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Development of GNSS-only On The Move-RTK Technique for Highly Maneuvering Ground Vehicles

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ABSTRACT

Conventional Real Time Kinematics (RTK) collect measurements in stationary state for several minutes to resolve the integer ambiguity in the carrier phase measurement or resolve the integer ambiguity on the move assuming low maneuvering movement. In this paper, an On The Move-RTK (OTM-RTK) technique that resolves the integer ambiguity on the move for fast and precise positioning of ground vehicles such as high maneuvering vehicles was proposed. The OTM-RTK estimates the precise amount of movement between epochs using the carrier phase measurements acquired on the move, and by using this, resolves the integer ambiguity within a short period of time by evaluating the integer ambiguity candidates for each epoch. This study analyzed the integer ambiguity resolution performance using field driving experiment data in order to verify the performance of the proposed method. The results of the experiment showed that the precise trajectory including the initial position bias can be obtained prior to resolving the integer ambiguity, and after resolving the integer ambiguity on the move, it was possible to obtain the bias-corrected precise position solution. It was confirmed that the integer ambiguity can be resolved by collecting measurements of about 10 epochs from the moving vehicle using a dual frequency receiver.

Keywords: GPS, GNSS, RTK, ICP, OTM-RTK

1. INTRODUCTION

Recently, autonomous vehicles and unmanned vehicles are drawing attention all over the world. The precise position information of the vehicle is crucial in order to control such vehicles. The development and enhancement of autonomous driving technologies such as lane keeping and longitudinal/lateral control is possible through integrating high-precision position information with camera images and road information. In general, to obtain a high-precision position with an accuracy of several cms using a Global Positioning System (GPS), carrier phase measurements should be used along with code measurements (Yoo et al. 2016). For precise positioning using carrier phase measurements, the integer ambiguity included in the carrier phase measurement should be determined. The integer ambiguity can be obtained through searching and evaluating integer ambiguity candidates since there is no analytical solution, and many studies have been performed in the past to reduce time and computation of resolving the integer ambiguity such as reducing search range. Among them, Least squares AMBiguity Decorrelation Adjustment (LAMBDA) and Ambiguity Resolution with Constraint Equation (ARCE) are the typical methods (Jonge & Tiberius 1996, Park et al. 1997). Fundamentally, LAMBDA is a method of obtaining a solution of Integer Least Squares (ILS), which has the condition of an integer and has excellent computational advantages in addition to systematic theories, and is applied to various high-precision positioning systems such as Real Time Kinematics (RTK) (Jonge & Tiberius 1996). In order to resolve the integer ambiguity in conventional RTK, the stationary

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state must be maintained for a long time because the integer ambiguity should be determined by collecting measurements for several tens to hundreds of epochs in the stationary state. In addition, it is difficult to apply the conventional method of resolving the integer ambiguity in the stationary state to precision navigation systems of unmanned vehicles because the integer ambiguity must be determined again if the satellite signal is blocked and re-received while the vehicle is moving or if a cycle slip occurs.

Previously, On-The-Move RTK (OTM-RTK) studies of various techniques were performed to determine the integer ambiguity of vehicles on the move. Two major integer ambiguity resolution techniques for conventional OTM-RTK are a filter fusion technique that combines various filters such as Kalman Filter and Hatch Filter, and an Inertial Measurement Unit (IMU) sensor fusion technique (Grejner-Brzezinska et al. 1998, Mohamed & Schwarz 1998, Henkel et al. 2011). The filter fusion technique estimates the position vector by fusing filters and setting a dynamic equation under the assumption of a low maneuvering movement, which is a low-speed standardized linear movement of a moving object in a standardized environment, and estimates the integer ambiguity using the estimated position vector. The sensor fusion technique estimates the position vector by integrating GPS measurements and IMU sensor measurements, and estimates the integer ambiguity using this. However, it is difficult to apply the filter fusion technique to high maneuvering autonomous vehicles moving at high speed because it can be used only in standardized environments, and the sensor fusion technique has a disadvantage since expensive IMU sensors must be installed additionally. Therefore, studies on new integer ambiguity resolution techniques are necessary for OTM-RTK of high maneuvering ground vehicle systems on the move.

