time delay results using the measurement device.

| Antenna # | 1   | 2   | 3   | 4   |
|-----------|-----|-----|-----|-----|
| Time delay (ns) | 72.8 | 74.8 | 72.2 | 70.3 |

In the above measurement system, the ADC data of the anti-jamming system are saved in the limited FPGA memory for about 2 ms in a 20 MHz sampling frequency. The limited memory is the main reason of the high power GPS signal usage for the precise time delay estimation. Then, the ADC data are extracted using RS-232 serial data communication. Finally, we measure the time delay of the anti-jamming system after signal processing of the ADC data.

The ADC data collected for the four RF channels are shown in Fig. 6. No specific signal type is seen because the anti-jamming system has an IF frequency of 7.4 MHz. However, the GPS signal spectrum is identified after down-converting to the baseband frequency, which is 0, as shown in Fig. 7. Furthermore, the chip pattern of the GPS C/A code is described (Fig. 8). Because the baseband C/A code signal has a smooth sine wave-like characteristic in Fig. 8, the time delay compensation algorithm of interpolation can be utilized in the next section.

In order to get the time delay of RF channels using the baseband signal, it is necessary to implement typical GPS signal-processing procedures. First, we implement the acquisition...
process that simultaneously matches the C/A code delay and the Doppler frequency. This serial search acquisition process was completed and the peak shape of the GPS signal was obtained, as shown in Fig. 9. Because the Doppler frequency input from the GPS simulator is 0, the Doppler frequency measured is the anti-jamming system’s clock frequency error.

After this acquisition process, it is necessary to process the fine carrier and code tracking procedures. We used the accurate phase \( \left( \tan^{-1}(I/Q) \right) \) difference discriminator over a 1 ms interval to find the precise Doppler frequency. The results of the GPS signal correlation function using this tracking procedure are shown in Fig. 10. The GPS signal amplitude is related to the peak value of the correlation function. From this property, the gains of RF channels are slightly different, and this is common for RF front-end hardware. Finally, the relative time delay is measured using this correlation function. The relative time delay values are found by the exact same values of ‘Early’ and ‘Late’ correlation values. For typical GPS receivers, 1-chip spacing, which is the chip difference between the ‘Early’ and ‘Late’ correlation time, was used to obtain the precise time delays of the RF channels. The tracking resolution of the time delay was designed as 0.02 ns, which is very small because of post-processing.

A comparison of the two methods for relative time delay measurement is shown in Fig. 11. The maximum time delay difference between the RF channels is about 4 ns, which is equal to a 1.2 m error in distance. Only the relative time delays are meaningful for obtaining precise position in a GPS receiver because the common time delay is extracted to the receiver clock bias term of the navigation solution. Two independent methods of time delay measurement show similar results per RF channel. From this aspect, we determined that an accurate time delay of 1 ns precision can be measured and the RF time delays can be compensated using these measurements.

### 3.3. Precise time delay compensation

The previous section indicated the precise time delay measurement of 1 ns accuracy. Without time delay compensation, 4 ns time delays from array antenna RF channels will affect the position accuracy of a GPS receiver. However, if we compensate for the time delay, then only a 1 ns time delay will affect position accuracy. In this section, we propose a baseband linear interpolation time delay compensation algorithm for a GPS array antenna, as explained in Eq. (20) and Fig. 12. Baseband linear interpolation means linear interpolation with a 0 Hz IF frequency signal, and processing of the in-phase and quadrature phase signals:

\[
X'_{BB}(k) = \begin{cases} 
X_{BB}(k) + (X_{BB}(k + 1) - X_{BB}(k)) \div T \times \tau_D & \text{for } \tau_D \geq 0 \\
X_{BB}(k) - (X_{BB}(k) - X_{BB}(k - 1)) \div T \times \tau_D & \text{otherwise} 
\end{cases}
\]

(20)
where,

\[ X'_{BB}(k) = \text{Compensated signal at kth sample} \]
\[ X_{BB}(k) = \text{Baseband input signal} \]
\[ \tau_D = \text{Time delay to be compensated (s)} \]

Generally, interpolation is used to obtain the intermediate value between samples. From this property, the time delay shift can be made by replacing the original value \( X_{BB}(k) \) for the intermediate value \( X'_{BB}(k) \). Additionally, a baseband signal that has a 0 Hz center frequency and low-frequency signal is adequate to implement this linear interpolation algorithm. Different from the baseband signal, the IF signal has high-frequency components, and the linear interpolation algorithm does not normally work.

