

Evaluation of Point Positioning Using the Global Positioning System and the Quasi-Zenith Satellite System as Measured from South Korea

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The Quasi-Zenith Satellite System (QZSS), a dedicated regional Japanese satellite system currently under development, was designed to complement the performance of the Global Positioning System (GPS). The high elevation angle of the QZSS satellite is expected to enhance the effectiveness of GPS in urban environments. Thus, the work described in this paper, aimed to investigate the effect of QZSS on GPS performance, by processing the GPS and QZSS measurements recorded at the Bohyunsan reference station in South Korea. We used these data, to evaluate the satellite visibility, carrier-to-noise density (C/No), performance of single point positioning, and Dilution of Precision (DOP). The QZSS satellite is currently available over South Korea for 19 hours at an elevation angle of more than 10 degrees. The results showed that the impact of the QZSS on users' vertical positioning is greatest when the satellite is above 80 degrees of elevation. As for Precise Point Positioning (PPP) performance, the combined GPS/QZSS kinematic PPP was found to improve the positioning accuracy compared to the GPS only kinematic PPP.

Keywords: GPS, QZSS, elevation angle, positions

1. INTRODUCTION

The Global Positioning System (GPS) provides accurate information with respect to time and position, regardless of the time or weather. The United States' GPS is the first global positioning system that was deployed, and this was followed by the GLObal Navigation Satellite System (GLONASS), which was developed by Russia. More recently, BeiDou and the Galileo navigation satellite system, under development by China and the EU, respectively, have been placed in partial service. Apart from these systems, Satellite Based Augmentation Systems (SBASs) were developed with the aim of improving the accuracy and reliability of GPS and are in operation. Typical examples of SBASs are the Wide Area Augmentation System (WAAS), European Geostationary Navigation Overlay Service (EGNOS), and GPS Aided Geo Augmentation Navigation (GAGAN) developed by United States (US), the European Union (EU), and India, respectively.

A regional positioning system known as the Quasi-Zenith Satellite System (QZSS) is under development by the Japan Aerospace Exploration Agency (JAXA). QZSS has two types of satellites: those Highly inclined Elliptical Orbits (HEOs) and those with GEocentric Orbits (GEOs), of which one unit with an HEO is in operation at present. The objectives of QZSS are to improve the availability of the Global Navigation Satellite System (GNSS) in Asia and Oceania and to enhance positioning performance (Choy et al. 2013). Especially, as the QZSS is supposed to remain in the sky over Japan for an extended period of time, it would contribute greatly to maintaining the reliability of positioning in towns and cities.

During the past 10 years, various research effects have attempted to improve user's positioning accuracy, for example by using the various navigation signals of GPS, GLONASS, etc., in combination (Li et al. 2009; Tolman et al. 2010; Choi et al. 2014). In particular, the results that were obtained by processing the data generated by integrating the GPS and BeiDou systems were reported recently (Zhao

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et al. 2013; Li et al. 2014). Research conducted to improve the visibility and availability of satellites has also been performed in parallel as the number of navigation satellites increase (Ji et al. 2013; Lee & Jee 2014).

In the present study, we evaluated the satellite availability, Carrier-to-Noise density (C/No), the performance of single point positioning, and Dilution of Precision (DOP) by combining the data generated by the measurement of GPS and QZSS signals received in the Korean Peninsula. Moreover, the variation in the initial converging time and positioning accuracy were analyzed together due to the integration of GPS and QZSS signals during Precise Point Positioning (PPP).

2. QZSS SATELLITE ORBIT AND MEASUREMENT MODELS

2.1 QZSS Satellite Orbit

The first QZSS satellite named “Michibiki” was launched in September 2010 for users of navigation service in the region of east-Asia and Oceania. This is an HEO satellite and

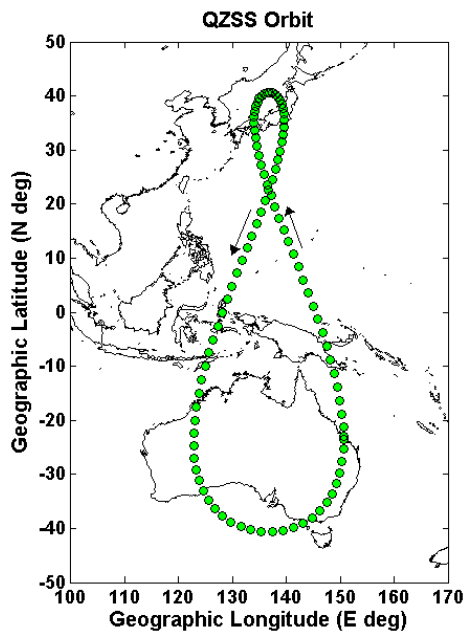


Fig. 1. QZSS ground track.

