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Performance Analysis of Pulse Positioning Using Adaptive Threshold Detector (ATD)

Jae Won Chang[1†], Sang Jeong Lee[2]

[1]Avionics Research Team, Korea Aerospace Research Institute, Daejeon 34133, Korea
[2]Department of Electronics Engineering, Chungnam National University, Daejeon 34134, Korea

ABSTRACT

This paper describes the measurement of pulse positioning (input time) to calculate a time of arrival (TOA) that takes from transmitting a signal from the target of multilateration (MLAT) system to receiving the signal at the receiver. In this regard, this paper analyzes performances of simple threshold method and level adjust system (LAS) method, which is one of the adaptive threshold detector (ATD) methods, among many methods to calculate pulse positioning of signal received at the receiver. To this end, Cramer-rao lower bound (CRLB) with regard to pulse positioning, which was measured when signals transmitted from a transponder mounted at the target were received at the receiver, was induced and then deviation sizes with regard to pulse positioning, which was measured with simple threshold and LAS methods through MATLAB simulations, were compared. Next, problems occurring according to a difference in amplitude of signals inputted to each receiver are described when pulse positioning is measured at multiple receivers located at a different distance from the target as is the case in the MLAT system. Furthermore, LAS method to resolve the problems is explained. Lastly, this study analyzes whether a pulse positioning error occurring due to the signal noise satisfies the requirement (6 nsec. or lower) recommended for the MLAT system when using these two methods.

Keywords: multilateration, pulse positioning, adaptive threshold detector

1. INTRODUCTION

Research on a navigation safety system started from 1983 in order to cope with rapidly increasing air traffic volume in the future air navigation system. In particular, a study on Communication, navigation, surveillance/air traffic management among navigation safety systems has been actively conducted (Sajatovic et al. 2005, Lin et al. 2014). The ground surveillance system in the aviation monitoring field can be divided into cooperative and non-cooperative systems according to whether inter-cooperation is performed between airplane and ground station as shown in Fig. 1 (Chang & Lee 2017).

In order to increase the resolution of positioning information of targets supplied by the secondary surveillance radar, which is an independent cooperative surveillance system currently used in airports, a multilateration (MLAT) system has been applied to aviation monitoring systems. MLAT is a system that calculates a position of target using a hyperbola or hyperboloid positioning method. A MLAT measures a time of arrival

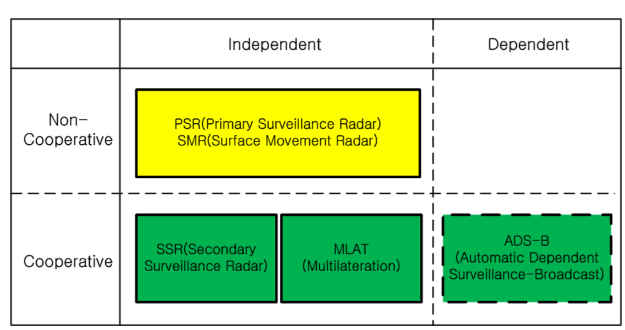

Fig. 1. Category of ground surveillance system.

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†**Corresponding Author**
E-mail: zdream@kari.re.kr
Tel: +82-42-860-2946 Fax: +82-42-870-3598

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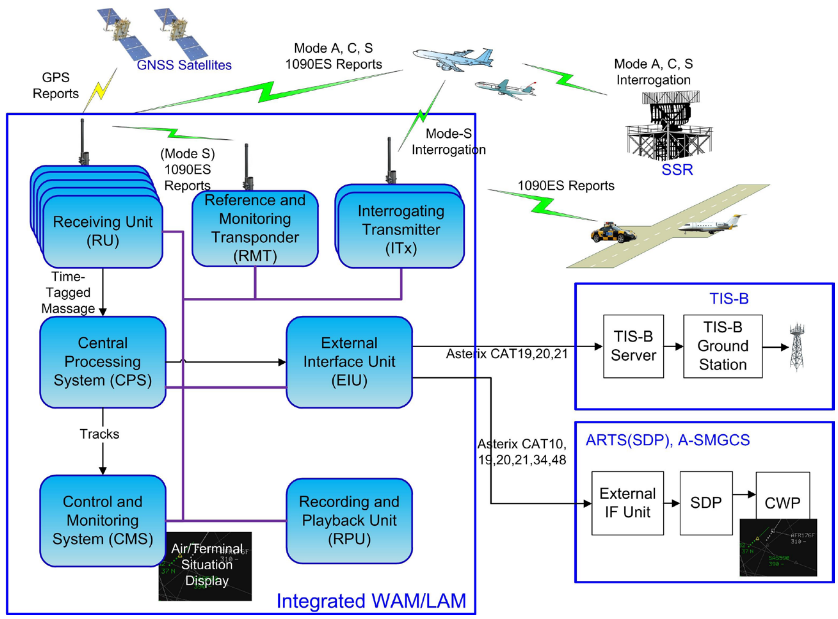

Fig. 2. Multilateration system configuration.

(TOA) value by receiving signals, which are transmitted periodically or non-periodically from a transponder mounted at airplanes, at four or more ground receivers positioned and installed precisely. The TOA value is used to calculate a position of airplane by means of time difference of arrival (TDOA) among the receivers at the central processing system. To increase the positioning accuracy of the MLAT, it is required to accurately measure a TOA of signal that is received at the receiver after being transmitted from the transponder. A transponder transmits a pulse waveform according to whether or not data is available, and a receiver measures an input time of the received pulse waveform. A radar system, which is one of the measurement devices of target position, utilizes a simple threshold, adaptive threshold detector (ATD), and matched filter methods to measure an input time of pulse waveform (Torrieri 1997). In the radar system, a simple threshold that employs only comparator and ATD method that uses a delay have been utilized to determine the transmission time of waveform and detect an input time of waveform received after being reflected from the target. Although the MLAT does not transmit electric waves to the target, it can also apply a simple threshold and ATD methods to determine an input time of the received waveform as used in radars. This paper calculated the Cramer-rao lower bound (CRLB) and analyzed the simulation results when the threshold method was applied to measure an input time of the received signals in the MLAT system. Furthermore, problems of simple threshold method were presented, and a level adjust system (LAS), which is one of the ATD methods, is explained. Moreover, simulation results using LAS are compared with those of CRLB.