Linear interpolation error can be proven using Rolle’s theorem, as shown in Eq. (21).\(^{18}\) The error is proportional to the square of the time interval \( T \) and the second derivative of the baseband signal \( g(t) \).

\[
\text{Error} \leq \frac{1}{8} \max |g''(t)| \times T^2
\]  

(21)

The time delay compensation error is related to the above linear interpolation error, which has a connection with the sampling frequency and baseband signal characteristics. The time delay compensation error decreases further as the sampling frequency increases and the baseband signal bandwidth decreases. The main frequency component of the baseband signal has a sine wave of about 0.5 MHz, which is half the GPS C/A code chipping rate, as shown in Fig. 8. Using this frequency component signal and a 20 MHz sampling frequency, we can conclude that the maximum compensation error of the time delay is 25 ns, and the minimum is 0 ns in the important zero-crossing area of the sine wave because the second derivative is 0 in that area. The GPS signal is processed using 1- or 2-bit ADC quantization and the zero-crossing area is directly related to the range measurement. From this aspect, the linear interpolation is adequate and sufficient to compensate the time delays of the array antenna to near 0 ns. The compensation error can be reduced to the tracking resolution level of the GPS signal and verified by estimating the range measurement differences between channels after compensation.

### 4. Experiment

We conducted experiments to confirm the GPS signal loss phenomenon in the near jamming direction and the time delay compensation effect of RF channels. With the theoretical gain pattern shown in Fig. 3, we can predict beforehand that the GPS signal is lost in the near jamming direction. To confirm this side effect, we used a RF four-channel real-time CRPA simulator to emulate the array antenna input signals, as shown in Fig. 13.

The signals of the four RF channels were connected to the 4-array antenna system equipped with a GPS receiver that tracked the minimum 23 dB-Hz GPS signal. The jamming signal power was \( J/S = 70 \) dB and its direction was set at an azimuth angle of 80° and elevation angle of 32°, which was the near point in the direction of GPS satellite No. 2 at the time of GPS week 1873 and GPS 200,000 s.

Figure 14 shows the experiment results for the GPS satellite No. 2 \( \text{CN}_0 \) with an array antenna when there was a jamming signal. The blue dotted data shows the GPS receiver’s \( \text{CN}_0 \), and the red line data indicates the estimated \( \text{CN}_0 \) from the ideal gain pattern which has 1° resolution. The reason for the difference between the experiment data and gain pattern data is regarded as the error of the array antenna phase calibration. Despite this difference, we can confirm that the GPS signal located in the near jamming direction is lost because of the nullification pattern that eliminates the jamming signal.
From the lay between RF channels. The results are shown in Fig. 15. and tracking procedures again to obtain the relative time
tinction algorithm. Finally, we processed GPS signal acquisition
acquired in Section 3.2 using the baseband linear interpola-
for each ADC logging data set using the RF time delay data
a single channel simulator. We compensated the time delay
enna. We obtained a total of 20 ADC logging data sets using
of the RF time delay compensation algorithm of the array an-

5. Further Analysis of Position Accuracy

In the previous section, we obtained the experimental re-
results of an array nullification pattern and the time delay com-
penensation residuals when the array antenna is used for anti-
ings in this section, we do a further analysis of position
accuracy using the array antenna. The GPS receiver position
error is affected by the number of satellites and range mea-
urement accuracy. The number of usable satellites is related
to the array nullification patterns, including the gain patterns
of antenna elements, and the range measurement accuracy is
affected by the time delay compensation residuals.

