Assessment of the Contribution of QZSS Combined GPS/BeiDou Positioning in Asia-Pacific Areas

Yize Zhang, Nobuaki Kubo, Junping Chen, Hu Wang and Jiexian Wang

Abstract Three QZSS satellites are launched in 2017, which implies that a four satellites regional system is to be established in 2018. There is no doubt that QZSS will play a more important role in the future global GNSS constellations. So it is quite necessary to investigate the importance of current QZSS constellation in positioning. In this paper, the number of visible satellite and PDOP (Position Dilution of Precision) value improvement by combining QZSS with the existing GPS and BeiDou system is analyzed among Asia-Pacific areas. 9 IGS stations are selected to evaluate the performance of SPP (Single Point Positioning) and PPP (Precise Point Positioning) using GPS, BeiDou and GPS + QZSS, BeiDou + QZSS system. Analysis results show that QZSS improves SPP performance for both GPS and BeiDou at different level. Especially when the satellite number is reduced, such as in urban areas or when the elevation cutoff is high, the positioning error will reduce after adding QZSS satellite and the availability of other GNSS systems will also improves. For kinematic PPP users, QZSS could also reduce the convergence period. Meanwhile, the dual frequency and single frequency RTK (Real Time Kinematic) positioning performance is compared after adding QZSS satellite into GPS and BeiDou. Kinematic car test in urban environment shows that when combining QZSS satellite with GPS and BeiDou, the rate of instantaneous ambiguity resolution will increase for both single and dual-frequency users.

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J. Sun et al. (eds.), *China Satellite Navigation Conference (CSNC) 2018 Proceedings*, Lecture Notes in Electrical Engineering 497,
https://doi.org/10.1007/978-981-13-0005-9_37

Keywords PDOP · SPP · PPP · RTK · Ambiguity resolution

1 Introduction

QZSS satellite system, known as Quazi-Zenith Satellite System, is a regional satellite navigation system developed by Japan. This first QZSS satellite, also named as Michibiki, was launched by JAXA (Japan Aerospace Exploration Agency) in September, 2010. From February, 2017 [1]. JAXA discontinues the operation of QZS-1 and the control of QZSSS is transferred to the Japan Cabinet Office [2]. After that, QZSS satellite speed up its launch plan. The 2nd to 4th QZSS satellites were launched from June to October in 2017 [3, 4]. So far, QZSS has preliminary finished its first step of QZSS system including 4 satellites. According to Japan Cabinet Office, QZSS system will start official service from 2018 and a system consists of seven satellites is planned as the second step of QZSS, which will be finished by 2024 [5].

Starts from the launch of first QZSS satellite, many researches have been done from QZSS signal transmission to POD (Precise Orbit Determination) and positioning. The satellite attitude and orbit determination was analysis by Hauschild and Montenbruck [6–8]. QZSS also releases the official satellite information and control mode in 2017, which would be great help for QZSS orbit determination [9]. The SISRE(Signal in Space Range Error) was analyzed by Montenbruck [10], which indicates that it can reach below 0.6 m and is comparable with GPS. Quan et al. assessed the signal quality of QZSS together with other GNSS systems using real-data [11] and Odolinski et al. analyzed the performance of long baseline and single frequency QZSS aided RTK [12, 13]. The QZSS ISB is also estimated with other GNSS systems [14].

However, almost all these researches only focus on QZS-01. With the available of other satellites of QZSS, it is necessary to investigate the contribution of QZSS constellation under multi-system.

Due to the constellation character of QZSS, the service area of QZSS is limited within Asia-Pacific region. In this paper, we mainly focus on its contribution in Asia-Pacific area.

2 QZSS System

Till the end of November, 2017, the satellites number of QZSS in orbit is 4. Among which QZS-3(PRN J07) is the GEO satellite above the longitude of 127°E, the other three satellites are QZO (Quazi-Zenith Satellite Orbit) satellites [5]. Different from the IGSO satellite of BeiDou, trajectory of QZO satellite is an asymmetric eight to keep the satellite stay longer in Japan.