2. MULTILATERATION SYSTEM

2.1 Configuration of Multilateration System

The MLAT refers to an aviation surveillance system that measures locations of airplanes and ground vehicles by acquiring signals, which are transmitted from transponders mounted at airplanes and 1090ES emitters mounted at ground vehicles, at multiple receivers located at precisely measured positions on the ground. A 1090 extended squitter (ES) employs 1090 MHz frequency, which is the same with the frequency used in transponders mounted in airplanes. It is a device that transmits signals periodically even without additional interrogation from the interrogating transmitter located on the ground. It attaches to a ground moving vehicle to measure a position of the vehicle in an airport using MLAT.

The configuration of the MLAT that detects a position of airplanes and ground vehicles is shown in Fig. 2 (Kim & Chang 2013).

As shown in Fig. 2, the MLAT system consists of multiple receiving units (RUs), central processing system (CPS), reference and monitoring transponder (RMT), control and monitoring system, external interface unit (EIU), and interrogating transmitter (ITX). Among them, an RU receives signals from a transponder mounted in an airplane, measures a TOA of signals based on the local time, and

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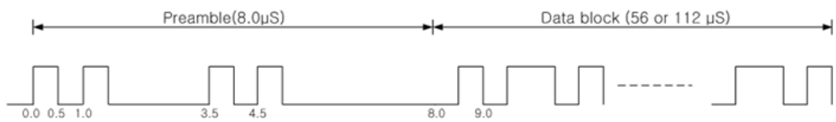

Fig. 3. The signal flame of mode S transponder.

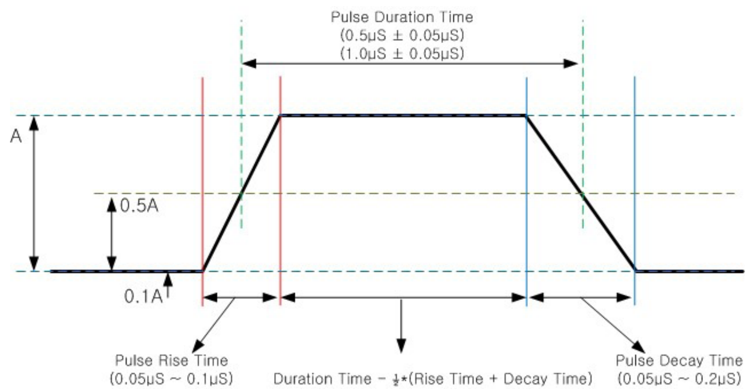

Fig. 4. Detail structure of the pulse of mode S transponder.

transmits the information to the CPS. The CPS calculates the TOA of signal transmitted from multiple RUs, and identifies and tracks the position of target using the TDOA algorithm. The RMT is used for time synchronization at each of the RUs by transmitting signals. Since the CPS knows the locations of the RMT and RUs, it calculates a difference in information about time-tagging of the RMT measured at the RUs, thereby correcting a time difference error to perform time synchronization. The EIU plays a role in transmitting data to external users. The ITX transmits interrogations to induce a response from the transponder mounted in an airplane. The ITX in MLAT is not used if a separate ITX is available in the configuration of the aviation monitoring system in airports. This MLAT is called passive MLAT.

2.2 Requirement of TOA at the RU in the MLAT System

The requirement of TOA measurement of RUs in MLAT applied in this paper is to calculate a position of pulse waveform of a transponder transmitted from the same target within 8 nsec. A standard deviation σ_τ of TOA at the RU of MLAT occurs largely due to errors caused by signal-noise ratio (SNR) of received signals, errors caused by quantization of RUs, and errors caused by time synchronization. It can be expressed via Eq. (1).

$$\sigma_\tau = \sqrt{\sigma_{SNR}^2 + \sigma_q^2 + \frac{\sigma_{clk}^2}{2}} \tag{1}$$

where σ_{SNR} refers to an error occurring due to SNR, σ_q refers to an error due to quantization of RUs, and σ_{clk} refers to an error due to TDOA time synchronization.

To calculate an error due to quantization of RUs, it was assumed that a quantization noise was uniformly distributed in an interval of [-$\Delta t/2$, $\Delta t/2$] when a step increment of quantization was Δt regardless of sample time. A mean of quantization noise is zero, and noise power of quantization that is the square of the error due to quantization can be expressed via Eq. (2).

$$\sigma_q^2 = MSE = E\left[q^2\right] = \int_{-\infty}^{\infty} q^2 f(q)dq = \int_{-\Delta t/2}^{\Delta t/2} q^2 dq = \frac{\Delta t^2}{12} \tag{2}$$

where Δt refers to a quantization time (sample time), in which Δt is 10 nsec because RU is quantized at 100 MHz. Here, the error σ_q due to quantization of RUs is approximately 2.9 nsec.

The error σ_{clk} due to TDOA time synchronization can vary depending on which time synchronization method is used. If time synchronization is performed using the RMT, σ_{clk} is in a range of 1 to 6 nsec. In the development requirement of this study, σ_{clk} was set to 5 nsec.

The error σ_{SNR} due to SNR can be calculated via Eq. (3).

$$\sigma_{SNR} = \sqrt{\sigma_\tau^2 - \sigma_q^2 - \frac{\sigma_{clk}^2}{2}} = \sqrt{8^2 - 2.9^2 - \frac{5^2}{2}} = \sqrt{43.09} \approx 6.5\,\text{nsec} \tag{3}$$

Thus, the pulse positioning error requirement of pulse waveform generated by signal noise of MLAT RUs was set to 6 nsec or lower.

