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Assessment of positioning performances in Italy from GPS, BDS and GLONASS constellations

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ABSTRACT

The use of multiple GNSS constellations has been beneficiary to positioning performances and reliability in recent times, especially in low cost mass-market setups. Along with GPS and GLONASS, GALILEO and BDS are the other two constellations aiming for global coverage. With ample research demonstrating the benefits of GALILEO in the European region, there has been a lack of study to demonstrate the performance of BDS in Europe, especially with mass-market GNSS receivers. This study makes a comparison of the performances between the combined GPS-GLONASS and GPS-BDS constellations in Europe with such receivers. Static open sky and kinematic urban environment tests are performed with two GNSS receivers as master and rover at short baselines and the RTK and double differenced post processed solutions are analyzed. The pros and cons of both the constellation choices is demonstrated in terms of fixed solution accuracies, percentage of false fixes, time to first fix for RTK and float solution accuracies for post processed measurements. Centimeter level accuracy is achieved in both constellations for static positioning with GPS-BDS combination having a slightly better performance in comparable conditions and smaller intervals. GPS-GLONASS performed slightly better for longer intervals due to the current inconsistent availability of BDS satellites. Even if the static tests have shown a better performance of GPS-BDS combination, the kinematic results show that there are no significant differences between the two tested configurations.

1. Introduction

The progress of satellite navigation technology is evident through the increasing research and budget devoted to it by different countries and organizations. Along with the two pioneering systems the GPS and GLONASS which have been operational since the early 1990s, several other satellite navigation constellations have been set up today aiming for global or regional coverages including BDS, GALILEO, QZSS and IRNSS. Among these, BDS is the closest to achieving global coverage and with GALILEO hampered by delays, it should form a vital cog to the Global Navigation Satellite System (GNSS) technology in the coming decade. On the user side, the types of GNSS receivers used depends on the accuracy and precision desired with the high end geodetic receivers which support multiple frequency signals providing accuracies in millimeters. The recent low-cost mass-market single frequency (L1) GNSS receivers of today can provide centimeter levels of accuracy consistently using techniques such as RTK, DGPS, augmented systems, etc. both in real-time and in post processing. There is a strong interest in improving their performance with low-cost receivers dominating the GNSS market today [1] and different approaches are been explored including techniques in differencing, atmospheric error mitigation, and the use of multiple constellations. The benefit of improving performances of low cost GNSS receivers have led to its use in applications such as landslide monitoring [2,3], structural deformation [4], control surveying [5,6], drone [7], remote sensing [8] or pedestrian navigation [9] over the last decade and

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with the open source software such as RTKLIB [10] or goGPS [11] low-cost GNSS positioning systems [12] can be realized today.

The benefit of availing multiple GNSS constellations has been detailed in many researches in terms of coverage and accuracy in reliability [13]. Individually the performance of GPS has been regarded as the most reliable over most regions in the world [15], but the benefit from addition of GLONASS constellation has been demonstrated in conditions of urban canyon [16]. Comparison of GPS with BDS has also been made, mostly over the Chinese region [17] since it benefits from the additional coverage of the IGSO and GEO satellites of the BDS constellation [19] and the improved reliability of GPS-BDS integrated constellation [18,20] has been demonstrated over the individual constellations [14,21,22]. In Europe, the possibility of positioning using only BDS has been shown, but only for limited periods across the day. It has been seen to be naturally less reliable when compared to GPS performance [23], but with similar DOP values for both constellations the performances have been comparable with single frequency positioning [24]. At higher latitudes of Europe, the limitation of BDS only positioning and the benefits of using it in a multi-constellation system is documented in kinematic and static tests [25].

This study aims to derive the optimal low-cost GNSS positioning setup for Northern Italy looking into the performance between multi constellations GPS-GLONASS and GPS-BDS, Network real-Time Kinematic (NRTK) positioning and double differenced post processed solutions with the help of static and kinematic tests. The static tests were performed keeping two low cost master and rover receivers at a short baseline of 100 m and analyzing 24 h solutions. The kinematic tests were performed on top of a roving car, where a special support for a GNSS antenna was installed. A typical low-cost GNSS receiver has a limited amount of tracking channels and hence tracking more than two full constellations is not feasible.

2. Observations and methods

2.1. Constellation status

This work is based on comparison of performance between the integrated GPS-BDS and GPS-GLONASS constellations in the Piedmont Region (in red in Fig. 1), North of Italy. GPS and GLONASS are global constellations, and accordingly the number of GPS satellites visible during a 24 h period, varies between 7 and 11 considering 10° as a cutoff angle. For the same, 5 to 9 GLONASS satellites are normally visible.

The BDS constellation is yet to achieve global coverage and currently in the Piedmont Region, 2 to 6 satellites are visible throughout a 24 h period with one GEO satellite (C05) remaining intact throughout. There is a period of 1 h when only this GEO satellite is available. The 24 h availability of BDS satellites as seen on the 28th of June, 2017 can be seen in Figs. 2 and 3 with the help of the Navmatix planning online tool.

There are other navigational satellite systems moving towards operational capability which include the GALILEO GNSS system of the European Union, Indian Regional Navigation Satellite System (IRNSS) of India and the regional Quasi-Zenith Satellite System (QZSS) of Japan, but they are not relevant in this work due to the current number of satellite availability and coverage region.

2.2. Accuracy approach

In the Piedmont region, previous research [26] has shown centimeter levels of accuracy in estimated positions for GPS-GLONASS using a low-cost double constellation single frequency receiver and a geodetic multi constellation antenna. The difficulty of attaining a fixed solution in 5 min or 10 min measurement sessions and the lowering of percentage of fixed solutions in RTK when compared to post processed solutions is noted [26]. The benefit of