Table 1 Information of QZSS constellation

Sat_Name	QZS-1	QZS-2	QSZ-3	QZS-4
SCN	J001	J002	J003	J004
PRN	J01	J02	J07	J03
BLOCK	IQ	IIQ	IIG	IIQ
Sat_Type	GSO	GSO	GEO	GEO
Longitude	130–140°E	130–140°E	126.9–127.1°E	130–140°E
Launch date	2010.09.11	2017.06.01	2017.08.19	2017.10.09

Table 1 summarizes the basic information of current QZSS constellation.

According to QZSS ICD and the official information [9, 15], the coordinate system that QZSS adopts is JGS (Japan satellite navigation Geodetic System), which is similar with ITRS. The newest JGS2010 is established by more than 40 stations of SLR, GPS and QZSS [16]. JGS uses the Geodetic Reference System 1980 (GRS80) ellipsoid, while WGS84 uses the WGS84 ellipsoid. The difference between these two ellipsoids is only the flattening parameter, which can be neglected in most situations. QZSST is the time system applied in QZSS. Its definition is the same as GPST. QZSST is maintained by JAXA, its difference with UTC(NICT) maintained by NICT (National Institute of Information and Communications Technology) is less than 50 ns [15].

According to the pamphlet provided by QZSS [17], the SIS (Signal In Space) of QZSS broadcast ephemeris is under 2.6 m (95%); the URE (User Range Error) of ionosphere is below 7 m (95%); the time difference with UTC is 40 ns (95%) or less; the satellite service availability for QZO is 0.95 or more and 0.80 or more for GEO; the constellation service availability is 0.99 or more. Besides basic PNT (Positioning, Navigation, Timing) service, QZSS also provides code-based augmentation service of SLAS (Sub-meter Level Augmentation System) and DC Report (Satellite Report for Disaster and Crisis Management) on L1S band, together with PPP-RTK like precise service of CLAS (Centimeter Level Augmentation System) on L6 band.

Currently, the IGS ACs (Analysis Center) that provide QZSS precise orbit and clock include GFZ, CODE, WHU, TUM, et al. From the end of September of 2017, QZS-2 is included in POD processing [18]. Montenbruck assessed the SIS of broadcast ephemeris by comparing with POD result and concluded that the SIS of QZS-1 is less than 0.6 m. Richard assess the clock stability of QZS-1 and QZS-2 in 2017 and results show that the 100 s Allan Deviation is better than 3×10^{-13} and the long stability of QZS-1 and QZS-2 reaches the same level of GPS Block IIF satellite.

With the available of more QZSS satellites, users may enjoy a better positioning performance.

3 Data Description

The number of QZSS satellite is still too few to provide a stand-alone positioning service. To assess the contribution of QZSS, we combine QZSS with GPS and BeiDou in Asia-Pacific areas. The comparison of positioning results is used for the assessment.

Although J02 (QZS-2) started signal transmission from the end June in 2017, many IGS station haven't upgrade their receivers firmware and can't track the signal of J02 or J03. After carefully distinguish, 9 of IGS stations distributed in Asia-Pacific areas are selected, which shows in Fig. 1. All these stations can track signals of J01, J02 and GPS. BeiDou signals can also be tracked except stations of TWTF and JOG2. 10 days of data from Nov. 6th to 15th in 2017 are chose for the assessment in this paper.

4 Contribution of QZSS

4.1 Contribution of QZSS in DOP Value

Before the assessment of positioning performance, it is necessary to evaluate the contribution of QZSS in satellite number and DOP value.

