

Precise Point Positioning for Mobile Robots using Software GNSS Receiver and QZSS LEX Signal

Taro Suzuki, and Nobuaki Kubo, *Member, IEEE*

Abstract— This paper describes outdoor localization for a mobile robot using precise point positioning (PPP) based on the Quasi-Zenith Satellite System (QZSS) L-band Experiment (LEX) signal. For autonomous navigation applications, a real-time kinematic (RTK) global positioning system (GPS) technique is widely used to estimate user position with high-precision accuracy in real time. However, RTK-GPS requires a reference station, and there are data acquisition costs involved in estimating the position. Our approach corrects position error by applying PPP using the QZSS LEX message. PPP can estimate a single receiver position without any reference station or baseline, through use of satellite position fixing and clocks. We developed a method for extracting the QZSS LEX message in real time using a software GNSS receiver. We then constructed the PPP framework based on an LEX message containing the satellite ephemeris and clock errors. Finally, we conducted field experiments to evaluate the accuracy and precision of our proposed method. The experimental results confirmed that our method made a localization precision of 1.29 m possible without using a GNSS reference station.

I. INTRODUCTION

Recent developments in intelligent transportation system (ITS)-related technologies have actively promoted the increased application of autonomous mobile systems in outdoor environments. Examples of such systems include automatic vehicle navigation systems and unmanned construction systems with autonomous construction machinery. Mobile mapping systems [1], for example, require the ability to carry out continuous and accurate self-positioning. In these applications, high-precision satellite-based positioning constitutes a fundamental part of the application [2]. Global navigation satellite systems (GNSSs), such as the U.S.-based Global Positioning System (GPS), have traditionally been used to estimate the position of mobile robots in outdoor environments. The availability of GNSSs is anticipated to improve as new positioning satellites are launched.

In applications that require high-precision positioning in real time, a real-time kinematic (RTK) GPS technique is usually used [4]. RTK-GPS is one of the most precise positioning technologies and can be used to obtain centimeter-level accuracy of the position in real time by processing the carrier-phase measurements of GPS signals. In the Defense Advanced Research Projects Agency Grand/Urban Challenge involving driverless outdoor vehicle races, most

teams use RTK-GPS/inertial navigation system (INS) navigation. In 2005, the Stanford University Racing Team achieved autonomous running for over 200 km [3]. RTK-GPS is very popular; however, it requires GNSS base stations or simultaneous observations by dual-frequency GPS receivers, which is inconvenient where cost is a consideration. In addition, the maximum distance of the user from the reference station must be less than 20 km because of ionospheric error, which is dependent on the location [5]. Unlike single-reference station RTK-GPS approaches, where the positioning accuracy decreases as the baseline increases, network RTK (NRTK) approaches ideally provide positioning with errors independent of the rover position within the network [5]. However, NRTK also requires a communication link and costs are involved to receive the correction data in many cases.

In recent years, precise point positioning (PPP) has been anticipated as an alternative to RTK-GPS [6][9]. PPP can estimate a single receiver position without any reference station or baseline through the use of satellite position fixes and clocks, which are previously determined. In comparison with common techniques, the costs can be reduced. However, PPP requires fixed satellite positions and clocks, and the question is how to get these correction data. In this paper, we use the L-band Experiment (LEX) signal broadcasted by the Quasi-Zenith Satellite System (QZSS) to solve this problem. The first QZSS was launched from Japan in September 2010 [12]. QZSS uses an asymmetric figure eight orbit, and hence, the elevation angle of QZSS is more than 75° for approximately 8 h/d in Tokyo, Japan [13]. The LEX message provides GPS satellite clock and ephemeris errors for correcting the GPS positioning error via the QZSS satellite. This function allows the GPS accuracy to be improved. Unfortunately, the LEX messages cannot be received using current commercial GNSS receivers. In addition, for real-time applications, the LEX message needs be extractable for computing user positions in real time. In this study, we developed a framework for PPP using the QZSS LEX message for outdoor mobile robots. We also developed a novel technique for receiving the QZSS LEX message using a software GNSS receiver. In GNSS research, software-defined receivers (SDR) are widely recognized and utilized for their configuration flexibility and ease of use [10][11]. We were able to construct the PPP system based on the QZSS LEX message using a software receiver and to confirm the position estimation capability in an actual outdoor environment.

