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Expected RGDOP Based Satellite Selection Scheme for Performance Improvement of Precise Float Solution

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ABSTRACT

In this paper, the positioning performance index is proposed. The proposed index is used to find satellites that degrade positioning performance to improve the positioning performance. To do this, the proposed index is calculated using the code measurement quality and the DOP. And, through the experiment, the effectiveness of the proposed index is confirmed. In the experiment, the quality of the code measurements is analyzed, and the effectiveness of the proposed index is confirmed by comparing with the result of the precise float solution. Finally, it is shown that the precise float solution performance is improved by using the proposed index.

Keywords: precise positioning, measurement quality, dilution of precision

1. INTRODUCTION

The satellite navigation system is a typical system that provides Positioning, Navigation, and Timing (PNT) information and is widely used in various fields and daily life from industrial infrastructure to personal mobile phones. Research on precise positioning using Global Navigation Satellite System (GNSS) is also being performed in the field of land transportation. Positioning that could not distinguish traffic lanes in the past developed into precise positioning that distinguish traffic lanes today. Precise positioning is a positioning technique that uses code measurements as well as carrier phase measurements, which begins with precise positioning techniques in the fields of geodesy and surveying (Leick et al. 2015). However, the land transportation environment has difficulties in receiving GNSS signals due to structures such as skyscrapers which in turn degrades the precise positioning performance. In order to overcome this problem, solutions that use a single satellite navigation system are evolving into multi-GNSS that combine other satellite navigation systems such as China's BDS and Russia's GLONASS. Research on multi-GNSS solutions offers the advantage of securing more visible satellites than when using a single satellite navigation system and thus improving positioning environments. However, when performing research on multi-GNSS solutions, a way to find the combination of satellites that optimize the positioning performance should be considered. Recent studies on satellite selection schemes include the chaotic particle swarm optimization (CPSO)-based satellite selection method (Wang et al., 2018) and multi-Constellation Weighted DOP (MWDOP)-based satellite selection method (Kim et al. 2018). The CPSO-based satellite selection scheme proposed by Wang et al. (2018) is more adaptive than other algorithms and is capable of fast satellite selection. The MWDOP-based satellite selection scheme proposed by Kim et al. (2018) is a method that uses MWDOP sensitivity, which provides better performance than using dilution of precision (DOP) sensitivity.

In this paper, we propose a positioning performance index which considers the measurement quality and satellite

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positioning information to improve precise positioning performance. This study also proposed a measurement quality index that indicates the measurement quality to be reflected in the positioning performance index. The measurement quality refers to the delay locked loop (DLL) tracking error reflected in the code measurement and is influenced by the strength of the received signal. This paper is composed of 6 chapters. Chapter 2 analyzes the strength of the received signal and the quality of the code measurements according to the elevation angle and proposes a measurement quality index based on this. Chapter 3 describes the relationship between the accuracy of the float solution and the success rate of the fixed solution in precise position technology. Chapter 4 proposes a precise positioning performance index to improve precise positioning performance. Chapter 5 demonstrates the effectiveness of the proposed precise positioning performance index by using actual measurements and shows that the precise positioning performance improved when using the proposed index and Chapter 6 draws the conclusion.

2. MEASUREMENT QUALITY ANALYSIS FOR PRECISE POSITIONING

The relative positioning-based precise positioning solution uses the measurement which is the difference between the reference station measurement and user measurement. The differences between the receivers and the satellites were performed when differencing the measurements. The difference between the receivers has the effect of removing the error components such as the satellite clock error, the ionospheric delay, and tropospheric delay included in the measurement, and the difference between the satellites has the effect of removing errors generated at the receiver side. The power of the received signals varies according to the incident direction of the satellite signal and the tracking loop performance changes according to the received signal power, and the tracking error of the tracking loop is shown as a component of the measurement error. Since the tracking error is not a bias, it cannot be removed by differencing the measurements. Therefore, this section analyzed the measurement quality which indicates the measurement error, through the relationship between the received signal incidence angle, received signal power, and DLL jitter.

2.1 The Relationship Between The Elevation Angle and Received Signal Power

The measurement is influenced by the received signal power, resulting in changes in the quality of the measurement. The received signal power changes according to the elevation angle at which the satellite signal is received. Factors influencing the change of received signal power according to the elevation angle can be divided into the geometric distance between the receiver and satellite and the changes in gain of the transmitting and receiving antenna according to the elevation angle.

The geometric distance between the receiver and satellite is close when the elevation angle is high, and far when the elevation angle is low. However, since the transmission antenna is designed to have similar received signal power at the nearest and farthest points to the reception point when transmitting signals from satellites, the change in received signal power due to the geometric distance is considered to have a minimal effect on the measurement quality (Kaplan & Hegarty 2005).

Second, the power of the received signal is changed by the changes in gain of the receiving antenna according to the elevation angle. The GNSS reception antenna has the highest gain when the elevation angle is high and the lowest gain when the elevation angle is low. The difference between the antenna gains when the elevation angle is high and when the elevation angle is low is about 10dB with respect to commercial receivers. In other words, the received signal power according to the elevation angle is more influenced by the antenna gain change according to the elevation angle than by the geometric distance change between the satellite and receiver (Kaplan & Hegarty 2005).

2.2 The Relationship Between The Received Signal Power and Measurement Quality

In order to analyze the correlation between received signal power and measurement quality, it is necessary to know the process from the point of receiving the GNSS signal to generating the measurement.

