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Software-based Performance Analysis of a Pseudolite Time Synchronization Method Depending on the Clock Source

Ju Hyun Lee[1], Soyoung Hwang[2], Dong-Hui Yu[2], Chansik Park[3], Sang Jeong Lee[1†]

[1]Department of Electronics Engineering, Chungnam National University, Daejeon 305-764, Korea
[2]Department of Software, Catholic University of Pusan, Busan 609-757, Korea
[3]Department of Electronics Engineering, Chungbuk National University, Cheongju 361-763, Korea

ABSTRACT

A pseudolite is used as a GPS backup system, and is also used for the purpose of indoor navigation and correction information transmission. It is installed on the ground, and transmits signals that are similar to those of a GPS satellite. In addition, in recent years, studies on the improvement of positioning accuracy using the pseudorange measurement of a pseudolite have been performed. As for the effect of the time synchronization error between a pseudolite and a GPS satellite, a time synchronization error of 1 us generally induces a pseudorange error of 300 m; and to achieve meter-level positioning, ns-level time synchronization between a pseudolite and a GPS satellite is required. Therefore, for the operation of a pseudolite, a time synchronization algorithm between a GPS satellite and a pseudolite is essential. In this study, for the time synchronization of a pseudolite, "a pseudolite time synchronization method using the time source of UTC (KRIS)" and "a time synchronization method using a GPS timing receiver" were introduced; and the time synchronization performance depending on the pseudolite time source and reference time source was evaluated by designing a software-based pseudolite time synchronization performance evaluation simulation platform.

Keywords: time synchronization, pseudolite, GPS, clock sources

1. INTRODUCTION

In general, a pseudolite is used as a backup system of a GPS satellite, and is also operated for the purpose of indoor navigation. It is installed on the ground, and transmits signals that are similar to those of a GPS satellite. Thus, various GPS error correction systems using a pseudolite have been studied and operated. On the other hand, error correction systems are operated to improve the positioning accuracy and precision of GPS, and they are classified into Ground-Based Augmentation Systems (GBAS), Space-Based Augmentation Systems (SBAS), Airplane-Based Augmentation Systems (ABAS), and Ground-Based Regional Augmentation Systems (GRAS) depending on the correction information transmission method.

Among them, GBAS is used as a navigation aid system for the taking off and landing of aircraft, and is also used for the navigation positioning performance improvement of general users. If a pseudolite is used for the operation of GBAS, service can be provided without securing an additional band because a GPS receiver transmits correction data using the L1 band which has previously been used, and improvement in the navigation performance is expected using an additional pseudorange measurement through the signal received from the pseudolite. Currently, a study on the addition of a pseudolite to European Geostationary Navigation Overlay Service (EGNOS), which is a SBAS system in Europe, is in progress.

A pseudolite transmits PRN code, carrier, and navigation data that are identical to those of a GPS satellite, which is located on the Earth's orbit, on the ground, and has a signal structure that is identical to that of a GPS satellite signal. Also, the navigation performance of an existing GPS receiver can be improved using the pseudorange measurement of a pseudolite; operation is enabled at a low cost compared to a navigation satellite as a pseudolite is installed on the ground;

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†**Corresponding Author**
E-mail: eesjl@cnu.ac.kr
Tel: +82-42-825-3991 Fax: +82-42-823-4494

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and it can be operated in regions that satellite signals cannot reach. However, to use the pseudorange measurement of a pseudolite, a pseudolite time synchronization accuracy that is similar to the time synchronization level between GPS satellites is required because GPS is operated based on time of arrival (TOA) measurements. As for the effect of the time synchronization error between a pseudolite and a GPS satellite, a time synchronization error of 1 us generally induces a pseudorange error of 300 m; and to achieve meter-level positioning, ns-level time synchronization between a pseudolite and a GPS satellite is required. Therefore, for the operation of a pseudolite, a time synchronization algorithm between a GPS satellite and a pseudolite is essential.

In this study, methods for the time synchronization between a GPS satellite and a pseudolite for the utilization of the pseudorange measurement of the pseudolite were introduced, and an FIR-based pseudolite time synchronization algorithm, which is used as a representative time synchronization filter, was organized. In addition, for software-based synchronization performance analysis, a software-based simulation platform that consists of a clock generator, a time synchronization algorithm processor, and a performance analyzer was designed. The clock generator of the designed platform generates UTC (KRIS) reference clock, GPS timing receiver reference clock, and the TCXO, OCXO, Rb, and Cs clocks of a pseudolite; and the time synchronization algorithm processor synchronizes the pseudolite clock with the reference clock using an FIR filter. Also, the performance analyzer evaluates synchronization performance by analyzing the stability of the synchronized clock. Based on the designed simulation platform, synchronization performance was analyzed by configuring environments depending on the types of pseudolite and reference clock sources.

