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Performance Analysis of MLAT System Receiver for Aircraft Flight Control System

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ABSTRACT

In this paper, performance on receivers of multilateration (MLAT) system that uses ADS-B signal, which is recently becoming popular, was analyzed to overcome shortcomings of existing aircraft flight control systems or reinforce the capabilities. A link budget was analyzed using a channel model in the airport environment with regard to Local Area Multilateration (LAM) for ground-controlled landing around the airport. In order to detect signals that arrived at the receiver successfully, sensitivity of receiver was analyzed using a signal-to-noise ratio (SNR) worksheet, and a method that improves accuracy of the distance measurement was proposed by adopting a peak estimation using sampling signals. Through simulations, optimum specifications of receivers were analyzed to have high precision positioning of LAM, and accuracy of LAM distance measurements was presented.

Keywords: aeronautical surveillance system, ADS-B, MLAT, SNR worksheet

1. INTRODUCTION

In order to overcome the performance and operation limitations of primary and secondary surveillance radars, which are existing aeronautical surveillance systems, and accommodate ever increasing air traffic properly, systems have been now changed into a new concept of next-generational aeronautical surveillance systems called the communications, navigation, surveillance and air traffic management systems (CNS/ATM). Aviation control functions can be improved and safe flight through prevention of airplane collision can be promoted by periodically broadcasting positioning information of airplanes due to GPS information by using an Automatic Dependent Surveillance-Broadcast (ADS-B), which is a next generational aeronautical surveillance system. However, since ADS-B is dependent on positioning information provided by the GPS, if the GPS sends incorrect positioning information due to errors, jamming, or spoofing, it can result in fatality of aviation safety. In recent years, a multilateration (MLAT) system that is not affected by the GPS safety issue, which is a problem of ADS-B, has become an issue as a next generational surveillance system. The MLAT system is used along with the ADS-B system thereby making the current system into an improved aeronautics surveillance system.

The MLAT consists of a transmitter in the aircraft and a number of ground-base stations installed at several locations. Structure of the MLAT system is shown in Fig. 1. At the ground-base station, a receiver is installed to measure a distance and receives signals from the aircraft by synchronized clocks between base stations. One of the base stations has an interrogator thereby inducing signal transmittance from the aircraft transmitter and a signal that is used in the aircraft transmitter is ADS-B (RTCA SC-186). In general, GPS time synchronization is used as the basic time synchronization method for time synchronization and wired and wireless-based synchronization method is employed as the auxiliary synchronization method. Generally, common clock synchronization and reference

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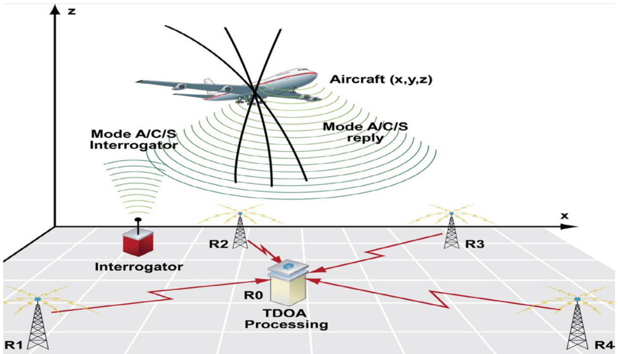

Fig. 1. Structure of the MLAT system.

transponder synchronization methods are used for the wired and wireless-based synchronization method. A position of aircraft is calculated using a Time of Difference of Arrival (TDOA) between measured values of distance from a number of base stations.

The MLAT can be divided into Wide Area Multilateration (WAM) and Local Area Multilateration (LAM) according to surveillance scope. WAM is a system that assists aircrafts under instrument flight over the airway within 40–50 miles from the airport using wide base stations deployed nationally. On the contrary, LAM is a system that supports aircraft moves in the runway, taking off and landing, and traffic circuit and control of moving objects in the ground runway within a 5 NM area using local base stations deployed around the airport.