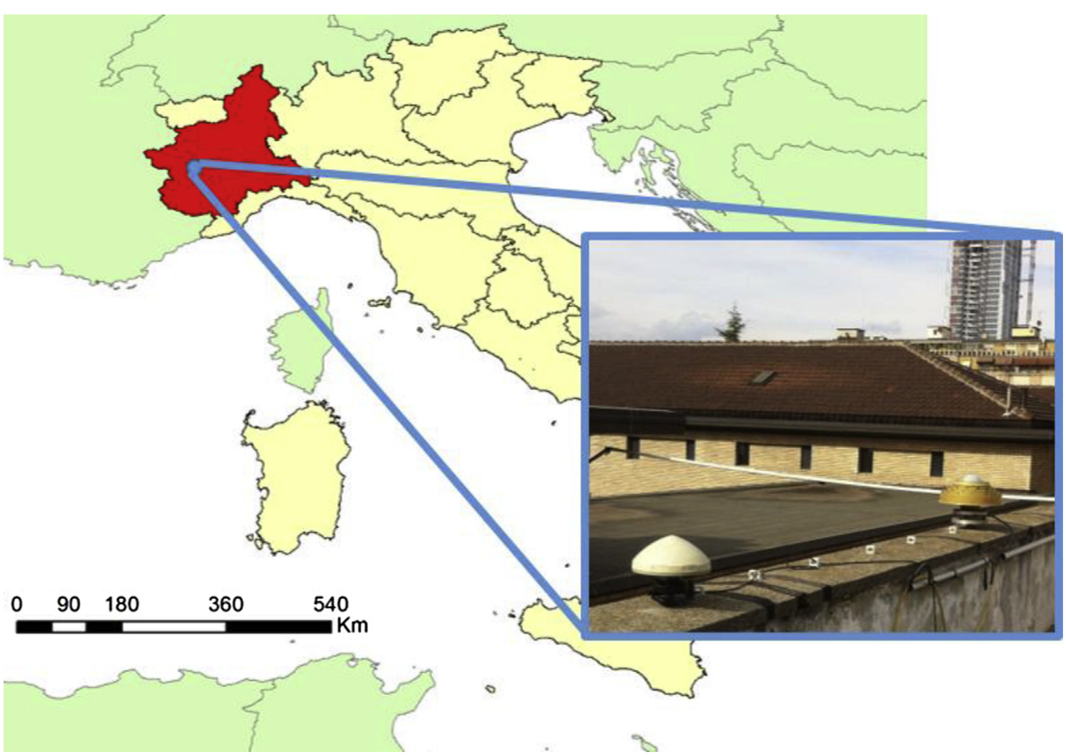

Fig. 1. The Piedmont region (in red) in Italy where the test site (surrounded in blue and visible in the right side of the figure) is considered.

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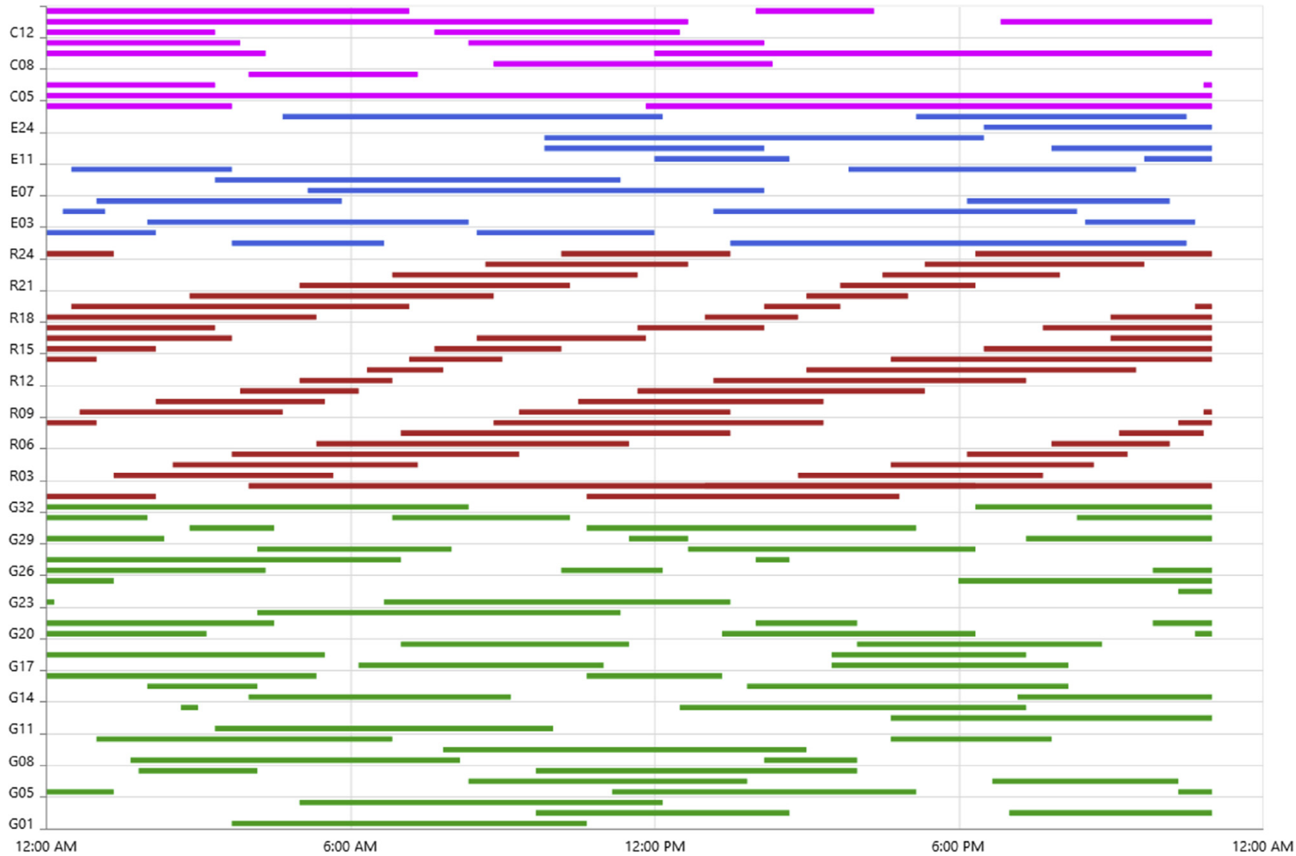

Fig. 2. BDS 24-hour satellite visibility (Source: http://www.gnssmissionplanning.com/).

RTK in GNSS and demand for instantaneous positioning solutions directs the study towards availing both RTK and post processed solutions for analysis and comparison.

A single frequency PPP-RTK approach which takes corrections and estimates from a regional CORS network is shown to provide comparable accuracies for mass-market and geodetic receivers while having time to first fix of 6–10 mins [27]. When comparing a low grade to a high grade geodetic set-up, the performance of both accuracy and time to first fix is shown to depend largely on the antenna quality and by contrast the performance difference is smaller between receiver qualities [28]. Single frequency RTK-GPS precision of a complete low cost antenna-receiver setup using RTKLIB for short intervals ($\simeq$10 min) has been demonstrated to be around 0.2 m in the Vietnam region [29].