2.3 Transponder Pulse Waveform

Mode S signal, which is a transmission signal of transponder, consists of preamble and data blocks. A

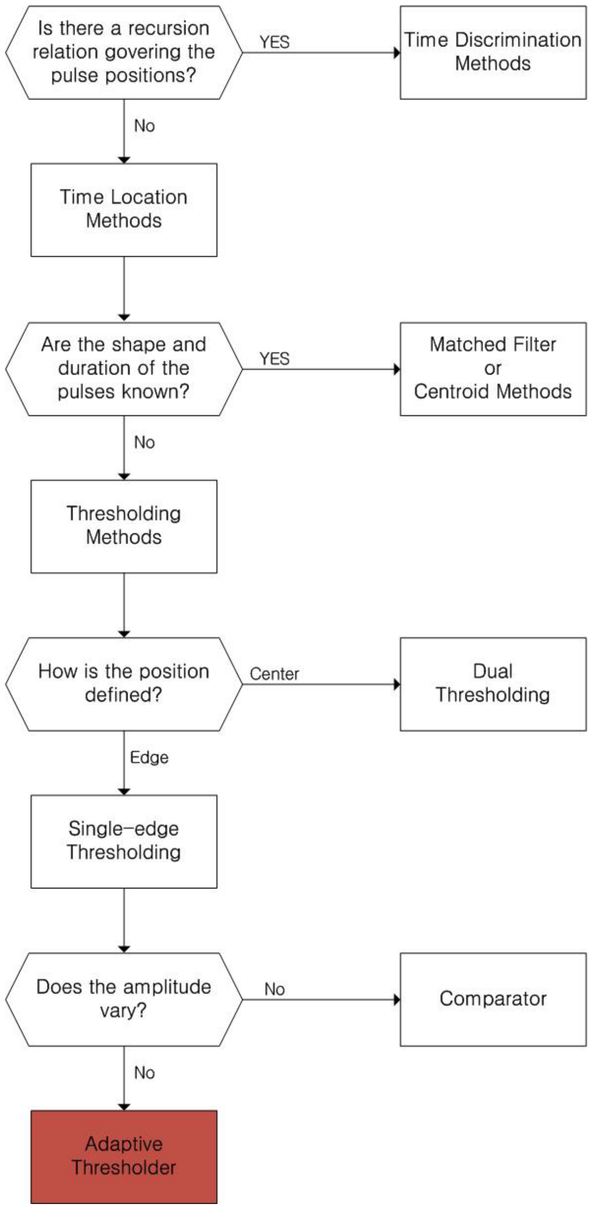

Fig. 5. Flow chart of pulse position determination.

preamble is composed of four sequential pulses, and data blocks follow the modulation method according to binary pulse location of 1Mega/s data. Fig. 3 shows the structure of signal data transmitted from the Mode S transponder. The detailed structure of a single pulse in Fig. 3 is shown in Fig. 4.

A transmission signal of transponder should satisfy rise time, duration time, and decay time of pulse waveforms defined by the Surveillance and Collision Avoidance Systems, which are found in Volume IV of Annex 10 Aeronautical Telecommunications in the International Civil Aviation Organization.

This paper implemented a pulse waveform generator that can change rise time, duration time, decay time, signal size, and SNR using MATLAB for simulations of pulse positioning.

3. PULSE POSITIONING

3.1 Measure of Pulse Positioning

A method that determines a pulse position, which is an input time of pulse waveform to RUs, follows the logical flow, as shown in Fig. 5 (Torrieri 1997).

Fig. 5 explains that pulse position can be measured using a matched filter if the shape and length of the received pulse is known in advance. Without pre-known information about received pulse, a threshold method using a threshold can be used. Assuming that the amplitude of received signal is the same among RUs, a single-edge thresholding method, which is a simple thresholding method, can be used. However, the amplitude of received signal at RUs, which have a different separation distance from that of transponder that transmits signals as is the case in MLAT, may be measured differently at each of the RUs. To determine a position of pulse whose amplitude is variable, ATD using an adaptive thresholder should be applied. This paper compared and analyzed the performance of simple threshold method, one of the single-edge thresholding methods to which only simple comparator was applied, and LAS, one of the ATD methods.

3.2 CRLB for Pulse Positioning

The CRLB means a minimum variance of estimation that is probabilistically distributed. The CRLB for pulse positioning is presented in Eq. (4).

$$\mathrm{CRLB} = \frac{1}{\mathrm{E}\left[\left(\frac{\partial}{\partial\tau}\ln p(x;\tau)\right)^2\right]} = \frac{1}{-\mathrm{E}\left(\frac{\partial^2}{\partial\tau^2}\ln p(x;\tau)\right)} \tag{4}$$

As shown in Fig. 6, Gaussian noise whose mean was zero and standard deviation was σ was used to calculate the minimum variance value of delay time of noise-added pulse signal at the pulse position using the CRLB.

The minimum variance value calculated from the CRLB is the inverse of the fisher information, which is calculated by conditional probability of double partial derivative value or square of partial derivative after putting a natural logarithm to the likelihood function. Thus, a likelihood function with respect to delayed pulse position τ from the probability density function whose mean is zero and standard deviation is σ can be calculated using Eq. (5) (McDonough & Whalen 2007).

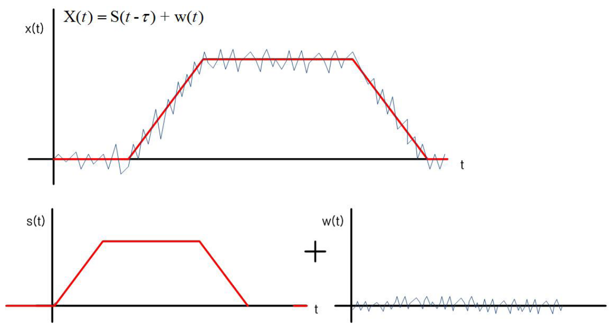

Fig. 6. The pulse signal with Gaussian noise.

$$\mathrm{pdf}(x;\tau) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{\{x(t)-s(t-\tau)\}^2}{2\sigma^2}} \tag{5}$$

The CRLB of pulse position calculated via Eq. (5) is presented in Eq. (6).

$$\mathrm{CRLB} = \mathrm{var}(\hat{\tau}) \geq \frac{1}{-E\left\{\frac{\partial^2 \ \ln \mathrm{pdf}(x;\tau)}{\partial \tau^2}\right\}} = \frac{1}{\frac{1}{\sigma^2} E\left[\left\{\frac{\partial s(t-\tau)}{\partial \tau}\right\}^2\right]} = \frac{\sigma^2}{\int \left[\frac{\partial s(t-\tau)}{\partial \tau}\right]^2 dt} \tag{6}$$

To calculate Eq. (6) that acquires the CRLB from pulse signals input to the RU of MLAT, pulse signals were assumed and explained, as shown in Fig. 7.