This study proposed an OTM-RTK technique to resolve integer ambiguity using only Global Navigation Satellite System (GNSS) measurements on the move in order to perform fast and precise positioning of high maneuvering ground vehicles on the move based on low-cost GNSS receivers that can be installed in vehicle navigation systems. In order to determine the integer ambiguity of the moving vehicle, floating ambiguity is estimated based on the initial code measurement, and the precise movement between epochs calculated using the carrier phase measurements that obtained on the move was corrected to the carrier phase measurements, showing that integer ambiguity resolution is possible for vehicles on the move. Chapter 2 introduces the conventional floating ambiguity resolution method and Wide Lane technique which uses dual-frequency measurements. Chapter 3 describes OTM-RTK technique proposed in this paper. Chapter 4 compares and analyzes the performance of the proposed technique using field driving experiment data, and finally draws conclusion in Chapter 5.

2. CONVENTIONAL RTK TECHNIQUE USING DUAL FREQUENCY MEASUREMENTS

2.1 Floating Ambiguity Estimation

Conventional RTK studies collected measurements for several tens to hundreds of epochs in the stationary state to determine the integer ambiguity included in the carrier phase measurements. Assuming that m satellites are observed in one epoch, the double differenced code and carrier phase measurements, measured during the n epoch at the stationary state are as shown in Eq. (1) (Son et al. 2000).

$$\delta\rho = \begin{bmatrix} \delta\rho_1 \\ \delta\rho_2 \\ \vdots \\ \delta\rho_n \end{bmatrix} = H\delta x + \varepsilon = \begin{bmatrix} H_1 \\ H_2 \\ \vdots \\ H_n \end{bmatrix} \delta x + \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_n \end{bmatrix}$$
$$\delta l = \begin{bmatrix} \delta l_1 \\ \delta l_2 \\ \vdots \\ \delta l_n \end{bmatrix} = H\delta x + \lambda N + w = \begin{bmatrix} H_1 \\ H_2 \\ \vdots \\ H_n \end{bmatrix} \delta x + \lambda N + \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} \tag{1}$$

where, $\delta\rho_i, \delta l_i (i = 1 \sim n)$ is 1a linearized double differenced code and a carrier phase measurement, respectively, and the vector of $(m-1)\times 1$, $H_i (i = 1 \sim n)$ is the line-of-sight differenced vector between the satellites of $(m-1)\times 3$, δx is the base line vector between the base station of 3×1 and the vehicle, λ is the length of the carrier wave, N is the integer ambiguity vector of $(m-1)\times 1$, and ε_i, $w_i (i = 1 \sim n)$ is the double differenced code and the carrier phase measurement noise, respectively, and the vector of $(m-1)\times 1$. Assuming that measurements are collected at the stationary state and there is no change in the satellites, δx and N are constant values regardless of the change in epoch, it is assumed that the measurement errors such as ionospheric delay and tropospheric delay are removed by double differencing because the distance between the two receivers is not too far (within 10 km) and there is no multipath error. The measurement noise ε, w is a White Gaussian noise, which is independent from each other, and it is assumed to have the characteristics of $\varepsilon \sim N(0,Q_\rho)$, $Q_\rho = (DD^T)^{-1}\sigma_\rho^2$ and $w \sim N(0,Q_l)$, $Q_l = (DD^T)^{-1}\sigma_l^2$, respectively. Where, D is a differentiation matrix.

In order to solve Eq. (1), Eq. (1) is arranged as Eq. (2).

$$\delta y = Aa + Bb + e = \begin{bmatrix} A & B \end{bmatrix} \begin{bmatrix} a \\ b \end{bmatrix} + e = M\tilde{x} + e \tag{2}$$

where, $\delta y = [\delta\rho \quad \delta l]^T$, $A = [H \quad H]^T$, $a = \delta x$, $B = [0 \quad \lambda I]^T$, $b = N$, $e = [\varepsilon \quad w]^T$, $M = [A \quad B]$, and $\tilde{x} = [a \quad b]^T$ are represented.

By applying the least squares method to Eq. (2), unknown $\tilde{x}$ can be estimated as shown in Eq. (3).

$$\hat{\tilde{x}} = \left(M^T M\right)^{-1} M^T \delta y \tag{3}$$

It is possible to resolve the integer ambiguity by applying techniques such as LAMBDA and ARCE using the floating ambiguity $\hat{N}$ estimated from Eq. (3) and the covariance of the integer ambiguity, which is a search range of the integer ambiguity, and a high precision positioning is possible using the carrier phase measurements by obtaining the integer ambiguity (Jonge & Tiberius 1996, Son et al. 2000).