II. OVERVIEW OF PROPOSED METHOD

The proposed method to estimate position using the QZSS LEX signal consists of (1) LEX message computation using a

Taro Suzuki and Nobuaki Kubo are with the Tokyo University of Marine Science and Technology, 2-1-6, Etchujima, Koto-ku, Tokyo 135-8533, Japan. (phone and fax: +81-3-5245-7376; e-mail: tsuzuk0@kaiyodai.ac.jp).

software GNSS receiver, and (2) localization of mobile robots using PPP with LEX messages. Fig. 1 shows the system flow with a PPP using the LEX messages. First, we developed the software GNSS receiver to extract the LEX message. In this study, rather than tracking the LEX signal, the LEX message was extracted with the aid of the conventional L1CA code phase and the Doppler signal obtained by the L1CA signal tracking. Using this method, each GPS satellite ephemeris error and clock error could be easily used for PPP in a simple configuration. The precise satellite position and clock were calculated by the PPP framework. We computed the location of the mobile robot and other unknown values using a Kalman filter.

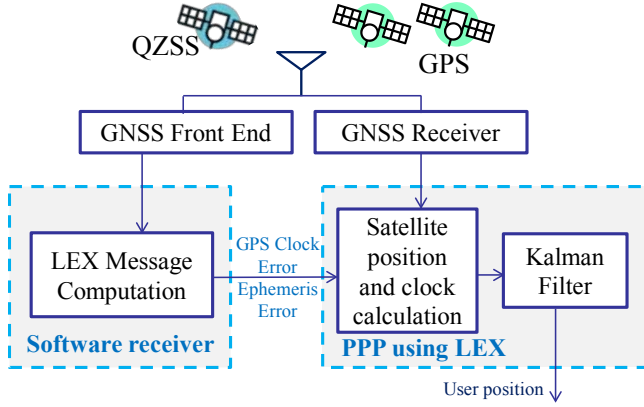


Figure 1. Overview of proposed positioning method. There are two parts: (1) LEX message computation using a SDR, and (2) PPP with LEX messages.

III. DECODING OF LEX MESSAGE USING SOFTWARE RECEIVER

A. QZSS LEX Signal

The LEX signal, an augmentation signal in the 1278.75-MHz band broadcasted from QZSS, is anticipated to provide fine positioning up to the centimeter level [7][8]. Fig. 2 shows the structure of the LEX message used for the broadcast of the augmentation information. The LEX message consists of a 49-bit header, 1695 bits of data, and 256 bits for error correction using Reed-Solomon coding; the total size of one message is 2000 bits. The actual data transfer volume for the augmentation information is 1695 bps, with a basic structure of one message transmission per second. The augmentation information for the whole of Japan needs to be incorporated into 1695 bps. The LEX signal is overlaid by the ranging code, which has a period of 4 ms and a chip rate of 10,230 MChip/s.

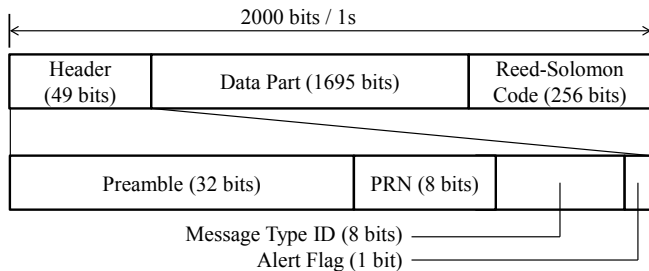


Figure 2. LEX message structure.

The LEX message contains the signal health, ephemeris error, clock error, and ionospheric correction. The correction items such as satellite ephemeris and clock errors are updated every 12 s for high-speed corrections, and a low-speed correction item such as ionosphere error is updated every 30 min.