The CRLB of pulse position measured at the RU of MLAT in Fig. 7 can be calculated via Eq. (7) (Bensky 2016).

$$\mathrm{CRLB} = \mathrm{var}(\hat{\tau}) \geq = \frac{\sigma^2 t_r}{2A^2} = \frac{N t_r^{\,2}}{4A^2} = \frac{t_r^{\,2}}{4SNR} \tag{7}$$

$$(N : NoisePower, A^2 : SignalPower, t_r : RiseTime)$$

Eq. (7) exhibits that the minimum variance with respect to pulse position measured at the RU of MLAT is only related to the rise time (t_r) of pulse and SNR.

Eq. (7) is implemented via MATLAB, and the effect of rise time and SNR on CRLB was analyzed through simulations.

Fig. 8 shows the CRLB simulation results of pulse position with regard to rise time and SNR. The simulation verified that a variance became smaller as SNR increased and rise time was shorter.

3.3 Simple Threshold Method

A method of estimation on pulse position using a threshold such as comparators is a measure that has a simplest structure. A time where pulse signal input to the RU of MLAT exceeds a threshold is regarded as a pulse position using a simple comparator. Noise is included in the pulse waveform, and pulse position can vary according to this noise. Fig. 9 shows the tendency of deviation with respect to pulse position in the simple threshold method according to changes in SNR. Pulse position is difficult to be estimated if SNR is less than 10 dB when a threshold is set to 50% of the maximum value.

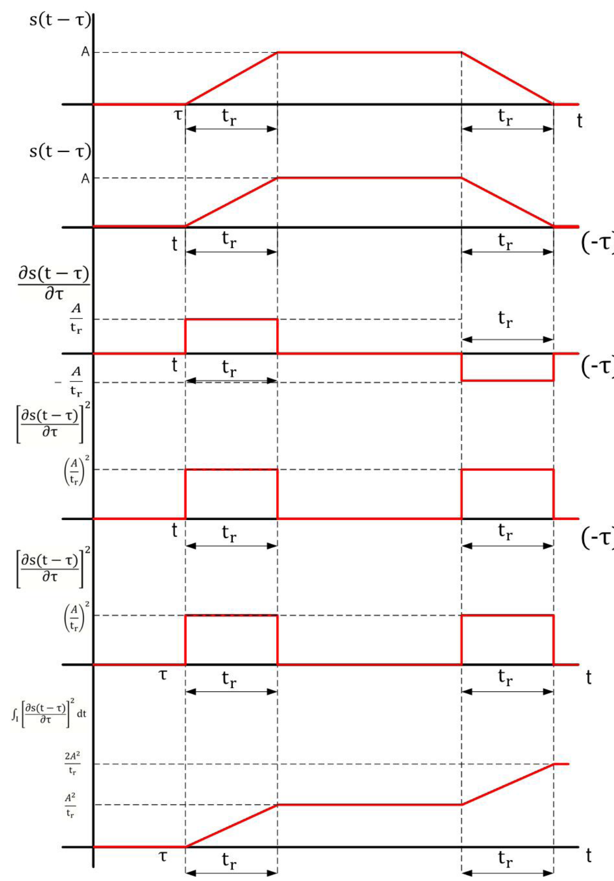

Fig. 7. The processing to calculate CRLB of pulse positioning.

Fig. 10 shows the simulation results of CRLB variance using simple threshold and CRLB methods to estimate a pulse position. The rise time was assumed to 100 nsec, and SNR was divided from 5 to 50 by increasing one increment in the simulation.

The simulation results in Fig. 10 show that since the variance should be less than 36 nsec in order to satisfy 6 nsec of the TOA accuracy required by MLAT, the requirement can be satisfied when the SNR is approximately 18 dB or higher in the case of CRLB. In the case of simple threshold, the requirement is satisfied when the SNR is approximately 21 dB or higher.

Although a structure using a threshold method as shown in the above is simple, an error due to the setup of threshold occurs when a size of signal input to each of the RUs is not constant, i.e, when a distance from the target to each of the

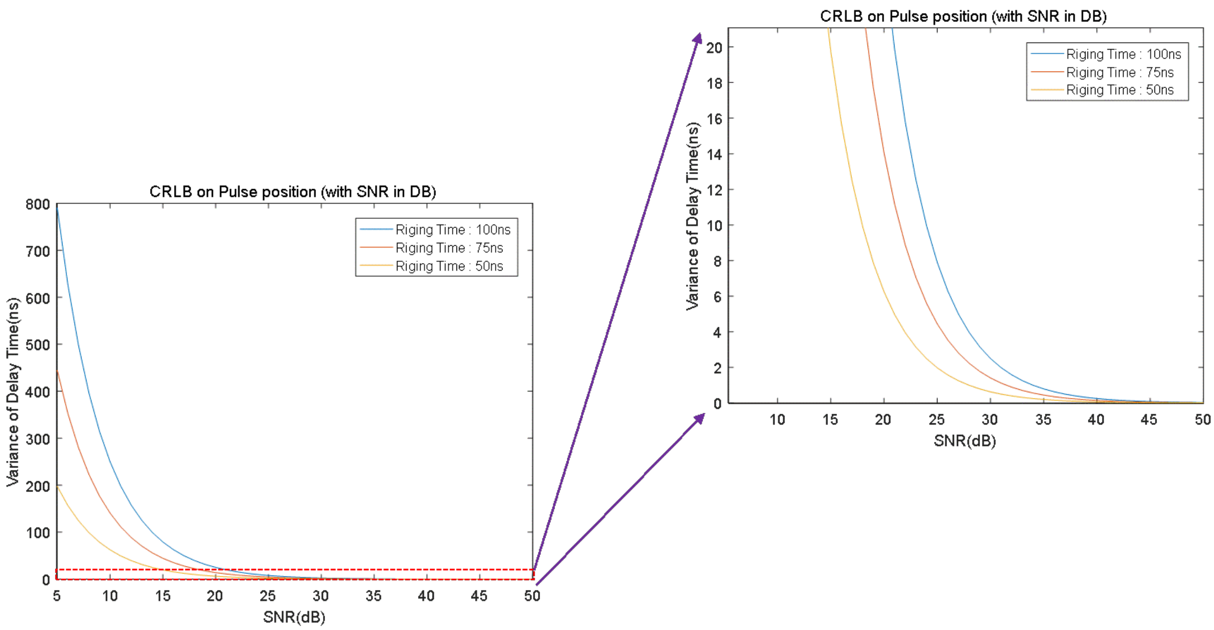

Fig. 8. Simulation result of CRLB with SNR & rise time.