It has been demonstrated [21] that realization of dual frequency BDS only RTK is feasible in China and BDS/GPS RTK can significantly

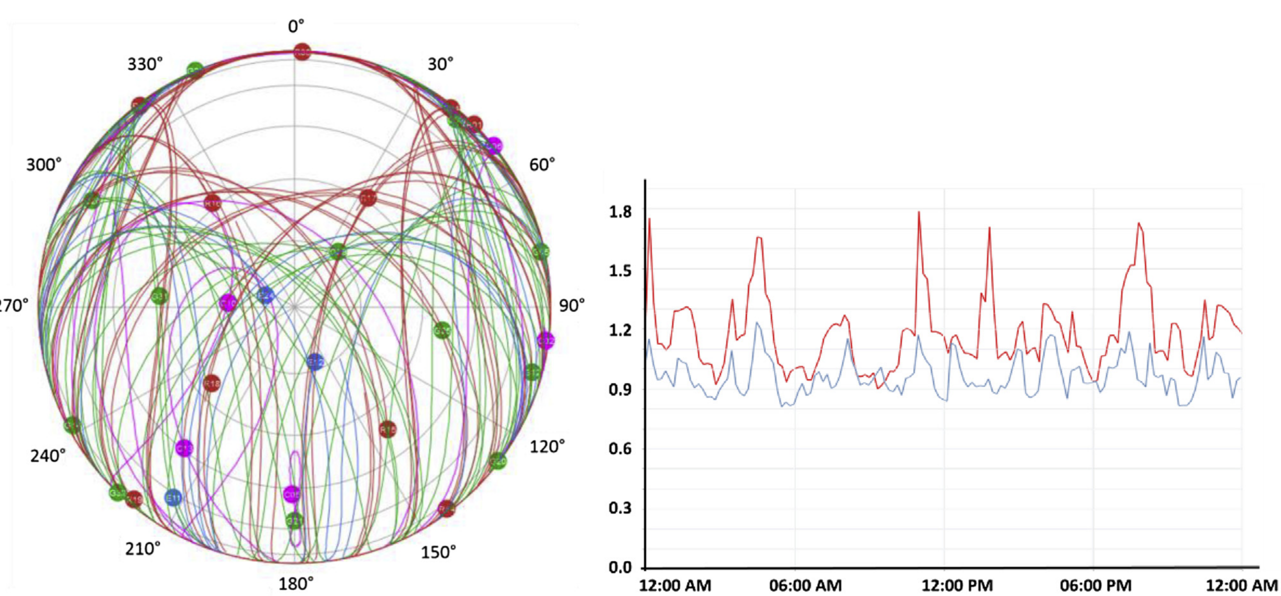

Fig. 3. Sky tracks of BDS/GPS/GLONASS/Galileo satellites for 24 h on the left and the DOP values on the right (source: http://www.gnssmissionplanning.com/App/Skyplot).

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enhance reliability when compared to either of the constellations alone. Centimeter level of positioning accuracy has been demonstrated in both kinematic and static mode. A Kalman filter based RTK algorithm for single frequency GPS-BDS combination has achieved higher percentage of fix (greater than 75%) and shorter time to first fix (TTFF, less than 150 s) compared to single constellation solutions [30]. The difficulty of instantaneous RTK using single frequency single GPS constellation is documented in the Perth region of Australia and on using a GPS-BDS constellation, the success of single frequency RTK is presented [31] considering a short baseline i.e. ionosphere-fixed model.

In Ningbo, China, the accuracies of a zero baseline test were found to be less than a few millimeters and the superiority of the BDS/GPS constellation has been shown [25]. Closer to the considered study region, a comparison study between GPS and BDS shows accuracy of meters in differential positioning and centimeters in precise positioning for BDS [14]. The issue of gaps in positioning due to satellite unavailability throughout the day is also seen [32]. The research documented so far has been performed with geodetic grade instruments in general and a low cost approach to a GPS-BDS integration hasn't been seen.

This study approaches the comparison between the GPS-GLONASS and GPS-BDS constellations for the Piedmont region using a low cost receiver and looks at the accuracies obtained through RTK and post processed positioning. A very short baseline between the master and rover antennas is used where the common atmospheric and ephemeris errors would be neglected. The focus is on accuracy and hence a comparison is made between the estimated and measured position of the rover in kinematic positioning approach to get the accuracies every epoch. The observations are split up into sessions of 5 mins, 1 h and 24 h data and an analysis of the TTFF is also done for the different methods. The accuracy performance is measured in terms of the differences between the estimated rover coordinates from the session considered when compared to the calculated ones, obtained after an adjustment thanks to the Bernese 5.2 software.

2.3. Experiment

Static Test: 24 h RTK solutions and raw measurements were collected for the GPS-BDS and GPS-GLONASS constellations on the 19th and 20th of April, 2017 respectively. Two dual frequency multi constellation GNSS antennas (LEIAR10 and LEIAR23.R3 by Leica Geosystems) were placed on the roof of a building around 100 m apart at Politecnico di Torino (Italy) coupled with L1 mass-market multi-constellation u-blox M8T receivers to collect the signals. The choice of the higher grade antennas was important for a comparative study between the constellations, in order to obtain the "best" possible solutions, excluding problems due to the antennas. The receivers were powered by two different personal computers where they were configured through the u-center software [33] and a homemade software was used to process the RTK solution and save raw measurements. Parameters configured in the software include availing the satellite broadcast ionospheric and ephemeris correction, Saastamoinen tropospheric correction with an elevation mask of 15° to neglect the noisy low elevation satellite signals. Data was broadcasted and received from the master side to the rover receiver via internet connection. Fig. 4 displays the two antennas used in these experiments.

Kinematic Test: a stretch of the Turin road network was considered (Fig. 5), which presents different characteristics in terms of obstructions (few obstruction in terms of buildings, a section with sub-urban nature, and finally a portion with urban canyon characteristics). The length of this trajectory was about 7 km for a session of about 40 mins. In order to evaluate the reliability of the positioning techniques with mass-market receivers [34], a dual-frequency multi-constellation GNSS receiver was settled on the roof of the same car in order to obtain a reference trajectory. Two different antennas were considered: a geodetic one (LEIAR10) was connected to the geodetic receiver for obtaining the reference solution, while the mass-market one (Garmin GA-38) was connected to the low-cost single-frequency receiver for estimating the performances of the low-cost solution. It is important to underline that both RTK solutions and raw measurements were collected during the tests in a time period where at least 4 BDS satellites should be visible. The post-processing solution obtained with the geodetic instruments has been used as reference.