B. Software GNSS Receiver

The LEX signal utilizes code shift keying (CSK) [7]. CSK modulation shifts the phase of the LEX code by the number of chips indicated in the 8-bit encoded message symbol. The idea proposed in this paper is to decode the LEX messages without the LEX signal tracking loop for estimating the code phase and Doppler frequency of the LEX signal, but with the aid of the conventional L1CA signal simultaneously broadcasted from the QZSS. Fig. 3 illustrates the LEX decoding algorithm based on the L1CA signal. This algorithm requires a code phase and Doppler information computed by the L1CA signal tracking result to extract the QZSS LEX message. The algorithm was executed as follows:

(i) Acquisition and tracking of the QZSS L1CA signal were performed. In the signal acquisition, a circular correlation based on the fast Fourier transform (FFT) was used to estimate the rough Doppler frequency and rough code phase of the L1CA signal. In the tracking process, the accurate Doppler frequency and code phase were continuously estimated every 1 ms using the frequency lock loop (FLL), phase lock loop (PLL), and delay lock loop (DLL). During this time, the LEX code phase, which occurs every 4 ms, was unknown.

(ii) Synchronization of the navigation bit overlaid in L1CA code was performed. If the navigation bit is synchronized, the ambiguity of the LEX code phase (nonshifted phase) can be resolved. We then estimated the LEX Doppler frequency using the L1CA Doppler frequency. The code phase and Doppler frequency of the LEX signal were denoted using the L1CA signal as follows:

$$C_{LEX} = C_{L1CA} + \varepsilon \quad (1)$$

$$d_{LEX} = d_{L1CA} f_{LEX} / f_{L1CA} \quad (2)$$

where C_{L1CA} and C_{LEX} are the code phases, d_{L1CA} and d_{LEX} are the Doppler frequencies in L1CA and LEX, and f_{L1CA} and f_{LEX} are 1575.42 and 1278.75 MHz, respectively. The variable ε is the differential code bias (DCB) between QZSS L1CA and LEX signals, and it can be calibrated in advance.

(iii) The LEX code phase (shifted phase) C'_{LEX} was estimated using FFT based on the circular correlation technique. The LEX message symbol L can be calculated using the nonshifted code phase and estimated code phase using the following equation:

$$L = N_{LEX} + C_{LEX} - C'_{LEX} \quad (3)$$

where $N_{LEX} = 10,230$ was the number of chips of LEX code.

(iv) The error of the estimated message symbol was corrected by the Reed-Solomon code. On the basis of the above, the GPS satellite ephemeris error and clock error can be extracted from the LEX message using the software GNSS receiver, without tracking the LEX code.

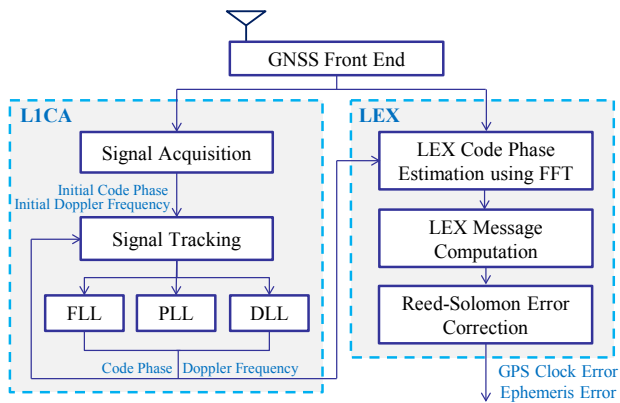


Figure 3. Flowchart of LEX message extraction aided by LICA tracking using software GNSS receiver.

C. Experiment

We conducted initial tests to evaluate the decoding part of the proposed method, using the test setup shown in Fig. 4. We used a front end (NSL Stereo, UK), GNSS antenna (Trimble Zephyr Model 2, US), and a laptop PC to receive and decode the LEX message. Fig. 5 shows the estimated LICA and LEX code phases. We computed the LEX message symbol by taking the difference between the LICA code phase and LEX code phase in Fig. 5. The decoding error rate for the LEX message was evaluated using the Reed-Solomon error correction code. Fig. 6 shows the relationship between the QZSS elevation angle and the decoded symbol errors. When the number of symbol errors is less than 16, the error can be corrected by the Reed-Solomon code. In this test, the correct LEX message was received when the QZSS elevation angle was over 13° . In general GNSS positioning, a 15° elevation masking is usually used. For this reason, the QZSS elevation angle presented little problem for the GNSS positioning.