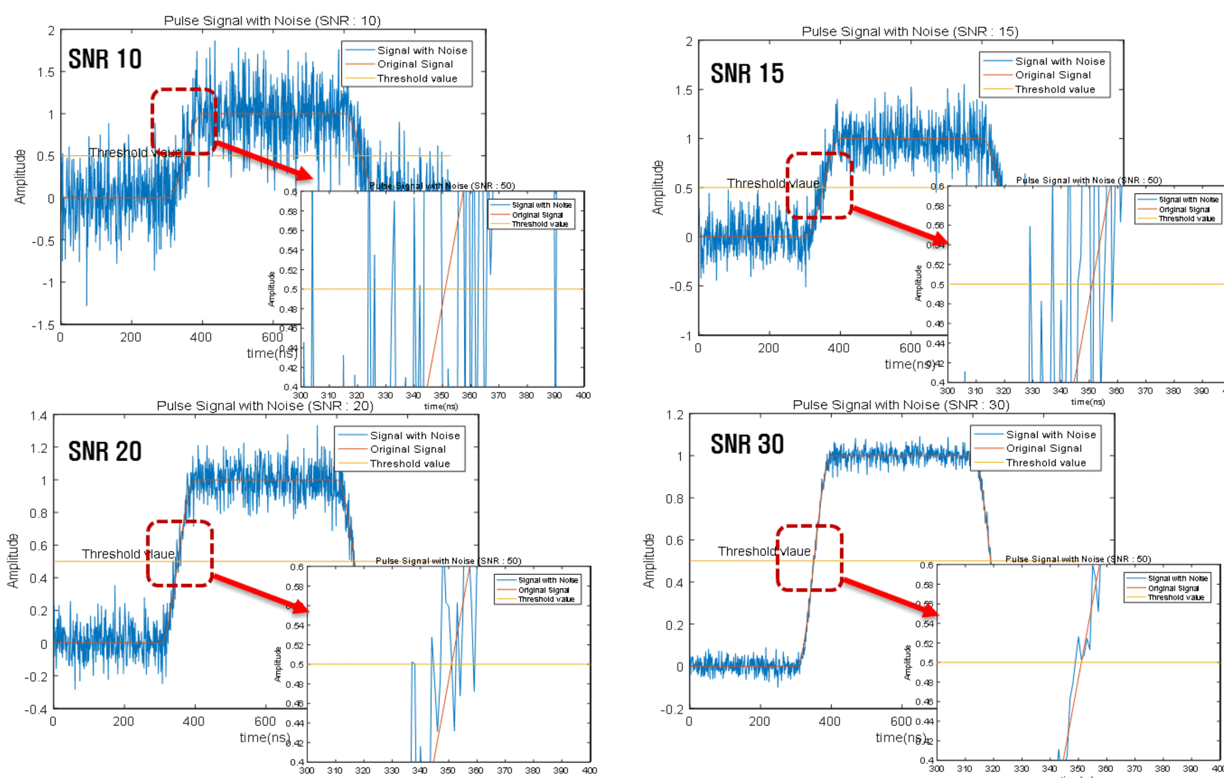

Fig. 9. Simulation result of simple threshold system with SNR.

RUs is different and a amplitude of signal input to each of the RUs varies.

As can be seen in Fig. 11, an estimation of pulse position can vary depending on the input signal amplitude, when the threshold is set the same in two RUs. Assuming that the rise time is 100 nsec, and a threshold is set to 50% of signal amplitude input to RU A. When this threshold is used to estimate pulse position of RUs A and B, a pulse position estimated at two RUs may have an error of up to 50 nsec depending on a signal amplitude. That is, pulse position

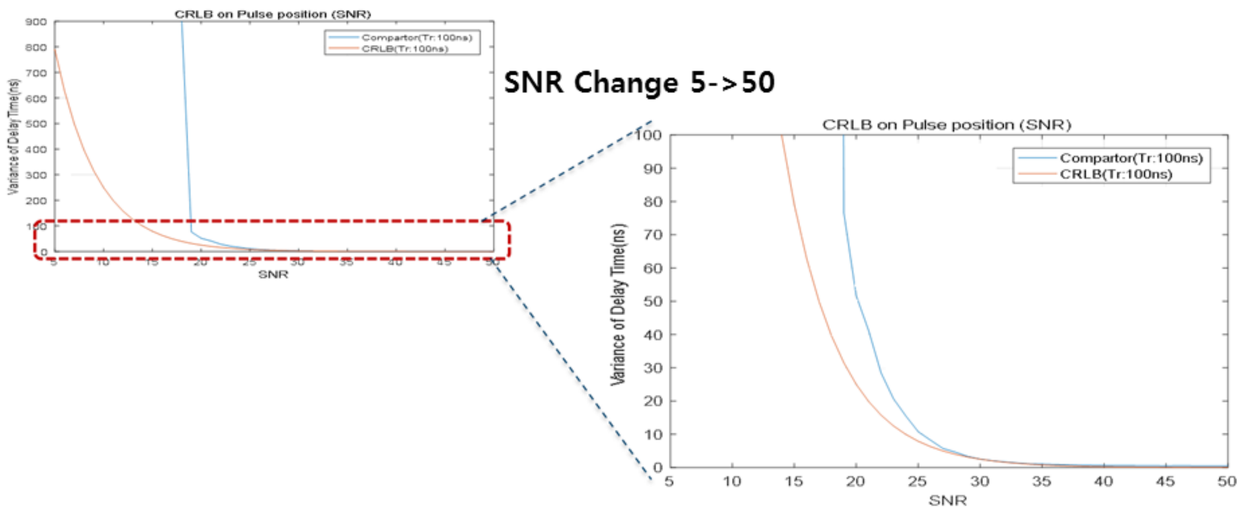

Fig. 10. Simulation result of simple threshold system & CRLB of pulse positioning.