3. Results and discussion

The results are divided into static and kinematic analysis. In the static results analysis, the RTK and post processed performances of GPS-BDS and GPS-GLONASS constellations is seen for 24 h, 1-hour and 5-minute observation periods. Tables of the fixed solution error, standard deviation and root mean square (RMS) error values are displayed. The percentage of fixed solution and the time to first fix comparisons are also made.

For the kinematic tests, the difference between the low-cost and geodetic solutions are shown. Considering the mass-marked devices, both GPS-GLONASS and GPS-BDS results are presented,

Fig. 4. Rover antenna (right) and master antenna (left).

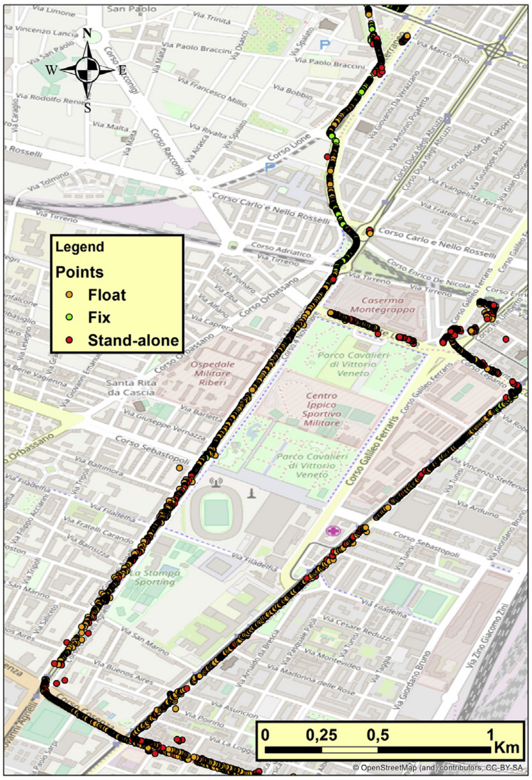

Fig. 5. The stretch of the Turin road network where the kinematic test was conducted: red dots (11%) represent the stand-alone solutions, the yellow ones (62%) the epochs with float ambiguities while the green dots (27%) all epochs with phase ambiguities fixed as integer values.

while for the other instruments only the GPS-GLONASS configuration is considered.

3.1. Static tests

Table 1 shows the accuracies of the fixed solutions obtained for both the constellations across for different length of observations for RTK and post processed solutions. It can be seen that millimeter level accuracies of the RTK solution are comparable for both constellations for longer periods of observation However the percentage of fixed solutions is greatly reduced in the GPS-GLONASS constellation and there was no fixed solution obtained for GPS-GLONASS for the 5-minute period. A centimeter level of accuracy was reached considering float solutions for both constellations with GPS-GLONASS performing slightly better.

The post processed accuracies are mostly similar to the RTK results with millimeter accuracy obtained for most cases as seen. The discrepancy in the 5 min observation of GPS-BDS data indicates a number of false fix in the initial solutions. Hence the false fixes which skewed the accuracy which can be seen in the high standard deviation of the 5-minute period in Table 2 as well. Across the 24 h period, the GPS-GLONASS solutions were marginally better, but it could not obtain a fix solution in the 5 min observation period. However, it has been seen that at different 5-minute intervals across the day, GPS-GLONASS was able to acquire a fixed solution, sometimes in less than a minute as well. The percentage of fixed solutions naturally goes up in the post processed solution. Overall the performance of GPS-BDS slightly worsened in the post processed solutions when compared to RTK while the performance of GPS-GLONASS remained comparably the same.

The RTK algorithm of the software used seems to be more stringent giving fewer false fixes (i.e. solutions where the phase ambiguities are declared as fixed while the results are 20 cm far from the reference solutions at least) than the post processed solution. With the technique presented in this work of using a low cost master receiver set-up, the algorithm seems to have difficulty in getting higher number of fixed GPS-GLONASS solutions in RTK although the number of visible satellites always remained above 10. It is interesting to note that the average number of satellites for the GPS-BDS constellation was 10 (6 GPS + 4 BDS) during the 1-hour time period and 14 for the GPS-GLONASS constellation (6 GPS + 8 GLONASS) and yet the difference in percentage of fixed solution was huge. False fixes were below 0.01% for both constellations in RTK as well post processed across 24 h.

Considering the accuracy results, the standard deviation of the fixed solutions across the 24 h RTK observation period for GPS-BDS was 4 mm East and 5 mm North and 13 mm Up. For GPS-GLONASS the performance was slightly worse with 8 mm East, 10 mm North and 23 mm in the Up direction. The standard deviation decreased for both the constellations the 1-hour observation period which indicates that the time of observations were closer to ideal. Fig. 6 and Fig. 7 represent the time series of the RTK solution of the UP component of GPS-BDS and GPS-GLONASS respectively. The percentage of fixed solution for the observation lengths can be matched with the length of the fixed solutions in the figures. For example, the difficulty in attaining a higher fix solution percentage

Table 1
Fixed solution position accuracies.

RTK SOLUTION with respect to reference coordinates								
Observation length	GPS-BDS				GPS-GLONASS			
	Mean Error (mm)			% of fix solution	Mean Error (mm)			% of fix solution
	East	North	Up		East	North	Up	
24 h	1	1	3	87.7%	1	<1	3	26.9%
1 h	1	2	12	83.7%	3	3	6	2.9%
5 mins	2	2	10	97.2%	n/a	n/a	n/a	0%
Post Processed Solution with respect to reference coordinates								
Observation length	GPS-BDS				GPS-GLONASS			
	Mean Error (mm)			% of fix solution	Mean Error (mm)			% of fix solution
	East	North	Up		East	North	Up	
24 h	1	1	3	98.3%	<1	<1	2	77.9%
1 h	1	4	17	91.2%	4	7	10	41.1%
5 mins	59	15	11	6.6%	n/a	n/a	n/a	0%

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Table 2
Standard deviation of fixed position solutions (mm).