GNSS signals are sent to the GNSS receiver via the GNSS reception antenna and the intermediate frequency (IF) signals are obtained through the RF front-end of the GNSS receiver. IF signals are multiplied by the replica code and replica carrier and then transported to the correlator. The correlator output is used to acquire and track the GNSS signals. The GNSS receiver then keeps track of the GNSS signals and collects the positioning data and synchronizes it with the positioning data to generate measurements of the corresponding satellite at the GNSS receiver. In order to maintain signal tracking in the GNSS receiver, a DLL and a frequency locked loop (FLL) or phase locked loop (PLL) is used and the correlation value is used as input for the DLL

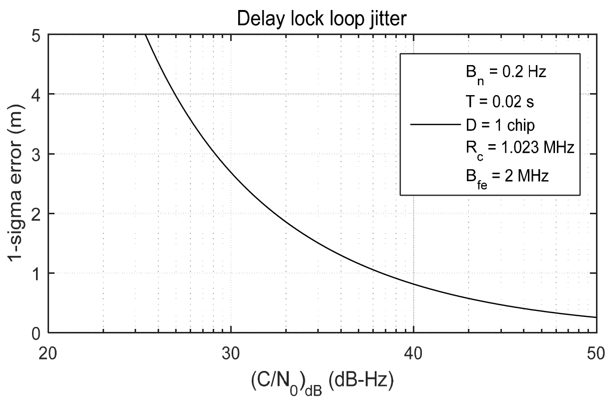


Fig. 1. Delay lock loop jitter versus C/N_0.

and FLL/PLL to maintain synchronization between the received signal and replica signal.

GNSS signal tracking must be maintained to obtain measurements, and changes in the power of the received signal affect the discriminating performance of the discriminator, which in turn leads to the loop filter and affects the signal tracking performance. For example, when the received signal power is low, the influence of the noise on the correlation value increases relatively which causes a large jitter in the output of the discriminator, which in turn increases the signal tracking errors and eventually degrades the quality of the measurement. On the other hand, when the received signal power is high, the influence of noise on the correlation value relatively decreases, which reduces the jitter in the discriminator output, and the reduced jitter improves the measurement quality by reducing the signal tracking errors. Therefore, when the received signal power is high, the quality of the measurement is improved, and when the received signal power is low, the quality of the measurement is reduced (Kaplan & Hegarty 2005).

The DLL error (σ_{DLL}) can be expressed as a function of the received signal power as shown in Eq. (1) (Kaplan & Hegarty 2005).

$$\sigma_{DLL} = \begin{cases} \sqrt{\dfrac{B_n}{2C/N_0} D\left[1+\dfrac{2}{TC/N_0(2-D)}\right]} & , D \geq \dfrac{\pi R_c}{B_{fe}} \\ \sqrt{\begin{array}{l}\dfrac{B_n}{2C/N_0} D\left[1+\dfrac{2}{TC/N_0(2-D)}\right] \\ \times\left(\dfrac{R_c}{B_{fe}}+\dfrac{B_{fe}}{R_c(\pi-1)}\left(D-\dfrac{R_c}{B_{fe}}\right)^2\right)\end{array}} & , \dfrac{R_c}{B_{fe}} < D < \dfrac{\pi R_c}{B_{fe}} \\ \sqrt{\dfrac{B_n}{2C/N_0}\left(\dfrac{R_c}{B_{fe}}\right)\left[1+\dfrac{1}{TC/N_0}\right]} & , D \leq \dfrac{R_c}{B_{fe}} \end{cases} \tag{1}$$

where C/N_0 is the received signal power, B_n is the code loop noise bandwidth (Hz), D is the E-L correlator chip spacing (chips), T is the integration time, B_{fe} is the front-end double side-band bandwidth (Hz), and R_c is the chip rate.

The DLL error according to the received signal power can be obtained using Eq. (1) as shown in Fig. 1. In Fig. 1, the horizontal axis represents the received signal power and the vertical axis indicates the DLL error. The DLL error increases as the received signal power decreases, and the DLL error decreases as the received signal power increases. Since the DLL error is reflected in the measurement error, the impact on the measurement quality according to the received signal power can be inferred through Fig. 1.

2.3 Measurement Quality Analysis Using Actual Measurements

The changes in the measurement quality according to the elevation angle analyzed in Section 2.1 and 2.2 were analyzed using actual measurements. To analyze the quality of the measurement, this study used double difference measurements, because it was easy to analyze the measurement quality according to the elevation angle by removing other components other than those for measurement quality.

The measurement model simulating the measurements can be expressed as Eq. (2) (Misra & Enge 2006).

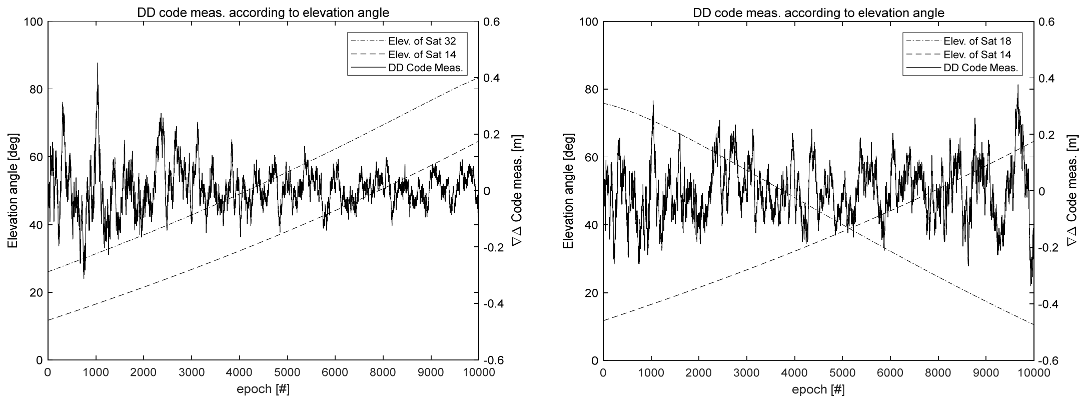
$$\rho_u^i = r_u^i + c \times \delta t_u^i + T_u^i + I_u^i + \varepsilon_u^i \tag{2}$$

