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A Study on Compact Network RTK for Land Vehicles and Real-Time Test Results

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ABSTRACT

In recent years, the need of high accuracy navigation for vehicles has increased due to the development of autonomous driving vehicles and increase in land transportation convenience. This study is performed for vehicle users to achieve a performance of centimeter-level positioning accuracy by utilizing Compact Network Real-time Kinematic (RTK) that is applicable as a national-level infrastructure. To this end, medium-baseline RTK was implemented in real time to estimate accurate integer ambiguities between reference stations for reliable generation of Network RTK correction using the linear combination of carrier-phase observations and L1/L2 pseudo-range measurements. The residual tropospheric error was estimated in real time to improve the accuracy of double-differenced integer ambiguity resolution between network configuration reference stations that have at least 30 km or longer baseline distance. In addition, C++ based software was developed to enable real-time generation and broadcasting of Compact Network RTK correction information by utilizing an accurately estimated double-differenced integer ambiguity values. As a result, the horizontal and vertical 95% accuracy was 2.5cm and 5.2cm, respectively, without performance degradation due to user's position change within the network.

Keywords: compact RTK, network RTK, spatial decorrelation, land vehicle

1. INTRODUCTION

The Network Real-time Kinematic (RTK) is a satellite-based augmentation system based on multiple reference stations in order to enlarge the coverage of correction information of conventional single reference station-based RTK. Since the coverage of correction information can be increased approximately from a radius of 10-20 km to 50-70 km and centimeter-level accuracy can be achieved, the Network RTK has a potential to be used as a nationwide infrastructure. In this regard, correction information of Network RTK has been provided as a form of Virtual Reference Station and Flächen Korrektur Parameter through the National Geographic Information Institute in Korea. The Network RTK has been used by static users such as surveying. However, since the late 2000s, studies on the Network RTK have been actively conducted to apply the technology to dynamic users such as vehicles for lane classification and autonomous driving (Stephenson et al. 2011, Stephenson et al. 2012). Since vehicle users move at a fast speed in contrast with static users, tens of meters of vehicle movement can occur even in several seconds of unavailable navigation, during which users cannot use location-based services. Even if users receive satellite navigation signals, high precision navigation is not continuously possible if they fail to receive Network RTK correction information. A user can receive correction information utilizing 3G or LTE communication, which is a mobile phone communication network. However, several seconds of communication outage has been reported for this type of network when a base station is changed due to user movements, that is, when a handover occurs. In addition, communication base stations are installed more

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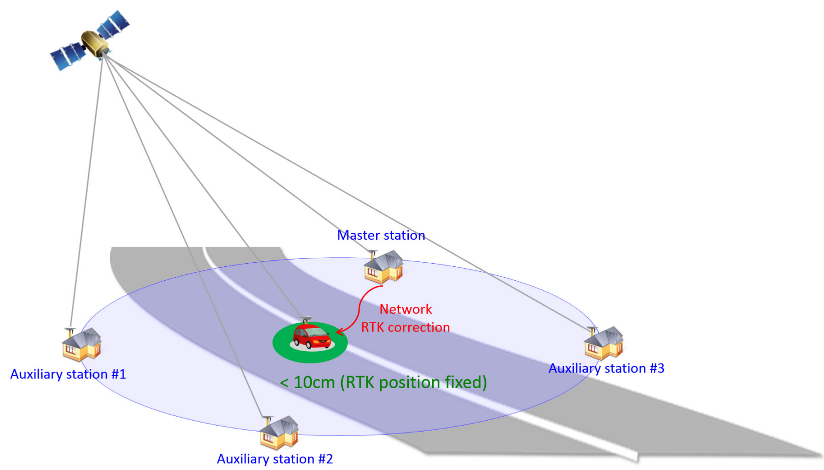


Fig. 1. Configuration of network RTK.

densely in a place where population density is higher and thus, quality communication may not be guaranteed at a place of less dense population. When such communication outage occurs, users are unable to receive Network RTK correction information for several seconds up to a few tens of seconds, resulting in difficulties in using the up-to-date correction information. When using past correction information, a time delay occurs due to a difference between time of reception of correction information and current time. Seoul National University has developed the Compact RTK that can continuously carry out high accuracy navigation under such case in 2002 (Kim & Kee 2004). The post-processing-based compatibility between Compact RTK and existing Network RTK has been validated in 2008 (Park & Kee 2010).

Accurate integer ambiguity resolution between reference stations is needed to generate correction information of Network RTK. A baseline distance between reference stations in a network is about 30 km to 70 km, which is longer than a distance of 10 km to 20 km that existing single reference station-based RTK can carry out. Thus, it is not viable to resolve accurate integer using existing RTK mode in a single reference station, because the assumption that the ionosphere and troposphere are completely removed via differential operation if a baseline is short enough is not valid anymore. Thus, this paper implemented medium-baseline RTK to deal with those problems. In this process, the ionosphere was removed by forming the linear combination of measurements and a tropospheric vertical delay could be estimated with the Kalman filter, thereby enabling accurate integer estimation and resolution.