Table 1. Physical parameters of QZSS satellite orbit

Parameter	Nominal
Semi-major axis	42,164.169 km
Eccentricity	0.075
Inclination	43°
Center longitude	135° E

will be followed by the launch of two more HEO satellites by 2018. Each satellite is placed into a unique orbital plane and the system is designed to follow the ground track shown in Fig. 1, with satellites orbiting at fixed intervals. The orbit aims to ensure that at least one of the QZSS satellites is located in the sky over Japan with the zenith direction. This helps to stabilize point positioning through the GPS in downtown areas noted for a high density of skyscrapers. The ground track shown in Fig. 1 is that of the QZSS satellite based on the almanac received at the Bohyunsan GNSS reference station (BHAO) in Korea.

QZSS satellites are designed to remain in the sky over Japan for a minimum of 8 hours and maintain an elevation angle greater than 75 degrees. The current QZSS satellites have a semi-major axis of 42,164.169 km, an eccentricity of 0.075, the elevation angle of 43°, and a reference longitude of 135° E. Table 1 summarizes the orbital characteristics of QZSS satellites.

2.2 Measurement Models for Single-Frequency Users

QZSS satellites utilize the same frequencies (L1-1,575.42 MHz, L2-1,227.60 MHz) as GPS to provide information to users. In other words, QZSS signals can be processed similarly to GPS signals. In this research, the L1 C/A (Coarse/Acquisition) codes of GPS and QZSS were utilized for combined positioning. Measurement equations using each code are given by Eq. (1) and Eq. (2).

$$P_{GPS L1} = \rho + c\delta t^r - c\delta t^s + Trop + Iono_{GPS} + GD_{GPS} + m_{GPS} \quad (1)$$

$$P_{QZSS L1} = \rho + c\delta t^r - c\delta t^s + Trop + Iono_{QZSS} + GD_{QZSS} + m_{QZSS} \quad (2)$$

where, ρ indicates the geometrical range between a satellite and a receiver, δt^r and δt^s indicate the respective errors of the receiver and the satellite time, $Trop$ is the tropospheric delay error, and $Iono_{GPS}$ and $Iono_{QZSS}$ are ionospheric delay errors for GPS and QZSS, respectively. In addition, GD indicates group delay value, m is multi-path error, and c indicates the speed of light. In this research, the Klobuchar model, which is used for the GPS, is used in order to calculate ionospheric delay errors (Chung et al. 2009; Choi et al. 2013). The ionospheric parameters applied to each model as input variables are listed in Table 2. These parameters can be obtained from the header of navigation files. The equation to calculate the multi-path error is obtained from the specifications provided by JAXA of Japan (JAXA 2012) and is shown below as Eq. (3).

$$m = \sqrt{\left\{0.13 + 0.53 * \exp\left(-\frac{EL}{10deg}\right)\right\}^2 + 0.4^2} \quad (3)$$

where, EL is the elevation angle of a satellite in degree.

In this paper, the weighted least squares method (Tarrío et al. 2011) of Eq. (4) is used to estimate the location and clock errors of a receiver.

$$\vec{X} = (H^TWH)^{-1}H^TW\vec{v} \quad (4)$$

where, H represents the design matrix (33×33), W indicates the weighted matrix (33×33) based on the elevation angle of a satellite, and \vec{v} is the pseudo-range residual vector (33×1). World Geodetic System 84 is used as a reference coordinate system assuming the GPS and QZSS have the same coordinate system. The state vector calculated by using Eq. (4) is $\vec{X} = [x, y, z, \Delta t]$, where x, y, z are the coordinates of the user position, and Δt indicates the receiver clock error.

3. RESULTS

3.1 Satellite Visibility and C/No

Fig. 2 shows the variation in the GPS and QZSS satellite visibility observed at the BHAO GNSS reference station which is operated by Korea Astronomy and Space Science Institute (KASI). The observation was made on September 14, 2014. At the BHAO reference station, the number of GPS satellites for which signals were received ranged from a minimum of 6 units to a maximum of 12 units on a single day, whereas the QZSS satellite reception was from one unit. In Fig. 2, the QZSS satellite signal reception was maintained from 0 hours to 19 hours Universal Time (UT), but the connection was lost for 4 hours from 19 hours to 23 hours. During these 4 hours, it was found that the elevation angle was less than 10 degrees.

