

A Design of Dual Frequency Bands Time Synchronization System for Synchronized-Pseudolite Navigation System

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ABSTRACT

Time synchronization system using dual frequency bands is designed and the error sources are analyzed for alternative synchronized-pseudolite navigation system (S-PNS) which aims at military application. To resolve near/far problem, dual frequency band operation is proposed instead of pulsing transmission which degrades level of reception. In dual frequency operation H/W delay should be considered to eliminate errors caused by inter-frequency bias (IFB) difference between the receivers of the pseudolites and users. When time synchronization is performed across the sea, multipath error is occurred severely since the elevation angle between pseudolites is low so total reflection can be happened. To investigate the difference of multipath effects according to location, pseudolites are set up coastal area and land area and performances are compared. The error source related with tropospheric delay is becoming dominant source as the coverage of the PNS is broadening. The tropospheric delay is measured by master pseudolite receiver directly using own pseudorange and slave pseudorange. Flight test is performed near coastal area using S-PNS equipped with developed time synchronization system and test results are also presented.

Keywords: pseudolite navigation system, time synchronization

1. INTRODUCTION

A pseudolite navigation system (PNS) is a system where users can measure their position, velocity, or time using pseudo-satellites that generate navigation signals, such as GNSS. The first pseudolite was developed for test purposes before the active operation of GPS. Since then, it was mainly used as a navigation augmentation system that improves the accuracy or availability of GNSS using pseudolites that generate GNSS-like signals (Wang 2002). However, in recent years, attention has been drawn to PNS for an alternative navigation system that operates independently of GNSS and provides independent navigation service in GNSS shadow zones or jamming environments. In the case of

PNS that operates independently of GNSS, an independent proximity radio navigation signal system can be established by encrypting navigation signal code, concentrating and intensifying transmitted radio waves, and not disclosing the band and modulation method. Based on this technical background, PNS has been in the spotlight as a method for an alternative navigation system that can operate in GNSS jamming environments as well as for a commercial system such as indoor navigation and geographic survey (Craig & Locata Corp. 2012).

Depending on the time synchronization status of pseudolites, PNS is classified into an asynchronous-pseudolite navigation system (A-PNS) and a synchronized-pseudolite navigation system (S-PNS), as shown in Fig. 1. In the case of A-PNS, which consists of pseudolites, a user, and a reference station, the times of pseudolites are not synchronized, and thus, a transmission time error occurs when the user measures a pseudorange. To correct this error, the reference station generates transmission time error information by receiving the signals of all the pseudolites, and sends it to the user. Then, the user calculates the user

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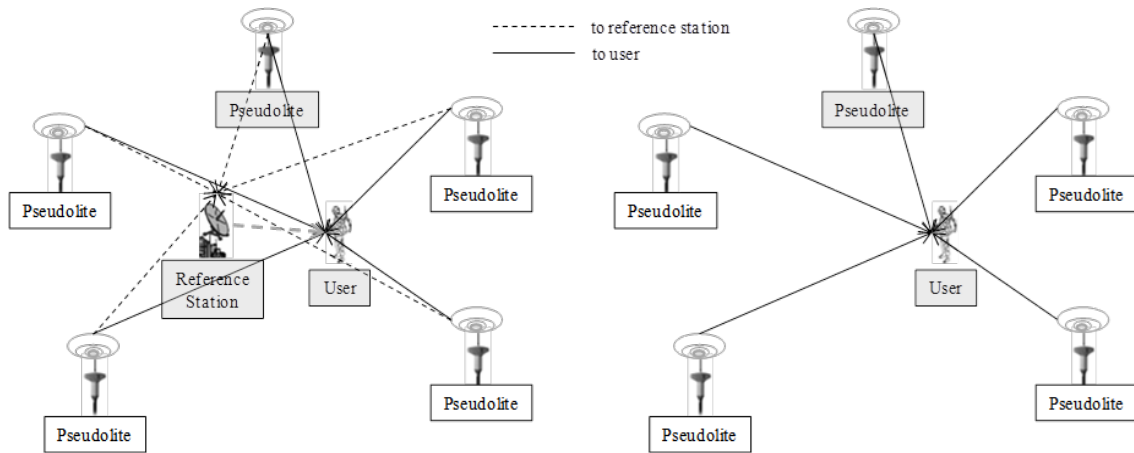


Fig. 1. System configurations of A-PNS (left) and S-PNS (right).

position by correcting the pseudorange measurement using the correction information received from the reference station (Kee et al. 2003). In this regard, if the timing of the correction information generated by the reference station is different from the timing of the pseudorange measured by the user, the accuracy of the correction information generated by the reference station degrades as time passes, which decreases the navigation accuracy. Therefore, A-PNS cannot have a wide operation range because it should secure the navigation communication link between the reference station and all the pseudolites and should also secure the data communication link between the reference station and the user at the same time. In addition, A-PNS has a low reliability in terms of system survivability because abnormal operation of the reference station has fatal effects on the entire system.

If the transmission times of pseudolites are synchronized, a user can perform navigation without the correction information generated by a reference station. This system is S-PNS. In general, S-PNS sets the time of a specific pseudolite as the reference, and synchronizes remaining pseudolites. The pseudolite that is the reference of time is called a 'master pseudolite', and the pseudolite that is the target of time synchronization is called a 'slave pseudolite'. A slave pseudolite is equipped with a receiver, and measures the pseudorange of a master pseudolite and its own pseudorange. Then, by comparing them with the true distance, it calculates the time error of the two pseudolites. For precise time synchronization, the errors included in the pseudorange measurements should be eliminated. If the distance between the pseudolites is far due to the wide operation range of the system, the power of the navigation signal of the master pseudolite received by the receiver is much smaller than that of the navigation signal of the slave

pseudolite. Thus, a near/far problem occurs. The problem can be avoided by using a pulsing technique, which transmits signals at different times during the transmission of signals. However, this degrades the reception sensitivity due to the decrease in the length of the correlation code.