2.2 Wide Lane

The linearized model of a double differentiated L1 and L2 carrier phase measurements is shown in Eqs. (4) and (5).

$$\frac{1}{\lambda_{L1}}\delta l_{L1} = \frac{1}{\lambda_{L1}} H\delta x + N_{L1} + \frac{w_{l,L1}}{\lambda_{L1}} \tag{4}$$

$$\frac{1}{\lambda_{L2}}\delta l_{L2} = \frac{1}{\lambda_{L2}} H\delta x + N_{L2} + \frac{w_{l,L2}}{\lambda_{L2}} \tag{5}$$

where, λ_{L1} and λ_{L2} are the wavelengths of L1 and L2, δl_{L1} and δl_{L2} are the linearized double difference carrier phase measurements of L1 and L2, H is the differenced line-of-sight vector between satellites, δx is the baseline vector between the base station and vehicle, and N_{L1} and N_{L2} are the integer ambiguity of double differenced L1 and L2, respectively.

By defining the Wide Lane integer ambiguity as $N_{WL} = N_{L1} - N_{L2}$, it is possible to generate Wide Lane measurement as shown in Eq. (6) by combining Eqs. (4) and (5) (Kaplan & Hegarty 2006, Misra & Enge 2011).

$$\frac{1}{\lambda_{WL}}\delta l_{WL} = \frac{1}{\lambda_{WL}} H\delta x + N_{WL} + \frac{1}{\lambda_{WL}} w_{WL} \tag{6}$$

where, $f_{WL} = f_{L1} - f_{L2}$ is approximately 347.8 MHz, the wavelength is $\lambda_{WL} = \frac{\lambda_{L1}\lambda_{L2}}{\lambda_{L1} - \lambda_{L2}}$ and its length is about 86 cm. Wide Lane combination has the advantage of reducing the number of integer ambiguity candidates that need to be searched due to the increased ambiguity spacing. However, there is a disadvantage since noise is amplified by a linear combination of measurements (Jeon 2018).

3. THE PROPOSED OTM-RTK TECHNIQUE

This paper proposes an OTM-RTK technique to determine the integer ambiguity using only GNSS measurements while moving based on a low-cost GNSS receiver for fast and precise positioning of a high maneuvering ground vehicle on the move. In order to resolve the integer ambiguity of a moving vehicle, floating ambiguity is estimated based on the initial code measurement, and after setting the search range of integer ambiguity, the initial integer ambiguity is resolved in the moving vehicle by correcting the precise movement between epochs calculated using the carrier phase measurement obtained on the move to the carrier measurement. The state diagram of OTM-RTK proposed in this study to resolve the integer ambiguity on the move is as shown in Fig. 1.

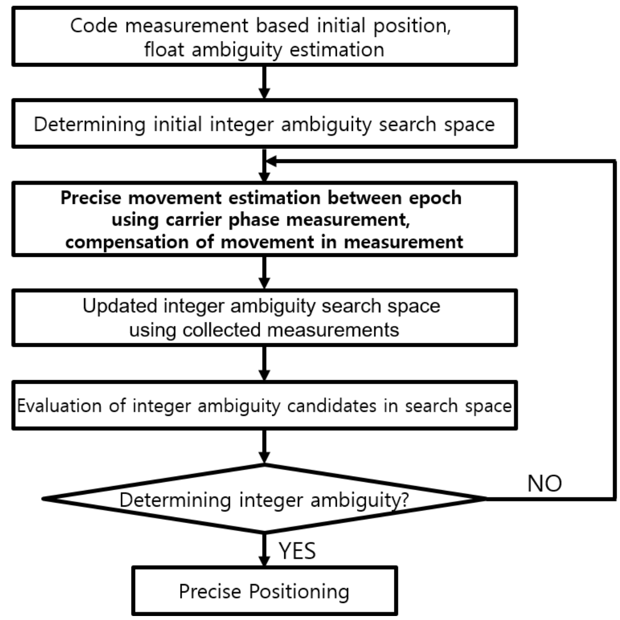

Fig. 1. Proposed OTM-RTK technique state diagram.

