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Design of Roll Rate Estimator using GPS Signal for Spinning Vehicle

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ABSTRACT

The present paper proposes a method that can estimate a roll rate of spinning vehicles utilizing GPS receivers. The proposed method analyzes a relation between received signal and correlation value and utilizes a phenomenon that received signal power that changes according to a signal incident direction affects a correlation value. That is, a roll-rate estimation method using zero crossing detection method for correlation value, which has sinusoidal periodicity according to rotations of vehicles, is proposed. A correlation value in real environments experiences a jitter so that the proposed method includes a pre-processing filter and detection threshold setting way is also considered to reduce the effect of received signal power. In order to verify the operation of the proposed method and analyze the performance, a signal generator and software-defined receiver (SDR) are designed. The signal generator generates intermediate frequency (IF) signal by taking the rotation of vehicles, antenna gain, and signal power into consideration, and a correlation value is acquired by taking the generated IF signals into consideration. Using the generated correlation value, the operation of the proposed roll rate estimation method is verified and the performance is analyzed.

Keywords: spinning vehicle, roll-rate estimation, GPS signal

1. INTRODUCTION

It is highly important to know location and attitude information of spinning vehicles such as ballistic missiles and shells to complete their mission. In general, location information is obtained from the global positioning system (GPS) or GPS/INS-integrated navigation systems and attitude information is acquired from the inertial navigation system (INS). However, since these spinning vehicles receive high G impact immediately after the time of launch and rotate at a high speed, the INS cannot be operated normally as it is deviated from the dynamic rage (Kim et al. 2009, Edwan et al. 2011). Due to the above reason, a number of studies on estimation of attitude information have been conducted and many measures including the use of additional sensors (pressure sensor, geomagnetic sensor, and accelerometer etc.) have been proposed (Rider 1985, Mickelson 2000, Schiffmann 2001, Doty & McGraw 2003, Lindquist & Kreichauf 2008, Changey et al. 2012). However, the use of additional sensors has drawbacks such as increases in system complex and additional cost.

To solve the drawbacks, Rockwell Collins, Inc. proposed a new method that used GPS receivers only that were installed in vehicles (Doty 2001, Doty & McGraw 2003, Doty et al. 2004). Their method estimated the rotation of spinning vehicles using changes in correlation value in GPS receivers according to rotations of vehicles, which had advantages of relatively low system complexity and low cost compared to other systems. However, their method had a limitation that a roll rate of vehicle must be known at the early time of operation to ensure reliable operation. The present paper proposes a method that can estimate a roll rate of spinning vehicles utilizing GPS receivers only without additional

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sensors. The proposed method is characterized by using a correlator of GPS receiver that uses only a single GPS antenna.

The present paper is organized with five sections. Section 2 analyzes a relation between received signal and correlation value when only a single GPS antenna is used and summarizes the effect of changing received signal power on correlation values according to the signal incident direction due to antenna gain. In addition, a method to estimate a roll angle of vehicles using GPS signals is briefly explained. Section 3 proposes an estimation method of roll rate using a relation between correlation value and signal incident direction and explains the operation principle and a method of how to derive a detection threshold. Section 4 presents simulations on various received signal powers using a signal generator to analyze the availability of the proposed estimation method of roll rate and operations of the proposed estimation method and performance evaluation are performed by calculation of correlator output through software-defined receiver (SDR). Section 5 presents the conclusion of the present paper.

2. CHARACTERISTICS OF GPS SIGNAL RECEPTION ACCORDING TO ROLLING OF SPINNING VEHICLES

The rapid rotation of spinning vehicles can generate a change in relative position between GPS satellite and GPS antenna. Since a GPS antenna is attached to the surface of the vehicle, a rotation of the vehicle affects the incident direction of the GPS signal. Changes in relative position and signal incident direction affect the Doppler of received signals and received signal power. Furthermore, since GPS receiver generates a correlation value by the product of received and replica signals, rotation of vehicles affects the correlation value.

2.1 Receiver Antenna Gain and Correlation Value

A signal model of the GPS L1 C/A code received from GPS satellites is presented in Eq. (1) (Misra & Enge 2006).

$$S(t)=\sqrt{2P_{rcv}}D(t-\tau)x(t-\tau)\cos(2\pi(f_{L1}+f_D)+\theta) \quad (1)$$

where P_{rcv}, $D(\bullet)$, $x(\bullet)$, f_{L1}, f_D, θ and τ refer to received signal power, navigation data, C/A code, L1 carrier frequency, Doppler frequency, carrier phase, and signal propagation time between GPS satellite and receiver. Since antenna gain is different depending on signal incident direction, received