A number of studies have been conducted to improve positioning performance in the MLAT system. Horizontal Dilution of Precision (HDOP) was presented according to antenna layout in the WAM system and improved performance than the standard performance of the WAM system can be proposed through flight tests (Mantilla-Gaviria 2013). In order to prevent a positioning error from increasing as a distance is farther away, ADS-B was used together to increase a monitoring area of the WAM system and satisfy the standard performance (Miyazaki et al. 2011). A study was also conducted to satisfy performance index of the system through arrangements between receivers and topographical relationship in the airport in the LAM system (Johnson et al. 2012). In order to reduce a topographical multi-path error, Interacting Multiple Model (IMM) filter was applied to measured data thereby improving errors at the airport or around the airport (Miyazaki et al. 2010). However, few studies have been conducted to increase accuracy of distance estimates by analyzing receiver performance in the LAM system in Korea and other nations.

In this paper, a method is proposed to acquire a measured value of distance with high precision in the receivers of the LAM system. In Section 2, a structure of the ADS-B signal transmitted by a transponder in the aircraft is analyzed and indoor channel model and link budget are analyzed in the airport environment. Next, sensitivity of receivers in the LAM system is analyzed through the SNR worksheet in order to detect signals at the receiver. In addition, a maximum likelihood (ML)-based peak estimation method is applied to minimize a distance error due to the digital sampling resolution. In Section 3, sensitivity and accuracy of estimation distance according to a sampling frequency are analyzed through simulations and conclusions are made in Section 4.

2. ANALYSIS ON PERFORMANCE OF RECEIVERS IN THE LAM SYSTEM

2.1 LAM System

The LAM system measures a position of aircraft by measuring a reception time difference of signals transmitted from the transponder installed at the aircraft and ground equipment between a number of ground receivers in areas such as airport. The LAM system consists of interrogator, four or more receivers, and central unit processor that performs communication control and aircraft location calculation. It is classified into active and passive systems according to the presence of interrogator (Cho et al. 2012). The passive LAM system calculates a target position by using the ADS-B signal, which is an automatic broadcast signal while the active LAM system calculates a target position by inducing responses from transponders using interrogator (Kim et al. 2012). In this paper, a performance of the receiver in terms of the structure of the passive LAM system using the ADS-B signal was analyzed.

2.2 Transmission Signal Structure and Transmitter Structure

A signal used in LAM is Mode A/C/S. In this paper, ADS-B that uses GPS signal information out of Mode S signals is employed. Here, a raised cosine filter is used as pulse shaping to reduce interference between channels. Fig. 2 shows the ADS-B signal structure and an example of ADS-B signal created at the signal generator by applying a raised cosine filter at the transmitter.

2.3 Channel Model and Link Budget

Considering the real runway has no high buildings around due to the characteristics of airport and straight

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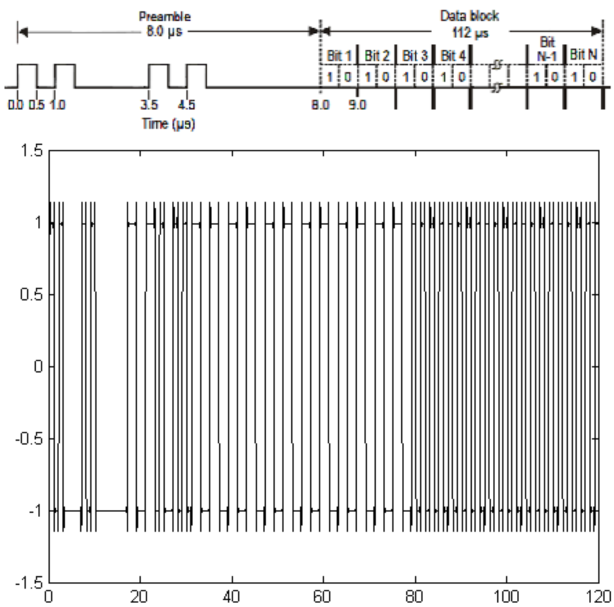