2. PSEUDOLITE TIME SYNCHRONIZAION METHOD

In this chapter, as techniques for pseudolite time synchronization, a method using the time source of the Korea Research Institute of Standards and Science and a method using the 1PPS of a GPS timing receiver were introduced.

2.1 UTC (KRIS) Reference Pseudolite Time Synchronization Method

In this section, a pseudolite time synchronization method using the Universal Time Coordinated of the Korea Research Institute of Standards and Science (KRISS) (hereinafter UTC (KRIS)) was introduced, and the overall time synchronization concept is shown in Fig. 1. In the case of UTC (KRIS) managed in Korea, national standard is maintained using four cesium atomic clocks and two hydrogen masers, and the generated time information is reported to the International Bureau of Weights and Measures (BIPM) every month. Also, BIPM generates UTC by calculating a weighted average of the data from about 260 atomic clocks around the world including UTC (KRIS). Based on the generated time source, UTC-UTC (k) information for each institution is published in BIPM circular T every month so that the time source of the corresponding institution can be corrected. Thus, if an error that corresponds to the leap second between GPS and UTC is corrected, it can be assumed that the UTC (KRIS) time source in Korea has been synchronized with the GPS time by BIPM; and the synchronization is generally maintained at an uncertainty of measurement of 10 ns. Therefore, time synchronization between a pseudolite and a GPS satellite can be achieved based on the suggested method using the UTC (KRIS) time source.

2.2 GPS Timing Receiver 1PPS Reference Pseudolite Time Synchronization Method

Fig. 2 shows the pseudolite time synchronization method using a GPS timing receiver. GPS timing receivers have various time accuracies depending on the product, and the 1PPS RMS accuracies of representative commercial

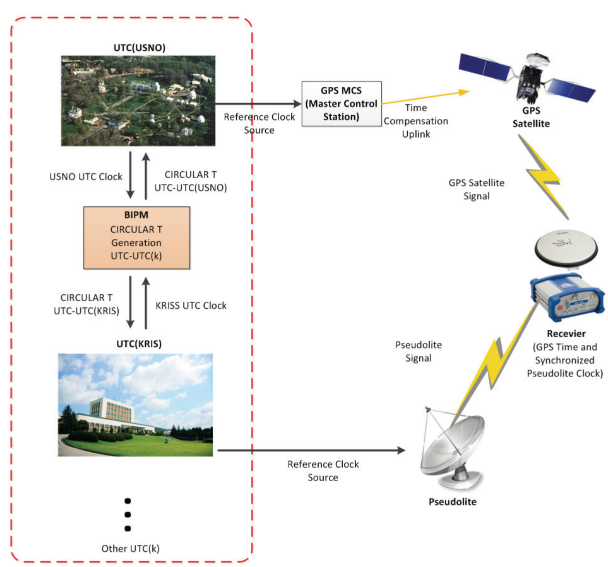

Fig. 1. UTC (KRIS) reference pseudolite time synchronization method.

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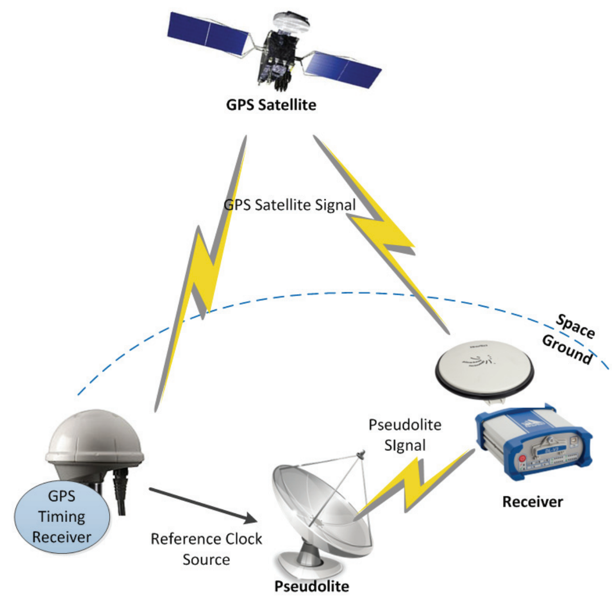

Fig. 2. GPS timing receiver 1PPS reference pseudolite time synchronization method.