This paper implemented Compact Network RTK, which was studied only based on existing post-processing methods, using C++ based real-time code. This paper also implemented medium-baseline RTK to accurately estimate integer ambiguity between reference stations to generate correction information. Section 2 presents a process to generate correction information of Compact Network RTK. It also briefly describes the filter configuration for medium-baseline RTK. Section 3 explains the developed algorithm and performance evaluation results of the system. First, the developed medium-baseline RTK is applied to dynamic users, and performance verification is conducted in real time. Second, positioning accuracy of Compact Network RTK users in real time is verified for field test.

2. CORRECTION GENERATION OF COMPACT NETWORK RTK

2.1 Overall procedure of Compact Network RTK

Fig. 1 briefly shows the Network RTK configuration. The Compact Network RTK has the same configuration of reference stations with that of existing Network RTK. In general, a single network consists of three to five reference stations. Each reference station collects Global Navigation Satellite System (GNSS) measurements, and double-differenced integer ambiguity between reference stations that make up the network is resolved. In this paper, the ionospheric delay included in the measurements was completely removed through linear combination of ionosphere-free (IF) measurements, in order to accurately estimate integer double differenced ambiguity between reference stations. The tropospheric delay residual error in the IF measurements is directly estimated through the Kalman filter. The integer estimated accurately through the above process is used to generate correction information

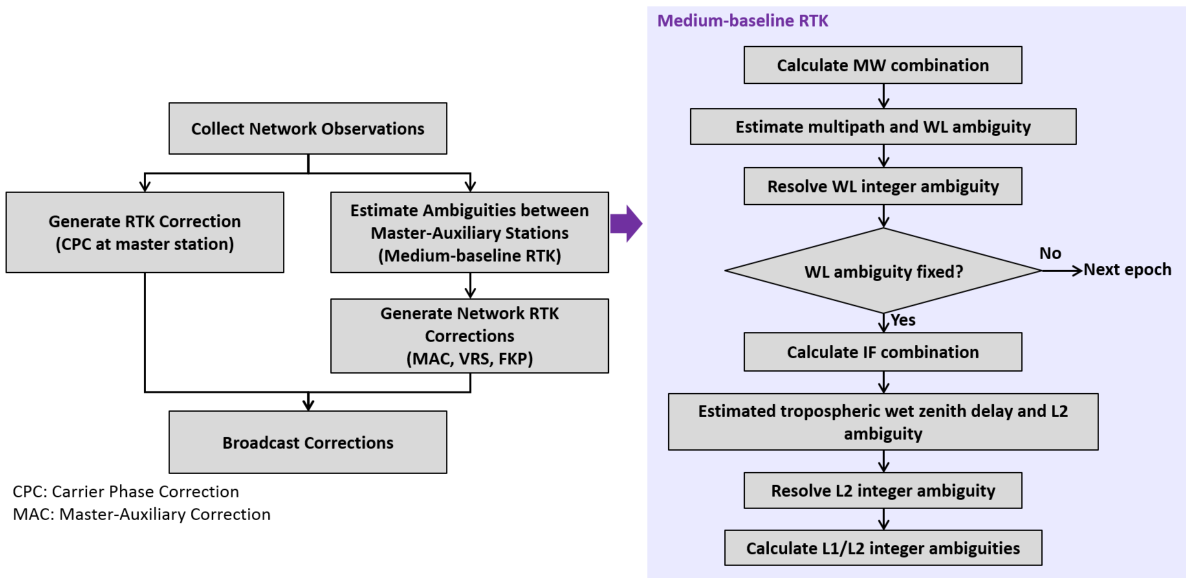


Fig. 2. Overall flow-chart of Network RTK correction generation.

of Compact Network RTK (Park & Kee 2010) and the finally generated correction information is broadcast to the user. Fig. 2 shows a flow chart to generate the correction information of Compact Network RTK.

2.2 Medium-baseline RTK

Medium-baseline RTK has been widely studied since the late 1990s and a variety of approaches have been proposed as follows: method of estimating the L1 and L2 integer ambiguities and residuals of the tropospheric and ionospheric delay by Kalman filter (Dai, Eslinger, & Sharp 2007, Takasu & Yasuda 2010), a method of estimating integer ambiguities and vertical delay in the ionosphere and troposphere (Kubo et al. 2012), a method of estimating ionospheric delay by using linear combination of ionosphere measurements via Kalman filter (Chen 2001), and a method to estimate the ionospheric delay as well as single difference of tropospheric delays between reference stations (Li et al. 2010). This study resolves widelane (WL) integer ambiguities with a Melbourne-Wübenna (MW) combination, and then, the resolved WL integer ambiguities are applied to the IF combination to maintain the integer nature for the ambiguity term in its measurements. After that, the L2 integer ambiguities included in the IF combination can be resolved through the estimation of tropospheric vertical delays and float ambiguities from Kalman filter (Song 2016). The combination of MW measurements can be calculated by combining WL carrier phase measurement combination and narrowlane (NL) pseudo-range combination, which can be expressed as Eq. (1).