3.1 Code-based Initial Position Calculation, Floating Ambiguity Estimation, and Integer Ambiguity Search Range Configuration

The linearized double differenced code and carrier phase measurements in the stationary state (0 epoch) are shown in Eq. (7).

$$\begin{aligned} \delta\rho_0 &= H_0 \delta x_0 + \varepsilon_0 \\ \delta l_0 &= H_0 \delta x_0 + \lambda N_0 + w_0 \end{aligned} \tag{7}$$

The initial code-based position can be estimated from the code measurements in Eq. (7), consisting of a single epoch or several multiple epochs. In the case of a single epoch, code-based estimate of the floating ambiguity is obtained as shown in Eq. (8) by substituting the code-based estimated initial position into the carrier phase measurement (Yoo et al. 2016).

$$\hat{N}_0 = \frac{\delta l_0 - H_0 \delta \hat{x}_0}{\lambda} \tag{8}$$

The search range of the integer ambiguity estimated based on the code of a single epoch is expressed as a covariance matrix as shown in Eq. (9) (Son et al. 2000, Jeon 2018).

$$\mathrm{cov}(\hat{N}_0) = E\left[N_0 N_0^T\right] \approx \frac{I}{\lambda^2}\left(\sigma_\rho^2 + \sigma_l^2\right) \tag{9}$$

3.2 Precise Movement Estimatiion Between Epoch using Carrier Phase Measurement, Compensation of Movement in Measurement

In conventional RTK, δx is fixed as (3×1) in Eq. (1), because measurements are collected in a stationary state, but δx is updated every epoch in a moving state, δx becomes ($3n$×1) if the measurements are collected during n epochs as shown in Eq. (10) thus, it is difficult to apply the conventional integer ambiguity resolution technique to measurements of moving vehicles.

$$\begin{bmatrix} \delta\rho_1 \\ \delta\rho_2 \\ \vdots \\ \delta\rho_n \\ \delta l_1 \\ \delta l_2 \\ \vdots \\ \delta l_n \end{bmatrix} = \begin{bmatrix} H_1 \\ H_2 \\ \vdots \\ H_n \\ H_1 \\ H_2 \\ \vdots \\ H_n \end{bmatrix} \begin{bmatrix} \delta x_1 \\ \delta x_2 \\ \vdots \\ \delta x_n \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ \lambda IN \\ \lambda IN \\ \vdots \\ \lambda IN \end{bmatrix} + \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_n \\ w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} \tag{10}$$

where, satellites observed every epoch are the same, and assuming that no cycle slip occurs, it is defined as $N = N_1 = \cdots = N_n$.

In this step, the precise position movement between epochs is calculated using double differenced Integrated Carrier Phase(ICP) variation between epochs, and this is compensated for the carrier measurement. Estimating the position movement between epochs using ICP variation between epochs is shown in Eq. (11) (Jeon 2018).

$$\delta\hat{x}_i = \left(H_i^T \left(DD^T\right)^{-1} H_i\right)^{-1} H_i^T \left(DD^T\right)^{-1} \lambda \delta\Theta_i \,(i = 1, 2, \cdots, n) \tag{11}$$

where, $\delta\Theta_i$ is ICP variation between epochs, and since the carrier phase measurement noise is assumed to be WGN, the ICP measurement noise between epochs can be modeled as the 1st order Markov process.

By updating $\delta\hat{x}_i$ from 1 epoch to n epoch, the measurements can be collected and summarized as shown in Eq. (12).

$$\begin{bmatrix} \delta l_1 \\ \delta l_2 \\ \vdots \\ \delta l_n \end{bmatrix} = \begin{bmatrix} H_1 \\ H_2 \\ \vdots \\ H_n \end{bmatrix} \delta\hat{x}_0 + \begin{bmatrix} H_1\delta\hat{x}_1 \\ H_1\delta\hat{x}_1 + H_2\delta\hat{x}_2 \\ \vdots \\ H_1\delta\hat{x}_1 + H_2\delta\hat{x}_2 + \cdots + H_n\delta\hat{x}_n \end{bmatrix} + \lambda \begin{bmatrix} N \\ N \\ \vdots \\ N \end{bmatrix} + \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} \tag{12}$$

Although Eq. (12) contains the initial position bias $\delta\hat{x}_0$, the error between $\delta\hat{x}_i$ and true value is very small and $H_i\delta\hat{x}_i (i = 1 \sim n)$ becomes the precise ICP correction value between epochs since the subsequent position movement between epochs $\delta\hat{x}_i$ is continuously estimated from ICP variation between epochs. If accumulated movement of the vehicle is calculated using Eq. (11) and then compensated for the carrier measurement, Eq. (12) may be rewritten as Eq. (13).