In this study, to resolve the degradation of reception sensitivity, a time synchronization system where a master pseudolite and a slave pseudolite use different frequency bands was designed. Also, for independent proximity radio navigation purpose, time synchronization error elements that occur when the operation range of PNS widens were analyzed, and a method for resolving them was suggested. The designed time synchronization system was applied to S-PNS. Based on this, a test was performed, and the results were analyzed.

2. SYSTEM CONFIGURATION

Time synchronization systems for S-PNS can be broadly classified into two types, as shown in Fig. 2. For time synchronization system A, time synchronization is performed as a synch-station calculates time error by receiving all the time information of the master pseudolite and the slave pseudolite, and transmits a correction instruction to the slave pseudolite. The times of all the slave pseudolites are controlled by the synch-station. In this regard, as the synch-station directly controls the slave pseudolite, a user need not receive time correction information of, and also need not synchronize the timing with the synch-station. For this time synchronization system, one synch-station is in charge of the calculation of time error and the generation of correction instructions. Thus, it is easy to manufacture because the structures of the

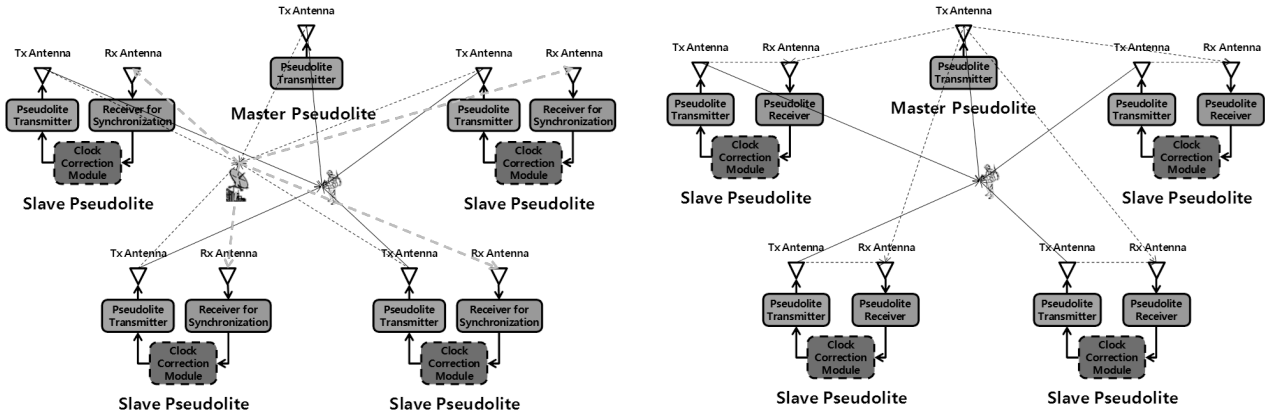


Fig. 2. Block diagrams and system configurations of S-PNS with (up, A) / without (down, B) synch-station.

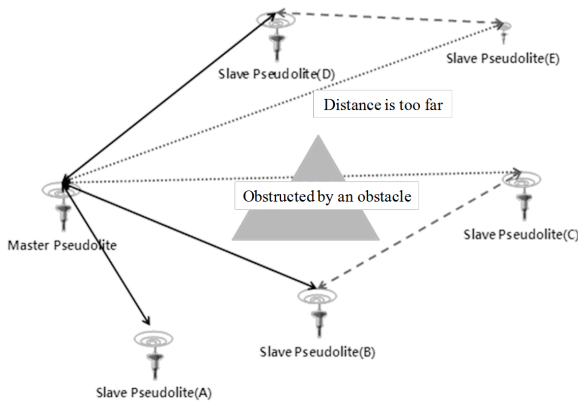


Fig. 3. S-PNS with decentralized-time synchronization system.

slave pseudolites are simple. However, it is inappropriate for operating a reliable system because the survivability of the system is low due to the same reason as that of A-PNS. For time synchronization system B, the slave pseudolite directly receives the time information of the master pseudolite, and calculates and corrects the time error for itself. Therefore, the slave pseudolites have independent timings of reception time and transmission time, and independently control their times. In this study, the purpose was to establish a GNSS alternative navigation system that can be operated at all times, and thus, a time synchronization system was designed based on system B.

A time synchronization system for PNS transmits time information using navigation signals without the use of separate wireless communication. In other words, by comparing the measurements of the navigation signals transmitted by a master pseudolite and a slave pseudolite, the slave pseudolite calculates the time error between the two pseudolites.

The method in which the times of all slave pseudolites are directly synchronized with the time of one master pseudolite is called a centralized-time synchronization system. In this case, if the distance between a master pseudolite and a slave pseudolite is too far or there is a problem in securing the line of sight (LOS) since the space between the two pseudolites is obstructed by an obstacle, time synchronization cannot be performed. The method in which the time synchronization of a slave pseudolite is performed based on the time of other slave pseudolite whose time synchronization has already been completed, rather than based on a master pseudolite, is called a decentralized-time synchronization system. This is shown in Fig. 3. In other words, direct time synchronization of slave pseudolites C and E cannot be performed because LOS with the master pseudolite is not secured and the distance between a master pseudolite and slave pseudolite is too far. However, time synchronization can be performed based on pseudolites B and D that have already been synchronized. Using this technique, the operation range of a pseudolite navigation system can be easily widened. However, in this regard, a system operation method needs to be effectively established considering the hierarchical structure of synchronization.