$$\begin{aligned}
\Delta\nabla\phi_{WL} &\equiv \frac{f_1}{f_1-f_2}\Delta\nabla\phi_1 + \frac{-f_2}{f_1-f_2}\Delta\nabla\phi_2 \\
\Delta\nabla\rho_{NL} &\equiv \frac{f_1}{f_1+f_2}\Delta\nabla\rho_1 + \frac{f_2}{f_1+f_2}\Delta\nabla\rho_2 \\
\Rightarrow \Delta\nabla\phi_{MW} &\equiv \Delta\nabla\phi_{WL} - \Delta\nabla\rho_{NL} \\
&\approx \Delta\nabla N_{WL}\lambda_{WL} + \Delta\nabla M_{NL} + \Delta\nabla\varepsilon_{NL} \\
&\quad \text{where, } \lambda_{WL} = \frac{c}{f_1-f_2}
\end{aligned} \tag{1}$$

In Eq. (1), ϕ and ρ refer to carrier phase and pseudo-range measurements and the subscripts 1 and 2 refer to L1 and L2 frequencies, respectively. Symbols Δ and ∇ are operators that perform difference between reference stations and between satellites, and f refers to frequency. The symbols of c, N, λ, M, and ε represent the speed of light, integer ambiguity, wavelength, multipath error, and noise, respectively. The IF measurement combination that guarantees the integer nature can be calculated using Eq. (2) when WL integer ambiguity is known.

$$\begin{aligned}
\Delta\nabla\phi_{IF} &\equiv \frac{f_1^2}{f_1^2-f_2^2}\Delta\nabla\phi_1 + \frac{-f_2^2}{f_1^2-f_2^2}\Delta\nabla\phi_2 - \frac{1}{2}\left(\lambda_{WL}+\lambda_{NL}\right)\Delta\nabla N_{WL} \\
&\approx \Delta\nabla T + \Delta\nabla N_2\lambda_{NL} + \Delta\nabla\varepsilon_{IF} \qquad \text{where, } \lambda_{NL} = \frac{c}{f_1+f_2}
\end{aligned} \tag{2}$$

In Eq. (2), variable T refers to the tropospheric delay error. The WL float ambiguity and multipath error are estimated by configuring Kalman filter that uses MW combination calculated via Eq. (1) as a measurement. The multipath error included in the MW measurement was a component that was mainly included in the pseudo-range and it can be estimated by modeling with the 1st order Gauss-Markov process (Dai et al. 1997). The time constant and variance value needed in the modeling are used to estimate the multipath error of reference station. For reference station, they can be pre-computed just for one time as long as there is no significant change in surrounding environments.

In the Kalman filter that uses the IF combination calculated by Eq. (2) as a measurement, tropospheric vertical delay and L2 float ambiguity are estimated. The vertical tropospheric values between two reference stations #1 and #2 are estimated by the following approximation, and they are used in the observation equation.

$$\Delta\nabla T \approx T_{v,rs\#1} \cdot \nabla m_{rs\#1} - T_{v,rs\#2} \cdot \nabla m_{rs\#2} \tag{3}$$

where variables T_v and m refer to tropospheric vertical delay and mapping function, respectively. In the system equation, the tropospheric vertical delay was modeled via the 1st order Gauss-Markov process, and values in the reference study were used for time constant and variance value (Tralli & Lichten 1990). A search space was set based on the estimated float ambiguity from the filter, and integer ambiguity was resolved through the ratio test (Koch 1999).

The overall flow chart of medium-baseline RTK is shown in Fig. 2.

2.3 Generation of Compact Network RTK Correction

This study conducted performance verification using the Master-Auxiliary Concept (MAC) among various Network RTK methods. Each realization method of Network RTK is compatible with other methods (Park & Kee 2010). The Network RTK user in the MAC mode performs navigation after receiving Compact RTK correction information, Carrier Phase Correction (CPC), and MAC correction information, which is differenced correction information between master and auxiliary reference stations.

The Compact RTK correction information, CPC, is calculated as presented in Eq. (4) at the master reference station (Kim & Kee 2004).

$$\begin{aligned} \delta\phi &\equiv \phi - \hat{d} - \hat{B} + b - N\lambda \\ &\approx -I + T + \delta R + \delta B + \delta N\lambda + \varepsilon \end{aligned} \tag{4}$$

where d, B, b, I, δR, N, and λ refer to a distance between reference station and satellite, receiver clock bias, satellite clock bias, ionospheric delay, satellite orbit error, integer ambiguity, and wavelength. In Eq. (4), hat (^) refers to an estimated value. The variable δB and δN are residual errors of receiver clock bias and integer ambiguity.