$$\begin{bmatrix} \delta l_1 \\ \delta l_2 \\ \vdots \\ \delta l_n \end{bmatrix} - \begin{bmatrix} H_1\delta\hat{x}_1 \\ H_1\delta\hat{x}_1 + H_2\delta\hat{x}_2 \\ \vdots \\ H_1\delta\hat{x}_1 + H_2\delta\hat{x}_2 + \cdots + H_n\delta\hat{x}_n \end{bmatrix} = \begin{bmatrix} H_1 \\ H_2 \\ \vdots \\ H_n \end{bmatrix} \delta\hat{x}_0 + \lambda \begin{bmatrix} N \\ N \\ \vdots \\ N \end{bmatrix} + \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} \tag{13}$$

If the left side of Eq. (13) is defined as $\delta\tilde{l}$, Eq. (13) is expressed in the same form as the carrier phase measurement of Eq. (1), and by applying the process in Eqs. (2) and (3) to the following steps, it is possible to estimate the integer ambiguity in the moving vehicle. The integer ambiguity of the moving vehicle can be resolved by applying LAMBDA method using the estimated floating ambiguity and covariance of the integer ambiguity error, which is the search range of the integer ambiguity, and when resolving the integer ambiguity, the number of evaluation candidates can be effectively reduced by applying techniques such as ratio test and integer rounding (Jonge & Tiberius 1996, Son et al. 2000, Jeon 2018).

4. EXPERIMENTAL RESULTS

The performance of proposed OTM-RTK technique was analyzed using filed experiment. First, this study analyzed the performance of conventional RTK and proposed OTM-RTK in the stationary state. The experiment was performed by collecting data for 5 minutes using a dual frequency receiver at a measurement point on the roof of Chungnam National University Engineering Department No. 3 in December 2017. In order to eliminate the measurement errors, a double difference was performed using data from Daejeon Monitoring Station of the National Maritime PNT Office, which is located approximately 5 km far from the measurement point. The positioning test results of RTK and proposed OTM-RTK in the stationary state are as shown in Fig. 2. Fig. 2a is the result of using L1 single frequency measurement and Fig. 2b is the result of applying Wide Lane using a dual frequency receiver. In Fig. 2, red box indicates the moment when the integer ambiguity was determined.

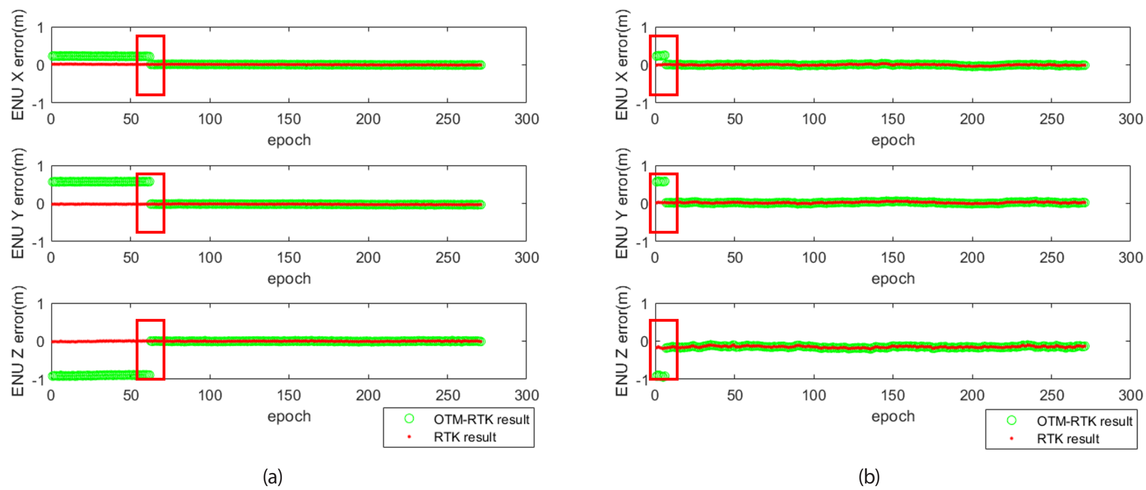

Fig. 2. Positioning result of RTK and the proposed OTM-RTK in stationary status. (a) is result of L1 only, (b) is result of Wide Lane

Table 1. RMS result of positioning error.