Table 1. The clock error of GPS timing receiver.

	Output type (PPS, MHZ)	1PPS accuracy (ns) (RMS)
Trimble resolution T	1	15
Digi-key Wi125	1, 10	25
Motorola M12+	1	8
Symmetricom XL-GPS	1, 10	30
NovAtel	1	20
U-blox	1	30 (60 99%)

GPS timing receivers are summarized in Table 1. When a GPS timing receiver is used, operation is enabled using a pseudolite clock source with low time accuracy, compared to when a pseudolite time synchronization station is used, because the process of error data accumulation and processing is not required. Also, it has the advantage of fewer limitations on the installation location compared to the method using the UTC (KRIS) time source. However, a GPS timing receiver with a high time accuracy is expensive; and as the pseudolite clock is entirely dependent on the 1PPS of a GPS timing receiver, the time synchronization between the pseudolite receiver and the GPS satellite cannot be maintained when the GPS timing receiver is out of order.

3. TIME SYNCHRONIZAION SIMULATION PLATFORM

In this study, for the analysis of pseudolite time synchronization performance, a simulation platform that consists of a clock generator, a clock synchronization algorithm processor, and a performance analyzer was designed as shown in Fig. 3. To perform simulation, four kinds of pseudolite clocks (TCXO, OCXO, Rb, and Cs) were selected, and an FIR synchronization algorithm was used as the clock synchronization algorithm.

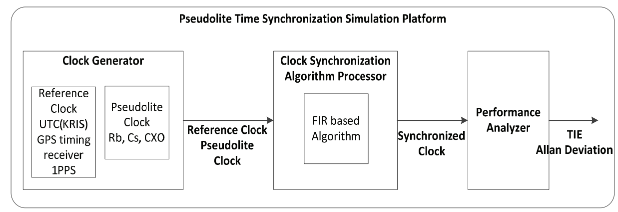

Fig. 3. Pseudolite time synchronization simulation platform.

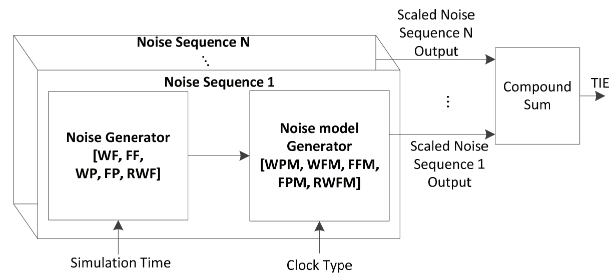

Fig. 4. The pseudolite and reference clock generator.

3.1 Clock Generator

As shown in Fig. 4, the clock generator selects the type of atomic clock (TCXO, OCXO, Rb, and Cs), and determines a scaling parameter based on the short- and long-term stability levels of each atomic clock and the pattern depending on the clock type. The time error was generated by generating five kinds of noise: white noise on phase (WP), flicker noise on phase (FP), white noise on frequency (WF), flicker noise on frequency (FF), and random walk on frequency (RWF), and by applying a scale factor from the parameter h.

Using the clock generator designed in this study, Allan deviations for each clock error were analyzed as shown in Fig. 5. Based on the clock generation, results similar to the measured Allan deviation error range for each clock type shown on the left side of Fig. 5 could be obtained (Allan 1987, Galleani et al. 2003).

In addition, to imitate the UTC (KRIS) clock source, two HM and four Cs clocks were generated, and an ensemble algorithm was applied using the Allan deviations of each generated clock as the weights. The Allan deviations of the