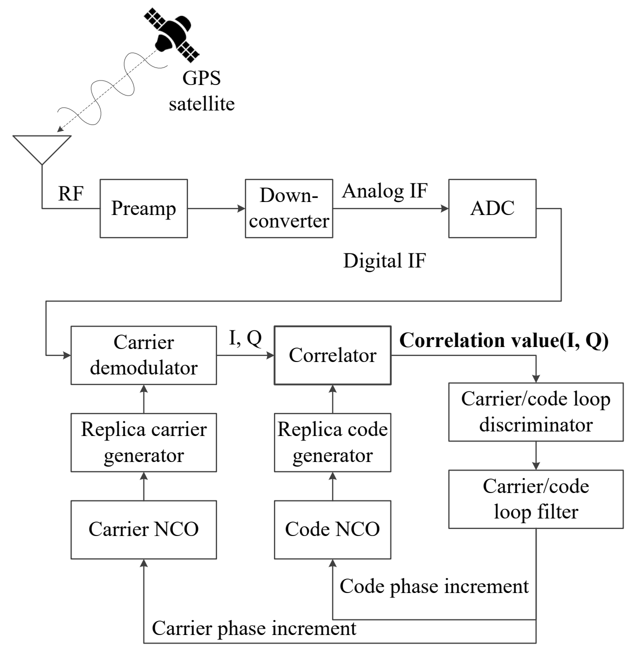

Fig. 1. GPS receiver structure.

signal power can be expressed by a product of signal power at the antenna location and antenna gain in the signal incident direction as presented in Eq. (2).

$$P_{rcv}=P_{sig}A(\phi) \quad (2)$$

where P_{sig}, A(•), and ϕ refer to signal power at the receiver location, antenna gain, and GPS signal incident angle based on the antenna.

Fig. 1 shows a typical structure of GPS receiver (Kaplan & Hegarty 2005). Down converted intermediate frequency (IF) signal is expressed as shown in Eq. (3) (Misra & Enge 2006).

$$S_{IF}=\sqrt{P_{sig}A(\phi)}D(t-\tau)x(t-\tau)\cos(2\pi(f_{IF}+f_D)+\delta\theta) \quad (3)$$

where f_{IF} refers to the IF and $\delta\theta$ refers to the carrier phase offset. The receiver generates a replica carrier and replica C/A code and then wipes off the carrier and C/A code from the received signal. During the process, the receiver adjusts the replica carrier's phase and replica C/A code's phase and synchronizes received signal and replica signal in the receiver. The IF signal is separated into in-phase channel signal $S_{IF,I}$ and quadrature channel signal $S_{IF,Q}$ during the demodulation process that wipes off carrier as indicated in Eq. (4) (Misra & Enge 2006).

$$S_{IF,I}=\sqrt{P_{sig}A(\phi)}D(t-\tau)x(t-\tau)\cos(2\pi\Delta f_D t+\Delta\theta)$$
$$S_{IF,Q}=\sqrt{P_{sig}A(\phi)}D(t-\tau)x(t-\tau)\sin(2\pi\Delta f_D t+\Delta\theta) \quad (4)$$

where Δf_D refers to a difference between true Doppler and estimate of the receiver's Doppler and $\Delta\theta$ refers to a difference between $\delta\theta$ and phase estimate $\hat{\theta}$ of receiver. $S_{IF,I}$ and $S_{IF,Q}$ refer to inputs of the correlator and the correlator outputs the value as shown in Eq. (5) (Misra & Enge 2006).

$$S_I(\Delta\tau, \Delta f_D, \Delta\theta) = \frac{\sqrt{P_{sig}A(\phi)}D}{PIT}\int_0^{PIT} x(t-\tau)x(t-\hat{\tau})\cos(2\pi\Delta f_D t + \Delta\theta)dt$$
$$S_Q(\Delta\tau, \Delta f_D, \Delta\theta) = \frac{\sqrt{P_{sig}A(\phi)}D}{PIT}\int_0^{PIT} x(t-\tau)x(t-\hat{\tau})\sin(2\pi\Delta f_D t + \Delta\theta)dt \quad (5)$$

Here, *PIT* refers to a predetection integration time.

Assuming that replica signal is synchronized with input signal ($\Delta\tau = \tau - \hat{\tau} = 0$, $\Delta f_D = 0$, $\Delta\theta = 0$), correlation value $|S|$ can be represented by the product of received signal power and antenna gain as shown in Eq. (6) (Misra & Enge 2006).

$$|S|^2 = S_I^2 + S_Q^2 = P_{sig}A(\phi) \quad (6)$$

An output value in the correlator includes term $A(\bullet)$ by which it can be seen that antenna gain affects the correlation value.

2.2 Changes in Correlation Value Due to Vehicle Spinning

Normally, antennas have different antenna gains according to signal incident directions and received signal power is different depending on antenna gains. Since spinning vehicles are rotated continuously, signal incident directions are also changed continuously thereby changing received signal power of vehicles continuously as well. Since received signal power is represented in correlation values due to the characteristics of the GPS, the rotation of spinning vehicles is expressed as changes in correlation values. The geometry between spinning vehicle and GPS satellite is shown in Fig. 2. By the geometry, changes in incident direction as well as antenna gains occur due to the rotation of vehicles. In Fig. 2, **n** refers to a vertical vector to the incident surface of the GPS patch antenna, **m** refers to a LoS unit vector between spinning vehicle and satellite, and ϕ refers to an angle (incident angle) between **n** and **m**.

Fig. 3 shows a distribution of the antenna gains typical patch antennas have. Here, 0 degree (°) refers to the vertical direction of the incident surface in the GPS receiver antenna. The antenna gain is reflected in term $A(\bullet)$ in Eq. (6).