RTK SOLUTION with respect to reference coordinates						
Observation length	GPS-BDS			GPS-GLONASS		
	East	North	Up	East	North	Up
24 h	4	5	13	8	10	23
1 h	3	6	8	4	5	8
5 mins	2	2	10	n/a	n/a	n/a
POST PROCESSED SOLUTION with respect to reference coordinates						
Observation length	GPS-BDS			GPS-GLONASS		
	East	North	Up	East	North	Up
24 h	5	5	13	2	4	8
1 h	20	10	10	3	3	4
5 mins	247	78	65	n/a	n/a	n/a

for GPS-GLONASS is visible clearly in Fig. 7. Similarly, Fig. 8 and Fig. 9 represent the time series of the post processed solutions of the UP component.

The RMS values in Table 3 display the worse GPS-BDS performance in the post processed solution as seen before and the presence of false fixes in the 5 min observations can be confirmed.

Time To First Fix (TTFF) comparisons: Analyzing 1 h of RTK solutions, it is seen that GPS-BDS constellation achieves fix within 1 min which is much faster than GPS-GLONASS constellation which took around 19 min. Faster TTFF has been achieved with GPS-GLONASS on other independent tests, but the minimum time has been around 5 min. Across the 1-hour observations, the maximum time to regain fix in the GPS-BDS constellation was 1 min while the average time for the same has been 4 min for GPS-GLONASS. Hence, the TTFF has been observed to be better in GPS-BDS in general. The TTFF across different intervals of a day with respect to the number of satellites and GDOP seen after post processing is given in Table 4.

3.2. Kinematic tests

Table 5 shows the accuracy of the fixed solutions obtained for both constellations, with respect to the reference solution, obtained with the geodetic configuration. As it is possible to see, there are no great differences between the two GNSS configurations. It is only possible to note that the GPS-GLONASS configuration provides a little bit noisier results (Fig. 10) and a slightly less percentage of solutions with phase ambiguities fixed as integer values if compared to the GPS-GLONASS configuration. In this context, it is possible to affirm that there are no substantial differences for kinematic tests in urban scenario.

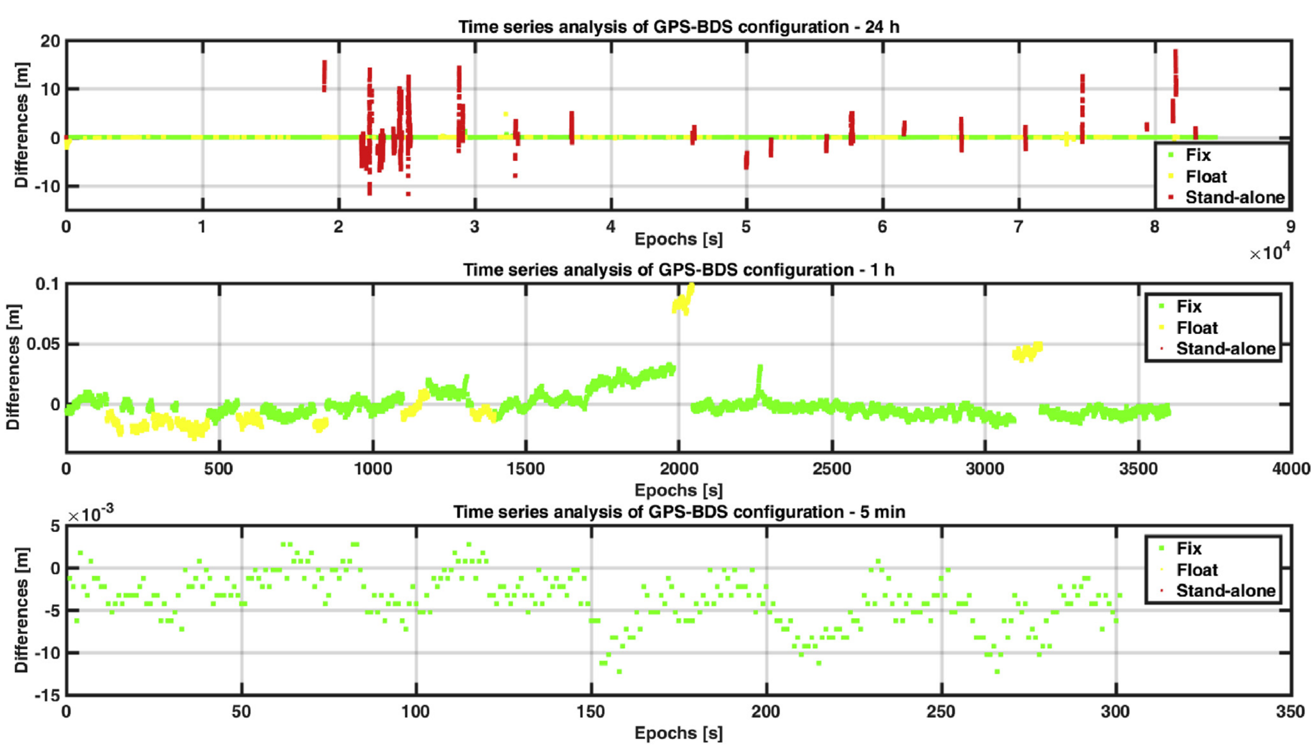

Fig. 6. Time series of UP component corresponding to RTK solution of GPS-BDS constellation.