	L1 only		Wide Lane	
	RTK result [m]	OTM-RTK result [m]	RTK result [m]	OTM-RTK result [m]
x	0.0081	0.0075	0.0141	0.014
y	0.0088	0.0079	0.0263	0.0259
z	0.0731	0.0715	0.1527	0.151

Table 2. Average time of determination of integer ambiguity according to the number of measurements.

Time [sec]	RTK		OTM-RTK	
	L1 only	Wide Lane	L1 only	Wide Lane
6 measurements	58.2	7.1	58.5	7.3
5 measurements	58.3	7.3	58.7	7.4
4 measurements	61.7	8.7	62.3	8.6

Table 1 shows Root Mean Square (RMS) of RTK and OTM-RTK positioning errors to analyze the accuracy of the positioning results. For accurate RMS analysis, OTM-RTK calculated RMS value after integer ambiguity determination.

The experimental results show that proposed OTM-RTK includes an initial position bias before integer ambiguity determination, but an accurate position solution was obtained as the initial position bias was corrected after determining the integer ambiguity. In addition, the position accuracy of using a single frequency was found to be 3.28 times better than that of Wide Lane. This is because noise is amplified by the linear combination of measurements when creating Wide Lane measurements. Although six measurements were used in the current experiment, in order to compare the integer ambiguity resolution performance of proposed OTM-RTK, elevation angle was adjusted to compare the number of residual integer ambiguities per epoch of RTK and OTM-RTK in the case of five and four measurements. The number of residual integer ambiguities per epoch according to the number of measurements is shown in Fig. 3. Figs. 3a-f show the number of residual integer ambiguities per epoch of RTK and OTM-RTK in the case of a single frequency and the case of Wide Lane using dual frequency measurements with six to four measurements, respectively.

As a result of the experiment, Dilution of Precision (DOP) is large when the number of measurements is small, which increases the number of initial ambiguity search candidates as the initial ambiguity search range increases. And, the integer ambiguity resolution performance of proposed OTM-RTK was confirmed to be similar to conventional RTK. In order to quantitatively analyze search speed of integer ambiguity according to the number of measurements, the experiment was repeated about 10 times, and the integer ambiguity determination time according to the number of measurements is shown in Table 2.

The experimental results showed that the number of initial integer ambiguity search candidates was large when using a single frequency measurement, so it is difficult to determine the true integer ambiguity even by accumulating about 50 epoch measurements. Therefore, this study applied Wide Lane using dual frequency measurements in the field driving experiment so that it can be applied to actual vehicle navigation system.

The driving test was conducted at a vacant lot next to Mokwon University located in Daejeon in May 2018, and compared the results of the navigation solution of proposed OTM-RTK technique and the navigation solution of Virtual Reference System (VRS)/IMU integrated equipment (Novatel SPAN-CPT) for the reference trajectory. The experimental trajectory is shown in Fig. 4, where the same section was repeated twice, and the experiment was performed in a variable environment at a speed of about 50 km/h in the