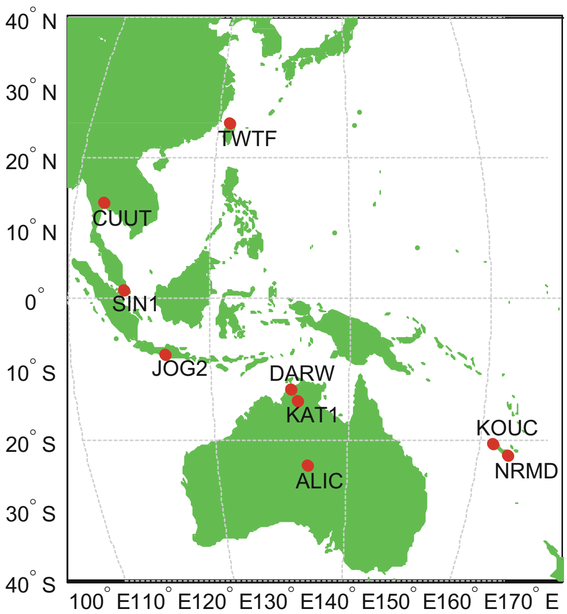

Fig. 1 Tested IGS stations

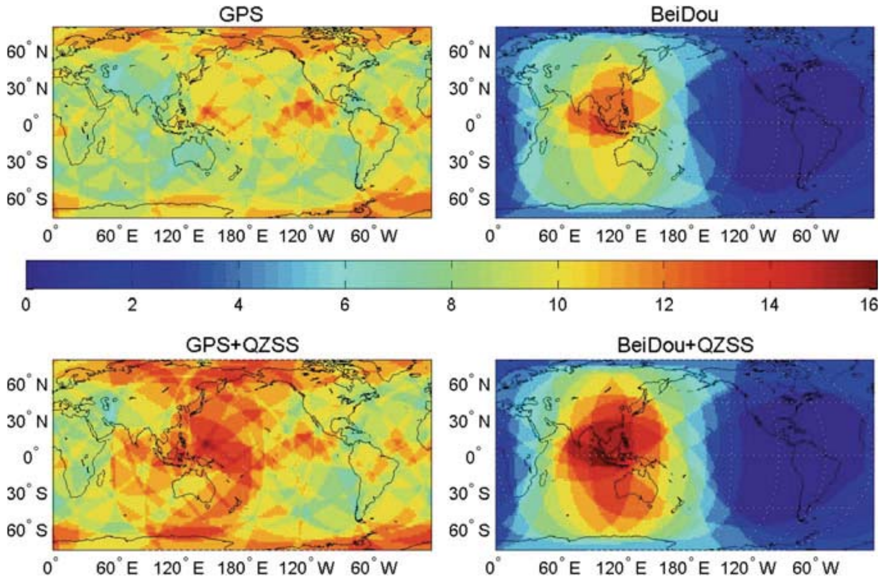

Fig. 2 Satellite number comparison for difference GNSS system (2017/11/15 23:00:00)

Figure 2 explains the visible satellite number change after combining QZSS with GPS and BeiDou at the epoch of November 15th 23:00(UTC) in 2017. The satellite elevation cutoff is 10° and the left two subplots compare the satellite number for GPS and GPS + QZSS, while the right two subplots compare that for BeiDou and BeiDou + QZSS. The corresponding Fig. 3 illustrates the improvement of PDOP for GPS and BeiDou after combining with QZSS.

As can be seen from Figs. 2 and 3, QZSS satellites shows a better improvement in Southeast Asia and West Pacific, where the mean improved satellite number can reach up to 3. With the help of QZSS, this area is the hottest GNSS area in the world and shows a best PDOP value. At the same time, for the current regional satellite system of BeiDou, QZSS would help to enlarge its service area.

4.2 Contribution of QZSS in SPP

From analysis in the section above, we can find the improvement of QZSS in Asia Pacific areas in satellite number and DOP value, which means that it would be great help in user positioning, theoretically. In this part, we will analysis the SPP performance after adding QZSS to GPS and BeiDou.