where ρ is the code measurement, r is the geometric distance between the receiver and satellite, c is the speed of light, δt is the clock error, T is the tropospheric delay error, I is the ionospheric delay error, ε is the residual error, subscript u is the receiver, superscript i is the satellite, and the influence of the multipath signals is ignored. At this time, the residual error includes the components of the quality of the measurements to be observed and analyzed in this section. Double difference calculation was performed on the measurements because removing or minimizing the effects of any component other than the components associated with measurement quality of the measurement makes it easier to analyze, and the double difference measurement model can be expressed as Eq. (3). At this time, a zero baseline was assumed to remove other components (Misra & Enge 2006, Zekavat & Buehrer 2012).

$$\rho_{ur}^{ij} = \left(\rho_u^i - \rho_r^i\right) - \left(\rho_u^j - \rho_r^j\right) = \varepsilon_{ur}^{ij} \tag{3}$$

Next, this study used Eq. (3) to analyze the quality of the double difference measurements. The data used for the analysis were actual GPS measurement data of a static zero baseline in an open area.

When analyzing the measurement quality according to



(a) (b)

Fig. 2. Double-differenced code measurements according to elevation angle.

the elevation angle, the double difference measurement was derived by combining the measurements of a low elevation satellite and a high elevation satellite in the same time zone, and the double difference measurements according to elevation angle combinations are shown in Fig. 2.

Fig. 2a shows the double difference measurement between satellites with similar elevation changes, and Fig. 2b shows the double difference measurements between satellites with different elevation changes. In Fig. 2a, it can be confirmed that the quality of the measurements in sections where both satellites have high elevation angles is better than the quality of the measurements in sections with low elevation angles. On the other hand, the quality of Fig. 2b is generally lower than that of the sections with high elevation angles in Fig. 2a. This can be considered as a basis for the changes in measurement quality depending on the elevation angle.

Sections 2.1 and 2.2 summarize the influence of the received signal power according to the elevation angle on the measurement quality. However, Section 2.3 analyzes the results of computing the difference of the measurements of different satellites, deriving relative results that can be changed according to the combination of differential satellites rather than fixed results during measurement quality analysis. This means that it is difficult to derive numerical measurement quality independently for each measurement. When deriving measurement quality, a method to derive measurement quality using only the measurements of the corresponding satellite is needed, and the following section summarizes the method for deriving independent measurement quality for each satellite.

2.4 Code Measurement Quality Index

This section proposes an independent code measurement quality index for each satellite. The proposed index indicates the effect of DLL tracking errors reflected in the code measurements of satellite i as shown in Eq. (4). This index is used for relative comparison between measurements by visible satellite. In Eq. (4), CMQI means the code measurement quality index.

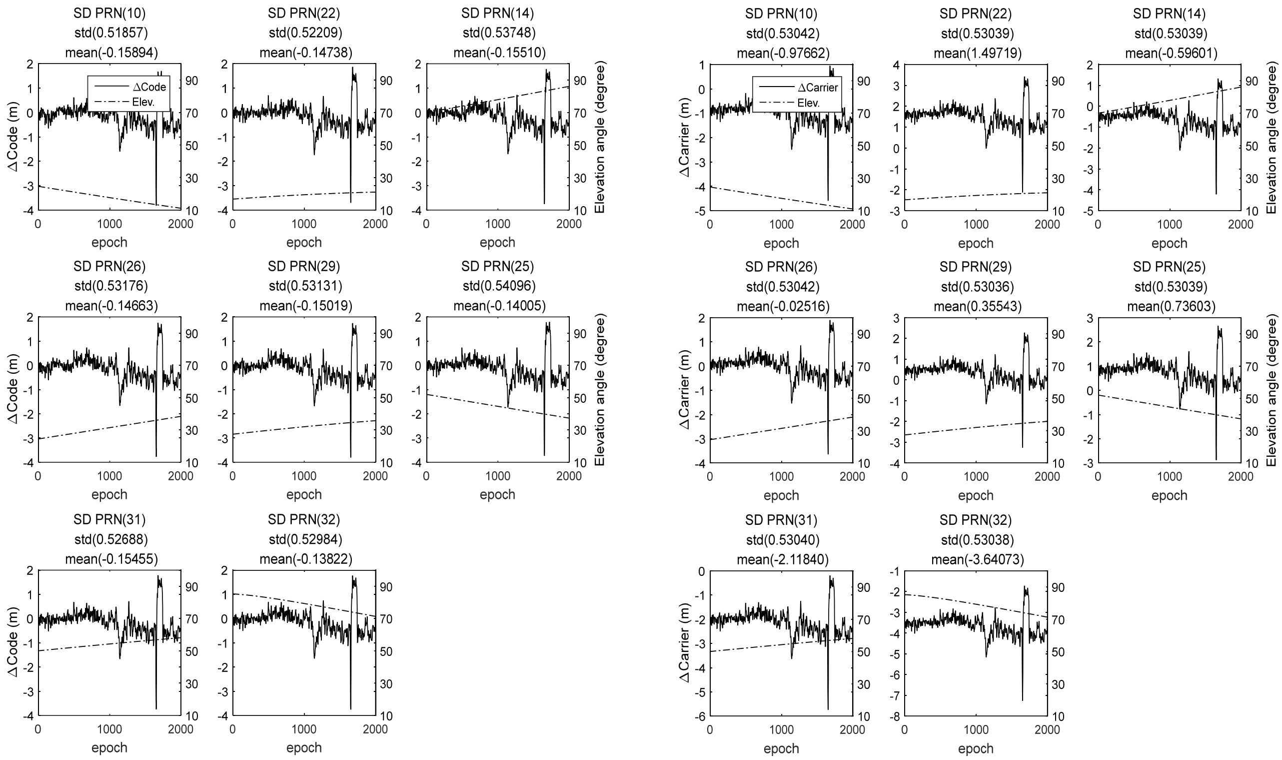
$$CMQI(i) = STD\left\{\left(\rho_u^i - \rho_r^i\right) - \left(l_u^i - l_r^i\right)\right\} \tag{4}$$