Fig. 2. ADS-B signal structure and example of ADS-B signal to which raised cosine filter is applied.

open space for long runway, the Hata model is applied assuming that it is suburban or rural area and runway is 5 NM (Park et al. 2010). Through the Hata model, channel environments in the suburban region can be taken into consideration and its path loss is as follows:

$$\mathrm{L} = 69.55 + 26.16 \log f_c - 13.82 \log h_t - A(h_r) + (44.9 - 6.55 \log h_t) * \log d - K \quad (1)$$

where f_c refers to a center frequency, h_t is an antenna height at the base station, h_r is an antenna height at the mobile station, and d is a distance between base station and aircraft. $A(h_r)$ refers to a calibration coefficient of antenna height at the mobile station and K is a calibration coefficient set to suit suburban region or open region, which can be given as follows:

$$A(h_r) = (1.11 \log f_c - 0.7)h_r - (1.56 \log f_C - 0.8) \quad (2)$$

$$K = 2\left[\log\left(\frac{f}{28}\right)\right]^2 + 5.4 \quad (3)$$

Considering transmit power and channel model at the transmitter end of the aircraft, received power arrived at the front-end of the receiver is verified through the link budget. The link budget in the LAM system using ADS-B signals can be as follows, in which a fact that runway was 5 NM was taken into consideration.

In the above Table 1, a Minimum Trigger Level (MTL) refers to the minimum power received to obtain reliable information and reliable information can be acquired for ADS-B report at the receiver only over the MTL of the power received. Normally, the MTL is set to power that can obtain 90% or higher accurate information at the receiver.

Table 1. Link budget of the LAM system using ADS-B.

properties	value
Transmitter power (dBm)	57
Transmit antenna gain (dBi)	0
Path loss (dB)	148.12
Receiver cable loss (dBi)	-3
Receiver antenna gain (dBi)	9
Received power (dBm)	-85.12
Receiver MTL (dBm)	-92
Link margin (dB)	6.88

In the channel model, not only path loss but also multi-path model shall be taken into consideration. For the corresponding environment, the tapped delay line (TDL) channel model was considered. The TDL channel model is defined as an impulse response system as follows (ITU-R M.1225 1997).

$$h(t) = \sum_{i=0}^{L} a_i e^{j\phi_i} \delta(t - \tau_i) \quad (4)$$

where L is the number of multi-path, a_i is a size of i-th multi-path signal, ϕ_i is the i-th multi-path signal phase, and τ_i is a delay time of the i-th multi-path signal. Accordingly, a size of the multi-path signal is assumed as an irregular variable in which the path loss signal size has the Rayleigh distribution. The phase of the multi-path is assumed that it is an irregular variable that has Uniform distribution and a delay time of the multi-path signal is assumed that it is an irregular variable that has Poisson distribution.

2.4 Structure of the Receiver

Once base band signals at the receiver is sampled, the signals are detected and traced using a correlator. Since a SNR of the received signal should be sufficiently large to be detected, detection ability of the receiver shall be analyzed through the SNR worksheet analysis. A position of aircraft can be calculated if TDOA measured value obtained using correlator power at each base station is used. The signal detection is done by using a preamble of the transmission signal frame. In this paper, it is assumed that a distance measured value is calculated using a single pulse signal whose length is 0.5 µs among the preamble signals. The characteristic of frequency in the preamble signal is represented as shown in Fig. 3 and a frequency bandwidth including the side lobe is 5 MHz so that the minimum sampling frequency determined by the Nyquist theory is 10 MHz.