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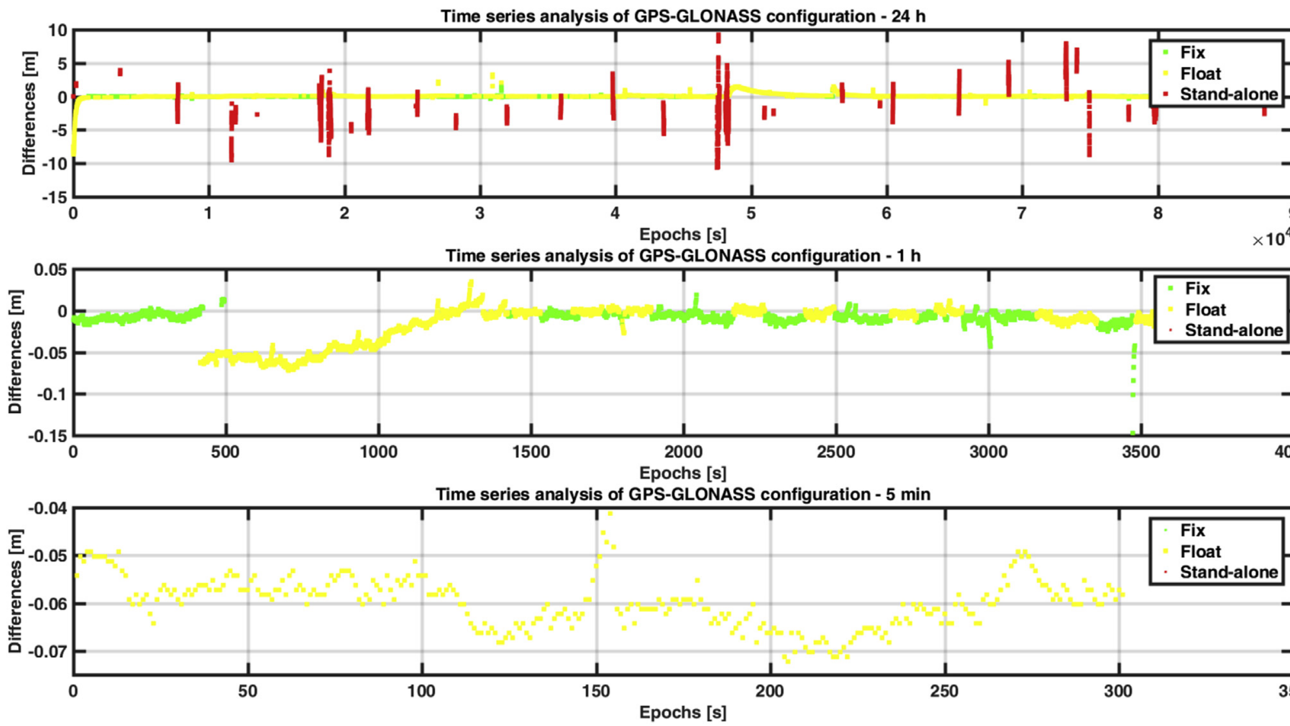

Fig. 7. Time series of UP component corresponding to RTK solution of GPS-GLONASS constellation.

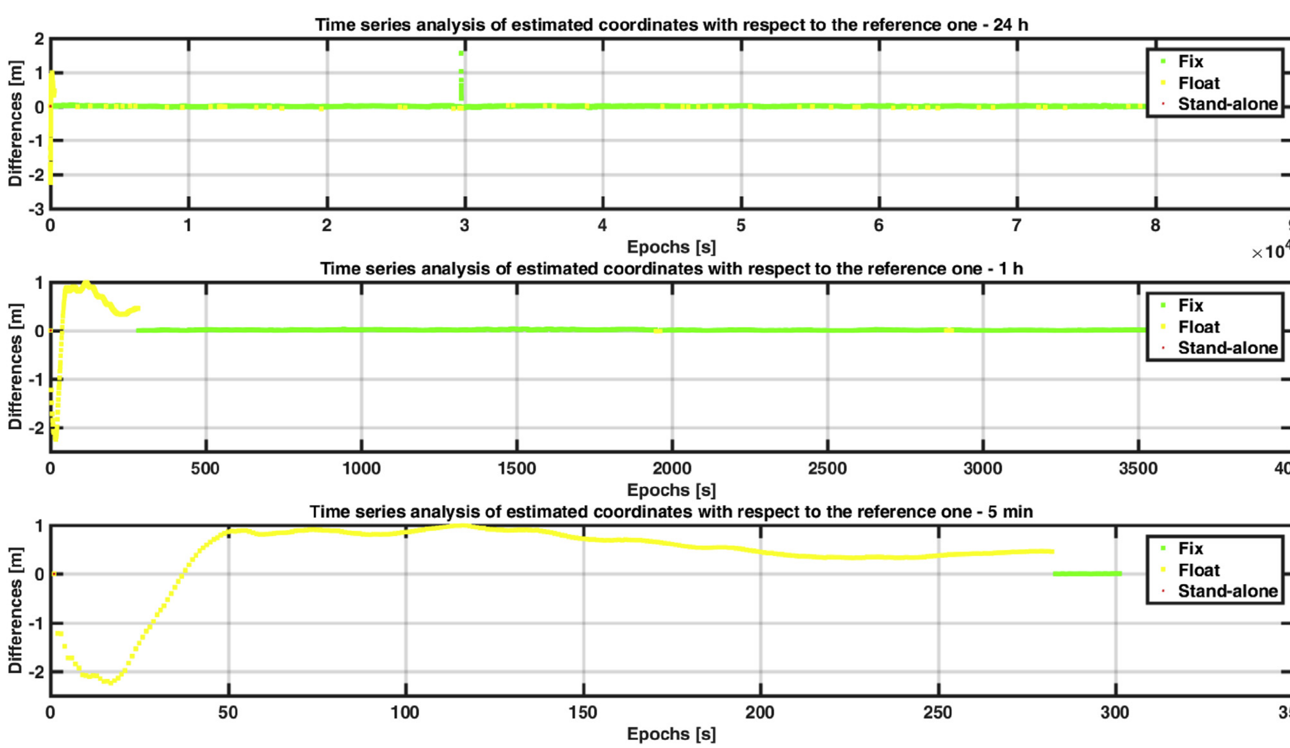

Fig. 8. Time series of UP component corresponding to post processed solution of GPS-BDS constellation.