A change in correlation value according to attitude change in vehicle can be summarized based on incident angle ϕ, which is shown in Fig. 4. Fig. 4a shows a graph of patch antenna gain distribution in the ϕ and $A(\bullet)$ axes and Fig. 4b shows the results of correlation value by reflecting antenna gains according to ϕ to the replica of received

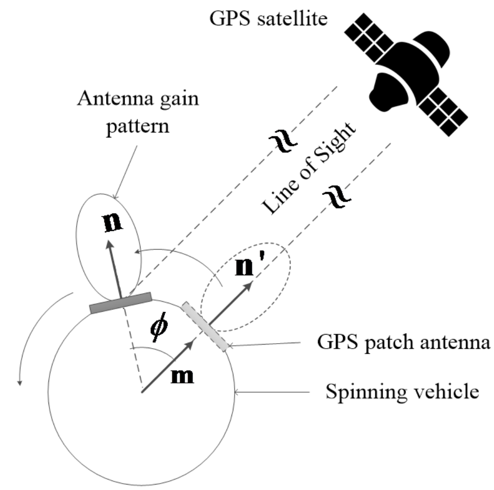

Fig. 2. Geometry between spinning vehicle and GPS satellite.

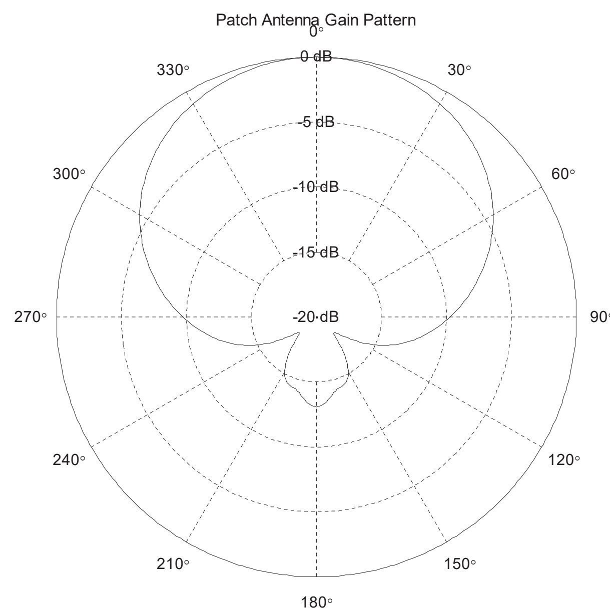

Fig. 3. Patch antenna gain pattern.

signal. When incident angle ϕ is 0°, GPS antenna gain becomes 0 dB thereby obtaining the largest correlation value and when ϕ is changed from 0° to ±90°, GPS antenna gain becomes -10 dB thereby obtaining gradually reduced correlation value. At a section where incident angle ϕ is deviated from ±90°, GPS signals can be rarely received, resulting in obtaining a correlation value of noise level.

The aforementioned attitude change in vehicle refers to the rotation of spinning vehicles. When a vehicle is rolled, an incident angle ϕ of the GPS signal has periodicity with a sinusoidal wave type. When an incident angle ϕ has periodicity, received signal power has also periodicity by antenna gain, which is then followed by correlation values with periodic characteristic. Fig. 5 shows changes

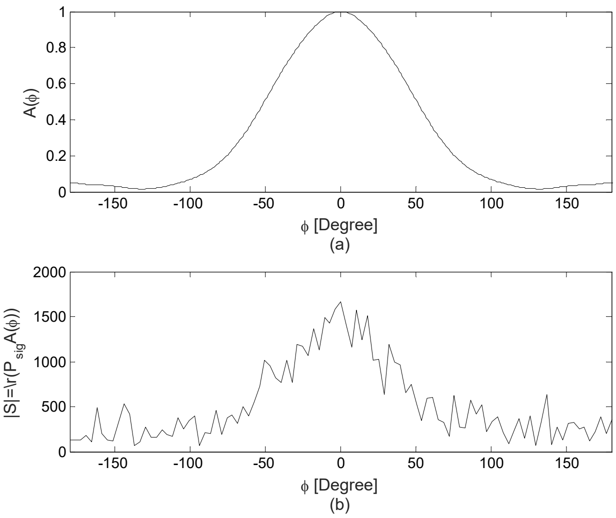

Fig. 4. Relations between antenna gain and correlation value, (a) Antenna gain, (b) Correlation value.