Based on the data introduced in 1.3, we perform GPS and BeiDou based SPP. After that one and two QZSS satellites are added into the solution

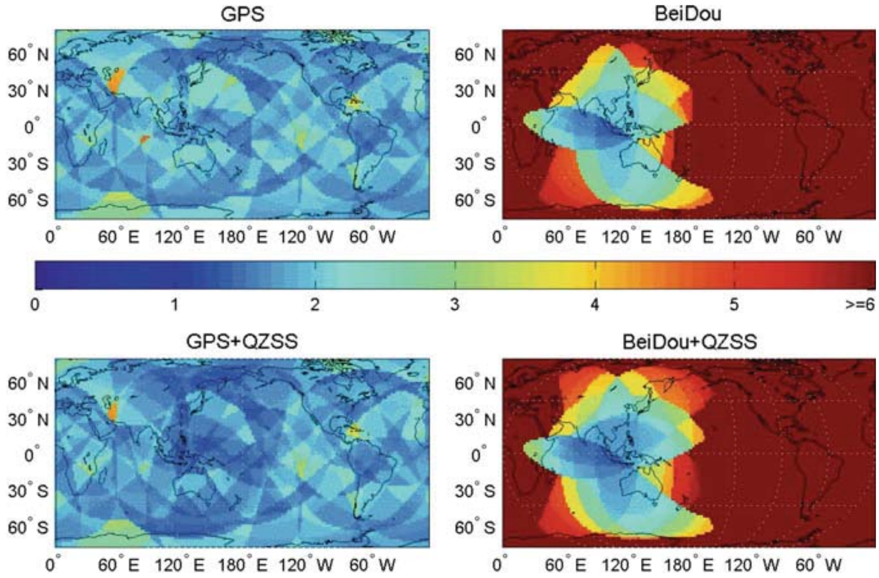

Fig. 3 PDOP comparison for difference GNSS system (2017/11/15 23:00:00)

successively. Due to the high elevation of QZSS, we set the elevation cutoff every 5° from 10° to 25°.

Take BeiDou as example, Fig. 4 compares the SPP error in NEU(North, East, Up) direction of BeiDou alone and BeiDou + QZSS combined SPP at station KAT1 on November, 6th, 2017. The elevation cutoff in the left subplots is 10° and the right one is 25°. Tables 2 and 3 summarize the GPS and BeiDou SPP performance after combining with 0 to 2 QZSS satellites.

From Fig. 4 and Tables 2, 3, one can clearly see that the positioning performance will improve for both GPS and BeiDou at the elevation cutoff from 10° to 25°. The more QZSS satellites, the better positioning RMS. And we can find that with the increase of elevation cutoff, the positioning accuracy decreases in general. However, when combined with QZSS, this trend of decreasing seems to be not so dramatically, which shows the advantage of high elevation for QZSS.

Besides, compared with GPS, this elevation depended decreasing of precision is more slight for BeiDou. This may due to the reason that most BeiDou GEO and IGSO satellites are at a high elevation in this areas.

From Fig. 2 we know that the service area of BeiDou and QZSS is limited due to the limit of satellite number, which influence the service availability. We assume that the service is unavailable when PDOP value is less than 6 [15]. Table 4 is a statistical result of time percentage when PDOP is less than 6 for different system at different elevation cutoff. From the table we can see that the availability of GPS is better than BeiDou even in Asia-Pacific areas. However, when adds QZSS, the