The MAC correction information of Network RTK can be expressed as follows (Park & Kee 2010).

$$MAC \approx \Delta\delta\phi = -\Delta I + \Delta T + \Delta\delta R + \Delta\delta B + \Delta\delta N\lambda + \Delta\varepsilon \tag{5}$$

A user utilizes the finally received CPC and MAC correction information to eliminate error components by combining the information, as presented in Eq. (6).

$$\begin{aligned} \delta\hat{\phi}_{user} &\equiv \delta\phi_{Mas} + \sum_{r=1}^{m} wt_r \cdot MAC_r \\ &\approx -\hat{I}_{user} + \hat{T}_{user} + \delta\hat{R}_{user} + \delta N\lambda + \varepsilon' + \Theta \end{aligned} \tag{6}$$

The subscript, 'Mas' refers to master reference station and wt represents a weight determined according to the horizontal distance between reference stations or distance in the east and north directions. The symbol of Θ refers to a term that is eliminated when taking a difference between satellites after a user performs a differential calculation on its own measurement from Eq. (6). The residual error of integer ambiguity, δN, which maintains the integer nature in Eq. (6), is to be combined with the user ambiguity and the combined value will be estimated as a whole.

3. TEST RESULTS

3.1 Performance Validation of Medium-baseline RTK

The algorithm was applied to vehicle users in real time to validate the performance of the developed medium-baseline RTK. The test was conducted in the Seoul Grand Park in Gwacheon for three hours from 1:22:30 PM on October 17, 2014. The vehicle was stationary for first 200 seconds and then drove along the trajectory, as shown in Fig. 3, for 10 minutes and then stopped. The estimation of integer ambiguity using IF measurements was performed after 200 seconds so that the user could estimate integer ambiguity in the dynamic state. The medium-baseline RTK was performed using CHEN as a reference station, which was approximately 63.4 km away from the user. For the user's true trajectory, the Global Positioning System (GPS) measurements from GUMC reference station, which was around 10 km away from the user, was post-processed using commercial post-processing software Trimble Business Center (TBC).

Fig. 4 shows the estimation results of WL and L2 float ambiguities of PRN 2 and PRN 12. The results were analyzed by setting the ambiguity processed with batch mode as the true ambiguity. When the ambiguity state covariance was converged to some extent, a search space was set based

Fig. 3. Test configuration for performance validation of medium-baseline RTK.

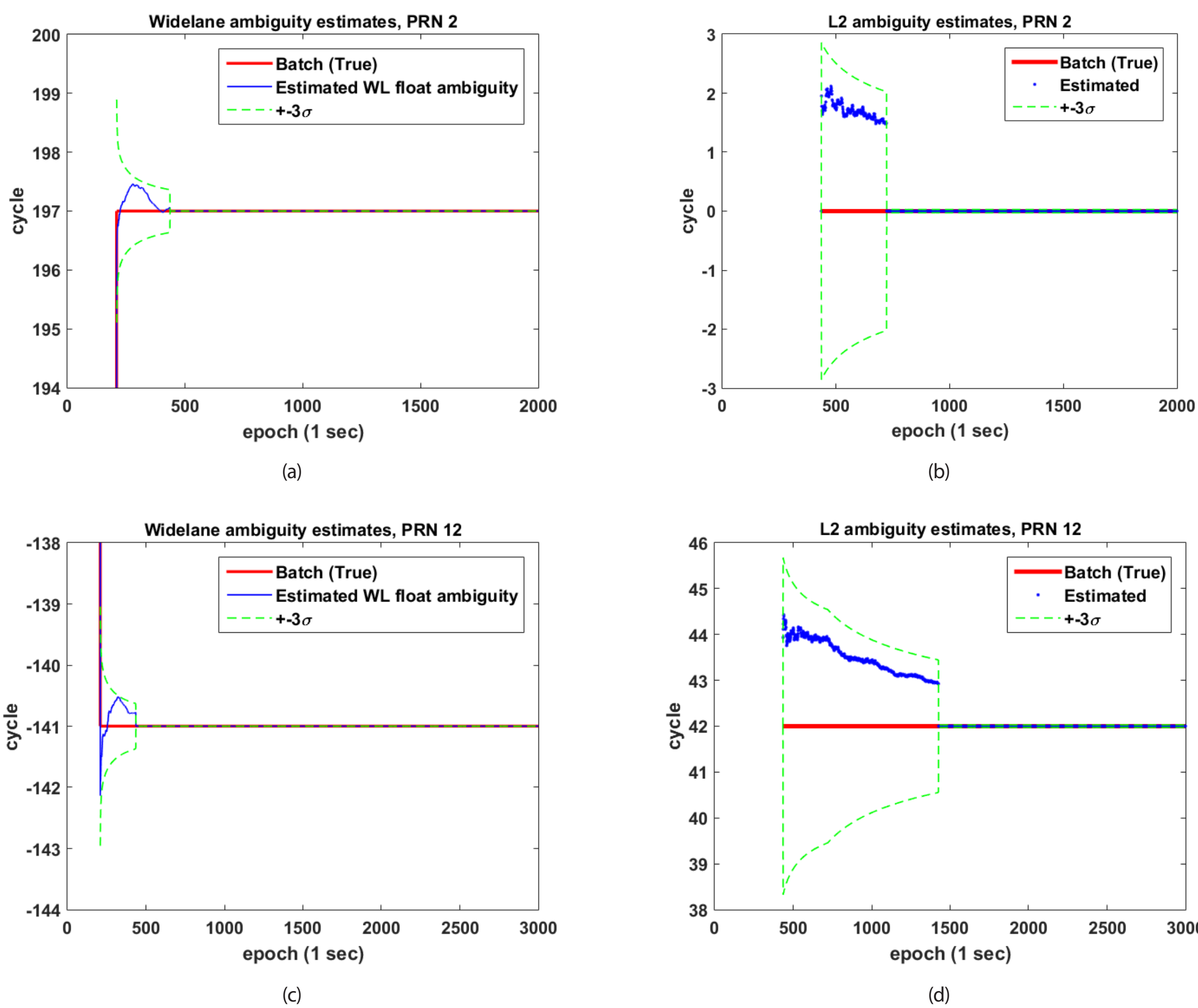
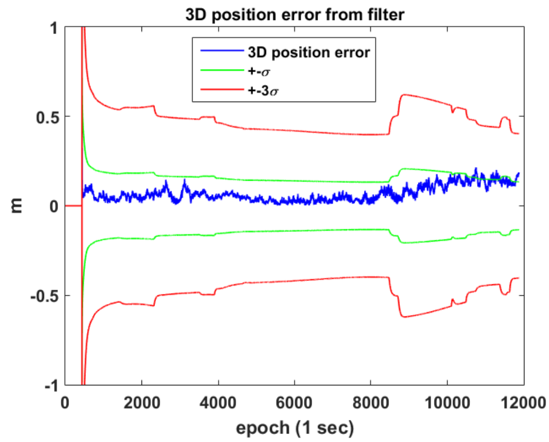
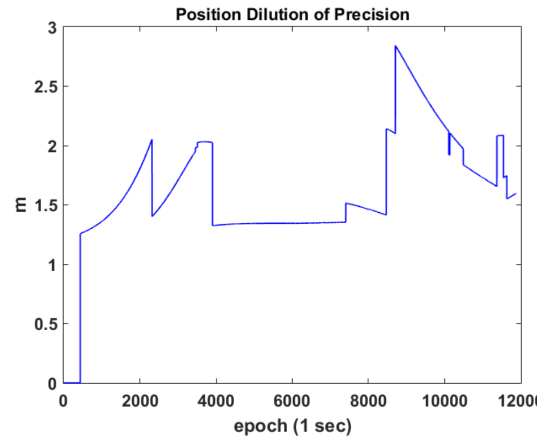