3. CLOCK ERROR MEASUREMENT ALGORITHM

For PNS, time synchronization refers to the simultaneous transmission of navigation signals from pseudolites. To achieve this, the frequency and phase of the system clock should be synchronized. Therefore, for the time synchronization between pseudolites, the differences in

the system frequency and the phase need to be known. A slave pseudolite can calculate them using the pseudorange and Doppler that have been measured by receiving the navigation signals transmitted by a master pseudolite and the slave pseudolite.

As shown in B of Fig. 2, a slave pseudolite includes a navigation signal receiver. Thus, the frequency difference between the master pseudolite and the slave pseudolite can be directly measured through Doppler measurements, as shown in Eq. (1).

$$\Delta f_{MS} = \phi_{MS}^A - \phi_{SS}^B \tag{1}$$

where Δf_{MS} is the system clock frequency difference between the master pseudolite and the slave pseudolite, ϕ_{MS}^A is the Doppler measurement for the navigation signal of the master pseudolite measured at the receiver of the slave pseudolite, and ϕ_{SS}^B is the Doppler measurement for the navigation signal of the slave pseudolite measured at the receiver of the slave pseudolite. A, B represent the frequency bands of the navigation signals; and M and S represent the master pseudolite and the slave pseudolite, respectively.

To obtain phase difference, the pseudorange measurements of the master pseudolite and the slave pseudolite are required. In this regard, each pseudorange can be modeled as Eqs. (2) and (3).

$$\rho_{MS}^A = R_{MS} + \rho_{Mul} + \rho_{Tro} + c \cdot \left\{ T_T^A + (t_{rx} - t_M) \right\} \tag{2}$$

$$\rho_{SS}^B = R_{SS} + c \cdot \left\{ T_T^B + (t_S - t_S) \right\} \tag{3}$$

where c is the speed of light, ρ_{MS} is the pseudorange measurement for the navigation signal of the master pseudolite measured at the slave pseudolite, ρ_{SS} is the pseudorange measurement for the navigation signal of the slave pseudolite measured at the slave pseudolite, R_{MS} is the true distance between the master pseudolite and the slave pseudolite, R_{SS} is the true distance between the transmission and reception antennas of the slave pseudolite, ρ_{Tro} is the tropospheric delay pseudorange error that occurs between the pseudolites, ρ_{Mul} is the pseudorange error that occurs due to the multipath signals, T_T^A is the propagation delay for the A band signal that occurs at H/W during the transmission and reception of navigation signals between the pseudolites, T_T^B is the propagation delay for the B band signal that occurs at H/W during the transmission and

reception of navigation signals between the pseudolites, t_S is the reception clock error of the slave pseudolite, t_S is the transmission clock error of the slave pseudolite, and t_M is the transmission clock error of the master pseudolite. In Eq. (3), it was assumed that the positions of the transmission and reception antennas of the slave pseudolite are relatively very close and thus pseudorange errors due to tropospheric delay and multipath do not occur through the optimization of the antenna positions. In addition, pseudorange noise was also omitted for the simplification of the equations. If the difference value of the pseudoranges that have been measured as discussed above is compared with the difference value of the true distance, the pseudo-synch error, $\widehat{\Delta}_{MS}$, can be obtained as shown in Eq. (4), and the transmission time of the slave pseudolite is synchronized as shown in Eq. (5).

$$\begin{aligned} \widehat{\Delta}_{MS} &= \frac{(\rho_{MS}^A - \rho_{SS}^B) - (R_{MS} - R_{SS})}{c} \\ &= \frac{\rho_{Mul} + \rho_{Tro} + T_T^{IFB}}{c} - (t_M - t_S) \\ &: \text{pseudo-synch error} \end{aligned} \tag{4}$$

$$t_S = t_M - \frac{\rho_{Mul} + \rho_{Tro} - T_T^{IFB}}{c} \tag{5}$$

where $t_M - t_S$ is the true-synch error, and $T_T^{IFB} = T_T^A - T_T^B$ is the IFB that occurs during the transmission and reception of navigation signals between the pseudolites.

The pseudorange measurement of a user for the navigation signals of the master pseudolite and the slave pseudolite that have the transmission time shown in Eq. (5) can be modeled as Eq. (6). When this is compared with the true distance to obtain the pseudorange error of the user, it can be expressed as Eq. (7). In this regard, to express only the pseudorange error of the user due to the time synchronization error between the pseudolites, errors due to the tropospheric delay and multipath between the pseudolite and the user were omitted.

$$\begin{aligned} \rho_{MR}^A &= R_{MR} + c \cdot \left\{ T_R^A + (t_R - t_M) \right\} \\ \rho_{SR}^B &= R_{SR} + c \cdot \left\{ T_R^B + (t_R - t_S) \right\} \\ &= R_{SR} + c \cdot \left[T_R^B + \left\{ t_R - \left(t_M - \frac{\rho_{Mul} + \rho_{Tro}}{c} - T_T^{IFB} \right) \right\} \right] \end{aligned} \tag{6}$$

$$\frac{(\rho_{MR}^A - \rho_{SR}^B) - (R_{MR} - R_{SR})}{c} = (T_R^{IFB} - T_T^{IFB}) - \frac{\rho_{Mul} + \rho_{Tro}}{c} \tag{7}$$