From these tests, it was concluded that it is possible to develop a method to receive the QZSS LEX message using the software GNSS receiver. In the following section, we describe the real-time kinematic PPP that uses the QZSS LEX messages.



Figure 4. Set-up of software GNSS receiver.

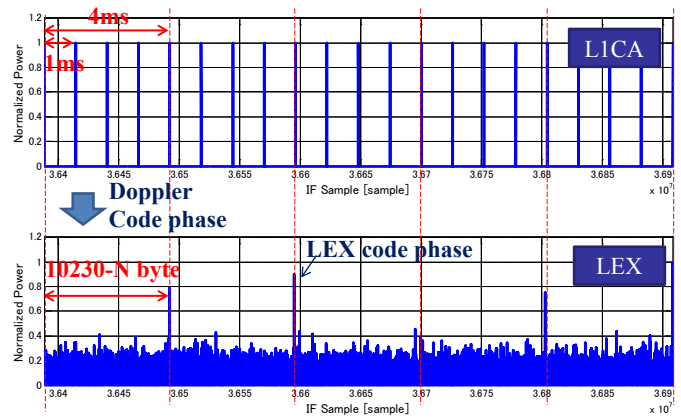


Figure 5. Code phases of LICA and LEX signals obtained by the proposed method.

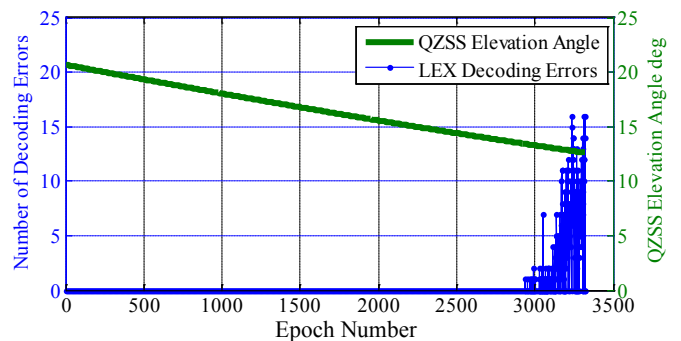


Figure 6. Relationship between QZSS elevation angle and LEX message symbol decoding errors.

IV. PPP WITH LEX MESSAGE

The PPP was introduced by Zumberge et al. as an efficient and robust analysis technique for large GPS receiver networks [6]. PPP can estimate a single receiver position without any reference station or baseline by fixing satellite positions and clocks to previously determined values. In addition, all positions are related to a well-defined geodetic datum which is valid globally. The International GNSS Service (IGS) provides accurate and high-quality products, including GPS satellite orbits and clocks, based on the post-mission analysis of observations at more than 300 permanent stations worldwide. Furthermore, PPP can be used for high-precision positioning without any baseline length limitation. For these reasons, PPP is anticipated to be a useful and efficient means of localizing mobile robots.

For the purpose of the real-time application, there was a question of how to get the precise satellite ephemeris and clock to process the PPP. As already mentioned, we used the QZSS LEX signal in this study as the precise ephemeris and clock source using the software receiver. By obtaining the precise satellite ephemeris and clock from positioning satellites using the GNSS receiver, then applications can easily determine the high-precision position without any data communication. QZSS is suitable for broadcasting the

augmentation information because QZSS has a high elevation angle, and it is visible over long periods in Japan.

We developed the PPP technique based on the QZSS LEX messages. In the first step, precise satellite clocks and ephemeris were used for correcting the GNSS observations. The GNSS carrier-phase observation was then modeled by Eq. (4) as follows:

$$\phi = r + I + T + c(dt - dT) + N + \varepsilon \quad (4)$$

Here ϕ denotes the carrier phase measurement; r , the geometric satellite-to-receiver distance; I , the ionospheric delay; T , the tropospheric delay; c , the velocity of light; dt , the clock bias of the receiver; dT , the clock bias of the satellite; N , the carrier-phase integer ambiguity; and ε , the measurement error including the multipath effect.