Fig. 4. (a) Estimated WL and (b) L2 float ambiguities for PRN 2. (c) and (d) shows those of PRN 12.



(a)



(b)

Fig. 5. (a) 3D position estimation error from filter and (b) position dilution precision during test.

Table 1. RMS error of the IF residual before and after estimation of tropospheric wet zenith delay.

	RMS errors of the IF residuals									
	PRN2	PRN5	PRN6	PRN9	PRN10	PRN12	PRN13	PRN20	PRN23	PRN26
Before	0.034	0.031	0.019	0.040	0.021	0.045	0.024	0.051	0.054	0.028
After	0.031	0.019	0.018	0.039	0.020	0.043	0.029	0.022	0.033	0.031
% variation	-6	-40	-8	-3	-6	-6	+17	-56	-40	+11

Table 2. Horizontal and vertical positioning results of medium-baseline RTK compared to commercial post-processing software.

	Proposed real-time medium-baseline RTK	Commercial post-processing software
Horizontal (2DRMS, m)	0.0495	0.0523
Vertical (2RMS, m)	0.1488	0.1050
Maximum PDOP	2.8427	2.0222
Average PODP	1.6716	1.3183

on the estimate of float ambiguity at the moment for the resolution of integer ambiguity. It was verified that the estimated WL and L2 integer ambiguities of all satellites including PRNs 2 and 12 were matched with the batch results. Fig. 5 shows both the error of the estimated position from the filter in the range domain and the corresponding covariance simultaneously. Fig. 5b shows the position dilution of precision (PDOP) during the test, which verifies the effect of satellite constellation on the position estimation result from the filter.

Table 1 presents root mean square (RMS) errors of IF measurement residual errors before and after the estimation of tropospheric vertical delay using IF measurements from the filter. The RMS values of the residual errors of most PRNs were reduced by up to 56%. The measurements of the user and CHEN reference station used in the developed algorithm were compared with the results processed with TBC, a commercial post-processing software in order to verify the performance of the developed medium-baseline RTK. Table 2 presents the real-time processing results using the developed algorithm and the horizontal and vertical position errors post-processed with the commercial TBC software. The horizontal position error was improved by approximately 5% when the developed algorithm was used, whereas the vertical position error showed that the results of post-processing with the commercial software were better. This may be because the PDOP in the post-processing mode was smaller due to the difference in the number of satellites used in the proposed real-time processing and post-processing with commercial software.

Since the medium-baseline RTK for generation of Network RTK correction information is performed with regard to a reference station whose position is accurately known, it does not need additional positioning estimation. Thus, the estimation of float ambiguity or tropospheric delay is expected to be easier and more effective with regard to Compact Network RTK.