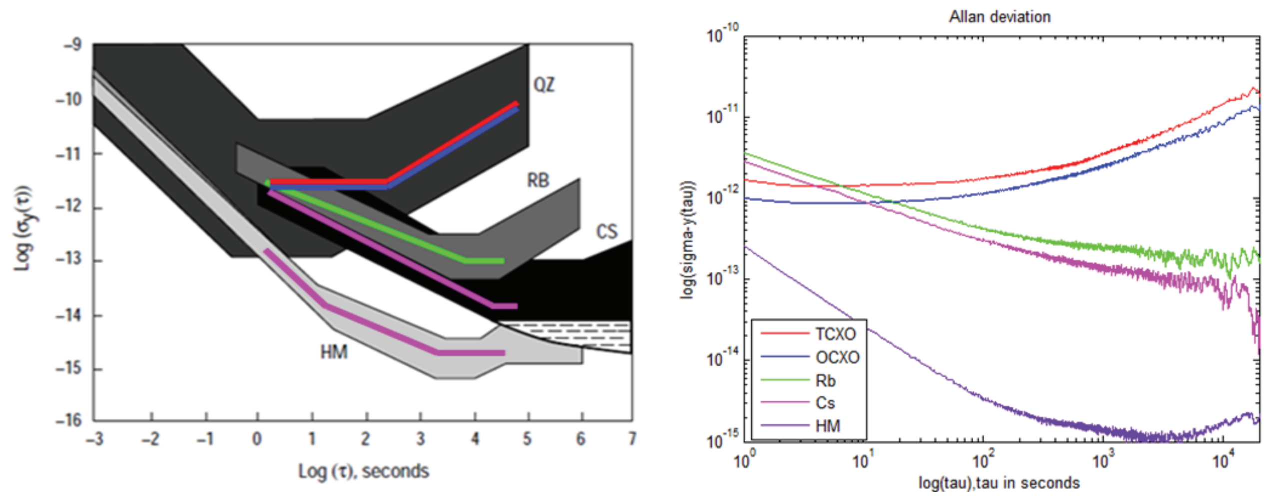

Fig. 5. The pseudolite and reference clock allan deviation.

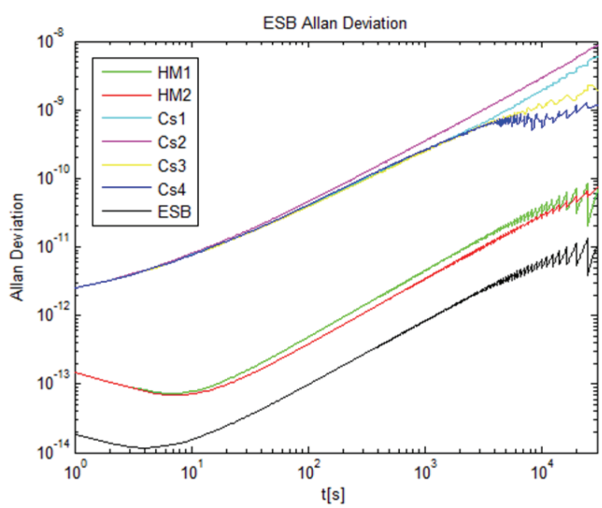

Fig. 6. The ESB allan deviation with 2 HM and 4 Cs clocks for imitating UTC (KRIS) reference clock.

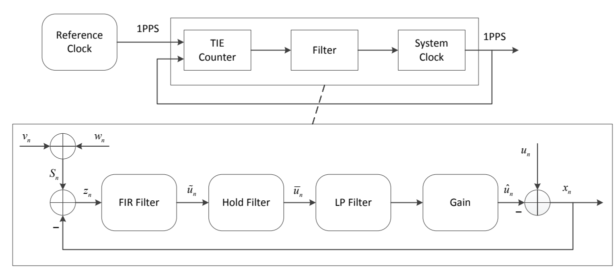

Fig. 7. The time synchronization algorithm structure using FIR filter.

imitated UTC (KRIS) are shown in Fig. 6 (Varnum et al. 1987).

3.2 Clock Synchronization Algorithm Processor

Fig. 7 shows the configuration of the FIR filter-based time synchronization algorithm. The time synchronization algorithm using an FIR filter receives TIE measurements, and performs the FIR filter, hold filter, and LP filter in sequence; and to reduce the effect of noise, it operates the filters by collecting measurements at regular intervals (Lewis 1991, Arceo-Miquel et al. 2009).

In Fig. 7, i is the index of the data sample, N is the interval at which the filter is applied, v_n is the reference clock, and w_n is the error component included in the clock. Also, S_n is a clock where an error is included in the reference clock, u_n is the system clock, and Z_n is the TIE result, which can be expressed as follows.

$$z_n = s_n - x_n \tag{1}$$

In general, a clock synchronization algorithm using an FIR filter can maintain a lower error compared to a case using the Kalman filter, and Lepek demonstrated that relatively superior synchronization performance can be obtained when a linear predictor is used.

$$h_{FIR,i} = \begin{cases} \dfrac{2(2N-1)-6i}{N(N+1)}, & 0 \le i \le N-1 \\ 0 & otherwise \end{cases} \tag{2}$$

when the hold filter and the LP filter are applied, the output can be expressed as follows.

$$\hat{u}_n = K \sum_{i=0}^{L-1} h_{LP,i} \tilde{u}_{\left|\frac{n-l}{M}\right|M} \tag{3}$$

