Effect of Quasi Zenith Satellite (QZS) on GPS Positioning

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Abstract: QZS was designed to supplement the performance of GPS civil use by Japan. It has the compatible signals of L1C, L2C and L5 to the future GPS, L1-SAIF and experimental LEX other than the legacy L1 signal. It will be launched in the summer of 2010. QZS will have a semi-major axis of 42,164 km, eccentricity of 0.075 ± 0.015 and inclination to Equator 43° ± 4°. The central longitude of the earth track is 135°E. In the present paper, positioning accuracy is evaluated by the simulation which uses a software simulator. To investigate the effect of QZSS on GPS positioning, we generate the simulated GPS and QZS observation data at some sites in Asian region. To simulate the sky view in urban area, the FOV model is included in the data generation process. By using these data, we evaluate satellite visibility, PDOP and the performance of single point positioning and RTK. As to the satellite visibility and PDOP, the solution availability is less than 90 % without QZSS. Large PDOP is also expected with only GPS in mid-latitude area. Meanwhile, additional QZSS satellites clearly improve the solution availability and PDOP. For both of single point positioning and RTK performance, solution accuracy is much improved in the GPS and QZSS case comparing to the GPS only case. More than 90 % of fixing ratio is also expected for RTK with QZSS satellites and triple frequency ranging signals. These simulation results clearly show the effect of the QZS to improve the GPS positioning performance especially in sever environment like at urban canyon.

Keywords: QZSS, GPS, Single Point Positioning, RTK, Simulation, Satellite Orbit

1. Introduction

The QZSS (Quasi-Zenith Satellite System) project was discussed in the special committee established in CSTP (Council for Science and Technology Policy) in Japan during 2003-2004. The position paper entitled “How best to ensure the space based PNT system in Japan” was published on January 2004. It set a long term goal to establish a regional space based PNT system which has close interoperability with GPS but independently works. The QZSS project is ongoing followed by this report. Its first satellite will be launched in the summer of 2010 to be used for verification experiments soon thereafter. Integrated use of GPS and QZSS is expected to significantly improve the performance of satellite navigation in Japan and neighbouring parts of Asia, especially in urban canyons and mountainous areas, as QZSS satellites will be seen at very high elevation angles in those regions. The continuity of the QZSS project will be assured by a positive outcome of the test period following the launch of the first satellite.

In the present paper, the authors evaluate the positioning accuracy by the simulation which uses a software simulator, in order to investigate the effect of QZSS on GPS positioning. The scenario of the simulation is comprised of two virtual systems after the successful verification experiment. One is two additional QZSs by 2013 according to an optimistic view. It is assumed that three QZSs which trace almost the same ground track of asymmetric figure eight shape are flying to the quasi zenith of Japanese islands every eight hours one after another to supplement the present GPS constellation. The other is additional four geostationary satellites to establish an independent regional positioning system in company with three QZSs in the further future. This constellation is named 7 QZSs in this paper.

We generate the simulated GPS and QZSS observation data at some sites in Asian region; Tokyo, Seoul, Beijing, Shanghai and Bangkok. FOV (Field of View) model, defined later, is included in the data generation process to simulate the limited sky view in urban area.

The availability ratio and PDOP are calculated as evaluation parameters for GPS only positioning, and additional 3 QZSs and 7 QZSs cases to show the QZSS effect on GPS. Three dimensional RMS errors both single positioning and RTK positioning and the fixing ratio of RTK positioning are also calculated.

In the next section, we describe the QZSS constellation and error models for GPS/QZSS single positioning simulation and the RTK positioning which uses three carriers of L1, L2 and L5. In Section 3, the simulation results are given which demonstrate the remarkable effect of QZSS in the FOV mask model of urban canyon.

2. Simulation and Evaluation

2.1 QZSS Satellite Constellation

To evaluate the QZSS effect on GPS positioning, we generate GPS and QZSS satellite orbit and make simulated observation data of GPS and QZSS satellite signal at some ground sites. For the QZSS, we simulate two constellation cases with 3 satellites and with 7 satellites. As the current plan, the space segment of QZSS consists of 3 IGSO (Inclined Geosynchronous Satellite Orbit) satellites with slight eccentricity in the system verification phase. These orbits were designed to keep at least one satellite available at the elevation angle of more than 60 degrees in Japan [1]. In addition to the formal satellite constellation, we also place more 4 GEO (Geostationary Orbit) satellites separated by 38˚ at 135˚E as the center longitude to improve the satellite geometry. Table 1 summarizes the characteristics of QZSS satellite orbits in this study. Figure 1 shows the ground tracks of these satellites in the case of 3 IGSO and 3 IGSO+4 GEO.