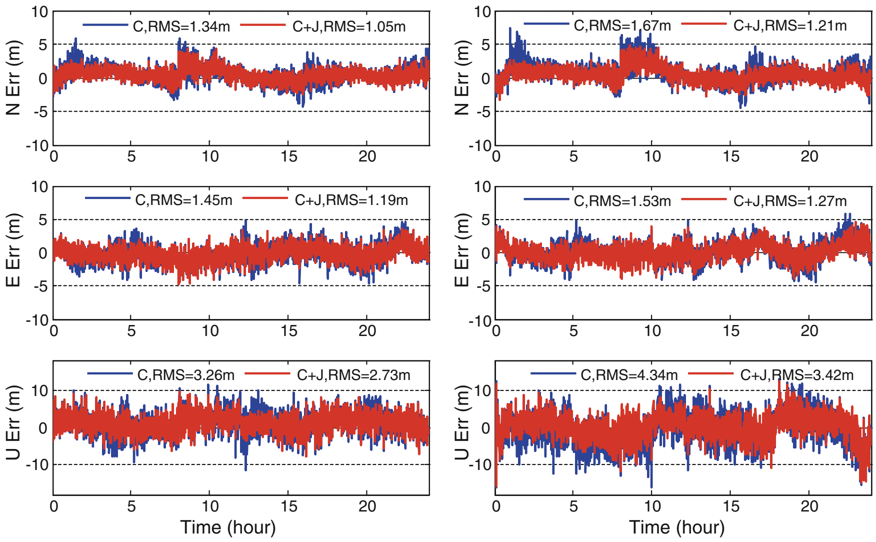

Fig. 4 SPP Performance for BDS after Adding QZSS at An Elevation Cutoff of 10° (left) and 25° (right) at Station KAT1

Table 2 GPS and GPS + QZSS SPP Result

Elevation (°)	10	10	15	20	25
G	N(m)	0.94	1.03	1.35	1.64
	E(m)	0.00	1.05	1.18	1.44
	U(m)	2.49	2.90	4.20	5.56
G + J01	N(m)	0.92	0.99	1.24	1.57
	E(m)	0.98	1.02	1.14	1.40
	U(m)	2.42	2.75	3.77	5.16
G + J01 + J02	N(m)	0.90	0.96	1.14	1.51
	E(m)	0.96	1.01	1.10	1.33
	U(m)	2.36	2.65	3.45	4.70

Table 3 BeiDou and BeiDou + QZSS SPP Result

Elevation (°)	10	10	15	20	25
C	N(m)	1.43	1.50	1.55	1.89
	E(m)	2.38	2.50	2.54	2.60
	U(m)	4.44	4.77	4.98	6.05
C + J01	N(m)	1.27	1.32	1.40	1.51
	E(m)	2.06	2.16	2.30	2.44
	U(m)	3.92	4.14	4.45	5.04
C + J01 + J02	N(m)	1.18	1.21	1.27	1.36
	E(m)	1.94	2.03	2.19	2.37
	U(m)	3.56	3.77	4.07	2.55

Table 4 Percentage of time when PDOP < 6 at different elevation cutoff

System	Elevation (°)	0 QZSS (%)	1 QZSS (%)	2 QZSS (%)
GPS+	10	99.8	99.8	99.8
	15	99.3	99.6	99.7
	20	95.3	96.4	97.9
	25	85.2	88.9	92.8
BeiDou+	10	75.4	87.2	95.8
	15	71.8	84.4	92.7
	20	68.8	78.9	85.3
	25	65.0	73.6	77.7

availability will greatly improve. For GPS, the availability would also improve at the situation of high elevation cutoff. This proves that QZSS would benefit the continuity and availability of other GNSS systems.

4.3 Contribution of QZSS in PPP

From September of 2017, some IGS ACs starts to provide precise orbit and of QZS-2. In this part we try to assess the contribution of current two QZSS satellite in PPP.

Again, we choose GPS and BeiDou as the base system, respectively. A kinematic PPP solution is carried here. To make full of the satellite observations, the satellite elevation cutoff is set as 10°. The precise multi-GNSS satellite orbit and clock are provided by GFZ. The estimated kinematic PPP positions are compared with true coordinates provided by IGS.