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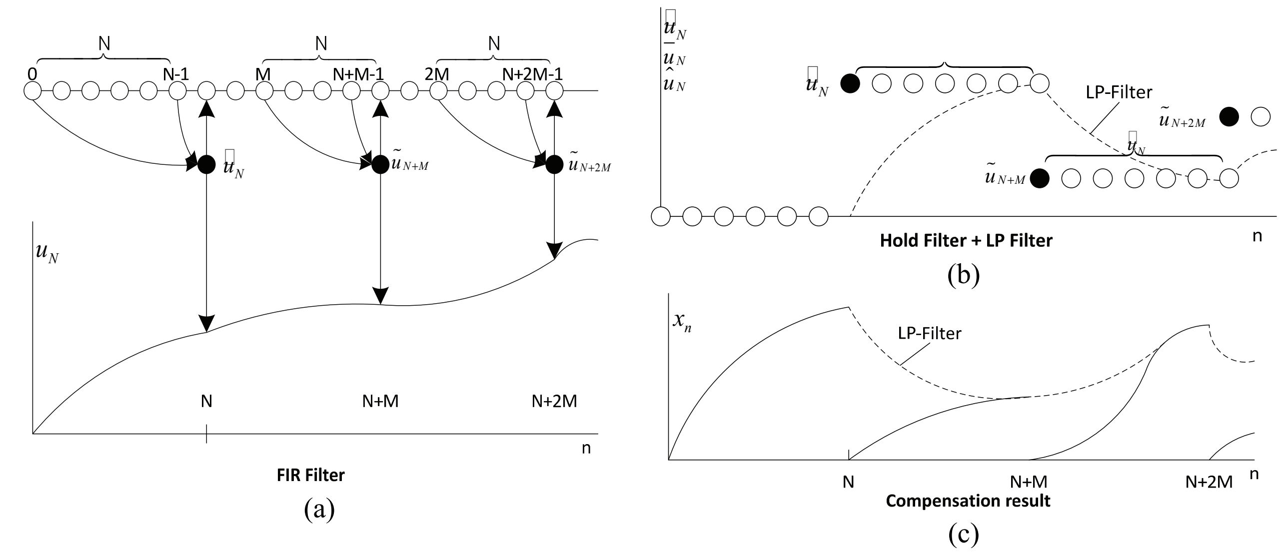

Fig. 8. The pseudolite and reference clock allan deviation.

In Eq. (3), $x_n = u_n - \hat{u}_n$, $z_n = s_n$, and thus the clock synchronization algorithm using an FIR filter can be finally expressed as follows.

$$x_n = u_n - K\sum_{l=0}^{L-1}\sum_{i=1}^{N} h_{LP,i} h_{FIR,i} \tilde{x}_{\left\lfloor \frac{n-l}{M} \right\rfloor M-i} + K\sum_{l=0}^{L-1}\sum_{i=1}^{N} h_{LP,i} h_{FIR,i} s_{\left\lfloor \frac{n-l}{M} \right\rfloor M-i} \quad (4)$$

Fig. 8 shows the filter outputs depending on the performing stages of the FIR filter-based clock synchronization algorithm. When there were TIE measurements, the FIR filter was applied to N samples at M intervals as shown in Fig. 8a; and the hold filter and the LP filter were applied to the FIR filter result as shown in Fig. 8b. Also, Fig. 8c shows the result that compensated the TIE error using the result shown in Fig. 8b.

In this study, the results of the FIR filter-based clock synchronization algorithm for the Cs clock were presented. Fig. 9 shows the result when only the FIR filter and hold filter were applied, the result when the FIR filter, hold filter and LP filter were applied, and the result that was synchronized with the reference clock source.