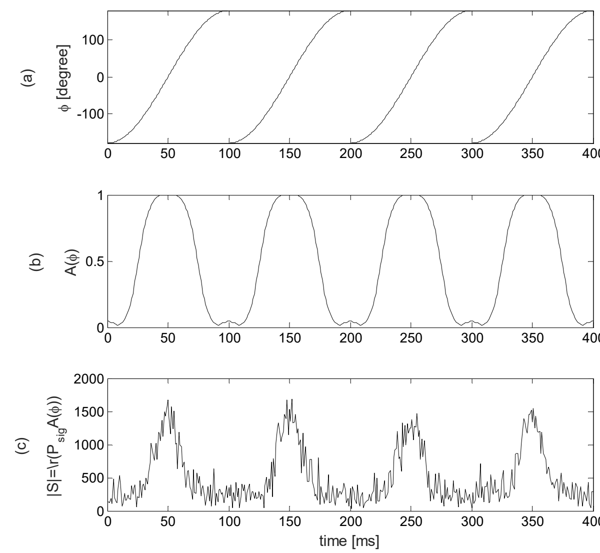

Fig. 5. Correlation value according to the rotation of spinning vehicle. (a) Incident angle, (b) Antenna gain, (c) Correlation value

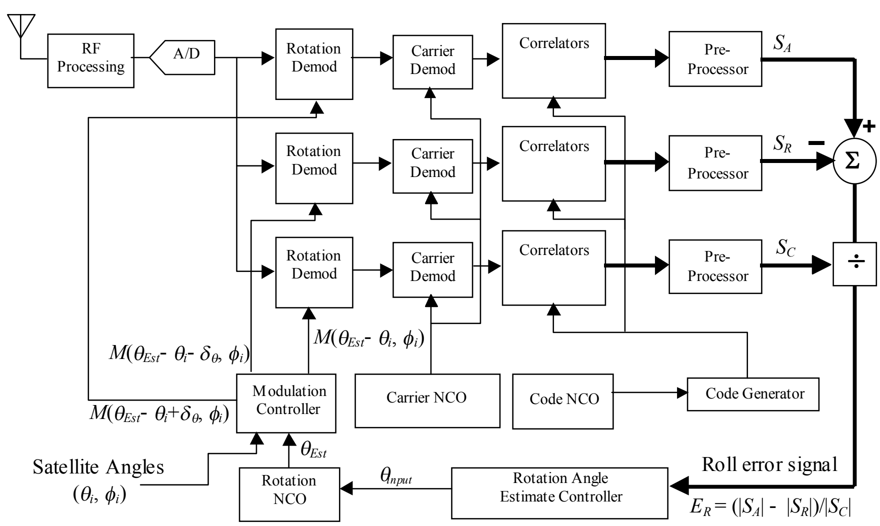

Fig. 6. Diagram of GPS signal processing modifications for rotation tracking.

in correlation values according to the rotation of spinning vehicles. Fig. 5a shows changes in incident angle ϕ according to the rotation of spinning vehicles and Fig. 5b shows changes in antenna gain according to changes in incident angle. Fig. 5c shows changes in received signal power due to changes in antenna gain in the name of correlation value.

In addition, received signal power is also changed in environments where an incident direction of signal is changed on the basis of rotational axis direction of vehicle. Nonetheless, a pattern of changes in correlation value is maintained despite the fact that a change in correlation value is changed according to the rotation of spinning vehicle as an incident direction is changed on the basis of the rotational axis direction. Thus, a pattern of correlation values will have a similar shape as shown in Fig. 5c upon the reception of GPS signals at spinning vehicles in all directions unless signal power is too weak.

2.3 Estimation Method of Roll Angle

Rockwell Collins, Inc. proposed a method that estimated a roll angle of spinning vehicles using only GPS signals without using additional sensors. Their method added a tracking function of rolling vehicle to a general structure of GPS receiver, which is shown in Fig. 6 (Doty 2001). However, their method must know a roll rate of spinning vehicles at the initial operation time in order to be run reliably, which required an additional roll rate estimation method.

3. ESTIMATION ON ROLL RATE

3.1 Estimation Method of Roll Rate

A change in correlation value according to the rotation of spinning vehicle is affected by a roll rate. Therefore, if a period of changes in correlation value can be estimated from GPS receiver in spinning vehicles, a roll rate of spinning vehicle can be estimated. In this section, a method that estimates a roll rate of spinning vehicle is proposed using changes in correlation values in GPS receivers. The estimation method of roll rate employs a zero-crossing detection method. The method detects a section where correlation value and detection threshold value are crossed on the basis of pre-set detection threshold thereby estimating a roll rate of spinning vehicles. The proposed estimator assumes that the operation is run over environments where GPS signals can be received. Without GPS signals, a zero-crossing section cannot be detected so that the proposed estimator cannot be run. Fig. 7 shows an estimation procedure of the roll rate estimator in an ideal environment.

The roll rate estimation process is conducted as follows: In an ideal environment, a correlation value is crossed with the detection threshold at ⓐ and ⓑ sections in the rising (A) and falling (B) regions, respectively as shown in Fig. 7. Since ⓐ cross and ⓑ cross are located at the same distance from the maximum correlation value, a position of mid-point ⓒ can be estimated using ⓐ and ⓑ. Here, a correlation value at ⓒ becomes the maximum value. Assuming that $ⓒ_k$ is a time that correlation value becomes maximum upon the k-th rotation of a vehicle and $ⓒ_{k+1}$ is a time of maximum correlation value upon the k+1-th rotation, the number of samples upon one-rotation of vehicle can be obtained through a difference in two times $\Delta ⓒ = ⓒ_{k+1} - ⓒ_k \triangleq ⓓ_{k+1}$. In general, since a correlation value is calculated based on 1 ms period at GPS receiver, T_{roll} can be converted to a time as shown in Eq. (7) and a time to take one rotation of vehicle can be acquired.