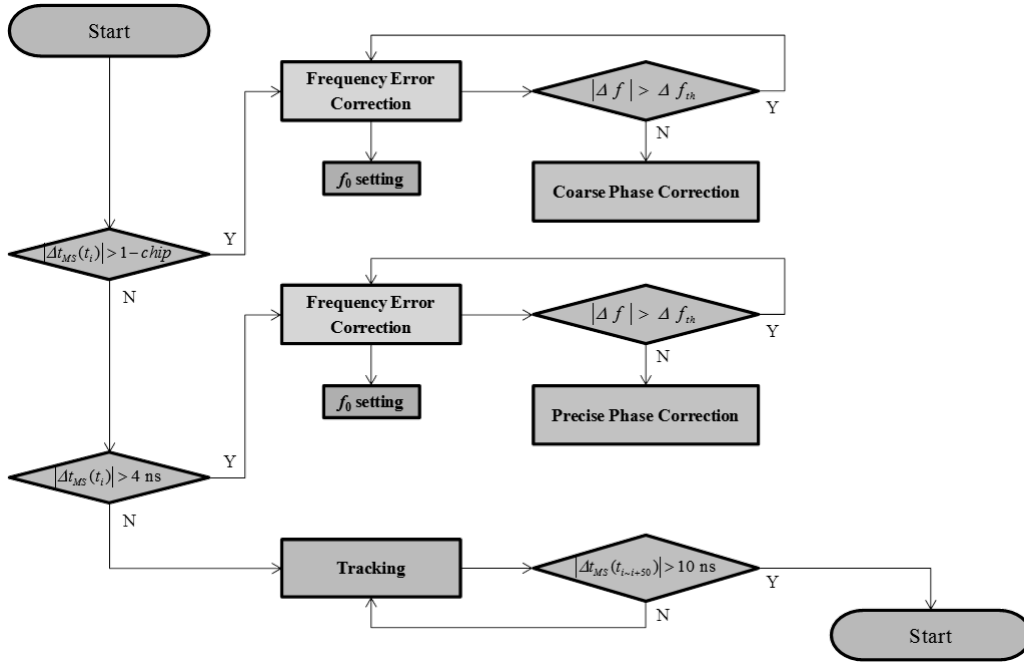


Fig. 4. Clock correction algorithm flow chart.

where ρ_{MR}^A is the pseudorange measurement for the navigation signal of the master pseudolite measured at the user receiver, ρ_{SR}^B is the pseudorange measurement for the navigation signal of the slave pseudolite measured at the user receiver, R_{MR} is the true distance between the user receiver and the master pseudolite, R_{SR} is the true distance between the user receiver and the slave pseudolite, T_R^A is the propagation delay for the A band signal that occurs at H/W during the transmission and reception of navigation signals between the pseudolite and the user receiver, T_R^B is the propagation delay for the B band signal that occurs at H/W during the transmission and reception of navigation signals between the pseudolite and the user receiver, ${}_{rx}T_R$ is the reception clock error of the user receiver, and $T_R^{IFB} = T_R^A - T_R^B$ is the IFB that occurs during the transmission and reception of navigation signals between the pseudolite and the user.

The pseudorange error of a user due to the time synchronization error of the slave pseudolite that has been synchronized via the algorithm shown in Eq. (4) based on the time of the master pseudolite is divided into the element relevant to the IFB between the pseudolite and the user and the elements relevant to the wireless channel for time synchronization. Each error element was discussed in the Section 5.

4. CLOCK ERROR CORRECTION ALGORITHM

The measured frequency error and phase error were

basically corrected through the system clock control of the slave pseudolite. Fig. 4 shows the flow chart of the correction algorithm. The correction was performed in stages depending on the size of the measured phase error, and it was designed so that it could become time synchronization error tracking status when the measured phase error was less than 4 ns. Also, considering the disconnection of the link between the master pseudolite and the slave pseudolite during the performance of time synchronization, the initial value of the system clock (f_0) was changed for every frequency correction.

A direct digital synthesizer (DDS) was used to control the system clock, and the instruction words for DDS control were calculated using Eqs. (8) ~ (10). t is the error measurement time, N is the number of samples for the measurement time, L_{FTW} is the number of bits for the instruction word of DDS, f_{sys_clk} is the operation clock frequency of DDS, T_{1-chip} is the length of one chip of the code, λ is the wavelength of the system clock frequency, and Δt is the phase error correction time.

In the coarse phase correction stage, to correct large initial time synchronization error in short time, the period of the signal that controls the message generation timing of a navigation signal (TFSD, Transmit Frame Start Delimiter) is controlled when the size of the measured phase error was larger than one chip. The instruction word for this was calculated using Eq. (9). In the precise phase correction stage, the measured phase error was corrected

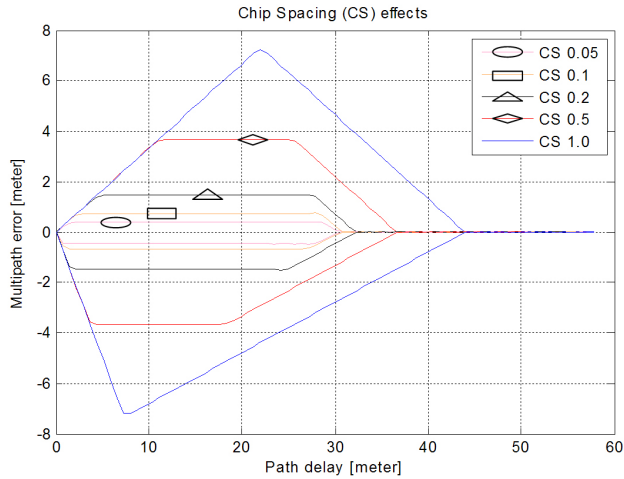


Fig. 5. Multipath error envelope at difference chip spacing.