Fig. 3 shows the variation in C/No of the QZSS satellite, which was measured through an antenna (TRM59800.00) and a Trimble GNSS receiver (Trimble NetR9) installed at the BHAO reference station. The C/No provides a quantitative indication of the signal-to-noise ratio. The value of C/No is a function of the transmission power of a satellite, atmospheric attenuation, receiver antenna gain, trace loop design, multi-path error, etc. (Bilich & Larson 2007). Fig. 3 displays the L1 and L2 C/No, and the elevation angle of the QZSS satellite.

Table 2. Ionospheric parameters for GPS and QZSS satellites

Satellite	Ionospheric parameters				
GPS	Iono Alpha	1.883e-8	2.235e-8	-1.192e-7	-1.192e-7
	Iono Beta	1.208e+5	3.277e+4	-1.966e+5	1.966e+5
QZSS	QZSA	4.843e-8	-3.576e-7	1.788e-7	2.503e-6
	QZSB	9.421e+6	1.475e+7	2.097e+8	-8.389e+8

The L1 C/No was about 40 dB·Hz at 0 hours in UT when the observation started and increased as the elevation angle of the satellite increased. The C/No value continued to increase up to 51 dB·Hz at 7 hours UT when the elevation angle of the satellite reached its maximum. Subsequently, the elevation angle decreased gradually but remained over 70 degrees for the time period from 7 hours until 13 hours UT. However, after 13 hours UT, a rapid decrease was observed. In contrast, the L2 C/No value showed little change until 13 hours UT, but experienced a rapid decrease after 15 hours UT. This confirmed that there is little variation in C/No when the elevation angle is greater than 70 degrees.

The variation in L2 C/No could also be correlated with the change in the elevation angle of a satellite with

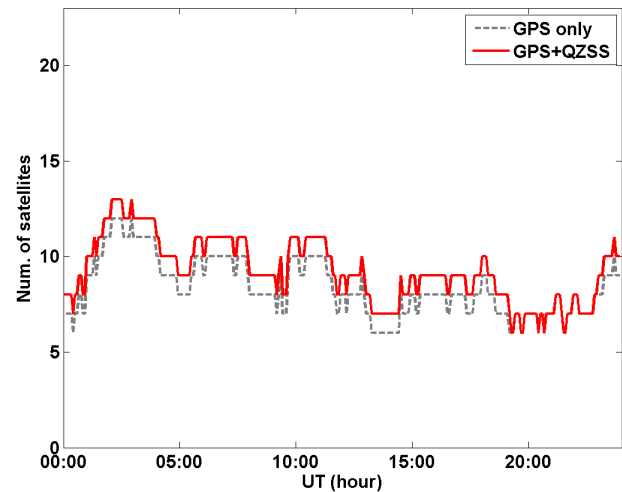


Fig. 2. Satellite visibility at BHAO reference station in South Korea for 24 hours. The dotted grey and solid red lines indicate the number of GPS and the total sum of GPS and QZSS satellites, respectively.

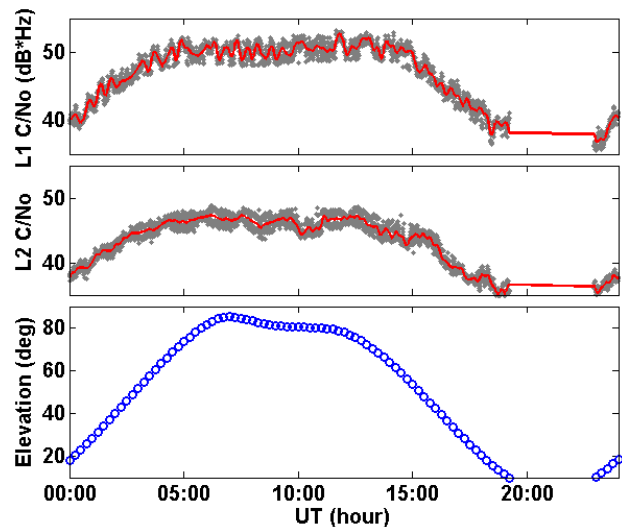


Fig. 3. C/No variations of QZSS L1 and L2 signals due to satellite elevation angle. In the upper and middle panels, the solid redlines indicate the results of applying band-pass filters.

a similar L1 C/No. The L2 C/No was lower than the L1 C/No by about 4 dB-Hz on average. The L2 C/No reached its maximum at 7 hours UT when the elevation angle was at its largest. It experienced a rapid decrease after 13 hours UT in conjunction with the elevation angle. In other words, the variation in L2 C/No observed at the BHAO reference station was more closely related to the change in the elevation angle than the L1 C/No value.