An ideal correlator power with regard to 0.5 µs pulse signal of preamble signal obtained using the sampling

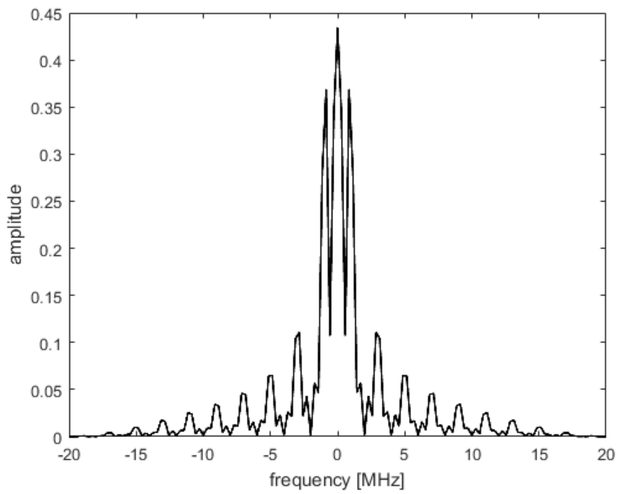

Fig. 3. Frequency characteristic of the preamble signal in the ADS-B.

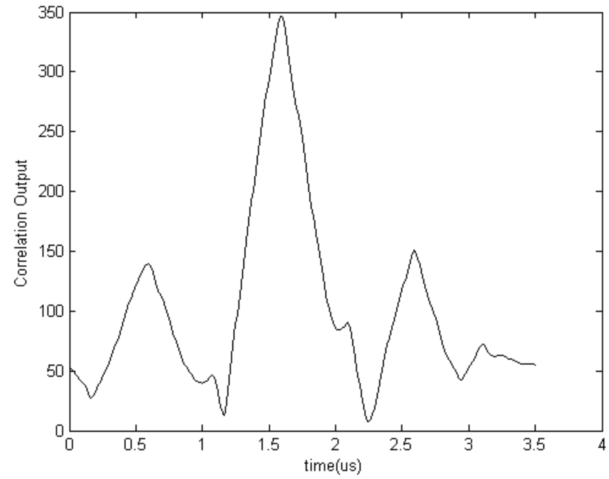

Fig. 5. Example of correlation using the preamble of ADS-B.

Table 2. SNR worksheet of LAM (5 NM).

properties	value
Signal Strength (dBm)	-92
IF bandwidth (MHz)	4
T_{eff} (K)	296.4
Noise power (dBm)	-107.9
IF SNR (dB)	15.9
Sample rate (MHz)	100
Coherent Interval (μs)	0.5
Number of Points	50
Ideal Coherent gain (dB)	16.98
Quantization error (dB)	-0.55
Freq.bin error (dB)	-0.5
Implementation Losses (dB)	-1.05
Actual Coherent gain (dB)	15.93
Final SNR (dB)	31.83

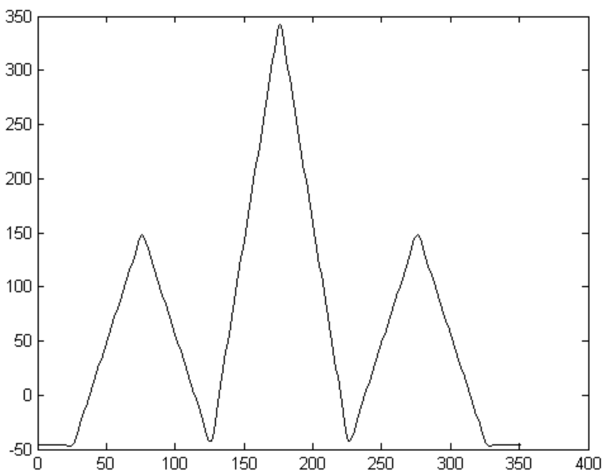

Fig. 4. Ideal correlator power using the preamble of ADS-B.

measured value is shown in Fig. 4. In addition, a correlator power with regard to 0.5 μs pulse signal of the preamble signal in the multi-path environment is shown in Fig. 5. In Figs. 4 and 5, sampling frequency is 100 MHz and received power is -92 dBm.

In order to improve the location accuracy of a MLAT system, high precision TDOA measured value shall be obtained. The correlator power profile is deformed by the multi-path as shown in Fig. 5 once the signal received from the aircraft is passed through the channel model. Since the sampling timing and correlator peak are not exactly matched with each other, the accuracy of a distance measured value is degraded due to the limitation of distance resolution if direct distance measured value is calculated using a sampling measured value. In this paper, signal detection abilities are analyzed using the SNR worksheet to analyze the performance of the receiver and performance of the peak estimation method according to sampling frequency in the multi-path environment and accuracy of distance measured value are analyzed.