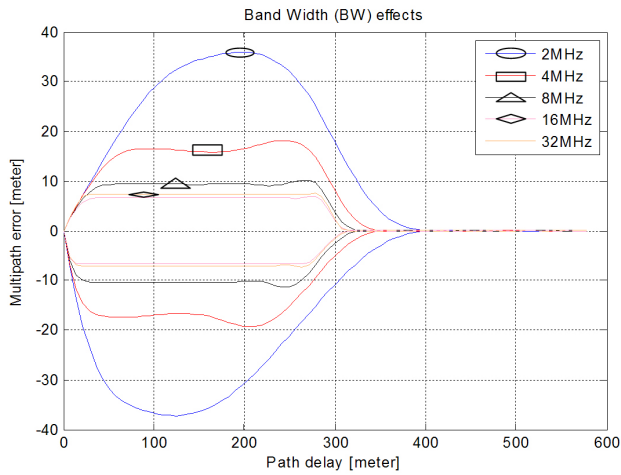


Fig. 6. Multipath error envelope at difference signal band width.

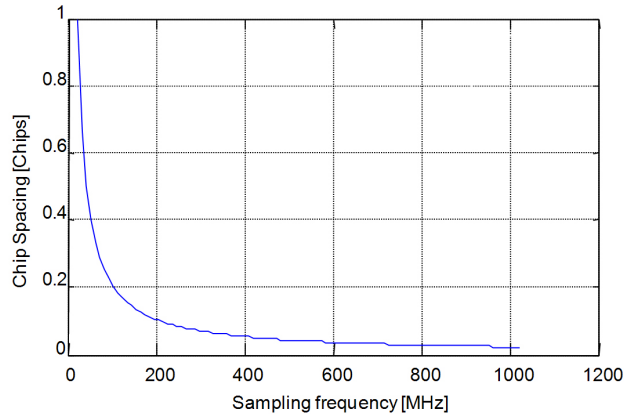


Fig. 7. Multipath error envelope at difference signal band width.

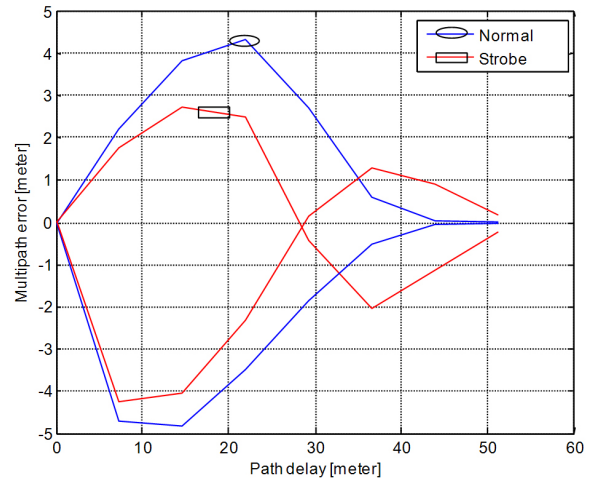


Fig. 8. Multipath error envelope at difference signal band width.

by controlling the frequency of the system clock. Using the upper equation in Eq. (10), the phase error that had been corrected for T hours (Δt_{MS}) was converted to a frequency value (Δf_{MS}). Then, using the lower equation in Eq. (10), the value that had been converted to a frequency value was again converted to a frequency control instruction value.

$$\left[\begin{aligned} \Delta f(\Delta t_{MS}) &= c \cdot \frac{\sum \Delta t_{MS}}{N_t} \times \frac{1}{\lambda \cdot T} \\ FTW_{phase} &= \frac{\{f_0 + \Delta f(\Delta t_{MS})\} \times 2^{L_{FTW}}}{f_{sys_clk}} \end{aligned} \right] \quad (10)$$

: Precise phase correction word

$$FTW_{freq} = \left(\left(f_0 + \frac{\sum \Delta f_{MS}}{N_t} \right) \times 2^{L_{FTW}} \right) \times \frac{1}{f_{sys_clk}}$$

: Frequency error correction word

(8)

$$MTW = \text{int} \left(\frac{\sum \Delta t_{MS}}{N_t} \times \frac{1}{T_{1-chip}} \right) \times T_{1-chip}$$

: Coarse phase correction word

(9)

5. ERROR SOURCE ANALYSIS

5.1 IFB Difference

For the time synchronization system designed in this study, the navigation signals of the master pseudolite and the slave pseudolite use different frequency bands, and thus an error depending on IFB occurs. This error occurs when