3.2 Real-time Test Results for Land Vehicle User

The real-time test was conducted using a land vehicle for about 30 minutes from 17:41:36 seconds (local time) on November 27, 2015 to verify the performance of the real-time Compact Network RTK software developed in this study. The network was configured with PAJU reference station as a master station and other reference stations: INCH,

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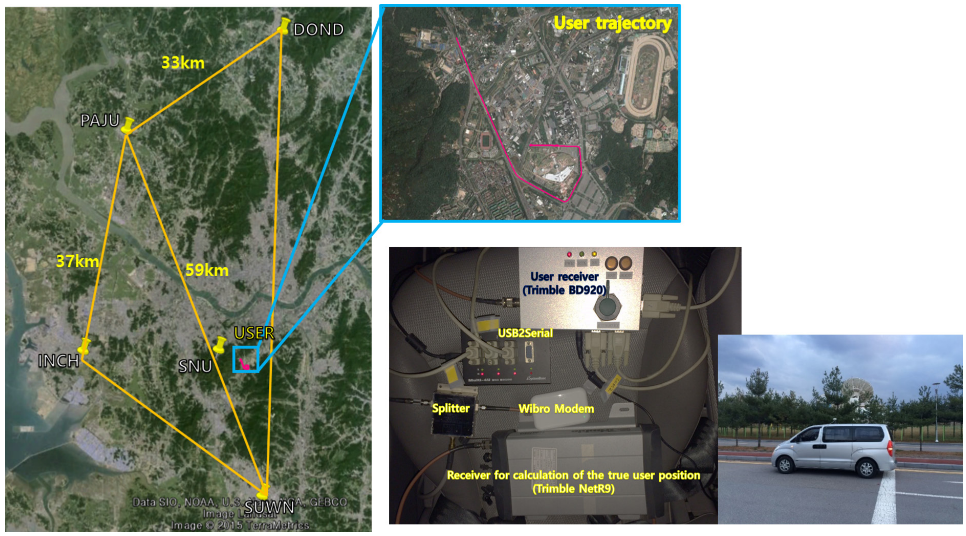


Fig. 6. Test configuration of the real-time performance validation for compact network RTK.

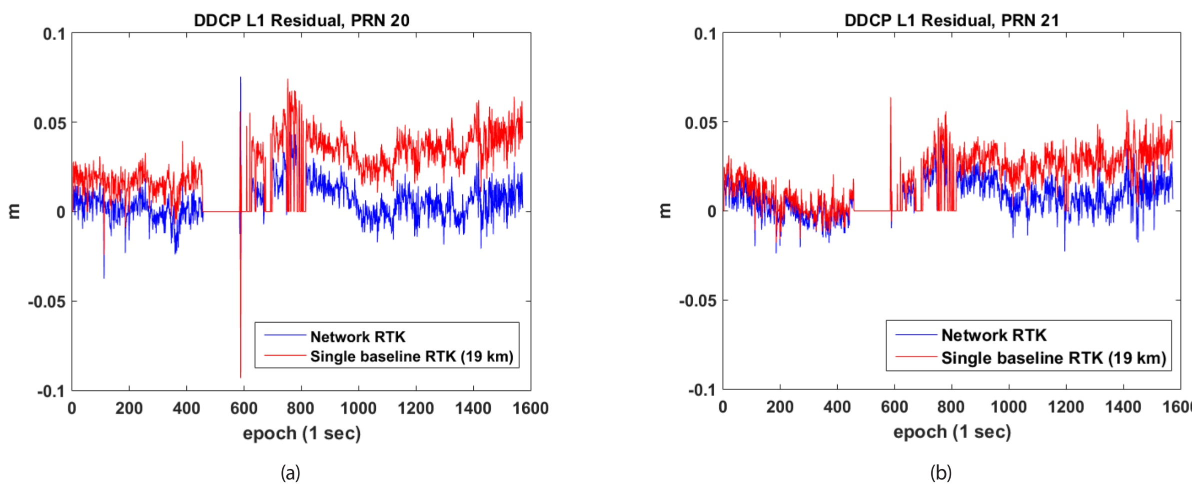


Fig. 7. Double-difference L1 carrier phase residuals of Compact Network RTK and single-baseline RTK (19 km baseline) for (a) PRN 20 and (b) PRN 21. Residual error of single-baseline RTK gradually grows as the baseline length increases.

SUWN, and DOND as shown in Fig. 6. The performance was compared with that of single-baseline RTK using SUWN reference station, which was approximately 19 km away from the user, to verify the user performance. The marginal baseline length is approximately 20 km to carry out conventional single-baseline RTK. For calculation of the true trajectory, the measurements at the reference station installed in Building No. 312 in Seoul National University, which was about 6 km away from the user, were processed with commercial software TBC. As shown in Fig. 6, the user drove the vehicle on the surrounding roads of the Seoul Grand Park in Gwacheon and then to the Sadang direction. During this drive, in the case of single-baseline RTK, which was used for comparison, it was expected that the decorrelation of the error between user and reference station would gradually increase as the user moved to Sadang, which increased the distance between the user and reference station SUWN.