In conventional RTK-GPS, the double-difference technique can be applied to cancel out most of the correlated errors in observations. In contrast, PPP uses the observable ionosphere-free linear combination (LC) of the dual-frequency carrier-phase GPS to estimate the user position. Using the ionosphere-free LC, the ionosphere delay can be completely cancelled. The ionosphere-free LC of the dual-frequency carrier-phase GPS observables was expressed as follows [14]:

$$\phi_{IF} = c \frac{f_1 \phi_1 - f_2 \phi_2}{f_1^2 - f_2^2} = r + T + c(dt - dT) + N_{IF} + \varepsilon_{IF} \quad (5)$$

where subscripts 1 and 2 refer to the L1 and L2 frequencies, respectively; ϕ_{IF} , the carrier phase of the ionosphere-free LC; N_{IF} , the carrier-phase integer ambiguity of ionosphere-free LC; and ε_{IF} , the measurement error, including the L1 and L2 multipath effects.

Here, the clock bias dT of the satellite can be calculated from the broadcasted clock and LEX clock error information. Once the low-rate clock errors are obtained, higher rate values can be acquired by a simple linear interpolation, wherein they are assumed to be stable for a short period. The geometric distance r was iteratively computed as follows, using the satellite and receiver positions and considering Earth's rotation during the signal travel time:

$$r = \left| U(t - r/c - dt)^T (\mathbf{r}^s(t - r/c - dt) - U(t - dt)^T \mathbf{r}_r \right| \quad (6)$$

where U is the Earth-centered Inertial (ECI) to Earth-centered Earth-fixed (ECEF) transform matrix, \mathbf{r}^s is the satellite position in ECEF coordinates, and \mathbf{r}_r is the user position in ECEF coordinates. This satellite position can be computed by the ephemeris information contained in the LEX message. The iterative method was used to solve this light-time equation. In Eqs. (5) and (6), the unknown parameters, the tropospheric delay T , and the carrier-phase integer ambiguity of ionosphere-free LC N_{IF} , remain. The tropospheric delay T was also obtained with the tropospheric zenith total delay (ZTD) and an appropriate mapping function. Values of ZTD, N_{IF} , and

user position \mathbf{r}_r were estimated simultaneously by the extended Kalman filter (EKF) in this study.

The state vector \mathbf{x} of EKF for state k is denoted as follows:

$$\mathbf{x}_k = \begin{bmatrix} \mathbf{r}_r^T & dt & ZTD & N_{IF}^1 & \dots & N_{IF}^n \end{bmatrix}^T \quad (7)$$

Here, \mathbf{r}_r is the 3-D position vector, and n denotes the number of satellites. In the EKF prediction step, the equation of state at prediction was as follows:

$$\mathbf{x}_{k|k-1} = \begin{bmatrix} \mathbf{r}_{r0}^T & dt_0 & ZTD_{k-1} & N_{IFk-1}^1 & \dots & N_{IFk-1}^n \end{bmatrix}^T \quad (8)$$

Where the suffix $k|k-1$ denotes state k predictions estimated from the $k-1$ state. The variables \mathbf{r}_{r0} and dt_0 are the receiver position and clock error that are calculated by the single-point positioning. In the kinematic PPP, the receiver position was reset to the single-point positioning solution in every epoch.

In the EKF observation step, the GPS observation vectors are denoted as follows:

$$\mathbf{z}_k = \begin{bmatrix} \phi_{IF}^1 & \dots & \phi_{IF}^n \end{bmatrix}^T \quad (9)$$

where ϕ_{IF} is the ionosphere-free LC carrier phase in Eq. (5). The observation matrix \mathbf{H} is denoted by the following equation:

$$\mathbf{H}_k = \begin{bmatrix} \partial r^1 / \partial \mathbf{r}_{rk|k-1} & c & \partial ZTD^1 / \partial T & 1 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ \partial r^n / \partial \mathbf{r}_{rk|k-1} & c & \partial ZTD^n / \partial T & 0 & 0 & 1 \end{bmatrix} \quad (10)$$

The state \mathbf{x} and the covariance matrix \mathbf{P} for state \mathbf{x} are updated by the general Kalman filter framework using Eq. (10). Using these equations, the states were compensated by the EKF, and the user position was estimated based on the single-receiver observations with the QZSS LEX message.