$$T_{roll} = ⓓ \times 1\,\text{ms} \tag{7}$$

Since a correlation value can be obtained based on 1 ms period, ⓐ and ⓑ can have an error within 1 ms. Considering an error in ⓐ and ⓑ, ⓒ and ⓓ can be re-calculated as shown in Eqs. (8) and (9).

$$\begin{aligned} ⓐ' &= ⓐ + \deltaⓐ \\ ⓑ' &= ⓑ + \deltaⓑ \\ ⓒ' &= (ⓐ' + ⓑ')/2 \\ &= (ⓐ + \deltaⓐ + ⓑ + \deltaⓑ)/2 \\ &= ⓒ + \deltaⓒ \end{aligned} \tag{8}$$

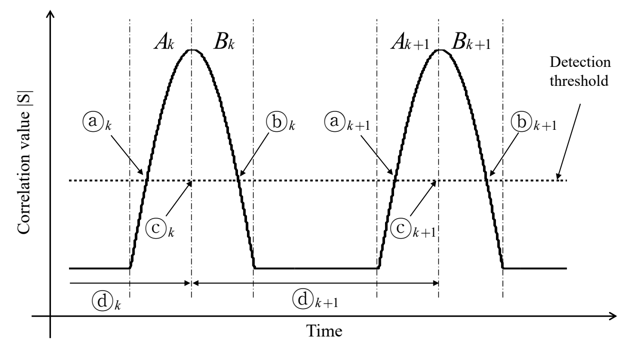

Fig. 7. Roll rate estimate process.

$$\begin{aligned} ⓓ'_{k+1} &= ⓒ'_{k+1} - ⓒ'_k \\ &= ⓒ_{k+1} + \deltaⓒ_{k+1} - ⓒ_k - \deltaⓒ_k \\ &= ⓓ_{k+1} + \deltaⓓ_{k+1} \end{aligned} \tag{9}$$

where the superscript $()'$ refers to a value including an error and δ refers to a corresponding error. Since errors $\deltaⓐ$ and $\deltaⓑ$ are less than 1 ms, error $\deltaⓒ$ is less than 1ms and error $\deltaⓓ$ is less than 2 ms. A theoretical estimation performance according to roll rate of spinning vehicle is as follows based on Eqs. (8) and (9): Since $ⓓ_{k+1}$ has a larger value than error $\deltaⓓ_{k+1}$ in a relative sense when a vehicle is rotated at a slow speed, the accuracy of estimation on roll rate is increased. On the other hand, when a vehicle is rotated at a high speed, an effect of error $dⓓ_{k+1}$ on roll rate estimation is increased thereby reducing the accuracy of estimation on roll rate.

Furthermore, since a pattern of changes in correlation value according to spinning vehicles is maintained even at environment where rotational axis direction of vehicles and signal incident direction are changed, signal incident direction does not impact on estimation on ⓓ significantly. Moreover, since a correlation value used in estimation on roll rate is calculated with 1 kHz rate, a maximum roll rate that can be estimated theoretically is 500 Hz according to the Nyquist criterion.

A correlation value at real environments will have a jitter since the receiver and signal reception environments are not ideal. More than two or more cross points can occur between correlation value and detection threshold at each section of A and B in case that a correlation value where a jitter occurs is used. If more than two or more cross points occur, it is difficult to predict ⓒ point and a roll rate estimation error will increase too. To overcome this, the effect of jitter of correlation value can be reduced through pre-processing procedure using a moving average filter before the roll rate estimation method is applied. A moving average filter in the pre-processor employs a fixed size window. Fig. 8 shows the result where jitter of correlation value is reduced due to the pre-processor. Here, Fig. 8a shows the output of correlator of SDR using replica signals by reflecting spinning vehicles and Fig. 8b shows the output of the pre-processing filter. In summary, jitters in correlation value can be reduced through pre-processing.

Since a low frequency component of jitter is still remained at a correlation value immediately after the correlator, cross points ⓐ and ⓑ can be duplicate at each of *A* and *B* sections. Each of the cross points are undergone through the detection reliability test considering the duplicate case of cross points ⓐ and ⓑ, and cross points with high reliability are used as data in the roll rate estimation method. The roll rate estimation method consists of rolling detection part and roll rate estimation part in addition to the above-mentioned parts. The rolling detection part determines whether vehicle is rotated for the estimation method of roll rate and the roll rate estimation part obtains ⓓ and estimates a roll rate by acquiring T_{roll} using Eq. (7). An overall structure of the roll rate estimation method is shown in Fig. 9.

3.2 Setup of Detection Threshold

Since signal power varies according to signal reception environment, a correlation value is affected by the reception environment. Since a correlation value is used in the roll rate estimation method, the method is affected by the reception environment as well. That is, a correlation value becomes smaller when received signal power is low depending on signal reception environment so that changes in correlation values according to the rotation of spinning vehicle may not be detected. In order to run the proposed estimation method reliably, detection threshold can be reduced even at low-power environments, which will cause the degradation of estimation performance due to correlation values of noise level. In order to overcome the effect of reception environment, how to derive the detection threshold is proposed in this section. This method employs a false alarm probability to reduce the effect of signal power as well as false detection probability due to noise (Kaplan & Hegarty 2005).