Fig. 7 shows the residual errors of L1 double-differenced carrier phase with regard to PRNs 20 and 21 when navigation was performed using Compact Network RTK and single-baseline RTK over the entire test time. The particular period whose residual error was 0 refers to a period where navigation could not be done due to interruption of satellite navigation signals caused by the surrounding environment. The test was conducted in a relatively good reception environment around the Seoul Grand Park in Gwacheon until around 450 epochs. Then, the vehicle was moved along the road and drove on the motorcar road between Gwacheon and Sadang after 600 epochs. The residual error of the measurement in the Compact Network RTK was

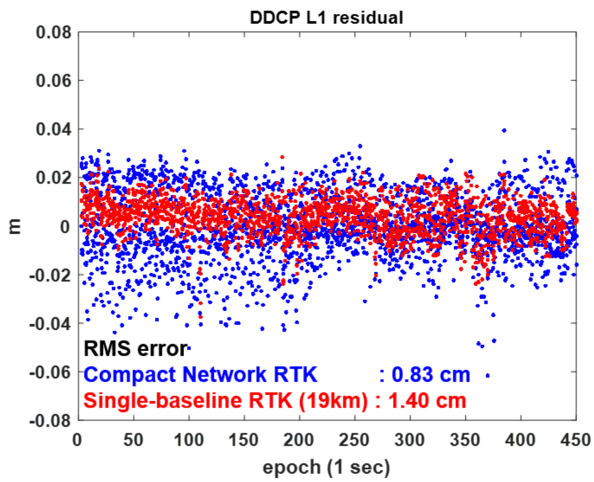


Fig. 8. Double-difference L1 carrier phase residuals of proposed real-time Compact Network RTK (blue) and single-baseline RTK (red) with marginal baseline length (19 km) for all visible satellites.

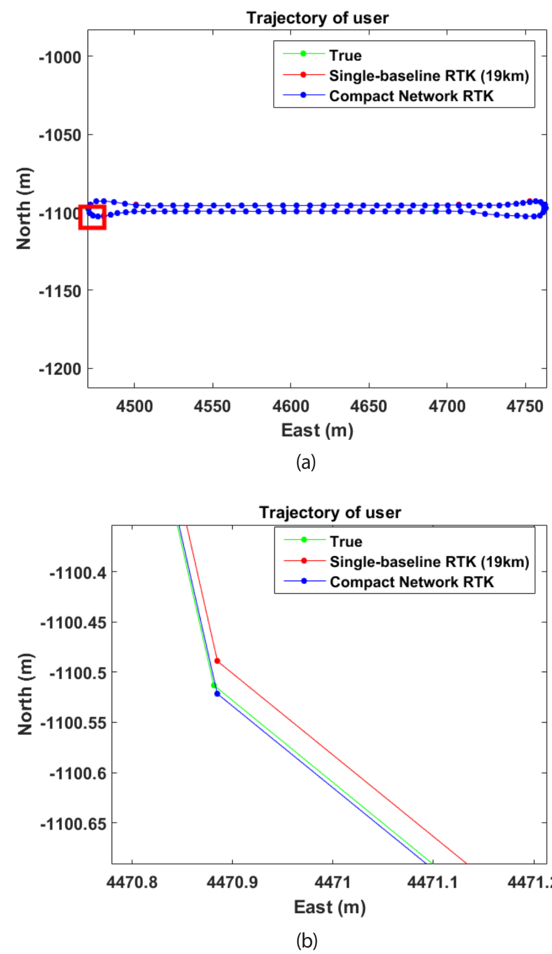


Fig. 9. (a) True (TBC post-processing) and estimated user trajectories of single-baseline RTK (19 km) and Compact Network RTK, (b) Zoomed-in figure indicates that Compact Network RTK result has more agreement with true trajectory.

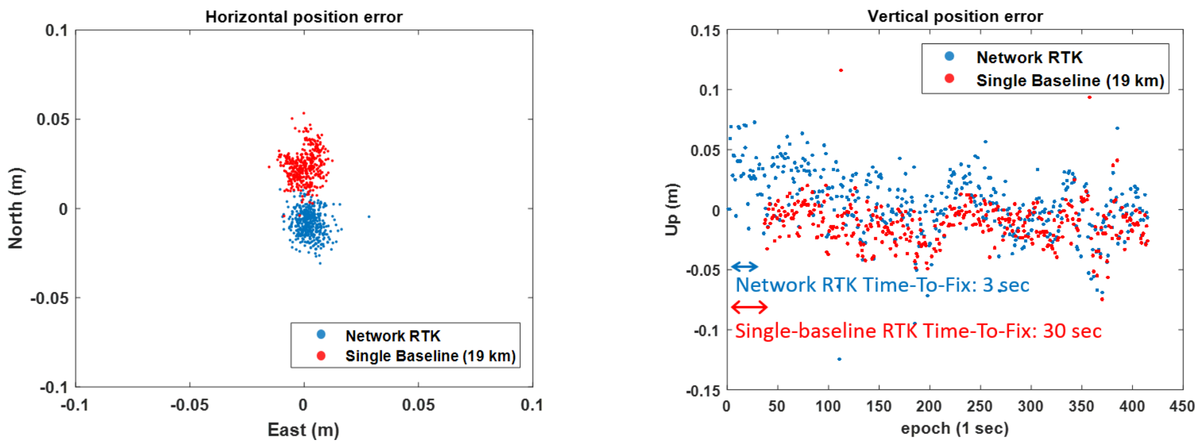
smaller than that of the single-baseline RTK. In particular, the residual error of the measurement in the single-baseline RTK increased as the user became closer to Sadang, thereby increasing a baseline distance between user and reference station. On the contrary, when the Compact Network RTK correction information was used, the residual error of the measurement was maintained below a certain level regardless of user's position change.