V. ROBOT EXPERIMENT

We conducted robot tests to evaluate our proposal for position estimation using the PPP based on the QZSS LEX signal. We compared the two positioning methods, which were (1) the normal point-positioning result output from the GPS receiver, and (2) the proposed PPP, which employed augmentation information of LEX messages obtained by using the software GNSS receiver.

A. Test Settings

The positioning test was performed during a robot competition for autonomous navigation of intelligent robots on a crowded walkway, called the Tsukuba Real World Robot Challenge. The Challenge was held in Tsukuba, Ibaraki, Japan, on November 15, 2011. The travel route was part of the Challenge course and is shown in Fig. 7. A time series of color fish-eye images that shows the course environment is also

included in Fig. 7. This figure shows that the surroundings of the travel route consisted of roadside trees in leafy areas and some buildings, making it an environment susceptible to satellite masking.

The mobile robot that we used for the test is shown in Fig. 8. We installed the dual-frequency GNSS receiver, antenna, and software GNSS receiver on the robot. A fiber optic gyroscope (FOG) and wheel encoder for measuring the attitude and velocity of the mobile robot were also installed. To compare the positioning accuracy, we computed the reference RTK-GPS solution using the GNSS observation data at the base station, which was set up near the test environment. We used dual-frequency RTK-GNSS fix solutions as reference positions for comparison with the results obtained by the proposed method. However, a RTK-GNSS fix solution cannot be obtained when the number of satellites is reduced in an actual outdoor environment. Therefore, we combined RTK-GNSS fix solutions and dead reckoning (DR) results based on the Kalman filter using the FOG and the wheel encoder to generate the reference path. The mobile robot traveled for approximately 1 km at speeds of less than 4 km/h. The GPS data were obtained at a rate of 10 Hz and the elevation angle mask was set at 10° .

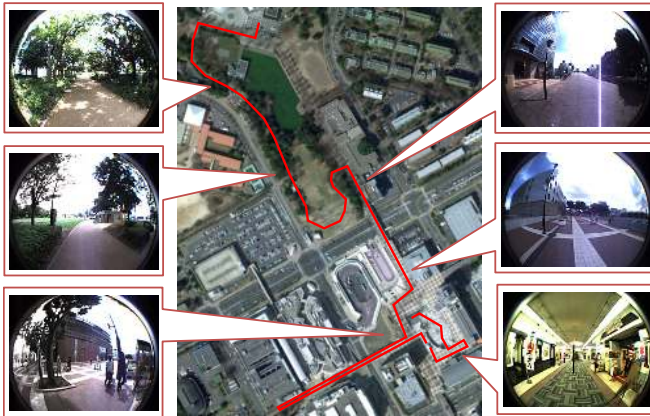


Figure 7. Test environment for dynamic evaluation. (The red solid line indicates the travel route.)



Figure 8. Robot configuration for localization experiment.

B. Results

The number of satellites used for positioning is shown in Fig. 9; Fig. 10 shows the satellite constellation at the times A and B indicated in Fig. 9. Fig. 10 shows that the QZSS has a high elevation angle and therefore we can receive the signal from the QZSS even when the robot is in an urban area. The period shown in Fig. 9 for which GPS signals could not be received corresponds to the time that the mobile robot was in the indoor area. In addition, there were many instances where the number of satellites was decreased because of obstruction by buildings or trees.

We compared the localization results to evaluate the two methods, the normal point positioning and the PPP using LEX messages. The results of the positioning estimations are shown in Fig. 11, including the estimated positions A and B corresponding to the times A and B indicated in Fig. 9. Fig. 12 shows a close-up of positions A and B. In both Figs. 11 and 12, the red lines denote the reference paths computed by the reference dual-frequency GNSS receiver and DR, the blue line indicates the results from the normal single-point positioning, and the green line indicates the results from our proposed method. These figures show that the normal point positioning data was very noisy. In contrast, the position estimation using our proposed method resulted in run trajectories nearly identical to the reference path, indicating that the positioning error was successfully corrected. Furthermore, the proposed method estimated a smooth and continuous trajectory.