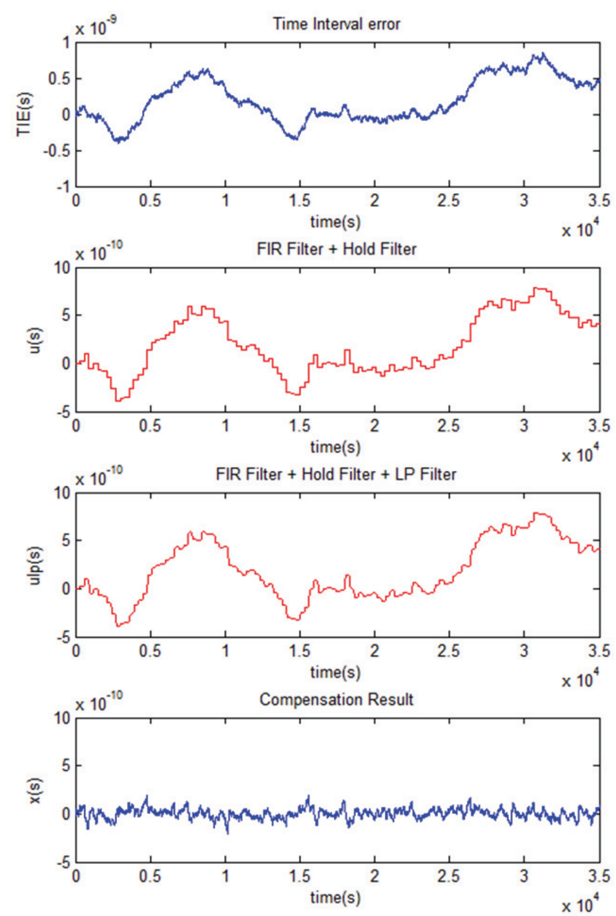

Fig. 9. The clock synchronization algorithm result using FIR filter in Cs clock.

4. TIME SYNCHRONZAION SIMULATION AS CLOCK SOURCE

4.1 Simulation Set-up

Table 2 summarizes the simulation environment for analyzing the performance of the time synchronization between the GPS satellite and the pseudolite. In this study, to perform simulation depending on the pseudolite clock and reference clock source, UTC (KRIS) and GPS timing

Table 2. Simulation set-up.

Simulation factors		Average
Clock error	Reference	UTC (KRIS)
		GPS Timing receiver (RMS: 10 ns)
	Pseudolite	Cs, Rb, TCXO, OCXO
Transmission line	250 um tight buggered	
Time interval counter	One counter error (20ps) Trigger error	
Clock synchronization algorithm	FIR filter based clock synchronization algorithm	

receiver 1PPS with an RMS error of 10 ns were used as the reference clock; delay error and TIC error assuming 1 km of 250 um tight-buggered transmission line were added; and the clock synchronization results were obtained using the FIR filter-based clock synchronization algorithm.

4.2 Simulation Result

Fig. 10 shows the Allan deviation results depending on the average time when the reference clock source was UTC (KRIS). When the pseudolite clock sources were the TCXO and OCXO crystal oscillators, the clock was more unstable compared to the Rb and Cs atomic clocks, and thus more time was required to reach the reference clock stability. In the case of the Rb and Cs clock sources, the Allan deviations were stabilized within 10^{-10}. On the other