Table 1. Characteristics of QZSS Satellite Orbits

Satellite	Orbit	Orbit Element			
		Semi-Major Axis	Eccentricity	Inclination	Center Longitude
QZS-1	IGSO	42164 km	0.075	43.0˚	130.0˚E
QZS-2	IGSO	42164 km	0.075	43.0˚	135.0˚E
QZS-3	IGSO	42164 km	0.075	43.0˚	140.0˚E
QZS-4	GEO	42164 km	0.0	0.0˚	78.0˚E
QZS-5	GEO	42164 km	0.0	0.0˚	116.0˚E
QZS-6	GEO	42164 km	0.0	0.0˚	154.0˚E
QZS-7	GEO	42164 km	0.0	0.0˚	168.0˚W

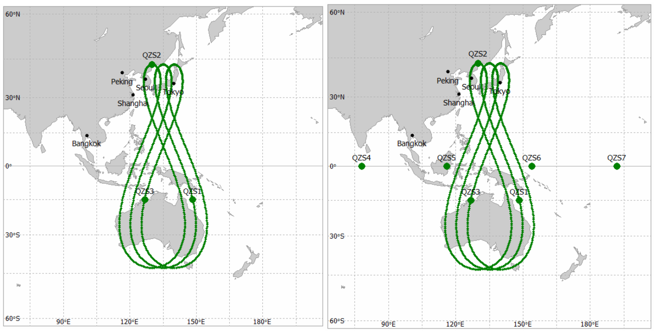

Figure 1. Ground Tracks of QZSS Satellites
(Left: 3 IGSO, Right: 3 IGSO+4 GEO)

2.2 Generation of Simulated Observation Data

Figure 2 shows the generation flow of the simulated observation data of the ground receiver. For the GPS satellite orbit and clock parameter, we use broadcast ephemerides on April 1st 2009. At that time, total 30 GPS satellites were available with healthy status. As to QZSS satellites, we create and edit the simulated ephemeris as a RINEX navigation data file according to the orbit constellation shown in Table 1. By adding orbit error for GPS and QZSS satellites, we obtain the satellite positions in the ECEF frame and the clock biases.

The ground GPS/QZSS receivers are assumed to be placed at some sites in Asian area as shown in Table 2. To simulate the urban canyon environment, where there are some tall buildings around the receiver, we introduce a FOV (Field of View) mask model as shown on the skyplot in Figure 2. The gray region in the skyplot indicates the buildings which obstruct the satellite visibility. The observation data of the satellite in the FOV mask are excluded from the generated simulation data.

Table 2. Ground GPS/QZSS Receiver Positions

Site	Position	
	Latitude	Longitude
Tokyo	35.68017˚N	139.76635˚E
Seoul	37.53369˚N	127.07062˚E
Beijing	39.90552˚N	116.40014˚E
Shanghai	31.20341˚N	121.48682˚E
Bangkok	13.72071˚N	100.50293˚E

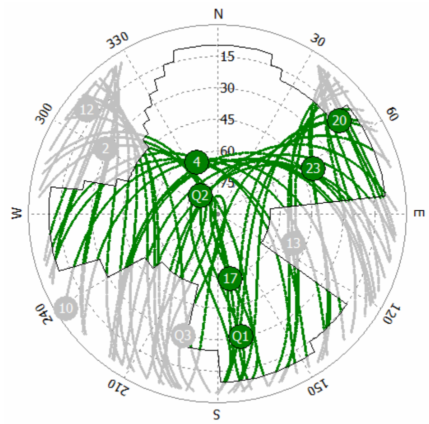

Figure 2. FOV Mask to Simulate Urban Canyon Environment. The circles on the skyplot indicate GPS and QZSS satellite positions and the lines are these paths for 24 hours at Tokyo.