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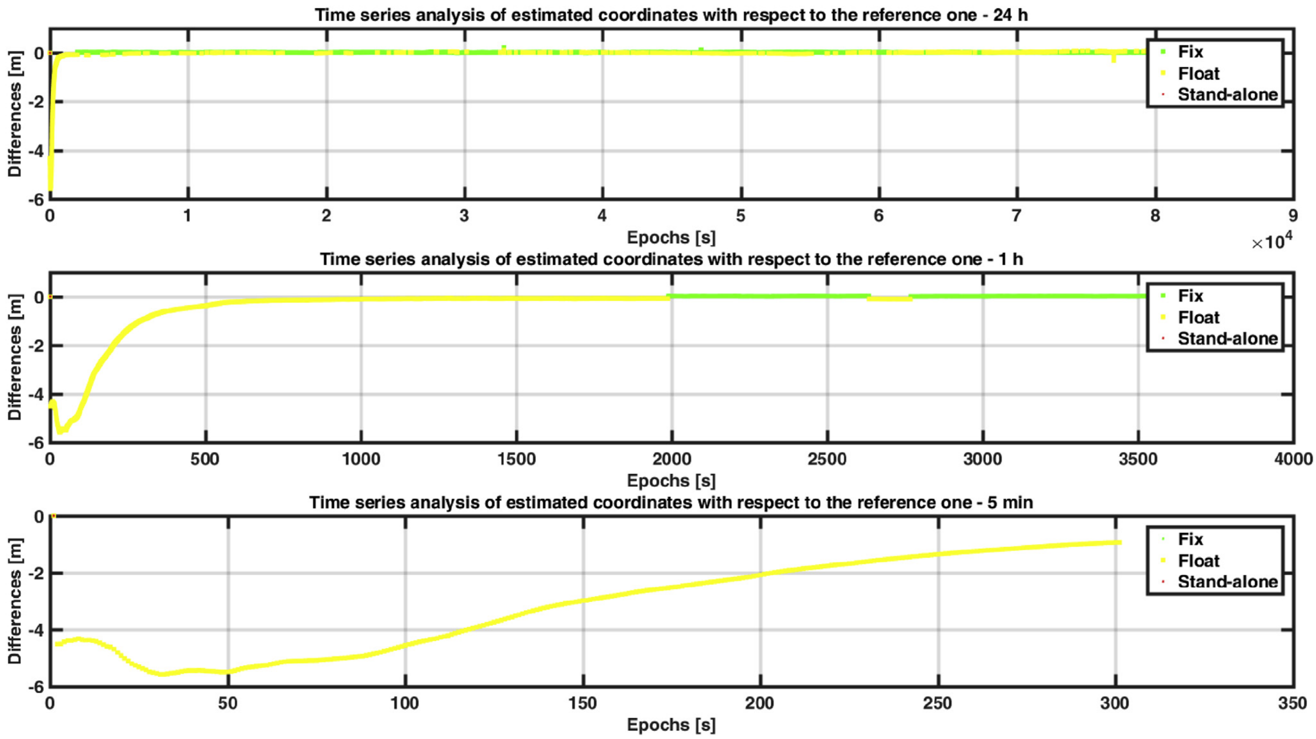

Fig. 9. Time series of UP component corresponding to post processed solution of GPS-GLONASS constellation.

Table 3
Root mean square (RMS) of fixed solution position error (mm).

RTK SOLUTION with respect to reference coordinates						
Observation length	GPS-BDS			GPS-GLONASS		
	East	North	Up	East	North	Up
24 h	1	1	1	1	1	1
1 h	1	3	12	3	2	6
5 mins	2	2	9	n/a	n/a	n/a
POST PROCESSED SOLUTION with respect to reference coordinates						
Observation length	GPS-BDS			GPS-GLONASS		
	East	North	Up	East	North	Up
24 h	5	6	13	3	4	8
1 h	20	11	19	5	8	10
5 mins	253	79	66	n/a	n/a	n/a

Table 4
Comparison of approximate Time to First Fix of constellations.

Time Interval	GPS-BDS			GPS-GLONASS		
	TTFF	N° Sat	GDOP	TTFF	N° Sat	GDOP
8.40–9.40 am	4–5 mins	6	2.4	25 mins	12	2.5
12.40–13.40 pm	8 mins	10	2.3	6 mins	13	1.9
15.40–16.40 pm	9 mins	6	2.5	6 mins	13	1.9
18.40–19.40 pm	2 mins	9	3.2	<1 min	14	2.0

4. Conclusion

The study explored a low cost approach to analyzing GPS-BDS and GPS-GLONASS performances in North Italy by using mass-market devices, such as the u-blox EVK-M8T, and a homemade software. The different variables in the study included the static open sky and kinematic urban tests with different constellations, different observation periods and their performances in both RTK

Table 5
Comparison of RTK results obtained with mass-market receiver with respect the geodetic one. All statistical parameters are evaluated considering only solutions with fixed phase ambiguities.

RTK SOLUTION with respect to geodetic solutions						
Statistical parameters	GPS-BDS			GPS-GLONASS		
	East	North	Up	East	North	Up
Mean [mm]	2.3	1.8	3.1	3.1	1.8	3.5
Std [mm]	1.6	3.2	4.7	4.2	2.7	5.3
% fix solutions	29.3%			26.7%		

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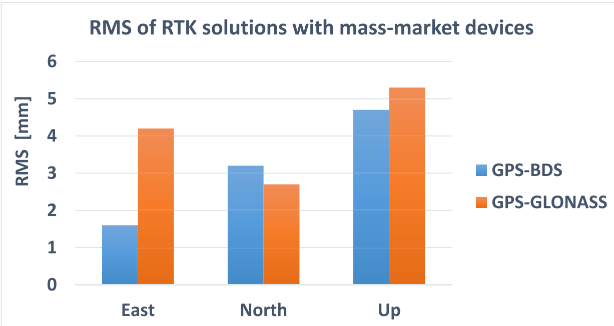

Fig. 10. Histogram of standard deviations of results obtained considering RTK solutions with mass-market devices with respect to the reference solution, obtained with the geodetic receiver.

and post processed positioning. There was the constraint of not having sufficient number of BDS satellites across a 24-hour period to perform a direct comparison of the constellations across all intervals in a day.

Under an open sky with a static receiver, millimeter level fixed solution accuracy could be obtained with both constellations across a 24 h and 1 h observation period which indicates that the performance of the mass-market setup is comparable to geodetic instruments performance. The accuracies of GPS-GLONASS was seen to be marginally better for the longer observation period. But GPS-BDS performed better for the 1 h period when the satellite geometry of GPS-BDS and GPS-GLONASS were comparable. BDS satellite availability was an undermining factor for GPS-BDS performance and due to the BDS constellation being incomplete, problems of satellite geometry and elevation of available satellites pose a problem currently in Europe. Periods of the day when there were 4–6 BDS satellites available, GPS-BDS performed better as seen by the 1 h performance comparisons. Also for short intervals of 5 min, fixed solution could mostly not be achieved by GPS-GLONASS. With comparable time to first fixes, there is no problem seen of multi constellation integration. A change in positioning algorithm could be explored to get better percentage of fixed solution for the GPS-GLONASS constellation.

The results of the kinematic test have shown a comparable behavior between both satellite's configurations, even if the GPS-GLONASS combination has provided more noisier results and a slightly less percentage of solutions with phase ambiguities fixed as integer values. In this context, the environment where the GNSS receiver works plays a crucial role especially if a mass-market receiver is considered. In the future, it could be possible to reach an higher percentage of fixed solutions if the number of visible satellites will increase, that maybe allow the users to increase also the quality of the positioning, in terms of accuracy and precision.