where ρ^i is the code measurement for satellite i, l^i is the carrier phase measurement for satellite i, and subscripts u and r represent the user receiver and reference station receiver, respectively.

Eq. (4) can be used for the following reasons. The single difference between receivers eliminates the satellite clock error and the tropospheric delay, and the influence of the receiver clock can be eliminated by again differencing the single difference of the code measurements and single difference of the carrier phase measurements. In general, the precision of the carrier phase measurement is higher than that of the code measurement, so the DLL tracking error reflected in the code measurement is not significantly affected as the influence of the receiver clock is eliminated when computing the difference again.

Fig. 3a shows the single difference of the code measurements, and Fig. 3b shows the single difference of the carrier phase measurements. The single difference of the clock error is an error factor that is common to the single difference of the code measurements and the carrier phase measurements, and has the greatest effect on the single difference results. For this reason, it is difficult to find the impact according to the elevation angle in the results of Fig. 3.

As mentioned above, since the receiver clock error is common to both the single difference of the code measurements and the carrier phase measurements, computing the difference between each measurement results



(a) (b)

Fig. 3. Single-differenced code and carrier phase measurements.

in eliminating the influence due to the single difference of the clock error.

The results of differencing the code measurements and carrier phase measurements for the same satellite number are shown in Fig. 4. From Fig. 4, it can be confirmed that the receiver clock error reflected in the measurement is removed. Although this includes the observation error of the carrier phase measurement, it is much smaller than the observation error of the code measurement, so it is valid for analyzing the code tracking error according to the elevation angle.

3. THE RELATIONSHIP BETWEEN FLOAT SOLUTION ACCURACY AND FIXED SOLUTION SUCCESS RATE

Precise positioning is a positioning technology based on relative positioning that uses both the carrier phase measurements and code measurements. Precise positioning performs ambiguity resolution because it uses the carrier phase measurements, and based on this process, estimates the float solution in the previous step and obtains the fixed solution in the next step. However, this paper only deals with the performance of the float solution, since there is a high chance that the fixed solution performance will improve if the float solution performance is improved. In addition, the main point of this paper is to propose a new method of selecting visible satellites considering the quality of measurements to improve the precise positioning performance. Therefore, this study only covers the float solution performance of precise positioning.

The following shows the relationship between float solution accuracy and fixed solution success rate. The float solution and fixed solution have the relationship as shown in Eq. (5) (Teunissen & Montenbruck 2017).

$$\breve{b} = \hat{b} - Q_{\hat{b}\hat{a}} Q_{\hat{a}\hat{a}}^{-1} \left(\hat{a} - \breve{a} \right) \tag{5}$$

where $\breve{b}$ and $\hat{b}$ are the baseline components of the fixed solution and float solution, $\breve{a}$ and $\hat{a}$ are the ambiguity components of the float solution and fixed solution, $Q_{\hat{b}\hat{a}}$ is the covariance matrix of the baseline component and ambiguity of the float solution, and $Q_{\hat{a}\hat{a}}$ is the covariance matrix of the ambiguity of the float solution.

By Eq. (5), the ambiguity residual is used to propagate the baseline component of the float solution to the baseline component of the fixed solution. At this time, the probability that the ambiguity fixed solution is true follows Eq. (6)