With the satellite and receiver positions, the geometric range between them is obtained considering the signal propagation delay by iterative computation. By adding terms of the satellite clock bias, receiver clock bias, tropospheric delay, ionospheric delay, multipath effect and receiver tracking noise, we can generate simulated pseudorange observables. Carrier phase observation data are obtained with an additional carrier-phase bias term as well. These pseudorange and carrier-phase observables are saved as the standard RINEX observation data

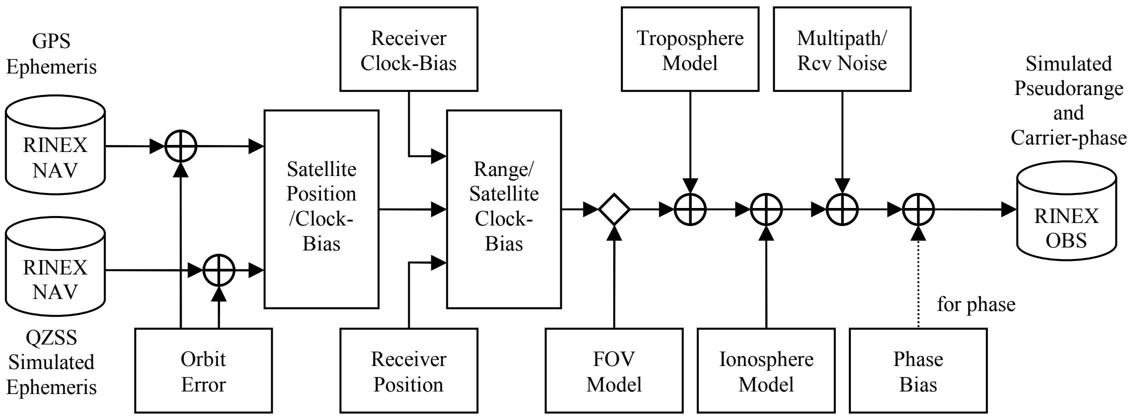

Figure 2. Generation flow of simulated observation data of GPS and QZSS

file for each receiver. To evaluate the performance of RTK (Real-Time Kinematic) positioning with multi-frequency signals, L2 and L5 code and phase observables in addition to L1 are included in the simulated observation data. For GPS, we assume that only 3 Block IIF satellites transmit L5 ranging signals. The number of the satellites is expected at the end of 2010. These observation data are generated every 10 seconds for the simulation period of 24 hours. Table 3 summarizes these simulation models used in this study.

Table 3. Error Models for GPS/QZSS Signal Simulation

Model	Description
Satellite Orbit Error	Fixed X/Y/Z Offsets for Each Satellites (Std: 0.8 m)
Receiver Clock Bias	Random Walk Model
Troposphere Delay	Standard Atmosphere and Saastamoinen Model + Random Error
Ionosphere Delay	Broadcast Ionosphere Model (Klobuchar Model) + Random Error
Multipath + Receiver Noise Model	Colored Noise Std: 20 cm+20 cm /sin(El) (Code) Std: 2 mm+2mm/sin(El) (Phase)

2.3 Evaluation of Positioning Performance

To investigate how QZSS affects the performance of GPS positioning, we evaluate two different techniques. One of these techniques is the standard single point positioning with only L1 C/A code, in which any external correction information is not applied. The other is RTK with multi-frequency carrier-phase observables of L1, L2 and L5 signals. To evaluate the RTK performance, we additionally generate the observation data for the base station, which is separated by 10 km from the rover GPS/QZSS receiver. This case simulate typical short-baseline carrier-based relative positioning environment. In the RTK case, the FOV model is applied only to the rover side receiver. The base station antenna is assumed to be placed with good sky view.

In company with the generated RINEX observation data described above, the real broadcast ephemeris for GPS and the simulated ephemeris for QZSS are used to the post processing analysis software. For the analysis, we utilize RTKLIB developed by the authors [2], which is an open source program package for RTK-GPS containing many useful APs (Application programs), which supports both of real-time positioning and post processing mode. RTKLIB can be freely available under GPLv3 license [3]. The newest version 2.3.0b of RTKLIB provides the extensions for QZSS data handling as well as GPS, GLONASS and Galileo satellites. In this study, the post processing function of RTKLIB is used to obtain the solutions for single point positioning mode and RTK mode. RTKLIB supports a standard least square estimation strategy for single point positioning. RTKLIB also implements the relative positioning algorithm based on Kalman filter with double-differencing technique. RTKLIB employs popular LAMBDA [4] strategy and its extension MLAMBDA [5] for integer ambiguity resolution. Table 4 shows the settings of RTKPOST, which is one of post processing AP in RTKLIB, for single point positioning mode. Table 5 also shows the positioning options for RTK mode. These options are for post processing but the same as for real-time mode. The elevation mask of the settings is applied as well as the FOV mask described above.