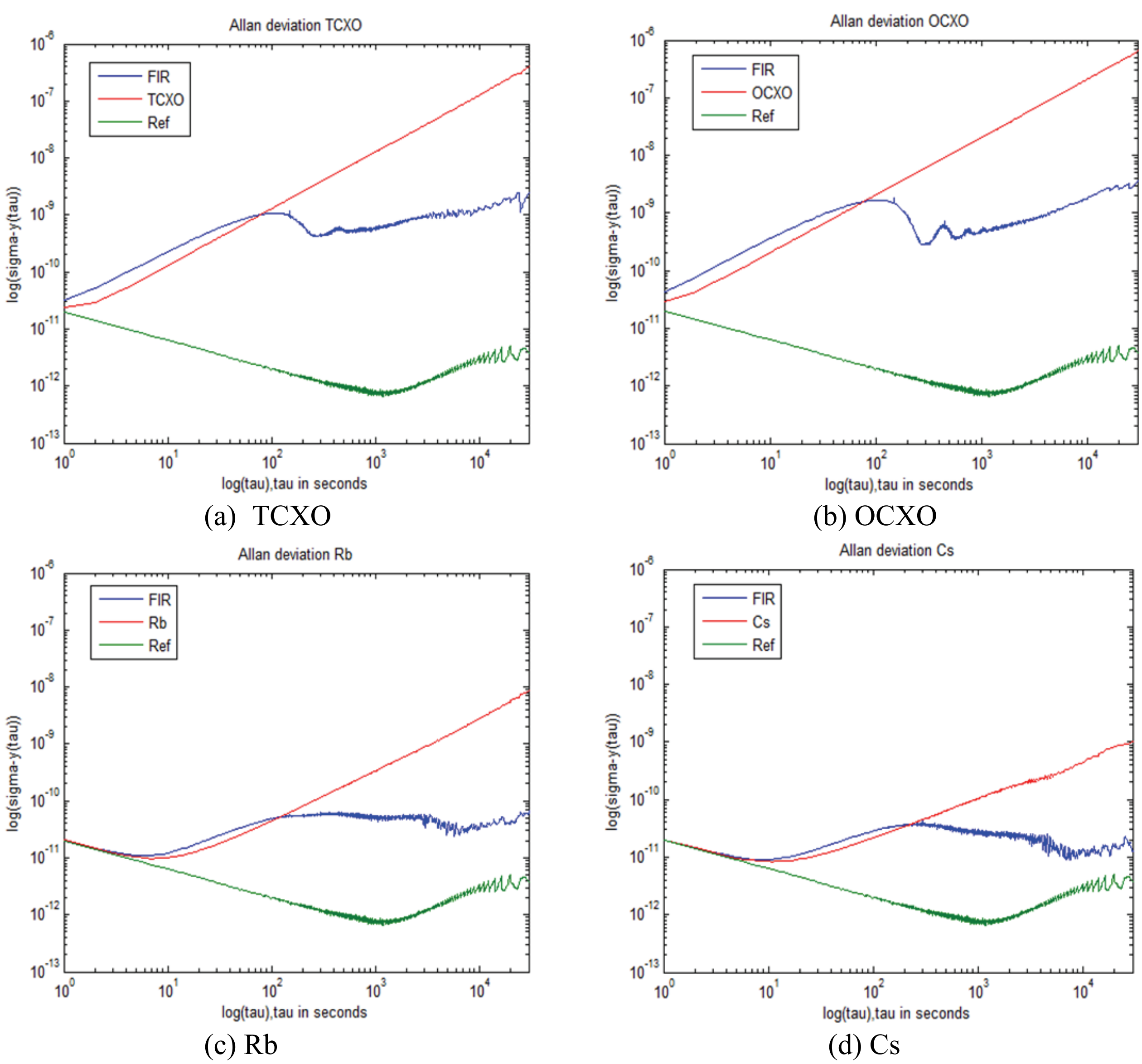

Fig. 10. Simulation result UTC (KRIS) reference time synchronization method.