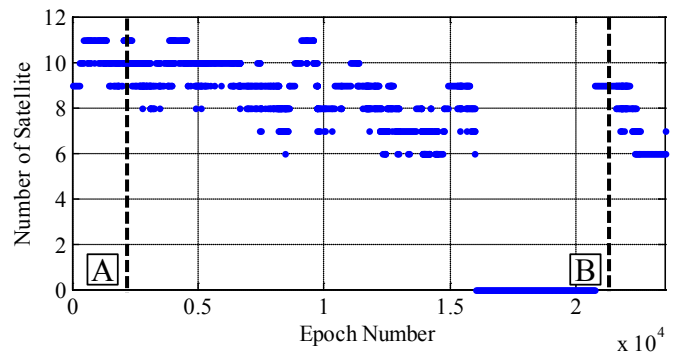


Figure 9. Number of satellites used in the test. The number of satellites is sometimes reduced because of satellite obstruction by buildings or trees.

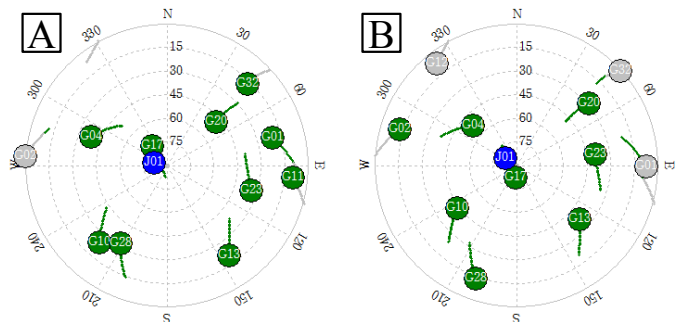


Figure 10. GPS and QZSS satellite constellation during the test.

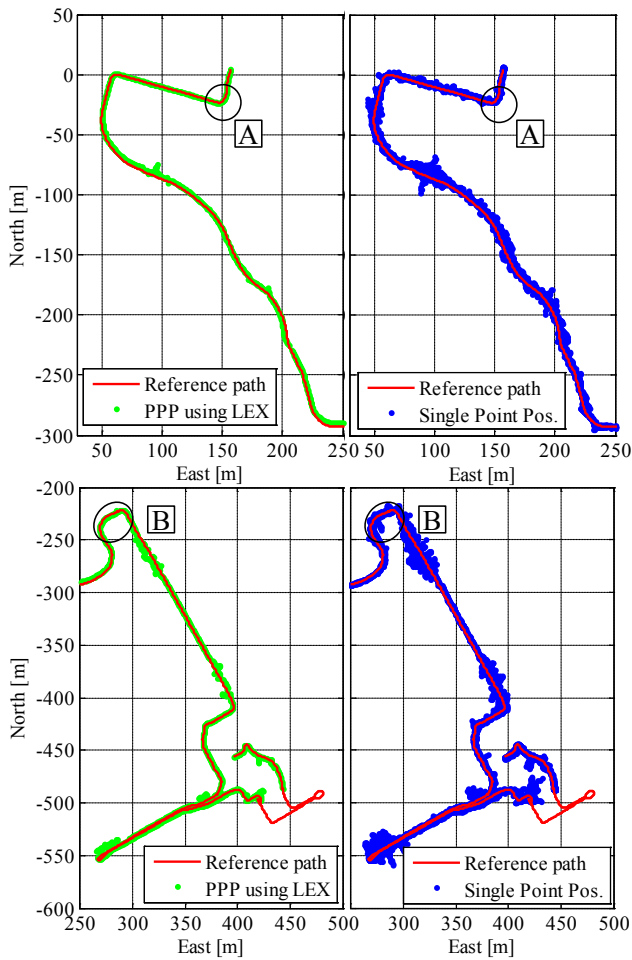


Figure 11. Comparison of positions estimated by each method. The proposed method, indicated by the green dots, is more accurate than the others.

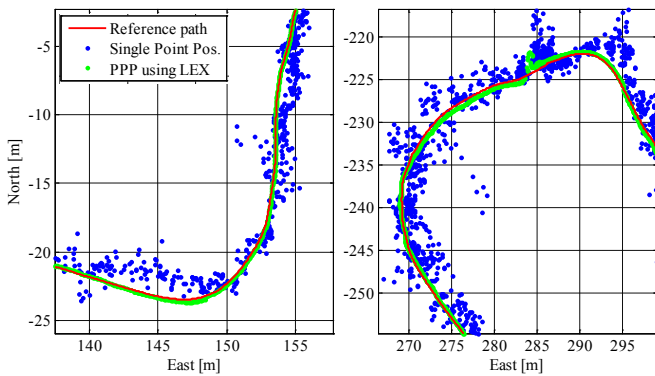


Figure 12. Close-up of position estimated by each method.