Fig. 8 shows the residual errors of double-differenced L1 carrier phase using the Compact Network RTK and single-baseline RTK in the test conducted near the Seoul Grand Park in Gwacheon, where the signal reception environment was relatively good. When the Compact Network RTK correction information was used, the error components included in the user measurements were more efficiently removed, and RMS errors were reduced by about 41%, compared to when the single-baseline RTK correction information was utilized.

Fig. 9a shows the user's true trajectory calculated from TBC post-processing commercial software and the user's trajectories estimated using single-baseline RTK and Compact Network RTK. Fig. 9b shows the enlarged trajectory of the region indicated by a red rectangle in Fig. 9a, and it reveals that the Compact Network RTK result was estimated more closely to the true trajectory than that of single-baseline RTK. Fig. 10 shows the error results in the horizontal and vertical directions of the user calculated over the entire trajectory. The integer ambiguity was resolved within 3 seconds when the Compact Network RTK correction information was used, whereas it took approximately 30 seconds when the single-baseline RTK correction information was used. Table 3 presents the RMS values of horizontal and vertical position errors. Overall, the three-dimensional position error showed that the Compact Network RTK achieved better positioning performance by about 15%, compared to the single-baseline RTK. The number of visible satellites in the Network RTK was smaller than that of the single-baseline RTK, because the user performs a navigation using satellites which were commonly visible by all reference stations. The better positioning accuracy in the Compact Network RTK despite of larger mean PDOP value was due to the fact that the Compact Network RTK could more accurately eliminate the user error component, as shown in Fig. 8.

4. CONCLUSIONS

This paper proposed the Compact Network RTK algorithm and a process to generate correction information considering both static and dynamic users such as vehicles.



(a) (b)

Fig. 10. (a) Horizontal and (b) vertical position errors of proposed real-time Compact Network RTK (blue) and single-baseline RTK (red) with marginal baseline length (19 km).

Table 3. Horizontal /vertical positioning errors and standard deviations (STD) of proposed real-time compact network RTK and single-baseline RTK with marginal baseline length.

	Compact network RTK	Single-baseline RTK (19 km)
Horizontal (DRMS, m)	0.0123	0.0258
Vertical (RMS, m)	0.0259	0.0208
3D position error (RMS, m)	0.0286	0.0332
Average PDOP	2.8370	2.1577
Maximum PDOP	3.0084	4.0593

It also conducted a real-time performance verification on vehicle users by using C++ based real-time program. In particular, this study proposed the medium-baseline RTK that estimated float ambiguity and tropospheric vertical delay through the Kalman filter by using the MW and the IF combinations to remove ionospheric delay and to estimate tropospheric delay, which were included in the double-differenced measurements between reference stations, in order to accurately estimate the integer ambiguity between reference stations, which is essential to generate correction information of the Compact Network RTK.

To verify the performance of the proposed medium-baseline RTK and Compact Network RTK algorithm, a real-time test was conducted for vehicle user, and the performance was evaluated through residual error of measurements and user position accuracy. The results showed that the medium-baseline RTK could reduce the residual error of the measurements through the tropospheric vertical delay estimation. Thus, it could obtain comparable position accuracy with that using commercial post-processing software. In addition, performances were compared between Compact Network RTK and single-baseline RTK for marginal baseline length. The performance comparison showed that the Compact Network RTK could effectively eliminate the error component included in the user measurements, resulting in integer ambiguity estimation within around 3 seconds. It was also confirmed that the residual error of the measurement was maintained at a certain level regardless of user position. On the contrary, the single-baseline RTK took around 30 seconds to resolve the integer ambiguity, and the residual error of the measurements increased as the user became farther away from the SUWN reference station. In conclusion, this study verified that the Compact Network RTK could eliminate user error components effectively regardless of vehicle user's movement and thus performed high-accuracy navigation within a short initial time.

For the future study, the performance of the Compact Network RTK is needed to be verified in terms of performance of user integer ambiguity resolution, and the performance due to communication time delay will be additionally conducted. Furthermore, a study on method of how to additionally apply multi-satellite navigation signals will be conducted to ensure sufficient visibility in land transportation environments.

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