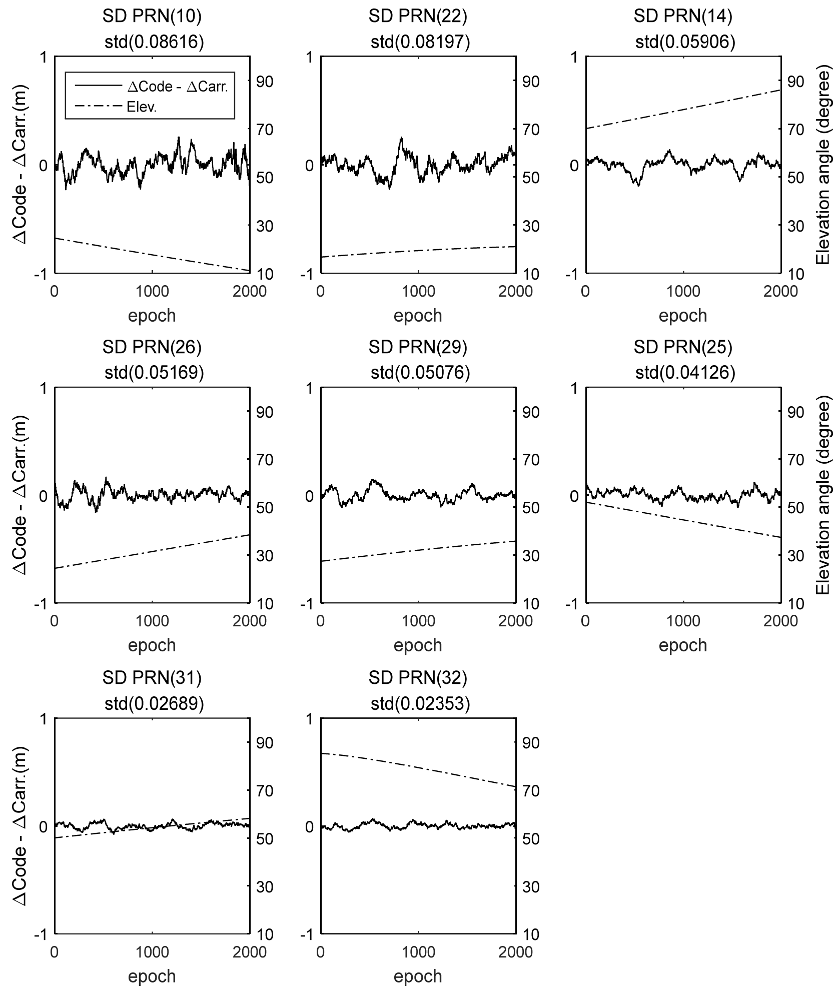


Fig. 4. Single-differenced code minus carrier phase measurement.

(Teunissen & Montenbruck 2017).

$$P(\breve{a}=a) \le P\left(\chi^2_{n,0} \le \frac{c_n}{ADOP^2}\right) \tag{6}$$

$$c_n = \left(\frac{n}{2}\Gamma\left(\frac{n}{2}\right)\right)^{2/n} \Big/ \pi \tag{7}$$

$$ADOP = \det\left(Q_{\hat{a}\hat{a}}\right)^{\frac{1}{2n}} \tag{8}$$

where $\chi^2_{n,0}$ is a random variable with a central chi-square distribution of n degrees of freedom, n is the number of visible satellites, the float solution ambiguity $\hat{a}$ is $\hat{a} \sim N(a, Q_{\hat{a}\hat{a}})$, and $\Gamma(x)$ is a gamma function.

The ambiguity dilution of precision (ADOP) is improved as the covariance of the ambiguity float solution becomes smaller, and as the ADOP is improved, the probability distribution section of the right term of Eq. (6) becomes wider, and the probability of finding the ambiguity fixed solution increases. In other words, the float solution performance affects the fixed solution performance, which indicates the performance of the precise positioning technique.

4. POSITIONING ACCURACY INDEX

The positioning performance is influenced by the arrangement of visible satellites used for positioning and the measurement quality of the corresponding satellites. This relationship can be derived from a relational expression for obtaining the covariance of the position estimates. Eq. (9) is the measurement model linearization equation for absolute positioning, and Eq. (10) estimates the change in position by Eq. (9) using the least squares method, and Eqs. (11) to (13) show the relationship between measurement quality, satellite arrangement, and covariance of estimated variables (Misra & Enge 2006).

$$\Delta\rho = H\Delta x + \varepsilon \tag{9}$$

$$\Delta\hat{x} = \left(H^T H\right)^{-1} H^T \Delta\rho \tag{10}$$

$$Cov\left(\Delta\hat{x}\right) = \sigma_{UERE}^2 \left(H^T H\right)^{-1} \tag{11}$$

$$GDOP = \sqrt{trace\left(\left(H^T H\right)^{-1}\right)} \tag{12}$$

$$RMS\left(Estimation\ \ Error\right) = \sigma_{UERE} \times GDOP \tag{13}$$

where $\Delta\rho$ is the measurement residual, H is the geometric matrix, Δx is the estimated position error, and ε is the residual error. σ_{UERE}^2 represents the measurement quality, and $GDOP$ is the term determined by satellite arrangement. The $GDOP$ value becomes smaller when the satellite arrangement is good and becomes larger when it is bad.

In the above context, the relationship between measurement quality, $GDOP$, and positioning accuracy can also be summarized for relative positioning. This paper assumes a short-baseline environment, and the linear equation for the double difference measurement model can be expressed as Eq. (14).

$$DD \cdot \Delta\rho_a = C \cdot H_a \Delta x_b + DD \cdot v_a \tag{14}$$

where DD is the double difference operator, $\Delta\rho_a$ is the measurement residual, C is the difference operator between satellites, H_a is the geometric matrix, Δx_b is the estimated baseline error, and v_a is the measurement residual error. The parameters above are as shown in Eq. (15).

$$\begin{aligned}
\Delta\rho_a &= \begin{bmatrix} \Delta\rho_u^1 & \cdots & \Delta\rho_u^M & \Delta\rho_r^1 & \cdots & \Delta\rho_r^M \end{bmatrix} \\
v_a &= \begin{bmatrix} v_u^1 & \cdots & v_u^M & v_r^1 & \cdots & v_r^M \end{bmatrix} \\
H_a &= \begin{bmatrix} h_{\hat{x}_o}^1 & h_{\hat{x}_o}^2 & \cdots & h_{\hat{x}_o}^M \end{bmatrix} \\
C &= \begin{bmatrix} -1 & 0 & 0 & \cdots & 0 & 1 \\ 0 & -1 & 0 & \cdots & 0 & 1 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & -1 & 1 \end{bmatrix} \\
SD &= \begin{bmatrix} I & -I \end{bmatrix} \\
DD &= C \cdot SD
\end{aligned} \tag{15}$$

where M is the number of visible satellites, u and r are the receiver and reference station receiver indications, $\hat{x}_0$ is the position vector estimated at the previous point, and SD is the difference operator between the receivers.