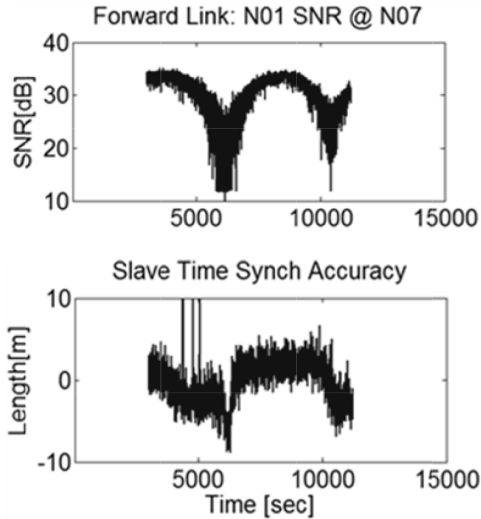


Fig. 9. SNR of master pseudolite's navigation signal measured at slave pseudolite near coastal area (up) and time synchronization accuracy which is calculated using pseudoranges (down).

a user measures a pseudorange for navigation, as shown in Eq. (7). If the receivers of the slave pseudolite and the user consist of the same H/W, this error is eliminated. In other words, if the IFB between the pseudolites is identical to the IFB between the pseudolite and the user, the error cancels out when the user measures the pseudorange even though the propagation delay due to the H/W of each band is not identical.

5.2 Multipath Delay

When a receiver receives a navigation signal transmitted by a pseudolite, it can receive a number of reflected waves generated by various reflectors as well as the direct wave transmitted through the shortest path. The signals received through a number of paths cause an error during the measurement of a pseudorange by distorting the correlation function of the receiver. This is called a multipath error (Kaplan & Hegarty 2006).

Multipath error varies depending on the correlator characteristics and bandwidth of a receiver. To analyze the time synchronization error due to multipath error when a pseudolite is installed in coastal area, a simulation of the multipath error that occurs when the intensity of the reflected wave is 0.5 times that of the direct wave and when only one reflected wave exists was performed for the signal with a chip speed of 10.23 MHz. The above simulation setting is valid because in coastal area, a strong reflected wave from the sea surface induces the most critical multipath error.

First, the multipath error depending on the chip spacing

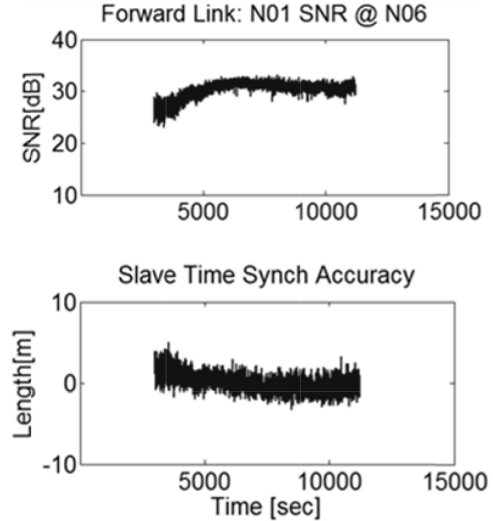


Fig. 10. SNR of master pseudolite's navigation signal measured at slave pseudolite in land (up) and time synchronization accuracy which is calculated using pseudoranges (down).

was analyzed as shown in Fig. 5. The multipath error characteristic was improved as the chip spacing decreased. This indicates that the narrow correlator was effective for decreasing the multipath error. Especially, when the chip spacing of the correlator was less than 0.1, the error level was less than 1 m.

Fig. 6 shows the multipath error depending on the bandwidth of the receiver when the chip spacing was 0.1. The multipath error was improved as the bandwidth of the receiver widened. The multipath error was no longer improved when the bandwidth was more than 32 MHz.

To decrease the chip spacing of the correlator, the ADC sampling of the receiver needs to be increased. Fig. 7 shows the sampling frequency depending on the chip spacing for a 10.23 MHz signal. The ADC sampling frequency of the receiver designed in this study was 40.92 MHz, and available chip spacing was about 0.5. Fig. 8 shows the multipath errors for a normal correlator and a strobe correlator when the chip spacing was 0.5. The maximum multipath error was about 5 m.

The most effective method of avoiding multipath error is to install an antenna at a location that does not have factors for multipath occurrence (Kaplan & Hegarty 2006). If PNS with an operation range of dozens of kilometers is installed in coastal area, the length of the distance between the pseudolites is longer than the altitude of the pseudolite. Thus, a reflected wave with strong signal intensity could be formed by the sea surface that has a high reflection coefficient. Therefore, pseudolites should be installed in inland area to avoid a strong reflected wave and to decrease multipath error. The effect of multipath error depending on

the position of a pseudolite was examined by comparing the difference values of the reception sensitivity and pseudorange for the pseudolite installed in coastal area and the pseudolite installed in inland area at the same time. The results were shown in Figs. 9 and 10. For the pseudolite installed in coastal area, sea surface reflected waves were received in an opposite phase of the direct wave at certain times depending on the variation of the sea surface, which decreased the reception sensitivity and increased the time synchronization error. For the pseudolite installed in inland area (about 1 km inland), stable reception sensitivity and time synchronization status were observed.

5.3 Tropospheric Delay

The troposphere is an atmospheric layer that is distributed at the lowermost part of the Earth's atmosphere. In general, it is distributed up to about 11 km from the Earth's surface. In the troposphere, the propagation of a navigation signal is delayed compared to a free space, and thus, an error occurs during the measurement of a pseudorange. This is called a tropospheric delay error. In the case of GNSS, various tropospheric delay error models are used to correct the error. These models are generally valid for an elevation angle of more than 10°, and thus cannot accurately correct the tropospheric delay error that occurs at a low elevation angle such as the transmission and reception of navigation signals for the time synchronization of pseudolites. Therefore, a tropospheric delay error correction method that is appropriate for pseudolites is required (Bouska & Raquet 2003).