Figure 5 shows the 24 h kinematic PPP error in North, East and Up direction at station KAT1 on Nov. 6th, 2017. The RMS is calculated after convergence of half an hour. From the result we can see that the RMS of GPS will improve from (1, 2, 6 cm) to (1, 2, 5 cm) after adding QZSS satellite. As for BeiDou, the value is from (2, 2, 8 cm) to (1, 2, 5 cm). The better improvement of BeiDou is due to the better performance of convergence period after adding QZSS satellite. In general, more QZSS seems not much improvement on GPS, but really do a good help for BeiDou.

To have a more reliable conclusion, we compute the convergence performance for all stations every day during the first one hour of PPP. For GPS, the result is defined as convergence when 3D positioning error is less than 0.2 m; for BeiDou, the value is 0.4 m. Percentage the convergence stations are calculated every 5 min. Figure 6 shows the statistical result, from which we can see that for BeiDou, the convergence speed improves after combining QZSS satellite. However, the current PPP performance of BeiDou is still not better than GPS, one reason is that the orbit and clock accuracy of BeiDou not as good as GPS, other may due to that the change of DOP value is much slower than GPS.

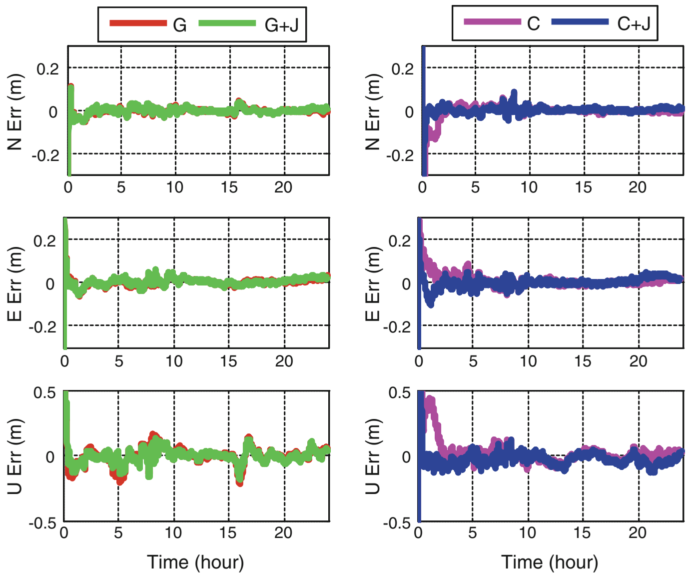

Fig. 5 PPP performance for GPS and BDS combined with QZSS at station of KAT1

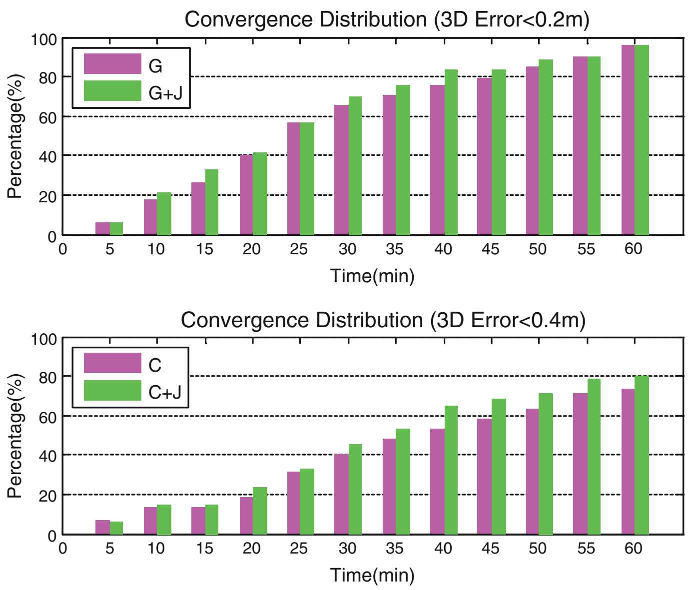

Fig. 6 Percentage of positioning error during convergence period

4.4 Contribution of QZSS in RTK

Thanks to the same frequency of QZSS with GPS, an additional QZSS satellite is almost equivalent with a high elevation GPS satellite for Asia-Pacific users during the process of RTK. However, in urban environments, blocking by the high buildings and serious multipath effect, it is not easy to fix the ambiguity even for short baselines. In this part, we attempt to investigate the contribution of QZSS in RTK.