Eq. (14) can be replaced and simply reorganized as shown in Eq. (16).

$$\begin{aligned}
\Delta\rho_{DD} &= H_C \Delta x_b + v_{DD} \\
v_{DD} &\sim N\left(0, Q_{DD,\rho}\right)
\end{aligned} \tag{16}$$

$$\begin{aligned}
Q_{DD,\rho} &= DD \cdot Q_\rho \cdot DD^T \\
Q_\rho &= \operatorname{cov}\left(\rho\right)
\end{aligned} \tag{17}$$

where Q_ρ is a matrix of covariance of the measurement residual errors at the reference station and user receivers.

If the measurements collected are independent of each other and size of the errors is the same, the relative positioning accuracy from Eq. (16) can be defined as Eq. (18) (Park 1997).

$$RGDOP \equiv \sqrt{trace\left(\operatorname{cov}\left(\Delta\hat{x}_b\right)\right)} \tag{18}$$

Expanding Eq. (18) by substituting Eq. (16) results in Eq. (19).

$$\begin{aligned}
RGDOP &= \sqrt{trace\left(\left(H_C{}^T H_C\right)^{-1} H_C{}^T DD \cdot Q_\rho \cdot DD^T H_C \left(H_C{}^T H_C\right)^{-1}\right)} \\
&= \sqrt{2 \times trace\left(\left(H_C{}^T H_C\right)^{-1} H_C{}^T C \cdot Q_{\rho,SD} \cdot C^T H_C \left(H_C{}^T H_C\right)^{-1}\right)}
\end{aligned} \tag{19}$$

The relative geometry dilution of precision ($RGDOP$) defined in Eq. (19) is an equation defined using the covariance matrix of relative position $\Delta\hat{x}_b$ estimated from Eq. (16). However, since $Q_{\rho,SD}$ in Eq. (19) cannot be calculated in general, we can calculate $RGDOP_{Expected}$ by substituting $CMQI$, which is proposed in this paper, into Eq. (19) as shown in Eq. (20).

$$RGDOP_{Expected} = \sqrt{2 \times trace\left(\left(H_C{}^T H_C\right)^{-1} H_C{}^T C \cdot CMQI \cdot C^T H_C \left(H_C{}^T H_C\right)^{-1}\right)} \tag{20}$$

$$CMQI = \begin{bmatrix} CMQI(1) & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & CMQI(M) \end{bmatrix} \tag{21}$$

Eq. (20) can be used as an index for improving the precise positioning performance by using the measurement quality index and satellite arrangement information. If the size of the measurement error is reduced or if the measurement of a large error is removed, the size of $CMQI$ becomes smaller, which makes $RGDOP_{Expected}$ smaller. On the contrary, if the magnitude of the measurement error increases, $RGDOP_{Expected}$ becomes larger. Likewise, when the satellite arrangement is good, $RGDOP_{Expected}$ becomes smaller by term H_c, and conversely, when the satellite arrangement is bad or when the number of satellites decreases, $RGDOP_{Expected}$ is increased by term H_c. In other words, when $RGDOP_{Expected}$ increases through Eq. (20), the positioning performance is lowered, and conversely, when $RGDOP_{Expected}$ becomes smaller, the positioning performance improves.