In this study, a method that directly measures the amount of delay through the differencing of the pseudoranges measured at the master pseudolite was used, instead of a method that estimates the amount of delay through a tropospheric delay model. Eq. (11) presents the pseudoranges for the navigation signals of the master pseudolite and the slave pseudolite, respectively, measured at the master pseudolite. ρ_{MM}^A is the pseudorange measurement for the navigation signal of the master pseudolite measured at the receiver of the master pseudolite, ρ_{SM}^B is the pseudorange measurement for the navigation signal of the slave pseudolite measured at the receiver of the master pseudolite, R_{MM} is the true distance between the transmission and reception antennas of the master pseudolite, R_{SM} is the true distance between the slave pseudolite and the master pseudolite, and $_{Rx}t_M$ is the reception clock error of the master pseudolite. If the differencing of the two equations is performed at the master pseudolite as shown in Eq. (12) and it is arranged using

Table 1. Error budget of one-way pseudorange measurement.

	Error source	1σ error (m)
Master to slave	Receiver noise	0.3
	Tropospheric delay	0
	Multipath	1
	Reference location	0.5
Slave to slave	Receiver noise	0.3
	Reference location	0.5
Pseudolite to user	Inter-frequency bias	0
	Total	1.3

Eq. (5), a tropospheric delay error can be obtained. In this regard, it was assumed that the multipath error occurring between the pseudolites was sufficiently reduced by the appropriate selection of the positions of the pseudolites. Then, by transmitting this value to the slave pseudolite through a navigation signal, the tropospheric delay error can be corrected during time synchronization.

$$\begin{aligned} \rho_{MM}^A &= R_{MM} + c \cdot \{T_T^A + ({}_{Rx}t_M - {}_{Tx}t_M)\} \\ \rho_{SM}^B &= R_{SM} + \rho_{Tro} + c \cdot \{T_T^B + ({}_{Rx}t_M - {}_{Tx}t_S)\} \end{aligned} \quad (11)$$

$$\begin{aligned} &(\rho_{MM}^A - \rho_{SM}^B) - (R_{MM} - R_{SM}) \\ &= c \cdot T_T^A + c \cdot ({}_{Rx}t_M - {}_{Tx}t_M) - \rho_{Tro} - c \cdot T_T^B - c \cdot ({}_{Rx}t_M - {}_{Tx}t_S) \\ &= c \cdot T_T^{IFB} - c \cdot {}_{Tx}t_M - \rho_{Tro} + c \cdot \left({}_{Tx}t_M - \frac{\rho_{Tro}}{c} - T_T^{IFB} \right) \\ &= -2\rho_{Tro} \end{aligned} \quad (12)$$

5.4 System Error Analysis

Table 1 summarizes the error budget of the time synchronization system designed in this study, for analyzing the effect of the time synchronization system on the pseudolite navigation system. The calculation indicated that an error of about 1.3 m would occur when the slave pseudolite calculates time synchronization error using the navigation signals of the master pseudolite and the slave pseudolite.

The noise characteristic of the receiver was reflected because the code measurement of the receiver was used to measure the time synchronization error. The error for the true distance between the master pseudolite and the slave pseudolite and the error that could occur during the installation of the pseudolites were also reflected in the time synchronization error. The error element for IFB was separately classified because it is not an error that occurs at the actual pseudolite but an error that occurs between the pseudolites transmitting in different frequency bands and a

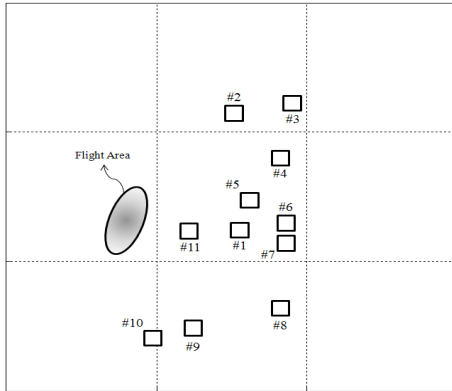


Fig. 11. Location of pseudolites and flight area.

user receiving them.

6. SYSTEM TEST

6.1 Test Configuration

S-PNS was configured by applying the time synchronization system using dual bands to pseudolites. The performance of the system was measured through a flight test, and the results were analyzed. Ten slave pseudolites were designed in addition to one master pseudolite, and the distance between the master pseudolite and the slave pseudolite was made to be dozens of kilometers. Fig. 11 shows the arrangement of the pseudolites and the approximate test area. For slave pseudolites #3 and #10 whose LOS was not secured, time synchronization was performed based on slave pseudolites #5 and #9, respectively.

Navigation was performed for dozens of minutes by installing the receiver at an aerial vehicle, where it ascended up to the altitude of thousands of meters and then landed. As all the systems were installed in the Earth System, Earth-Centered Earth-Fixed (ECEF) was used as the reference coordinate system. The navigation result of the receiver was evaluated through comparison with the post-processed GPS result.

6.2 Test Results

Due to the nature of the time synchronization system using dual bands, it is difficult to directly measure time synchronization error through the system clock between the pseudolites that are dozens of kilometers apart. Therefore, in this study, only the availability of the system was judged based on the navigation test, and the effect of the time synchronization error on the result of the navigation

Table 2. Design status & synchronization stability of pseudolites.