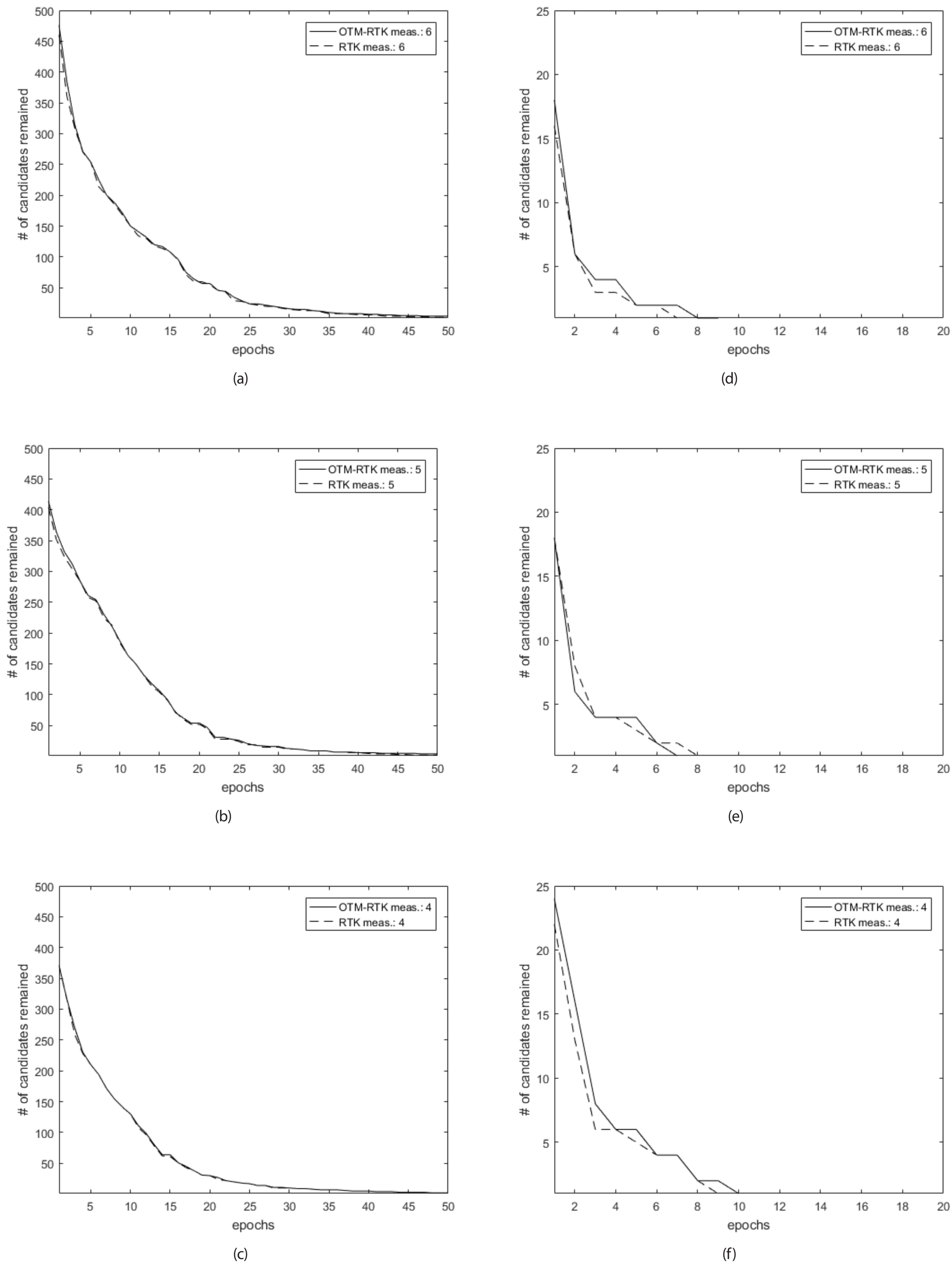

Fig. 3. Number of integer ambiguity candidates remained according to epoch. (a)~(c) is result of L1 only, (d)~(f) is result of Wide Lane

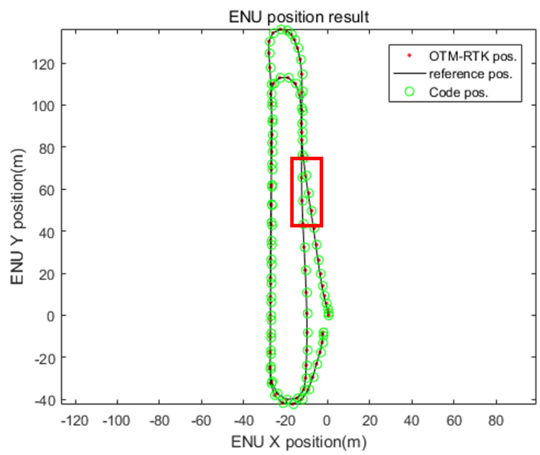

Fig. 4. Result of OTM-RTK positioning experiment.

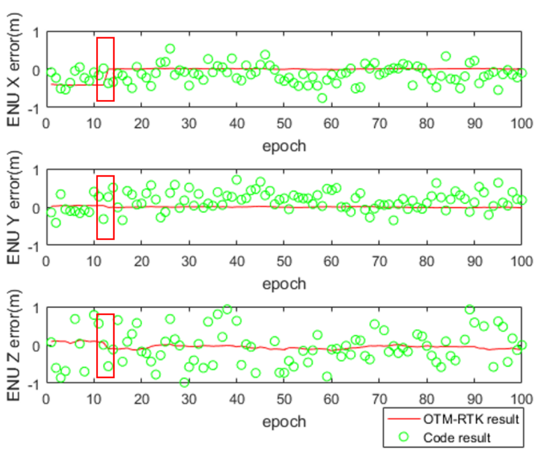

Fig. 5. Position error with reference position.