Table 4. RTKPOST Settings for Single Point Positioning Mode

Setting	Value
Positioning Mode	Single
Elevation Mask Angle	15 degree
SNR Mask	0 dBHz

Table 5. RTKPOST Settings for RTK Mode

Setting	Value
Positioning Mode	Kinematic
Frequencies	L1+L2+L5
Elevation Mask	15 degree
SNR Mask	0 dBHz
Ionosphere Estimation	OFF
Troposphere Estimation	OFF
Integer Ambiguity Resolution	Continuous
Validation Threshold to Fix Ambiguity	3.0

After completing the analysis with RTKPOST, we compare the results to the ground receivers positions in Table 2, which is used to generate simulated GPS and QZSS observation data, to evaluate the positioning performance in both for the single point positioning mode and for the RTK mode.

3. Results and Considerations

3.1 Satellite Visibility and PDOP

Figure 3 shows the satellite visibility at Tokyo for FOV mask model in GPS+7 QZSs case. In the figure, just a number indicates the GPS PRN number. The Q1, Q2, ... also means QZS-1, QZS-2,... satellite, respectively. The green lines in the figure indicate the epochs with the visible satellite from the receiver. Some GEO QZSS satellites are not visible due to the obstacles around the receiver in this case.

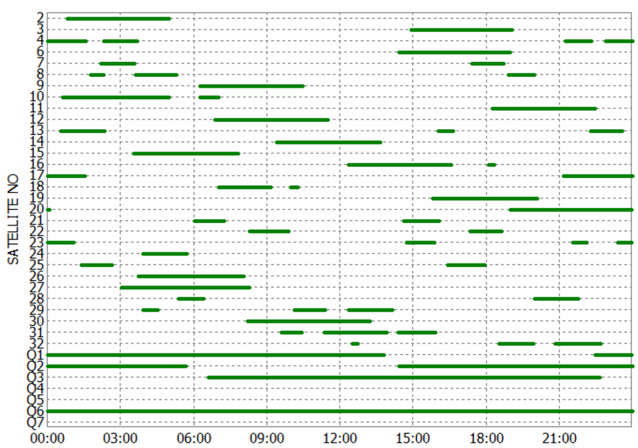

Figure 3. Satellite visibilities at Tokyo for FOV mask model in the case of GPS+7 QZSs

Figure 4 shows the PDOP (Position Dilution of Precision) for 24 hours at Tokyo in the case of GPS only, GPS+3 QZSs or GPS+7

QZSs. The epoch with 0 value in the PDOP chart represents that the number of visible satellites is less than 4, where the positioning solution is not available in a usual manner.

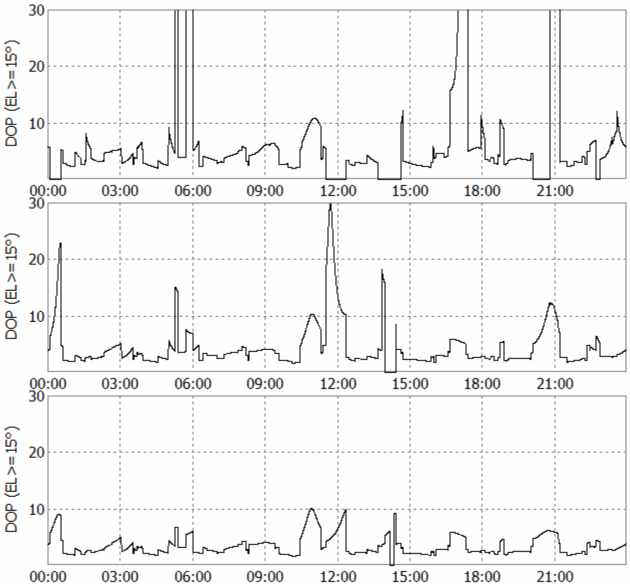

Figure 4. PDOP at Tokyo
(Upper: GPS Only, Middle: GPS+3 QZSs, Lower: GPS+7 QZSs)

For all sites of the simulation, the ratio of epochs with proper solutions and the average PDOP are summarized in Table 6. In this table, only the epochs with PDOP less than 30 are accounted for. In the case of GPS only, the availability of positioning solutions is not more than 90% and the average PDOP also remains large values. It seems hard to obtain good solutions at the downtown streets surrounded by high-rise buildings with only GPS. We often cannot obtain the solution due to the lack of visible satellites. Apparently additional QZSS satellites improve the availability and PDOP even in such situation.