3.2 Single Point Positioning (SPP) Results and DOP Variations

The characteristics of combined positioning based on the GPS and the QZSS were analyzed, by processing the data observed at the BHAO reference station. Fig. 4 shows a time series representation of the positioning errors of GPS only and of combined GPS/QZSS. As shown in Fig. 4, there is no significant difference between the positioning errors of GPS only and combined GPS/QZSS from the direction of the east, the north, and upwards. However, it is noticeable that when the elevation angle was greater than 80 degrees (rectangle A in the figure), the deviation in the positioning errors of the vertical (Up) direction was significant.

Fig. 5 shows the direction components of positioning differences for GPS only and combined GPS/QZSS in terms of absolute value. The maximum difference in the east-west direction was 1.2 m, whereas the difference was less than 0.5 m after 1 hour UT. The positioning difference of the north-south direction was slightly greater than that of the east-west direction and about 1 m of positioning difference was observed at 7 hours UT (16 hours KST) when the elevation angle was the largest (85.26 degrees). As described above in Fig. 4, there was a significant positioning difference in the vertical direction between GPS only and combined GPS/QZSS when the elevation angle of the QZSS satellite was greater than 80 degrees. In addition, in Fig. 5, the difference in the vertical direction is also clearly visible. A maximum difference of 3.1 m was observed when the elevation angle of the QZSS satellite was the largest, and there was a difference greater than 3.0 m at UT 8 hours when the elevation angle was greater than 80 degrees.

According to the data processing results, when the elevation angle of the QZSS satellite is greater than 80 degrees, it has a significant impact on the altitude component of positioning. In addition, the Root-Mean-Square (RMS) values of data processed in Fig. 5 were found to be 0.28 m, 0.41 m, and 0.88 m for the directions east-west, north-south, and vertical, respectively. From above results, the QZSS satellite had a greater impact on the positioning difference in the vertical direction.

In summary, at elevation angles greater than 80 degrees,

the QZSS satellite positioning difference was relatively larger for all directions and especially, the difference was greater than 3 m in the vertical direction. Because the arrangement of navigation satellites impacts positioning, the DOP was generated as a function of observation time, where the DOP measures evenness in the satellite arrangement. Fig. 6 shows the time series of DOPs.

In this research, three kinds of DOPs were generated and the effect of the addition of a QZSS satellite was analyzed for Geometric DOP (GDOP), Position DOP (PDOP), and Vertical DOP (VDOP). In Fig. 6, the average value of GDOP

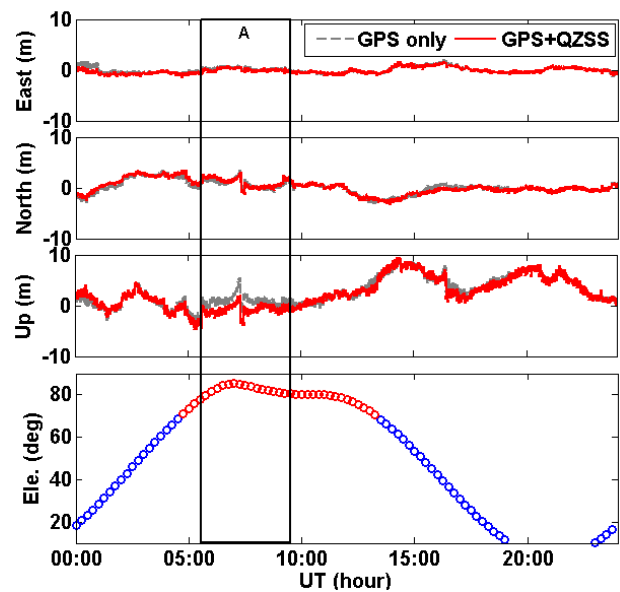


Fig. 4. SPP errors for the GPS only case and combined GPS/QZSS case. The bottom panel indicates the satellite elevation variations, with the red circles indicating an elevation angle greater than 70 degrees. The rectangle 'A' indicates the time when the satellite is above 80 degrees of elevation. The dotted grey and solid red lines indicate the positioning errors of GPS only and GPS/QZSS combined, respectively.