After the evaluations above, we evaluated the error in position estimated by our proposed method versus the reference position measurement results with RTK-GNSS/DR navigation. Fig. 13 shows the time-series position distance error with single-point positioning and with our proposed technique, compared to the reference path. Sometimes the error was increased because of the multipath effects, but our proposed method makes a fairly accurate, and in many instances continuous, estimation of position distance error.

Fig. 14 shows histograms of the distance error from single-point positioning and from our proposed method, compared to the reference path. Regarding the precision of the position estimation, the distance root mean square (DRMS) error versus the reference path was 3.05 m and the maximum distance error was 24.96 m for single-point positioning; these errors were 1.29 m and 9.22 m by PPP using LEX messages. These results show that our proposed method effectively estimated the position with high precision. Our experiments demonstrated the feasibility of high-precision position estimation in outdoor environments with a single software GNSS receiver using QZSS LEX messages obtained by the receiver.

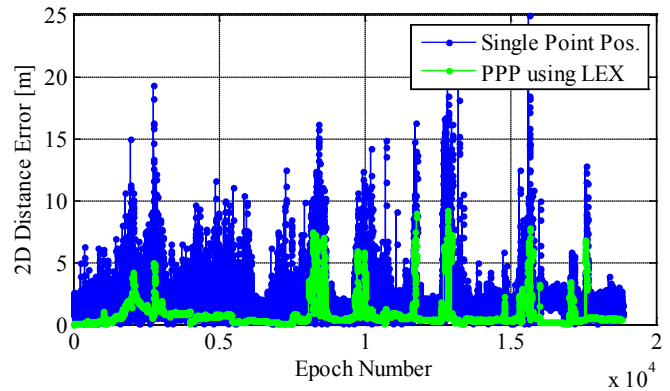


Figure 13. Comparison of distance error for the two methods. The proposed method, indicated by the green dots, is more accurate.

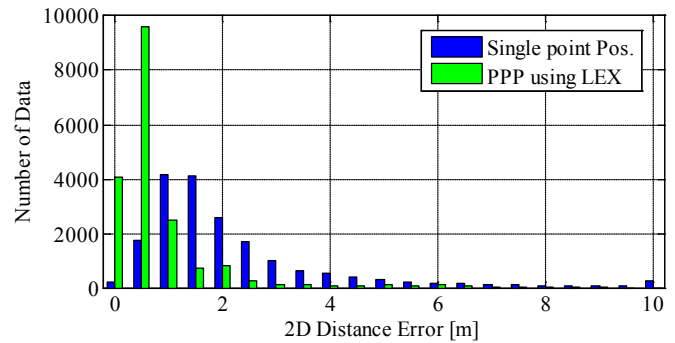


Figure 14. Comparison of errors in distance with respect to reference locations for the two methods.

VI. CONCLUSIONS

In this paper, we proposed a PPP technique using a QZSS LEX message for outdoor localization of mobile robots. PPP can estimate a single receiver position without any reference station, and is therefore expected to be a means of localization of mobile robots. We developed an algorithm for a software GNSS receiver to receive the QZSS LEX message and correct the satellite ephemeris and clock error. We have also proposed a precise point positioning technique using the single GNSS receiver based on the QZSS LEX message. We confirmed the usefulness of this technique through a comparison between tests run in outdoor environments and a reference path

generated by RTK-GNSS/DR navigation. We determined positions with a distance root mean square error of 1.29 m without use of the GNSS reference station when we used PPP with the LEX augmentation information. We also found that the proposed localization technique was useful and effective for position estimation in outdoor environments. A future challenge is to mitigate the multipath effect using the satellite selection technique. We expect that the positioning accuracy can be further improved using the determination of multipath signals by the software GNSS receiver. Furthermore, we will evaluate the proposed localization method in a greater variety of outdoor environments.

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