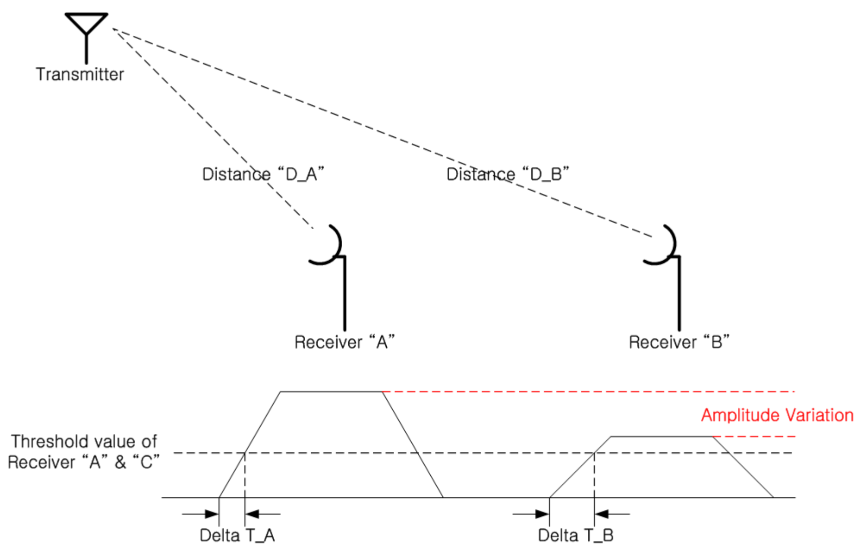

Fig. 11. Amplitude variation due to the different distance of receiver and transmitter.

can fluctuate due to variation of signal amplitude resulting from a difference in distance to the target from each of the RUs. Fig. 12 shows the verification of estimation on pulse position when the same threshold is applied to signals input to three RUs through MATLAB simulations. As shown in the figure, approximately 47 nsec of error component was revealed between earliest and latest estimated pulse locations assuming that there is no noise.

3.4 ATD Method

As explained in Section 3.3, ATD can be used to solve an error of pulse position generated due to a difference in amplitude of input signal occurring as a result of difference in separation difference between target and RU when a pulse position is estimated using a simple threshold method. ATD is a method that determines a pulse position or signal arrival time regardless of amplitude change, when there is only a difference in amplitude measured from RUs and the characteristics of pulse in the time axis are the same. That is, it is a method to cope with differences in amplitude resulting from separation distance according to a disposition of each of RUs from a single target. The following three measures were proposed regarding ATD (Torrieri 1997).

- Level Adjuster System (LAS)
- Constant-fraction Discriminator System (CDS)
- Double Differentiator (DD)

This paper analyzed a performance of pulse positioning

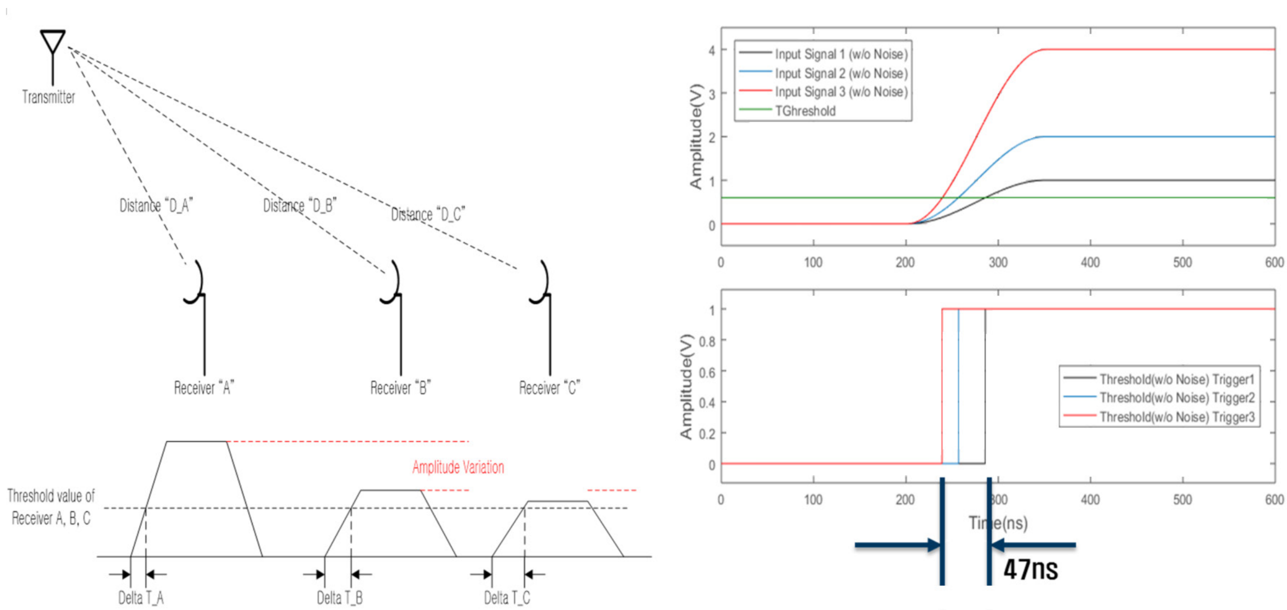

Fig. 12. The Simulation of Pulse positioning using comparator (w/o noise)

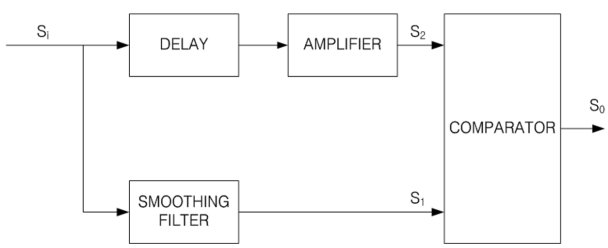

Fig. 13. Level adjuster system structure.

using LAS through simulations.

Fig. 13 shows the structure of LAS. LAS consists of delay, amplifier, comparator, and, if needed, smoothing filter. As shown in the above configuration, LAS is advantageous in that it can be easily and inexpensively implemented using general electronic devices. It can also be implemented using analog devices. To examine problem-solving performance depending on amplitude change, which is the problem of simple threshold, by LSA, simulations were conducted with LAS having a simple structure, without smoothing filter.