In order to derive an appropriate threshold, three reception environments are assumed. The first reception environment is where noise-reflected signal power is the maximum, the second environment is where the spinning operation of vehicle is added, and the third environment is where only noise is present. A correlation value after pre-processing is obtained at the above-assumed three environments and each probability distribution of

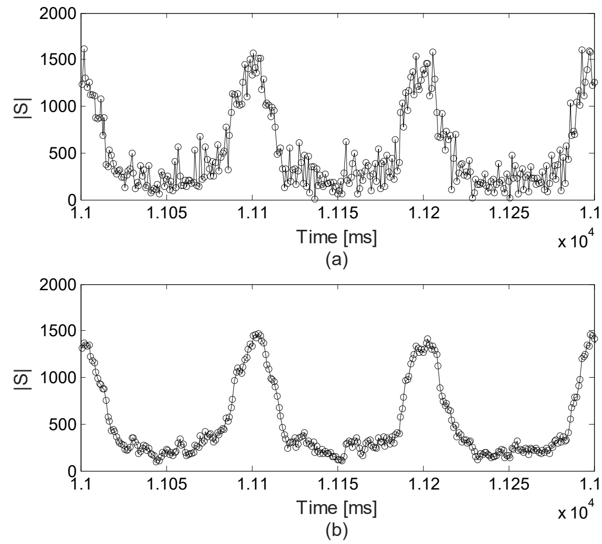

Fig. 8. Correlation value, (a) in real environment, (b) about filtered result.

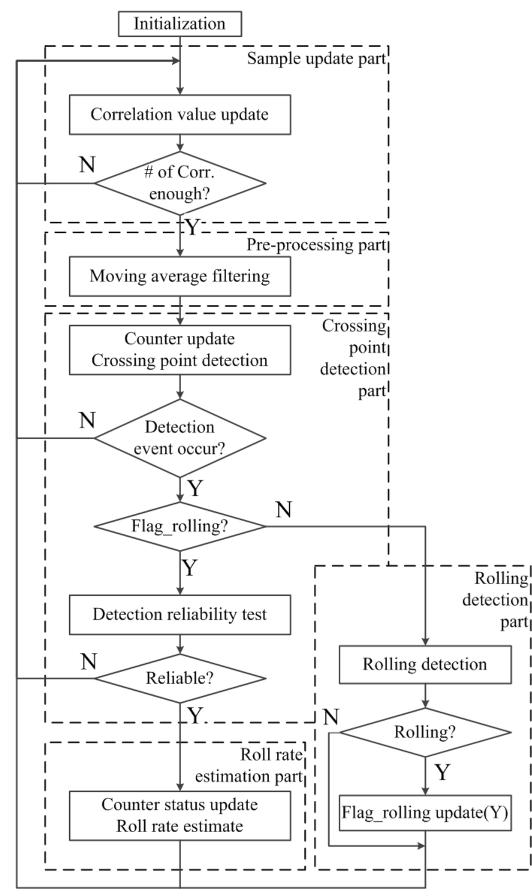

Fig. 9. Roll rate estimate flow.

correlation value at the three environments is derived, which is shown in Fig. 10.

In Fig. 10, the reception environment refers to the maximum antenna gain, in which there is an environment where continuous signals are received, an environment

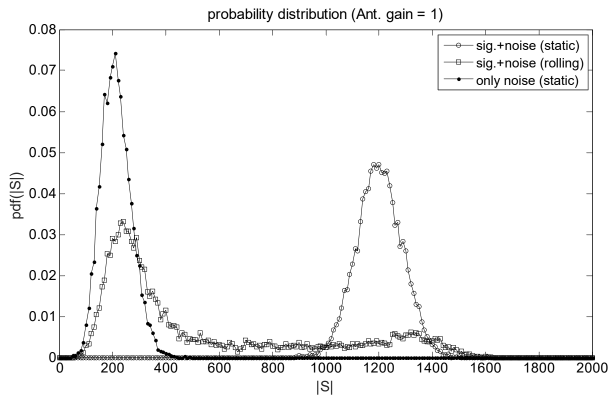

Fig. 10. Probability distribution with respect to |S|.