2.4.1 Analysis on the receiver sensitivity

A loss can occur via Analog-to-Digital (A/D) conversion error and frequency error among the factors that affect the SNR worksheet to analyze the sensitivity of the receiver, and signal processing gain is determined through sampling frequency and signal correlation interval length (van Diggelen 2009). The A/D conversion error occurs due to errors during the quantization process. In this paper, quantization error was assumed as -0.55 dB by considering 2 bit quantization (van Diggelen 2009). Since frequency error occurs due to receiver clock offset or aircraft velocities, it is difficult to predict the error and in general, a frequency error of several tens to several hundreds Hz occurs. In order to remove the frequency error, this paper assumed that frequency error is eliminated by scanning a certain range of frequencies (van Diggelen 2009). The sensitivity of LAM receiver can be verified by filling out the SNR worksheet in

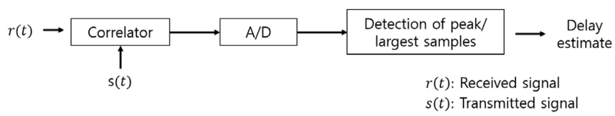

Fig. 6. Correlator peak estimation model.

consideration of error components and link budget. Table 2 summarizes the SNR worksheet of LAM.

Final SNR can be different depending on sampling frequency. If a sampling frequency is set from 10 MHz to 100 MHz, ideal coherent gain is 6.98 – 16.98 dB so that final SNR become 21.83 – 31.83 dB, which can obtain a SNR that can detect sufficient signals.

2.4.2 Distance error and peak estimation method

As main error factors that affect a distance error, time synchronization error between receivers, sampling resolution, and multi-path error can be found. An error due to time synchronization occurs when time synchronization between receivers at each base station is not matched. The time synchronization mode used can affect the accuracy significantly. In this paper, it is assumed that transponder synchronization mode is applied and a size of time synchronization error is tiny in order to increase scalability to not only airports but also access control areas.

The resolution error due to digital sampling shall be taken into consideration at low sampling frequency significantly and error can be compensated by estimating using various estimation methods. This method is called peak estimation (Qi & Kohno 2005). Fig. 6 shows the peak estimation method.

As existing delay error estimation methods, Maximum Likelihood (ML)-based peak estimation method and Multipath Elimination Technology (MET) that compensates multipath error by determining a slope at both sides can be found (Han 2012). The ML-based peak estimation method employs ML mode. Its accuracy is high but its structure is complex. The MET method requires a high sampling frequency to reduce the multipath error. In this paper, the ML-based peak estimation method is used to analyze distance estimation accuracy according to sampling frequencies in order to analyze the performance of peak estimation method according to a wide range of sample frequencies.

First, assuming that received signal at the receiver is continuous signal, $r(t)$ can be as follows:

$$r(t) = As(t-\tau) + n(t) \tag{5}$$

where A and τ are amplitude of the received signal $s(t)$ and time delay and $n(t)$ is assumed as white noise that has Gaussian noise distribution. The ML method that estimates $\hat{\tau}$ is to find the maximum value where the correlator power becomes the largest and correlator power is as follows:

$$\begin{aligned} h(v) &= \int r(t)\cdot s(t-v)dt \\ &= A\int s(t)\cdot s(t-v+\tau)dt + \int n(t)\cdot s(t-v)dt \\ &\equiv Ag(v-\tau) + z(v) \end{aligned} \tag{6}$$