Fig. 14 explains a waveform produced from each of the components in the LAS system in Fig. 13. An input signal, whose amplitude is A1, is divided into two: one is transmitted to a delay and the other to a smoothing filter. A delay in the LAS delays the input signal for longer time than the rise time and then changes the signal to S2 through the amplifier. Note that constant F should be determined to amplify A1. Generally, 0.5 is used in radars or communication systems. A pulse position is determined when the rise edge of the pulse reaches the fixed part of the amplitude in S1, as shown in S2 signal in the LAS

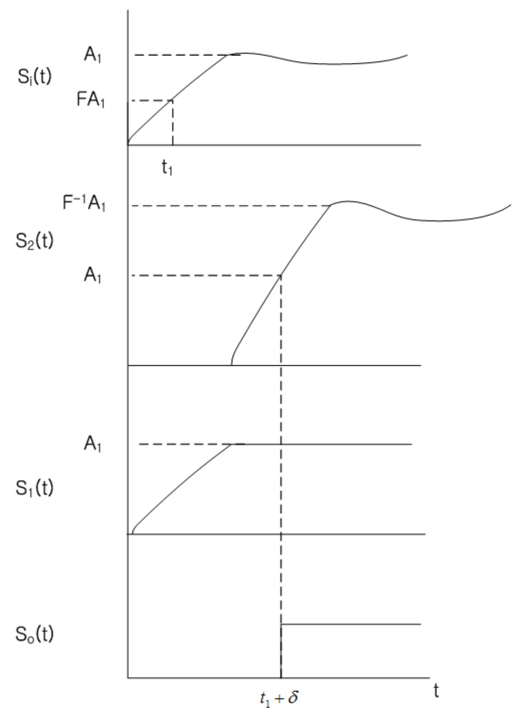

Fig. 14. Signal output of level adjuster system.

comparator.

Fig. 15 indicates the simulation results of LAS using MATLAB Simulink. Figs. 15-17 show the simulation results in the LAS without smoothing filter. The comparison of the results of Fig. 15 with those of Fig. 12 confirmed that the calculation of pulse position using the simple threshold method generates a deviation due to amplitude difference

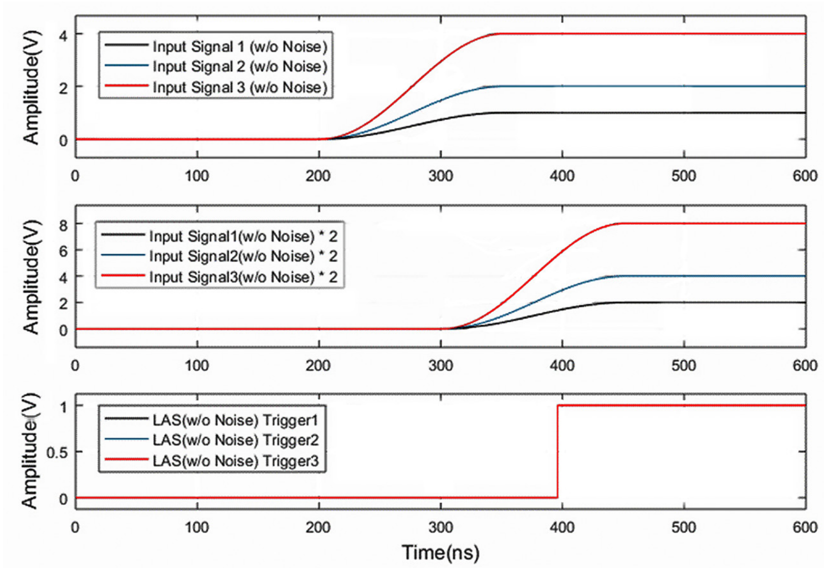

Fig. 15. The simulation result of LAS to determine pulse positioning.

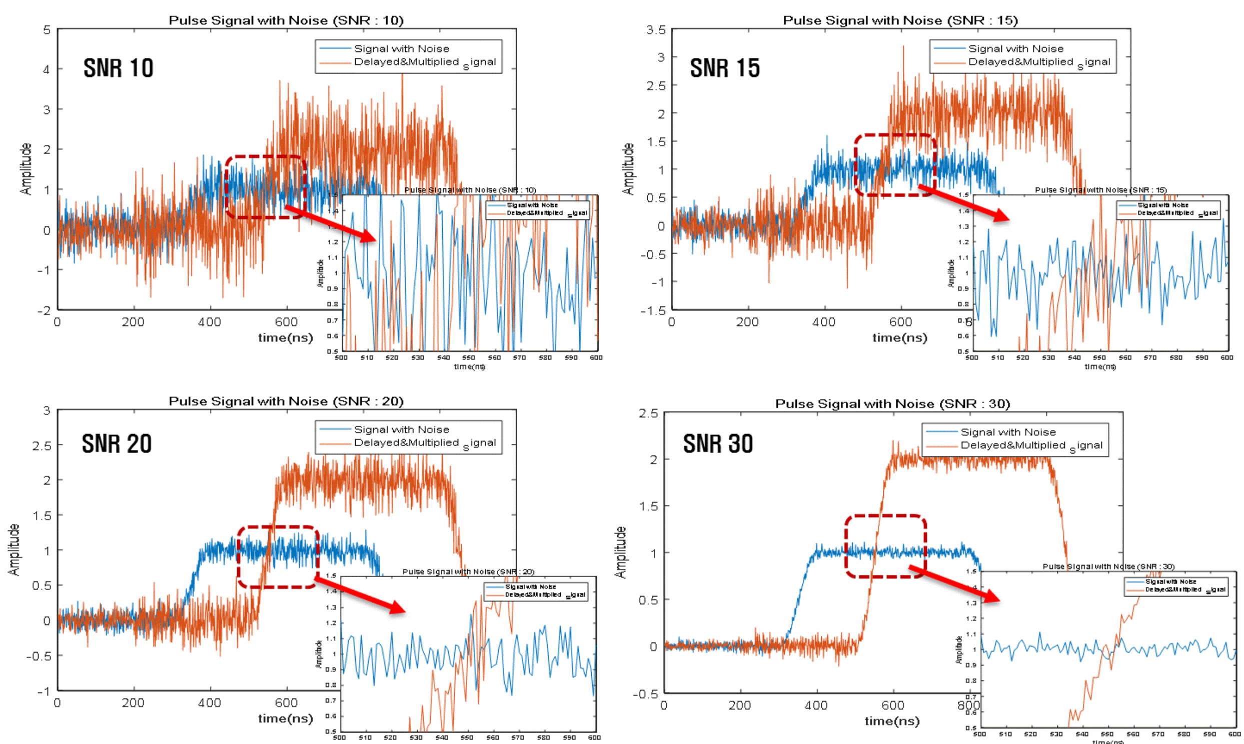

Fig. 16. Simulation result of level adjuster system with SNR.

of pulse waveform, whereas LAS can calculate the same pulse position regardless of pulse amplitude. The pulse position of LAS varies according to a delay in Fig. 13. The delay value applied to the LAS has a constraint that it should be larger than the rise time of pulse.