Table 6. Ratio of Epochs with Solutions and Average PDOP (PDOP ≤ 30)

Site	GPS Only		GPS+3 QZSs		GPS+7 QZSs	
	Ratio	PDOP	Ratio	PDOP	Ratio	PDOP
Tokyo	82.2%	4.6	98.1%	4.4	99.2%	3.5
Seoul	75.7%	4.9	98.5%	4.2	100%	3.3
Beijing	83.5%	5.5	96.6%	4.2	100%	2.9
Shanghai	78.6%	5.2	95.3%	4.1	100%	2.3
Bangkok	90.3%	4.5	98.8%	3.2	100%	2.5

3.2 Single Point Positioning Performance

As to the single point positioning with simulated GPS and QZSS satellite observation data, Figure 5 shows the distribution of the horizontal errors at Tokyo in the three cases of GPS only, GPS+3 QZSs and GPS+7 QZSs for FOV mask model. The PDOP degradation especially affects the north-south direction accuracy of the solutions in the case of GPS only. In contrast with these result, we can obtain more precise solutions with QZSS. In the 7 satellites case of QZSS, the solution shows just a slight improvement comparing to the 3 satellites case. It shows that GEO satellites are not so effective to improve the positioning performance at urban canyon because of the low elevation angle in the mid-latitude region.

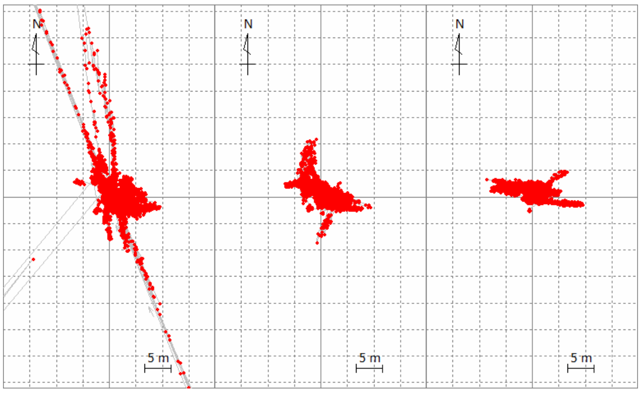

Figure 5. Horizontal Errors of Single Point Solutions at Tokyo for FOV mask model
(Left: GPS Only, Middle: GPS+3 QZSs, Right: GPS+7 QZSs)

Table 7 summarizes the RMS errors of single point solutions at all the sites of the simulation. According to the results, we can obtain reasonable performance with only GPS satellites at the sites near the equator. At higher latitude area, however, additional QZS satellites to GPS are efficiently improve the accuracy for single point positioning mode.

Table 7. RMS Errors of Single Point Solutions
(E: East-West, N: North-South, U: Up-Down Component) (m)

Site	GPS Only			GPS+3 QZSs			GPS+7 QZSs		
	E	N	U	E	N	U	E	N	U
Tokyo	6.2	8.1	15.2	2.0	1.5	4.3	2.1	1.3	3.7
Seoul	5.0	5.4	17.5	1.8	1.4	4.1	1.8	1.4	4.1
Beijing	5.7	5.4	11.1	1.3	1.3	3.1	1.4	2.0	3.6
Shanghai	3.5	3.2	8.3	2.8	2.4	6.0	1.1	1.4	2.8
Bangkok	1.8	2.0	6.8	1.2	1.8	3.6	1.2	0.7	5.0

3.3 RTK Positioning Performance

With the simulated observation data at the rover and base station for carrier-based relative positioning, the RTK positioning performance is evaluated. The baseline length between the rover and the base station is 10 km for all sites, which is selected as the typical RTK positioning condition. The standard RTK accuracy is sometimes stated as 1 cm + 1 ppm × (baseline length) as the horizontal RMS error. According to that, we expect the accuracy of 2 cm at the baseline of 10 km length. Additionally, in this study, all of the multi-frequency observables are used to compute the RTK solution. For QZSS satellites, L1, L2 and L5 triple frequency carrier signals are available for RTK positioning. Generally speaking, the usage of more frequencies improves the performance of integer ambiguity resolution.