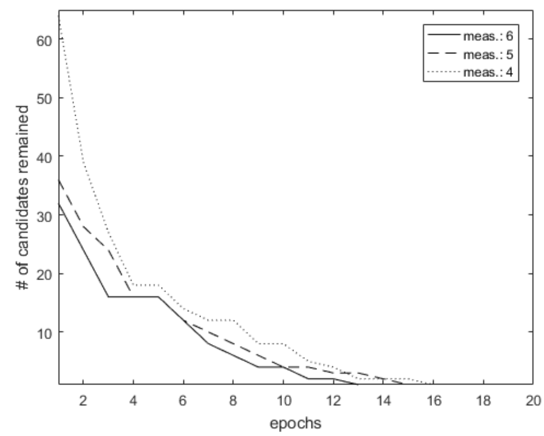

Fig. 6. Number of residual integer ambiguities per epoch by number of measurements.

Table 3. RMS result of positioning error with reference position.

	Code measurement result [m]	OTM-RTK result [m]
x	0.2673	0.0116
y	0.293	0.0097
z	0.6676	0.077

Table 4. Average time of determination of integer ambiguity according to the number of measurements.

	6 measurements	5 measurements	4 measurements
Time [sec]	10	11.14	12.57

straight section and at a speed of about 20 km/h in the curved section. As in the stationary state experiment, in order to analyze the integer ambiguity determination performance according to the number of measurements, the number of residual integer ambiguities per epoch in each experiment was compared by adjusting the number of measurements used in the experiment.

In order to compare the accuracy of the positioning results of proposed OTM-RTK technique, positioning error with the reference position is shown in Fig. 5, and RMS of the positioning error with respect to the reference position is shown in Table 3 in order to compare the accuracy. As a result of the experiment, although OTM-RTK contains an initial position bias before integer ambiguity determination as in stationary state experiment, continuity of the trajectory was ensured by calculating the precise position movement between epochs using ICP variation between epochs, and accurate positioning was possible as the position bias was corrected after determining the integer ambiguity. In OTM-RTK results of Table 2, positioning accuracy of OTM-RTK showed excellent performance.

Finally, in order to analyze the integer ambiguity resolution performance of proposed OTM-RTK technique, the number of residual integer ambiguities per epoch was compared according to the number of measurements as in the stationary state experiment. Although six measurements were used in the current experiment, elevation angle was adjusted to compare with cases of five and four measurements. The number of residual integer ambiguities per epoch according to the number of measurements is as shown in Fig. 6.

The DOP is large if the number of measurements is small, which increases the number of initial ambiguities to be searched as the initial ambiguity search range increases. In the case of four measurements, there were about twice as many initial integer ambiguity candidates than that of six measurements, and it took about 1.23 times longer to determine the integer ambiguity. The experiment was repeatedly performed to quantitatively analyze the integer ambiguity search speed according to the number of measurements, and the integer ambiguity determination time by the number of measurements is as shown in Table 4.

As a result of repeating the experiment, the integer ambiguity determination time changed due to the influence of DOP according to the number of measurements. However, all three cases determined the integer ambiguity within approximately 10 epochs, resulting in a relatively good performance.

5. CONCLUSION

This paper proposed an OTM-RTK technique to determine the integer ambiguity in a moving vehicle. The initial code-based measurements were used to resolve floating ambiguity, and the precise movement between epochs was calculated using the carrier phase measurements to correct the measurements, showing that the integer ambiguity can be determined in a moving vehicle. As a result of the experiment, although proposed OTM-RTK technique contains an initial position bias before integer ambiguity determination, the precise trajectory can be obtained by calculating the precise movement between epochs, and accurate position and trajectory with corrected position biases can be obtained after determining the integer ambiguity. In addition, this study compared the integer ambiguity determination performance according to the number of measurements. As the number of measurements is influenced by DOP, there was a performance difference in the number of integer ambiguity candidates and integer ambiguity determination time. Therefore, the proposed OTM-RTK technique can be applied to various vehicle navigation systems such as unmanned vehicles and autonomous vehicles by complementing the conventional RTK constraints.

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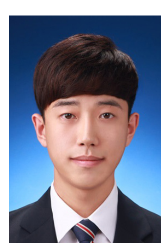

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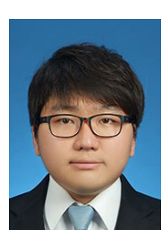

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