PRN	Frequency band	Status	Synch. stability (m, RMS)
1	B	Master	-
2	A	Slave	0.14
3	A	Slave	2.11
4	B	Slave	0.12
5	A	Slave Master of slave #3	0.30
6	A	Slave	0.80
7	B	Slave	0.19
8	A	Slave	0.70
9	A	Slave Master of slave #10	0.46
10	A	Slave	0.93
11	A	Slave	0.31

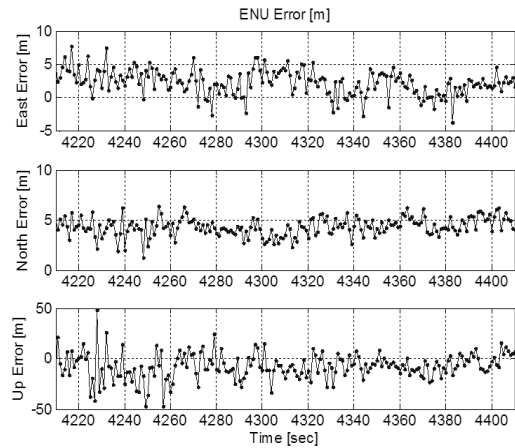


Fig. 12. ENU errors of user receiver (Time = 4210s ~ 4410s).

test could not be quantitatively analyzed. However, the time synchronization stability was measured through the pseudorange difference value measured at the slave pseudolite (pseudoranges of the master pseudolite and the slave pseudolite), and the results were summarized in Table 2. The results of the measurement indicated that pseudolite #3 had lower stability performance than the other pseudolites. This is because interference occurred by the signals of the adjacent pseudolites when pseudolite #3 received the signal of pseudolite #5.

Fig. 12 shows the east-north-up (ENU) errors between the DGPS that has been post-processed in the best DOP condition among the test section and the pseudolite navigation system of this report. The results of the performance evaluation indicated that the error in the horizontal direction was about 5 m, and the error in the up-direction was about 25 m. The error in the up-direction was large because VDOP was poor due to the nature of the arrangement of the pseudolites. Figs. 13 and 14 show the DOP and the horizontal error, respectively. 5 m level position accuracy performance was obtained when HDOP was about 1.65. In this regard, the accuracy of the DGPS, which served as the reference, was ± 1 m level.

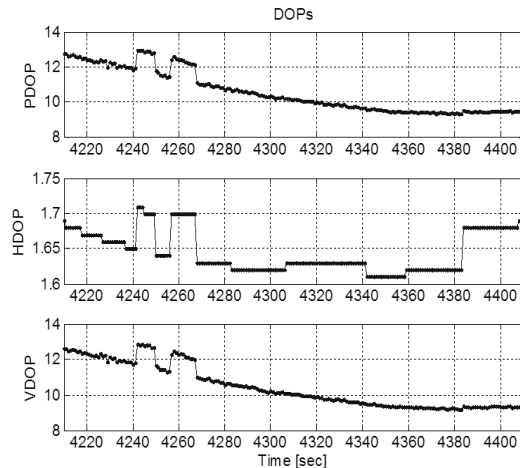


Fig. 13. DOPs (Time = 4210s ~ 4410s).

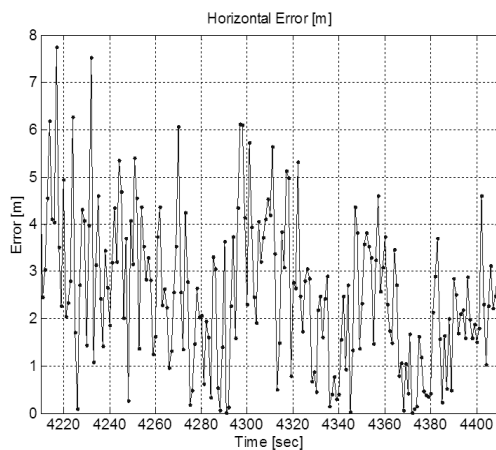


Fig. 14. Horizontal error (Time = 4210s ~ 4410s).

7. CONCLUSIONS

In this study, a time synchronization system using dual bands was designed; and error elements that occur during the operation of the system were analyzed and a method for resolving them was suggested. Also, S-PNS was configured by applying the designed system to actual pseudolites, and the performance evaluation was conducted.

The navigation system that includes the designed time synchronization system is an independent navigation system that can operate without GNSS, and is essential to cope with the recent indiscriminate jamming attacks from a hostile country. However, there are many elements to be developed so that this system can have higher accuracy and more stable performance; and the system designed in this study suggested the possibility. In the future, studies on high-precision measuring equipment that can measure the

time synchronization of S-PNS that is operated in a wide area are required.

REFERENCES

- Bouska, J. & Raquet, F. 2003, Tropospheric Model Error Reduction in Pseudolite-Based Positioning Systems, ION GPS/GNSS 2003, Portland, OR USA, 9-12
- Craig, D. & Locata Corp. 2012, USAF's New Reference System Truth on the Range, Inside GNSS Magazine May/June 2012, 37-48. <http://www.insidegnss.com/node/3071>
- Kaplan, E. D. & Hegarty, C. J. 2006, Understanding GPS: Principles and Applications. 2nd ed. (Norwood, MA: Artech House)
- Kee, C., Jun, H., & Yun, D. 2003, Indoor Navigation System using Asynchronous Pseudolites, The Journal of Navigation, 56, 443-455. <http://dx.doi.org/10.1017/S0373463303002467>
- Wang, J. 2002, Pseudolite Applications in Positioning and Navigation: Progress and Problems, Journal of Global Positioning Systems, 1, 48-56



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