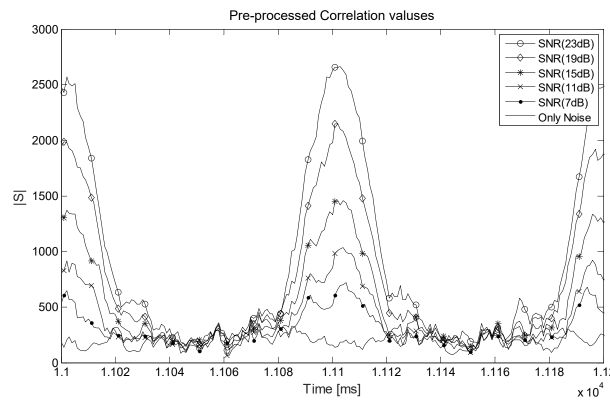

Fig. 11. Moving average filtered correlation values.

where a vehicle performs constant-speed rotating motion, and an environment where only noise is present. In the first environment where signals are received with the maximum antenna gain, a correlation value has high probability distribution at a section where a correlation value is 1000 or larger. In the second environment where a vehicle performs constant-speed rotating motion, a correlation value has a high probability distribution at a section where a correlation value is less than 400 and up to 1400 showing a similar low distribution. In the third environment where only noise is present, a high probability distribution is revealed at a section where a correlation value is 400 or smaller. In the first and second environments, a probability distribution section is expected to be variable according to reception environments and changes in probability distribution according to reception environments could give difficulties in setting a detection threshold. However, since a correlation value with respect to noise is not affected by reception environments significantly, false alarm according to reception environments can be reduced if a detection threshold is set based on false alarm probability with respect to noise. Therefore, a detection threshold is set to have false alarm probability to be minimized based on environments where only noise is present.

4. SIMULATION

4.1 Environment

To validate the proposed estimation method and analyze the performance, a signal generator and GPS SDR were employed. The signal generator generates 20 sec-long IF signals, which do not rotate at the initial 10-sec section while acquiring and tracking the signals. A scenario is set to have rotations immediately after 10 sec. Here, the signal generator generates IF signals taking spinning vehicle model, antenna gain pattern, and Signal-to-noise ratio (SNR) into consideration. The spinning vehicle model takes into consideration an environment where roll rate of vehicles is 10 Hz and the rotational axis of vehicle is perpendicular to the GPS signal incident direction. Only one antenna is used and antenna gain pattern employs the patch antenna gain pattern as shown in Fig. 4. In order to analyze the operation performance of the roll rate estimator according to received signal power, SNR is set to have 5 dB to 23 dB at 2 dB interval. The SDR receives generated IF signals and produces an output of correlation value at 1 ms period. The produced correlation value is undergone through the pre-processing procedure and used as input values in the proposed roll rate estimation method. The operations of the proposed method are validated and performance is evaluated through the results of the proposed estimation method.

Fig. 11 shows correlation values after pre-processing procedure for some replica signals according to SNR, in which a size of correlation value varies according to SNR. Furthermore, a correlation value is reduced to a level of correlation value with respect to noise at a section where GPS signals cannot be received according to the rotation of spinning vehicle.

A false alarm probability was set to 10^{-2}, 10^{-3}, and 10^{-4} in order to determine a detection threshold. In Subsection 4.2, the result of setup of detection threshold was summarized according to false alarm probability and results of verification and performance evaluation of the proposed roll rate estimator were analyzed according to SNR and false alarm probability.

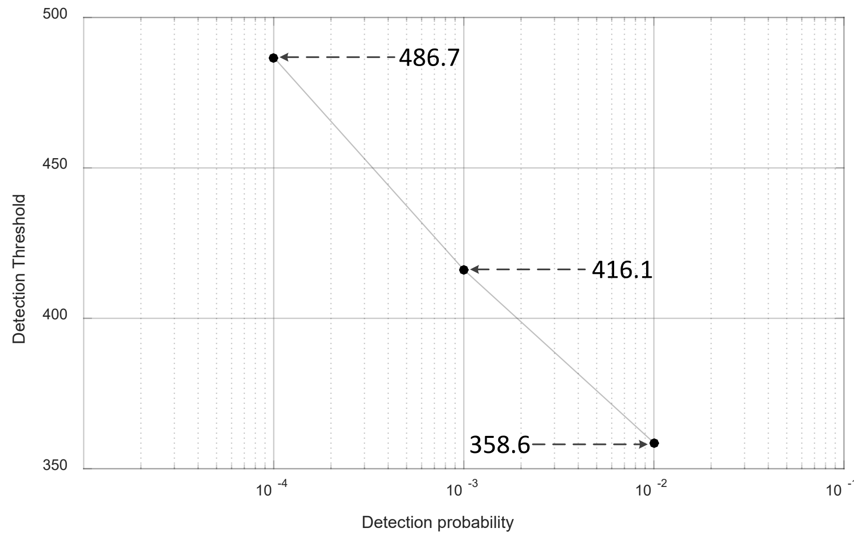

Fig. 12. Detection threshold corresponding to the detection probability.

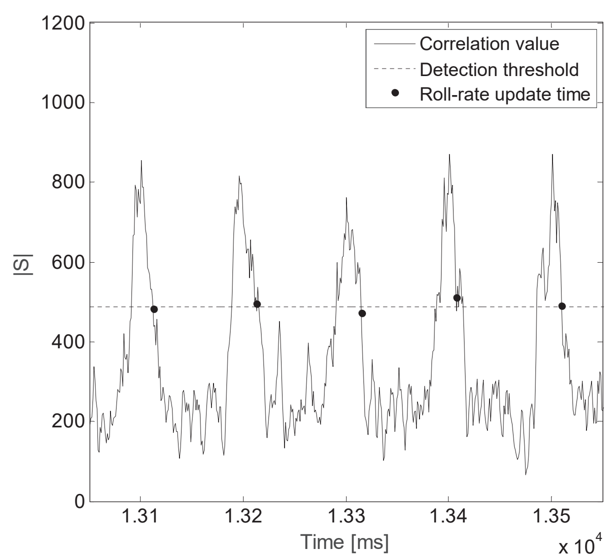

Fig. 13. Result of the roll rate estimation.