Correlator power when sampling is done at T interval can be defined as follows:

$$h(t_N) = (h(t_1), h(t_2), \cdots, h(t_N))^T \tag{7}$$

$$g_{t_N}(\mathrm{v}) = (g(t_1-v), g(t_2-v), \cdots, g(t_N-v))^T \tag{8}$$

$$z(t_N) = (z(t_1), z(t_2), \cdots, z(t_N))^T \tag{9}$$

In the above equation, $z(t_N)$ refers to colored noise that has co-variance matrix as follows:

$$V_N = N_0 \begin{pmatrix} g(0) & g(T) & \cdots & g\big((N-1)T\big) \\ g(T) & g(0) & \cdots & g\big((N-2)T\big) \\ \vdots & \vdots & \ddots & \vdots \\ g\big((N-1)T\big) & g\big((N-2)T\big) & \cdots & g(0) \end{pmatrix}$$

A delay time $\hat{\tau}$ estimated by the ML method can be arranged into the following equation (Qi & Kohno 2005).

$$\begin{aligned} \hat{\tau} &= \arg\max_{v}\, g_{\mathrm{t}_N}(v)^T V_N^{-1} h(\mathrm{t}_N) \\ &= \frac{t_Z^T V_Z^{-1} h(t_Z)}{1_Z^T V_Z^{-1} h(t_Z)} \end{aligned} \tag{10}$$

In the above equation, it satisfies $t_Z=[t_m\ t_{m+1}\ \ldots\ t_{m+Z-1})]^T$ and Z is the number of samples used in the ML method, which has a range of $2 \le Z < N$. m is determined according to the following criteria.

$$m = \arg\max_{n} \sum_{z=0}^{Z-1} h(t_{n+z}) \tag{11}$$

3. SIMULATION

In this section, the sensitivity of the receiver is analyzed through the resolution error estimation when peak estimation is applied using four samples when a sampling frequency is set to 10 – 100 MHz. The aforementioned channel model was applied and this channel model consists of Hata model, which is a path loss model, and TDL channel model, which is a multipath model. λ was defined as 0.01 in the Poisson probability variable of tapped delay time in

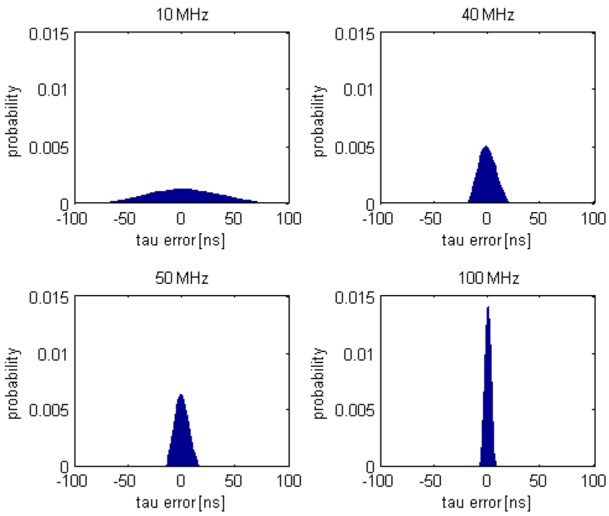

Fig. 7. Probability distribution diagram of delay time estimation error when sampling frequency is 10 – 100 MHz.

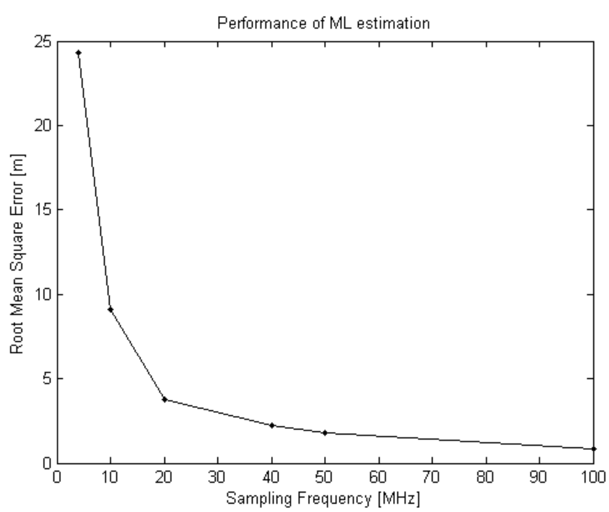

Fig. 8. Distance measured value error when sampling frequency is 10 – 100 MHz.

the TDL channel model. The ML method is used to perform peak estimation. Fig. 7 shows the probability distribution diagram of delay time estimation error according to sampling frequency. To obtain reliable probability distribution diagram, 10,000,000 times of simulations as per sampling frequency were conducted.