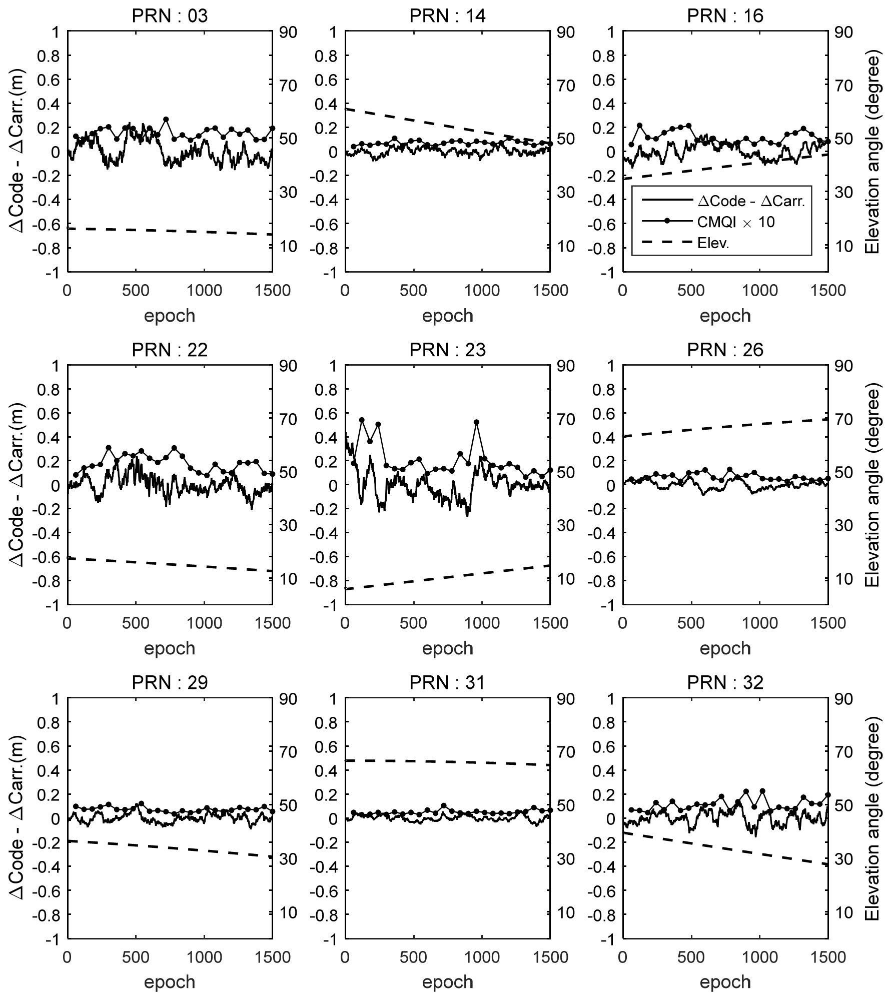


Fig. 5. The result of the code measurement quality.

In order to use $RGDOP_{Expected}$, it is necessary to know the measurement quality of the visible satellite. First, *CMQI* through a measurement of a random length is derived. Next, one of the visible satellites is removed and *CMQI* of the corresponding satellite is exclued to derive $RGDOP_{Expected}$. $RGDOP_{Expected}$ is obtained by removing visible satellites one by one, and $RGDOP_{Expected}$ which displays the most significant drop in precise positioning performance is determined. This reveals which of the visible satellites should be excluded when performing precise positioning, and then precise positioning should be performed by excluding the corresponding visible satellite.

5. EXPERIMENTAL RESULTS

This section analyzed the effectiveness of CMQI proposed in Section 2.4 and the Expected RGDOP proposed in Section 4. In addition, Eq. (6) of Section 3 was considered when analyzing the Expected RGDOP of Section 4. The experiment was performed by post-processing using actual measurements.

The actual measurements were collected in an open area in a static environment of zero baselines. We used 2 survey grade receivers (NovAtel DL-V3) and high performance antennas (NovAtel GPS-703-GGG). The measurement collection period was set to 1 second, and only GPS was considered as the navigation system.

The first analysis used CMQI to analyze the quality of code measurements. The quality of the code measurements using actual measurements values are shown in Fig. 5.

For measurements with low elevation angles, the CMQI is high due to low code measurement quality as shown in Fig. 5. Removing measurements with low CMQI may deteriorate the satellite arrangement and result in degrading the navigation performance. Therefore, we can pinpoint which measurement degrades the precise positioning performance when performing precise positioning by using the expected

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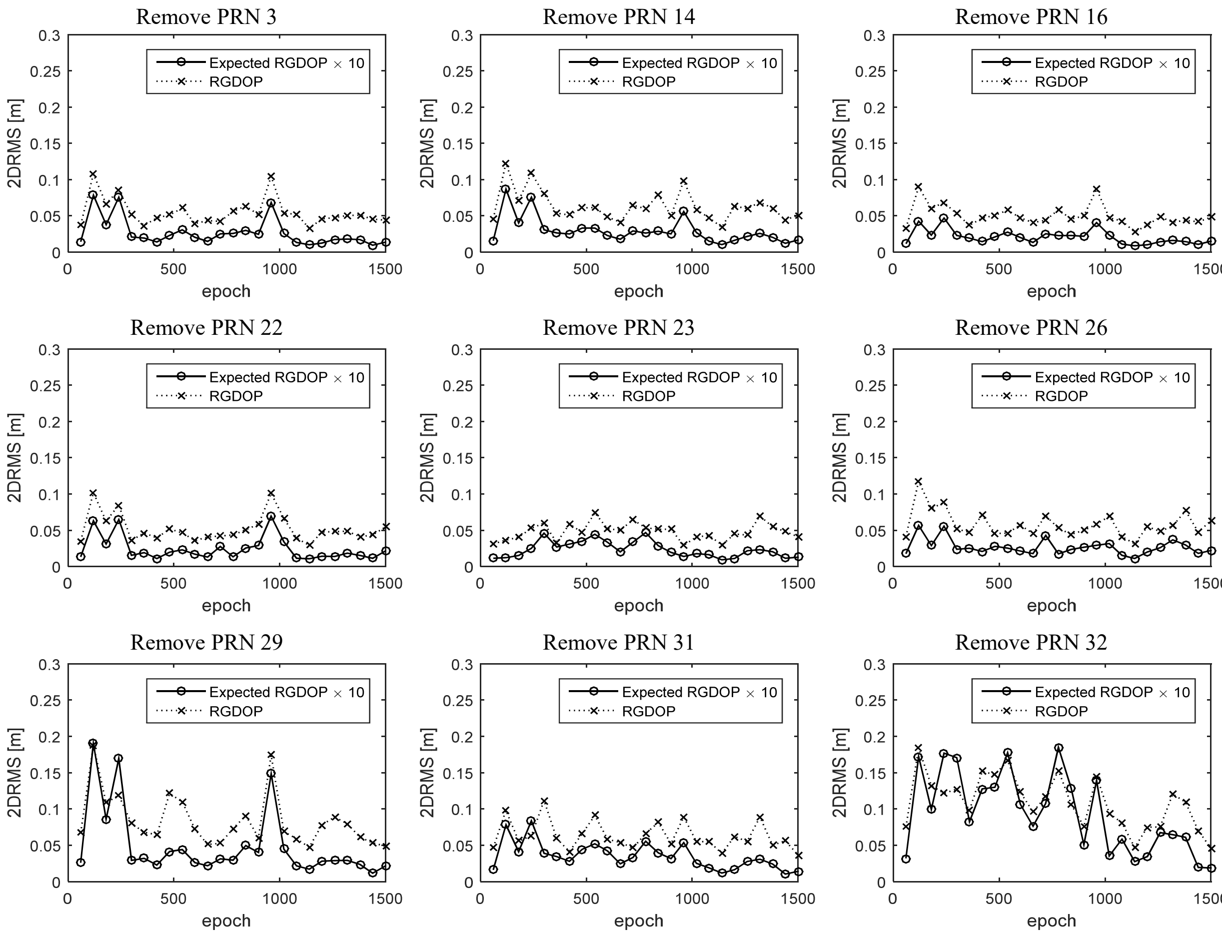
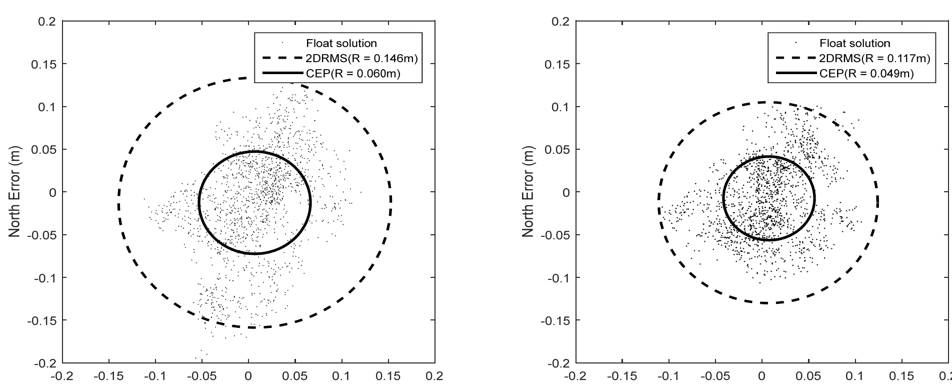