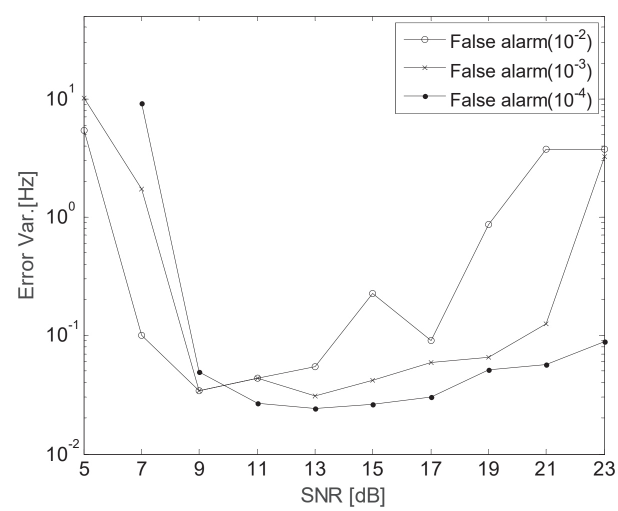

Fig. 14. Error variance of the roll rate estimate.

4.2 Results of Roll Rate Estimation

A detection threshold is needed to be set using false alarm probability prior to using the roll rate estimator. A detection threshold that satisfied a false alarm probability was derived using a correlation value with respect to noise, which is shown in Fig. 12. The detection threshold was derived as 358.6, 416.1, and 486.7 at 10^{-2}, 10^{-3}, and 10^{-4}, respectively.

The result of the roll rate estimation while vehicle is rotated is shown in Fig. 13 in order to verify whether the proposed method is operated correctly. In Fig. 13, A correlation value and detection threshold were crossed periodically while a vehicle was rotated and a roll rate of vehicle was estimated at every cross point where correlation value was reduced. A variance of estimation error according to signal intensity and false alarm probability is shown in Fig. 14.

A section whose SNR is less than 8 dB is considered as low power reception environment whereas a section whose SNR is more than 20 dB is considered as high power reception environment considering that SNR of GPS signals at general signal reception environment is ranged between 14 dB and 16 dB. The result of roll rate estimation at a section whose SNR was less than 8 dB had an error of 1 Hz or larger mostly regardless of which false alarm probability was satisfied. However, the roll rate estimation method failed roll rate estimation at an environment whose SNR was

5 dB when false alarm probability was 10^{-4}. The estimation performance in general reception environments had an error variance of 0.1 Hz or smaller mostly whereas an error variance of estimation became degraded due to large estimation error at high power reception environments. Except for low-powered reception environment, false alarm probability was 10^{-4}, which showed the best detection performance when detection threshold was taken into consideration. On the other hand, the lowest detection performance was revealed at 10^{-2}. A correlation value was high at a section where an incident angle of GPS signal was around 0° at the low-powered reception environment as shown in a low SNR environment but was close to the detection threshold. However, a cross point between correlation value and detection threshold was affected by noise significantly thereby causing a high estimation error. In contrast, a correlation value was also increased as received signal power was increased at a section (11.12 ~ 11.13 sec in Fig. 11) where an incident angle of GPS signal was around 70°~100° thereby producing an error at cross point detection between correlation value and detection threshold, resulting in degradation of the rate roll estimator at high powered reception environment. In the simulation result, the proposed roll rate estimator had different estimation performance according to signal reception environment and detection threshold but possibility of roll rate estimation of spinning vehicles can be verified.

5. CONCLUSION

In this paper, an estimation method of roll rate of spinning vehicles was proposed using a correlation value of GPS receivers at environments where only single GPS antenna was used. The proposed method detected a crossing point where changes in correlation value according to the rotation of spinning vehicle and detection threshold that satisfied false alarm probability were crossed to estimate a roll rate of spinning vehicle. To analyze the performance of the proposed estimation method, simulations were conducted to verify availability by setting a number of false alarm probabilities and received signal power. Although degradation in estimation performance was revealed depending on reception environments, a roll rate of spinning vehicle can be estimated mostly. At a low-powered reception environment where degradation in performance was significant, the maximum value of correlation value and detection threshold became close to each other so that the proposed method showed a low increase in errors of crossing detection. Furthermore, a correlation value was close to a constant at a section whose incident angle of GPS signal was around 70°~100° at a high-powered reception environment where performance degradation occurred, which was deemed to be affected by the preprocessing filter. It is expected that the proposed roll rate estimator will have a significant performance improvement if a smoothing filter that is appropriate for the pre-processor is used.

The proposed roll rate estimator can be employed to estimate a roll rate of spinning vehicles without using additional sensors at general circumstances except for special environments. For future research, a study on solution of exceptional cases at specific angles at high-powered or low-powered environments will be conducted.

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