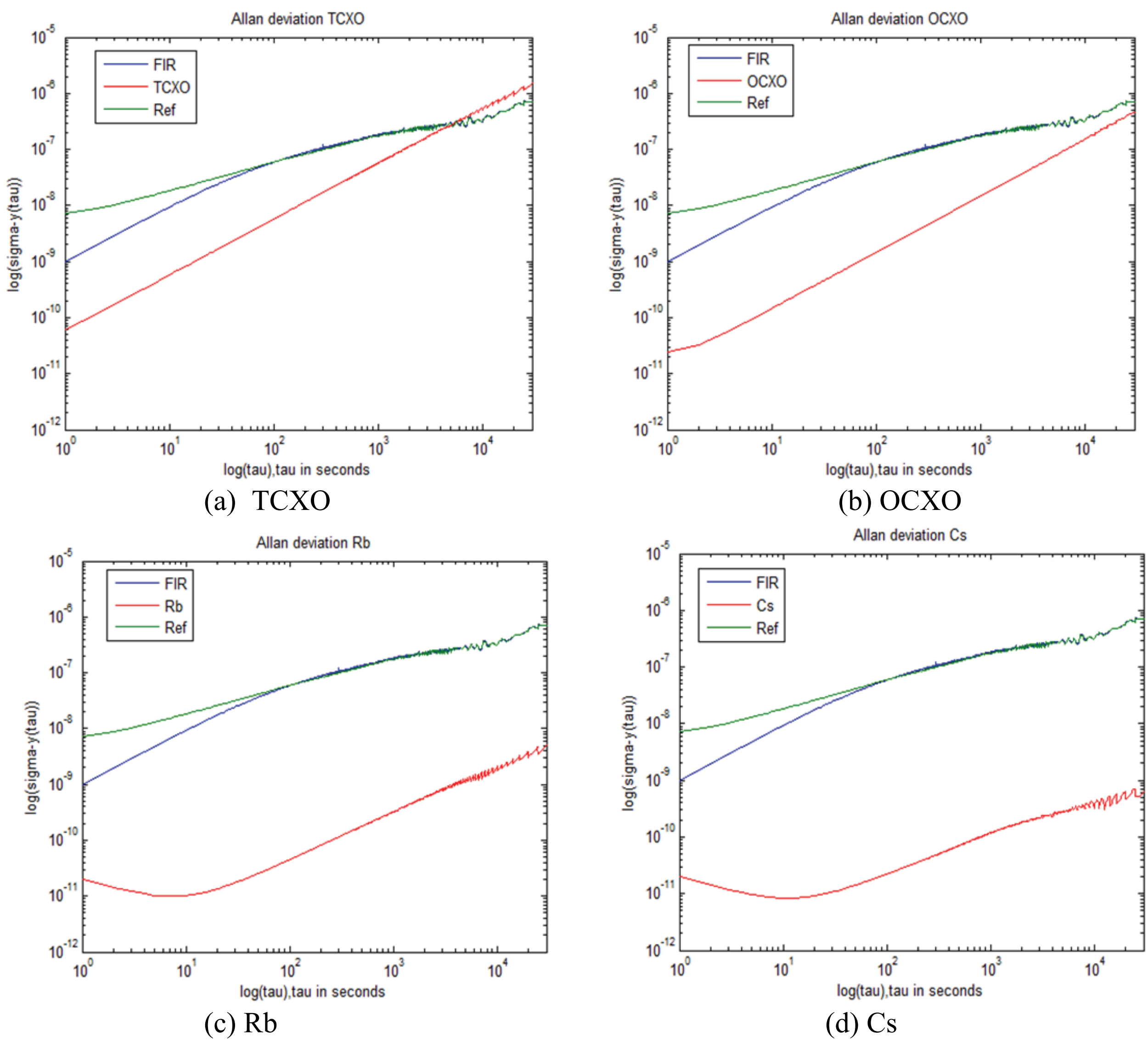

Fig. 11. Simulation result GPS timing receiver 1PPS reference time synchronization method.

hand, when the reference clock source was the RMS 10 ns GPS timing receiver, the reference clock source was more unstable compared to the pseudolite clock source, as shown in Fig. 11. When the Rb and Cs clock sources were used, the stability of the atomic clocks was superior to that of the reference clock source, and thus, the stability of the clock synchronized with the reference clock source was more deteriorated than that of the pseudolite clock source. When the pseudolite clock source was TCXO, it was stabilized at the level of the RMS 10 ns GPS timing receiver clock source after about 10,000 seconds.

5. CONCLUSIONS

In this study, as methods for pseudolite time synchronization, a pseudolite time synchronization method using the UTC (KRIS) time source and a time synchronization method using a GPS timing receiver were introduced. The pseudolite time synchronization methods using the UTC (KRIS) time source and a GPS timing receiver perform time synchronization using the UTC (KRIS) time source and the 1 PPS clock of a GPS timing receiver, respectively. They synchronize the pseudolite clock with the corresponding reference clock source, and thus achieve time synchronization with a GPS satellite indirectly. To analyze the aforementioned pseudolite time synchronization methods through simulation, a software-based pseudolite time synchronization performance analysis platform was designed. For the pseudolite clock source, Cs clock, Rb clock, TCXO, and OCXO were selected; and for the reference clock, ensemble 1 PPS TIE measurement for imitating UTC (KRIS) and 1PPS TIE of a GPS timing receiver with 10 ns RMS were generated. Also, in the case of the clock synchronization algorithm, simulation was performed depending on the pseudolite clock and reference clock by applying an FIR-based synchronization algorithm. The results of the simulation indicated that the most outstanding synchronization performance was obtained when the Cs pseudolite clock source was used; and that when UTC (KRIS) was used as the reference clock, relatively superior time synchronization stability was observed compared to when GPS 1PPS was used as the reference clock. However, to use UTC (KRIS) as the reference clock, there are limitations on the installation of a pseudolite; and when an atomic clock is used as the pseudolite clock source, relatively high initial cost is incurred. Therefore, pseudolite clock source and reference time source need to be selected considering the pseudolite operation environment.

The software-based pseudolite time synchronization performance analysis results of this study could be used for the selection of pseudolite clock source and reference time source during the operation of a pseudolite, and could also be used for the selection of clock source with the purpose of the time maintenance of other systems as well as the time synchronization of a pseudolite.

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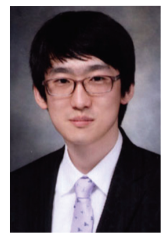

Ju Hyun Lee received the Bachelor of degree in Electronics from Chungnam National University in 2011. His research interests include GNSS, anti-jamming techniques and indoor navigation.

Soyoung Hwang received the Doctor's degree in Computer science from Pusan National University in 2006. her research interests include embedded system, time synchronization, e-navigation.

Dong-Hui Yu received the Doctor's degree in Computer science from Pusan National University in 2001. her research interests include GPS, Time synchronization, e-navigation.

Chansik Park received the Doctor's degree in Control and Measurement in Seoul National University in 1997. His research interests include GNSS, SDR, AJ, ITS and WSN.

Sang Jeong Lee received the Doctor's degree in Control and Measurement in Seoul National University in 1987. His research interests include GNSS and Robust Control.