The experiment is carried out using a Trimble Net_R9 geodetic receiver in the rooftop of a car. One hour of kinematic multi-GNSS system data was collected on July 19th, 2017.The trajectory of the kinematic RTK test is showed in Fig. 7.

An instantaneous AR(Ambiguity Resolution) is applied in processing for both single and dual frequency data. For dual frequency data, the fixing rate of QZSS combined GPS and GPS alone AR is compared. For single frequency data, the fixing rate of QZSS combined GPS + BeiDou and GPS + BeiDou AR is compared. Corresponding results are showed in Fig. 8, from which we can see that the fixing rate will improve from 62.9 to 77.0% for QZSS aided GPS dual frequency AR and from 60.0 to 68.8% for QZSS aided GPS + BeiDOu single frequency AR. Compare with the map in Fig. 7, we can clearly see that when the receiver is between high buildings or under high-way, the AR fixed rate would dramatically

Fig. 7 Trajectory of Kinematic RTK Test

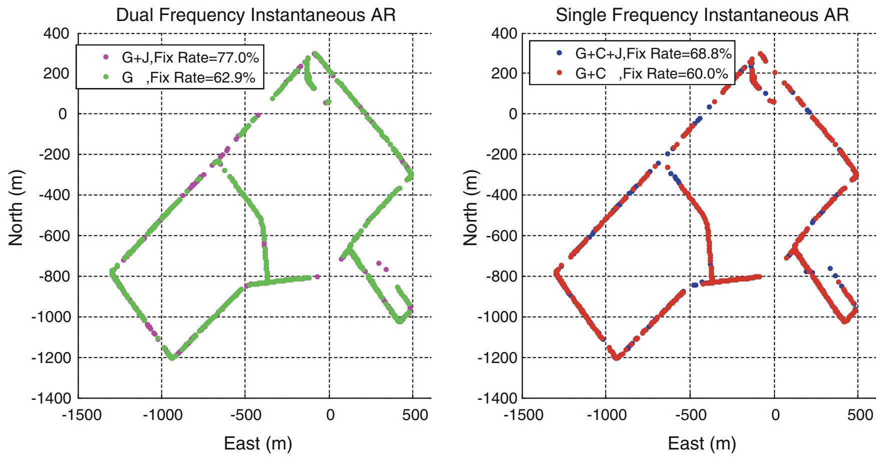

Fig. 8 Dual and single frequency instantaneous AR

decrease, this is due to the frequently satellite signal break off. The result indicates that the AR fixing rate of RTK would improves when high elevation QZSS satellite are introduced, especially in urban environments.

5 Conclusions

In this paper, we introduce the status and development of QZSS. The contribution of QZSS in Asia-Pacific areas is analyzed in DOP, SPP, PPP and RTK. Results show that:

(1) QZSS improves the visible satellite number and DOP value in Asia-Pacific areas. At the meanwhile, it can help to enlarge the service region of BeiDou.
(2) When QZSS is combined with GPS or BeiDou, the SPP accuracy would improve at different level, especially for the situation of high elevation cutoff. QZSS could also speed up the convergence period in PPP.
(3) The instantaneous AR fixing rate can improve with the help of QZSS in RTK.

With the development of QZSS and the ongoing official service of QZSS, it would be more and more important as part of GNSS.

Acknowledgements This work is support by the National Natural Science Foundation of China (No. 11673050) and the Opening Project of Shanghai Key Laboratory of Space Navigation and Positioning Techniques (No. KFKT_201706).

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