Fig. 6. The results of the RGDOP and the expected RGDOP.



(a) (b)

Fig. 7. The results of the precise positioning, (a) the normal float solution, (b) the float solution with the expected RGDOP.

RGDOP proposed in this paper.

The second analysis confirmed the effectiveness of Expected RGDOP by comparing the RGDOP (Eq. (18)) derived from the positioning results with the Expected RGDOP (Eq. (20)) using CMQI. Fig. 6 is a graph for the effectiveness analysis of Expected RGDOP.

Fig. 6 indicates that Expected RGDOP shows the same trends as RGDOP using positioning results. This shows that the combination of measurements with high precision positioning accuracy can be obtained by using only satellite arrangement information and CMQI, which is the measurement quality index before precise positioning.

As the last step, this study analyzed the precise positioning performance of applying Expected RGDOP to precise positioning and also derived and analyzed the ambiguity resolution success rate together. The precise positioning results of applying Expected RGDOP to precise positioning are shown in Fig. 7.

The method of applying Expected RGDOP to precise positioning is as follows. The measurements for several epochs are collected and the CMQI for each satellite number is calculated, then the expected RGDOP is calculated by using the calculated CMQI. At this time, each of the expected RGDOP is calculated by removing one for each measurement, and then precise positioning is performed using the lowest combination of measurements. As a result, the 2DRMS of the float solution of precise positioning improved by about 20% from 14.6 cm to 11.7 cm, while the CEP increased by about 18% from 6 cm to 4.9 cm. In addition, the probability of finding the true ambiguity is derived by using Eq. (5) of section 3. In order to use Eq. (5), it is necessary to know the ADOP. In this paper, it was reflected as the sampled covariance which used the float solution ambiguity estimated over a number of epochs of float solution ambiguity covariance. As a result, the probability of finding the true ambiguity before applying Expected RGDOP was 99.12%, and 99.49% after applying Expected RGDOP. The probability of finding the true ambiguity increased by 0.37% when applying Expected RGDOP. The results of performing experiments in this section confirmed the effectiveness of Expected RGDOP by showing improved positioning performance when conducting precise positioning using Expected RGDOP.

6. CONCLUSION

This paper proposed a precise positioning performance improvement index. For this purpose, it analyzed the correlation between received signal strength and DLL tracking error, which are factors that affect the quality of code measurements that affect the precise positioning performance. Through correlation analysis, it also proposed a code measurement quality index that indicates the degree of DLL tracking error reflected in code measurements. In addition, this study proposed expected RGDOP which could estimate the positioning accuracy using the proposed code measurement quality index and satellite arrangement information. In order to review the effectiveness of the proposed expected RGDOP, this study performed experiments using actual measurements collected in a static environment of zero baselines. In addition, the probability of finding the true ambiguity was also considered in the analysis. The results showed that in the case of using expected RGDOP, the precise positioning performance improved by about 18 ~ 20% and the probability of finding the true ambiguity increased by 0.37% to 99.49%.

As mentioned above, the precise positioning performance does not guarantee good performance unconditionally just because there are many satellites. There is a trade-off relationship between satellite arrangement and measurement quality. Finding a combination of satellites expected to improve precise positioning performance may be possible using the proposed expected RGDOP, which can express this trade-off relationship.

Future studies will include additional experiments using navigation receivers and experiments with various baseline settings. We also plan to analyze fixed solutions which this paper did not handle.

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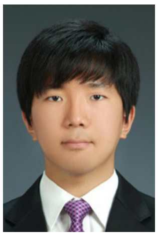

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