Simulations were executed to obtain realistic statistical
results for the array antenna GPS receiver itself, and the sim-
ulation conditions were as follows. First, the jammer direc-
tion was chosen randomly and the power was set as I/S =
70 dB. Second, the real gain patterns of antenna elements
shown in Fig. 4 were used to obtain realistic results. Thir-
d, the default range measurement error was modeled using a
airborne model, AAD-A $\sigma_{it} = \sqrt{\sigma_{noise} + \sigma_{multipath}}$ of
the Local Area Augmentation System (LAAS), which was con-
irmed by real measurement data, and $\sigma_{noise}, \sigma_{multipath}$ are af-
fected by the GPS satellite elevation angle. Finally, an
additional range measurement error was added due to the
time delay compensation residuals assumed as 0.95 ns
RMS, which was obtained in the experiment and discussed
in Section 4. We also assumed the basic 24 GPS satellite con-
stellation Minimum Operation Performance Standard
(MOPS) or the current 31 GPS satellite constellation. In
these simulations, we focused only on the GPS receiver error
itself, not on systematic errors like satellite orbit, clock and
atmospheric delay errors. The reason for this limitation is that
the minimum basic error is important for furthering perform-
ance analysis of the extensively developing Advanced Re-
ceiver Integrity Monitoring (ARAIM) and Space-Based
Augmentation System (SBAS).

We repeated the scenarios 500 times using Monte Carlo
simulations and the statistical position error results are sum-
marized in Table 2. In a normal case that assumes no jam-
ing without an array antenna, the best horizontal and verti-
cal position accuracy can be achieved within a few
decimeters, but in the case of jamming, a GPS receiver with-
out an array antenna cannot derive a navigation solution. Dif-
frent from this situation, a GPS receiver with an array anten-
a without time delay compensation gives navigation
solutions that have larger errors.

Whereas, the position accuracy of the array antenna GPS
receiver with our time delay compensation algorithm is ac-
ceptable considering the accuracy of today’s Differential
GPS (DGPS). From these simulation results, we can confirm
that the minimum position error is inevitably increased when
an array antenna is used, but the error can be minimized.
6. Conclusion

In this paper, we analyzed the effects on the position accuracy of a GPS receiver using a precise time-delay-compensated array antenna to effectively overcome a jamming situation. The theoretical gain pattern for a four-array antenna was induced by the array signal-processing algorithm. Additionally, the experimental verification of GPS signal attenuation was presented by obtaining the satellite $C/N_0$ value in the near jamming direction. We also presented time delay measurement data in an array antenna using two independent methods, and showed the new precise baseband linear interpolation algorithm to compensate for the invariant RF time delays resulting in a 0.95 ns RMS error. Using the theoretically synthesized gain pattern with the measured pattern of antenna elements, and the time delay compensation results, we assessed the position error of the GPS receiver with an array antenna in jamming environments. The position error of the GPS receiver after compensation showed the possibility of implementing an accurate DGPS navigation system.

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References

1) Kaplan, E. D. and Hegarty, C. J.: Understanding GPS, Principles and Applications, 2nd Edition, Artech House, Norwood, 2006.
2) Misra, P. and Enge, P.: Global Positioning System Signals, Measurement, and Performance, Ganga-Jamuna Press, Lincoln, 2006.
3) Zhang, Y., Wu, T., Liu, Y., Han, Y., Fan, C., and Yasuda, A.: Evaluation of GPS/Beidou Integration Positioning Performance, Trans. Jpn. Soc. Aeronaut. Space Sci., 58 (2015), pp. 113–120.
4) Pullen, S., Gao, G., Tedeschi, C., and Warburton, J.: The Impact of Uninformed RF Interference on GBAS and Potential Mitigations, Proc. of Institute of Navigation International Technical Meeting, San Diego, USA, January 2012, pp. 780–789.
5) Park, D. B., Shin, D., Oh, S., and Kim, H.: Velocity Aiding-Based Anti-jamming Method for GPS Adaptor Kits, Trans. Jpn. Soc. Aeronaut. Space Sci., 54 (2011), pp. 130–136.
6) Fante, R. L. and Vaccaro, J. J.: Wideband Cancellation of Interference in a GPS Receive Array, IEEE Trans. Aerospace Electronic Syst., 36 (2000), pp. 549–564.
7) Alshrafi, W., Engel, U., and Bertuch, T.: Compact Controlled Recep-