The Root Mean Square Error of the estimated delay time tau was 30.4 ns for 10 MHz, 12.6 ns for 20 MHz, 7.6 ns for 40 MHz, 5.9 ns for 50 MHz, and finally 2.7 ns for 100 MHz. When these are converted into distance errors, errors of 9.1 m, 3.7 m, 2.2 m, 1.7 m, and 0.8m for each sampling frequency can be obtained. These errors are shown in Fig. 8. The result confirmed that as sampling frequency became higher, delay time error became smaller.

Performances as shown in Table 3 are required in the

Table 3. Precision of the LAM.

Scope	Position error reference (95%, m)
Runway	≤ 7.5
2.5 NM	≤ 20
5 NM	≤ 40

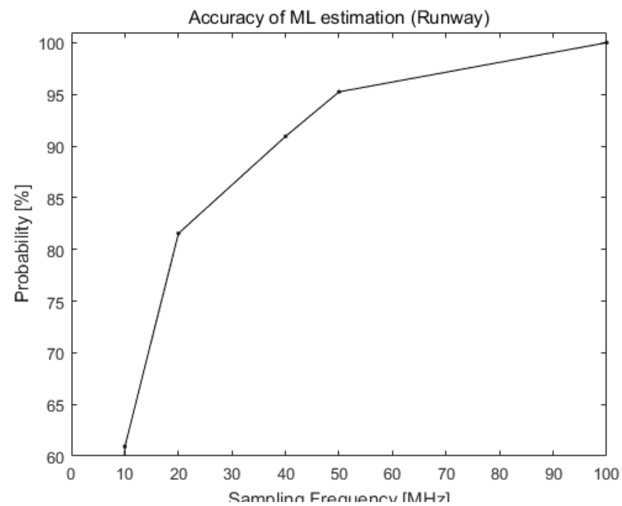

Fig. 9. Probability that satisfies the position error reference when sampling frequency is 10 – 100 MHz.

LAM system. Position Dilution of Precision was assumed as 2.5 since we assumed that layout of the base stations under the runway environment was appropriate. Assuming that a reference of distance measured value error is 2σ, errors of 18.2 m, 7.4 m, 4.4 m, 3.4 m, and 1.6 m for each sampling frequency were verified and through these values, it was found that a position error reference shall use a sampling frequency larger than 50 MHz. The errors of all measured values obtained through simulations were compared with position error references thereby calculating a ratio of measured value that satisfied the position error reference as a probability, which is shown in Fig. 9. Through the result, if a sampling frequency was larger than 50 MHz, it can satisfy the performance required by the LAM system. Under 2.5 NM and 5 NM environments, additional performance evaluation was not carried out since not only layout of the base stations but also surrounding topography have to be considered in contrast with the runway environment.

4. CONCLUSIONS

In this paper, the sensitivity of receivers used in the LAM system that assist aircraft taking off and landing as well as control of moving objects in the ground runway using ADS-B signals. A link budget was analyzed at the LAM transmitter using indoor distance channel model in the airport environment and the sensitivity of receiver was analyzed using a SNR worksheet to detect signals arrived at the receiver successfully. The performance of ML-based peak estimation method was analyzed to measure a distance with high precision using sampling signals. It was found that as sampling frequency became higher, the distance measured values became accurate. In particular, when peak estimation method was applied by sampling at 50 MHz or higher frequency, the position specification of the LAM system can be satisfied with 95% position accuracy. The study result in this paper can contribute to implementation of inexpensive receiver equipment at base stations.

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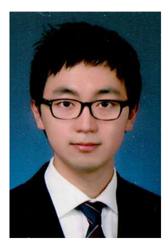

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