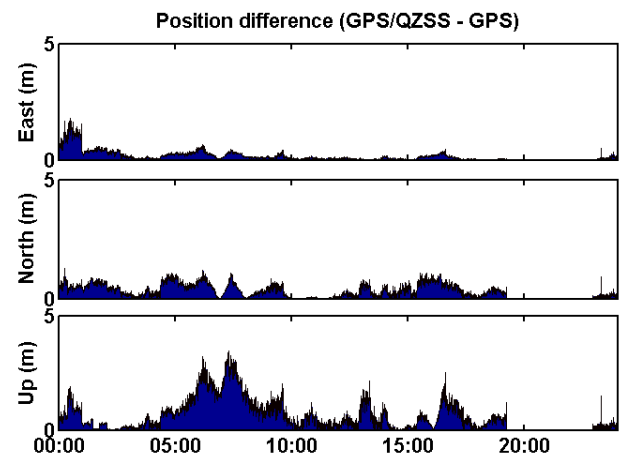


Fig. 5. Differences between the positions of the GPS only case and combined GPS/QZSS.

for the day was 2.29 considering the arrangement of GPS satellites only, whereas the value was reduced to 2.14 when the QZSS satellite was additionally taken into account. This indicates that the geometric arrangement was improved by the additional satellite. Similarly, the average value of PDOP was also reduced to 1.87 from 2.01 to improve the positioning accuracy. The average value of VDOP which is related to positioning in the vertical direction, decreased from 1.69 to 1.56, also indicating an enhancement in the positioning accuracy. Overall, the vertical direction was most affected by the elevation angle of the QZSS satellite.

The largest difference was observed after UT 13 hours when the number of satellites observed was the smallest, which is consistent with Fig. 2. In other words, the smaller the number of satellites observed, the greater the impact of the additional QZSS satellite. The interval showing no difference (0) corresponds to the time period in which the QZSS satellite was not observed (UT 19 hour - 23 hour). In conclusion, the DOP values were reduced by adding the single QZSS satellite to the GPS satellites and this was found to have an impact on the positioning accuracy.

3.3 Precise Point Positioning Results

As JAXA provides a web service with information of the precise orbit history with the precise time (<http://qz-vision.jaxa.jp/USE/archives/>), PPP data processing is enabled with GPS satellites. High-precision point positioning requires the acquisition of a precise orbit products with precise timing for satellites (Won & Park 2009). Hence, the positioning accuracy is closely related to these data. The impact of the QZSS satellite on point positioning calculated by GPS kinematic PPP was analyzed additionally. The measurement model and data processing filter used in kinematic PPP were the same as those suggested by Choi et al. (2014). Fig. 7 shows the time series of the positioning difference using kinematic PPP for GPS satellites only as well as for the combined GPS/QZSS satellites. Overall, it was found that the initial converging speed was faster for PPP of the combined GPS/QZSS than for GPS satellites only. Similarly, Choi et al. (2014) reported that the PPP of combined GPS/GLONASS satellites showed faster initial convergence than the PPP of GPS only. Moreover, it was reported that the RMS value for the positioning difference was reduced owing to the PPP of combined GPS/GLONASS. The RMS values of the positioning difference generated by GPS kinematic PPP were 5.1 cm, 1.7 cm, and 4.7 cm in the directions east-west, north-south, and up-down, respectively, for a 95% confidence interval. On the other hand, those of the combined GPS/QZSS kinematic PPP were found to be 4.6 cm, 1.7 cm, and

3.8 cm in the directions east-west, north-south, and up-down, respectively. The RMS values in the east-west and vertical directions were reduced but there was no change in the north-south direction. Consequently, by combining the GPS and the QZSS satellites, it was possible to accelerate the initial convergence and improve the positioning accuracy.