Fig. 16 shows the tendency of deviation with respect to pulse position in the LAS method depending on the changes in SNR. Pulse position is difficult to estimate if SNR is less than 10 dB when a threshold is set to 50% of the maximum value. The above result shows that a deviation is larger than the estimation result of pulse position using the simple threshold method described in the above section.

Fig. 17 shows the simulation results of variance values using LAS and CRLB methods to estimate a pulse position.

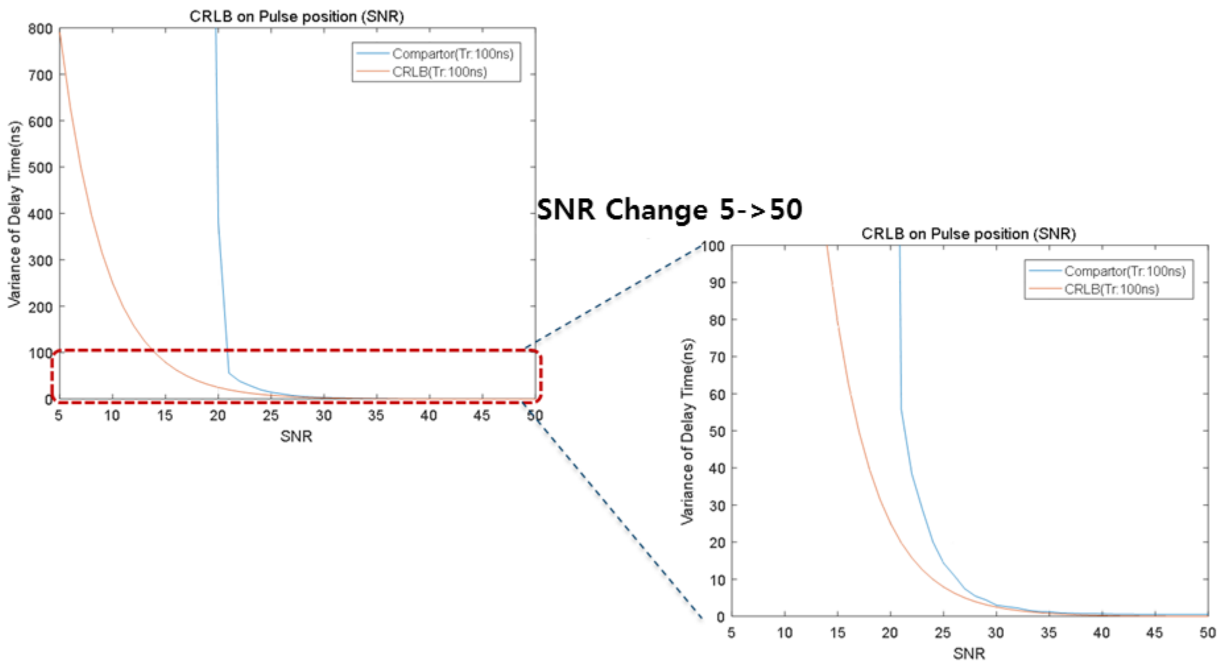

Fig. 17. Simulation result of level adjuster system & CRLB of pulse positioning.

The rise time was assumed to be 100 nsec and SNR was divided from 5 to 50 by increasing one increment in the simulation.

The simulation results show that since the variance should be less than 36 nsec in order to satisfy 6 nsec of the TOA accuracy required by MLAT, the requirement can be satisfied when the SNR value is approximately 22 dB or higher in the case of LAS. When comparing these results with those of simple threshold method, a deviation due to the SNR was relatively larger in the LAS. However, LAS had no effect due to different amplitude input to multiple RUs. Thus, since only the SNR and rise time affected the deviation of pulse position estimated by multiple RUs, LAS had a smaller deviation than that of simple threshold when applied to the MLAT.

4. CONCLUSIONS

This paper compared and analyzed the estimated deviation of pulse position after applying a simple threshold method and LAS method, which was one of the ATD methods, with that of CRLB. The simulation results verified that when only SNR and pulse position deviations were compared, a simple threshold method had a lower deviation than that of LAS. However, when a simple threshold method was applied to the MLAT, a deviation of pulse position due to a difference in amplitude of input signals, which resulted from a difference in distance between the target and each of the RUs, did not satisfy the TOA accuracy requirement (6 nsec) regardless of the SNR value. It was also verified through the simulation that when the ATD LAS method was applied to solve the problem of variation in deviation due to a difference in amplitude, a pulse position can be estimated without being affected by the change in amplitude. When the LAS was applied to the MLAT, signals, whose SNR was approximately 22 dB or higher, satisfied the TOA accuracy requirement (6 nsec). In other words, a TOA could be measured by applying the LAS to the MLAT at environment where noise was small. However, it was limited in measuring a TOA in accordance with the requirement using only the LAS at environments where noise was severe. For the future study, results of applying a noise-robust matched filter method and ATD method will be compared and analyzed.

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Jae Won Chang is a senior research engineer of Avionic Research Team at the Korea Aerospace Research Institute, Korea. He received M.S. degrees from Chungnam National University, Korea, in 2003. His current interests include multilateration, avionics system, and GPS.

Sang Jeong Lee is currently a Professor in the Department of Electronics Engineering at Chungnam National University, Daejeon, Korea. He received the Doctor's degree in Control and Measurement in Seoul National University in 1987. His research interests include GNSS and Robust Control.