Figure 6 shows the result of the RTK positioning simulation as the horizontal errors at Tokyo in 3 cases of GPS only, GPS+3 QZSs and GPS+7 QZSs. The green point indicates the fixed solution and the orange is the float solution. It means that the estimated float solution is obtained but the validation is failed for integer ambiguity resolution.

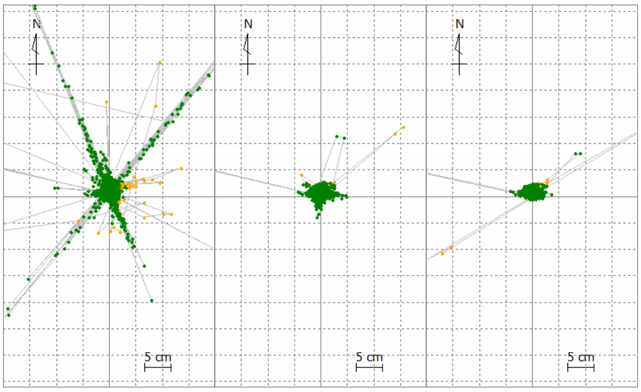

Figure 6. Horizontal Errors of RTK Solutions at Tokyo for FOV mask model
(Left: GPS Only, Middle: GPS+3 QZSs, Right: GPS+7 QZSs)

Table 8 shows the fixing ratio and RMS errors of the fixed solutions at all the sites of the simulation. The fixing ratio is defined as the ratio of the number of the fixed solutions obtained to the number of all the observation epochs. As shown in Table 4 , in the RTK positioning, additional QZS satellites in company with GPS improve both of the fixing ratio and the accuracy of the fixed solutions even in restricted sky view of satellites in urban area. With QZS satellites, we can obtain more than 90 % fixing ratio and less than 2 cm as the horizontal RMS error except for the case at Bangkok as the simulation. The difference between 3 QZSs and 7 QZSs cases is not so large similar to the single point positioning cases.

Table 8. Fixing Ratio and RMS Errors of Fixed Solutions
(E: East-West, N: North-South, U: Up-Down) (cm)

Site	GPS Only			GPS+3 QZSs			GPS+7 QZSs		
	Fixing Ratio			Fixing Ratio			Fixing Ratio		
	E	N	U	E	N	U	E	N	U
Tokyo	84.2%			97.5%			98.5%		
	1.6	3.0	3.1	0.6	1.2	1.5	0.6	1.2	1.2
Seoul	76.0%			98.6%			99.1%		
	0.9	2.0	3.3	0.6	1.4	1.7	0.5	1.4	1.0
Beijing	86.4%			95.6%			98.8%		
	1.2	2.0	2.9	0.4	1.6	1.2	0.3	1.5	1.0
Shanghai	76.7%			98.5%			98.2%		
	0.9	1.9	2.3	0.5	1.5	1.0	0.2	1.4	0.7
Bangkok	83.5%			95.6%			96.4%		
	0.8	2.7	2.1	0.4	2.6	1.8	0.2	2.5	1.3

4. Conclusions

To investigate the effect of QZSS on GPS positioning, we generate the simulated GPS and QZS observation data at some sites in Asian region. To simulate the sky view in urban area, the FOV model is included in the data generation process. By using these data, we evaluate satellite visibility, PDOP and the performance of single point positioning and RTK.

As to the satellite visibility and PDOP, the solution availability is less than 90 % without QZSS. Large PDOP is also expected with only GPS in mid-latitude area. Meanwhile, additional QZSS satellites clearly improve the solution availability and PDOP. For both of single point positioning and RTK performance, solution accuracy is much improved in the GPS and QZSS case comparing to the GPS only case. More than 90 % of fixing ratio is also expected for RTK with QZSS satellites and triple frequency ranging signals.

These simulation results clearly show the effect of the QZS to improve the GPS positioning performance especially in sever environment like at urban canyon.

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