4. SUMMARY AND CONCLUSIONS

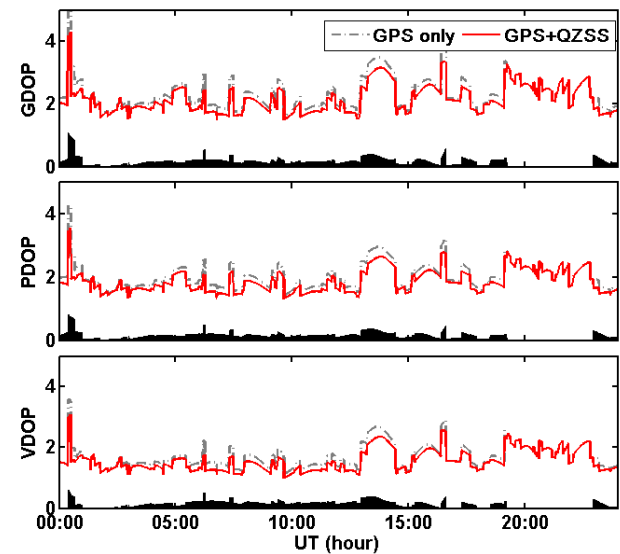


Fig. 6. DOP time series for the GPS only case (gray dotted line) and combined GPS/QZSS case (solid red line). The dark area indicates the DOP difference between both of them. The solid black area shows the difference between the DOP with GPS satellites only and the DOP with the additional single QZSS satellite.

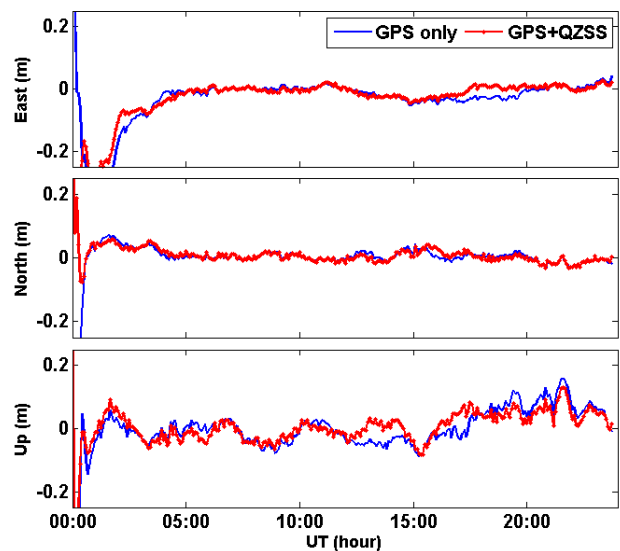


Fig. 7. Kinematic PPP solution (East, North and Up components) errors for the GPS kinematic PPP (blue line) and GPS/QZSS kinematic PPP (dotted red line).

In this study, the satellite availability, C/No, positioning difference, and DOP variation were analyzed by combining the GPS and QZSS data measured at the BHAO GNSS reference station in Korea. The effect of the presence of the additional QZSS satellite was investigated. Observations were made for a period of about 20 hours when the elevation angle of the QZSS satellite was greater than 10 degrees and the time during which with the elevation angle exceeded 70 degrees was about 9 hours. The L1 C/No value of the QZSS satellite varied in the range 40-41 dB-Hz and L2 signal was found to be lower than the L1 signal by 4 dB-Hz.

An analysis of the positioning results for GPS only and combined GPS/QZSS showed that when the elevation angle of the QZSS satellite was greater than 80 degrees, the positioning difference was relatively larger in all directions and especially, the difference was found to be 3.1 m in the vertical direction. This result indicates that QZSS satellites have a greater impact on the vertical direction than on the east-west and the north-south directions.

The effect of the additional QZSS satellite on the DOP variation was that the GDOP, PDOP, and VDOP values were all reduced. This indicates that the geometric distribution of satellites could be improved by deploying QZSS satellites in addition to the conventional GPS satellites to improve the point positioning. Furthermore it was found that the smaller the number of satellites observed at any given time, the greater impact of the additional QZSS satellite would have.

In addition, the impact of the additional QZSS satellite on high-precision point positioning was analyzed by performing kinematic PPP data processing. This enabled us to compare the positioning difference and initial convergence speed for GPS and combined GPS/QZSS kinematic PPP. Consequently, by using GPS and QZSS satellites in combination, it was possible to accelerate the initial convergence and improve the positioning accuracy.

This paper presented the results of analysis of the signal reception and positioning using QZSS data observed in the Korean Peninsula. The results confirmed that the combined deployment of GPS and QZSS satellites enhances the satellite availability and the point positioning accuracy.

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