References

[1] European GNSS Agency, GNSS Market Report Issue 3, European GNSS Agency: Prague. Czech Republic, 2013, pp. 7–10. Available online: https://www.gsa.europa.eu/sites/default/files/GNSS_Market%20Report_2013_web.pdf (Accessed on 20 June 2017).
[2] A. Cina, M. Piras, Performance of low-cost GNSS receiver for landslides monitoring: test and results, Geomat. Nat. Hazards Risk 6 (5–7) (2015) 497–514, https://doi.org/10.1080/19475705.2014.889046.
[3] T. Bellone, P. Dabove, A.M. Manzino, C. Taglioretti, Real-time monitoring for fast deformations using GNSS low-cost receivers, Geomat. Nat. Hazards Risk 7 (2) (2016) 458–470, https://doi.org/10.1080/19475705.2014.966867.
[4] S. Caldera, E. Realini, D. Yoshida, Geodetic monitoring experiment by low-cost GNSS receivers and goGPS positioning engine, 2015. Geomatics Workbooks n° 12, FOSS4G Europe Como 2015.
[5] M. Tsakiri, A. Sioulis, G. Piniotis, Compliance of low-cost, single-frequency GNSS receivers to standards consistent with ISO for control surveying, Int. J. Metrol. Qual. Eng. 8 (2017) 11, https://doi.org/10.1051/ijmqe/2017006.
[6] S.G. Jin, R. Jin, J.H. Li, Pattern and evolution of seismo-ionospheric disturbances following the 2011 Tohoku earthquakes from GPS observations, J. Geophys. Res. Space 119 (2014) 7914–7927.
[7] M. Sahmoudi, R. Kasaraneni, Precise and Low-cost GNSS Positioning for Mini-drones. G2 Conference, OMP, Toulouse, 17th November 2015, 2015. Available online: http://cnfgg.eu/pdf/G2_2015/Mohamed%20SAHMOUDI.pdf (Accessed on 20th June, 2017).
[8] S.G. Jin, G.P. Feng, S. Gleason, Remote sensing using GNSS signals: current status and future directions, Adv. Space Res. 47 (2011) 1645–1653, https://doi.org/10.1016/j.asr.2011.01.036.
[9] A. Masiero, F. Fissore, F. Pirotti, A. Guarnieri, A. Vettore, Toward the use of smartphones for mobile mapping, Geo Spat. Inf. Sci. 19 (3) (2016) 210–221, https://doi.org/10.1080/10095020.2016.1234684.
[10] Exploring precision GPS with RTKLIB open source software and low-cost GPS receivers, Available online: http://rtkexplorer.com (Accessed on 20th June, 2017).
[11] E. Realini, M. Reguzzoni, GoGPS: open source software for enhancing the accuracy of low-cost receivers by single-frequency relative kinematic positioning, Meas. Sci. Technol. 24 (11) (2013) 115010, https://doi.org/10.1088/0957-0233/24/11/115010; ISSN 1361-6501. October 2013.
[12] T. Takasu, A. Yasuda, in: Development of the Low-cost RTK-GPS Receiver with an Open Source Program Package RTKLIB, International Symposium on GPS/GNSS, Jeju, Korea, November 2009, 2009.
[13] X. Li, M. Ge, X. Dai, X. Ren, M. Fritsche, J. Wickert, H. Schuh, Accuracy and reliability of multi-GNSS real-time precise positioning: GPS, GLONASS, BeiDou, and Galileo. Springer-Verlag Berlin Heidelberg 2015, J. Geodyn. 89 (2015) 607–635, https://doi.org/10.1007/s00190-015-0802-8.
[14] R. Odolinski, P.J. Teunissen, Low-cost, high-precision, single-frequency GPS–BDS RTK positioning, GPS Solut. 21 (3) (2017) 1315–1330.
[15] S.G. Jin, N. Najibi, Sensing snow height and surface temperature variations in Greenland from GPS reflected signals, Adv. Space Res. 53 (11) (2014) 1623–1633, https://doi.org/10.1016/j.asr.2014.03.005.
[16] A. Tabatabaei, M.R. Mosavi, Reliable urban canyon navigation solution in GPS and GLONASS integrated receiver using improved fuzzy weighted least-square method, Wirel. Pers. Commun. (2016), https://doi.org/10.1007/s11277-016-3771-1. September 2016.
[17] X. Liu, Q. Zhang, W. Yang, The positioning performance analysis of BDS/GPS single frequency-single epoch of asia pacific region for short baseline, in: China Satellite Navigation Conference, Springer, Singapore, 2017, May, pp. 389–407.
[18] H. He, J. Li, Y. Yang, J. Xu, H. Guo, A. Wang, Performance assessment of single- and dual-frequency BeiDou/GPS single-epoch kinematic positioning, GPS Solut. 18 (3) (2013) 393–403, https://doi.org/10.1007/s10291-016-0520-6.
[19] S.G. Jin, R. Jin, D. Li, Assessment of BeiDou differential code bias variations from multi-GNSS network observations, Ann. Geophys. 34 (2) (2016) 259–269, https://doi.org/10.5194/angeo-34-259-2016.
[20] X. Zhao, S.G. Jin, C. Mekik, J. Feng, Evaluation of regional ionopsheric grid model over China from dense GPS observations, Geod. Geodyn. 7 (5) (2016) 361–368, https://doi.org/10.1016/j.geog.2016.04.011.
[21] Y. Zhang, T. Wu, Y. Liu, Y. Han, C. Fan, A. Yasuda, Evaluation of GPS/BeiDou integration positioning performance, Trans. Jpn. Soc. Aeronaut. Space Sci. 58 (3) (2015) 113–120, https://doi.org/10.2322/tjsass.58.113. May 2015.
[22] H. Caojun, Z. Jing, Z. Chen, L. Boshi, X. Dekui, BeiDou-GPS integrated dual-system with multi-satellites for positioning and navigating farm vehicles, Int. J. Agric. Biol. Eng. 8 (5) (2015) 79–85, https://doi.org/10.3965/j.ijabe.20150805.1400.
[23] D. Kwasniak, Using BEIDOU System for Precise Positioning in Europe, IAG Commission 4 Positioning and Applications Symposium, Wrocław, 4-7 September 2016, 2016. Available online: http://www.igig.up.wroc.pl/IAG2016/download/Kwasniak_Using.pdf (Accessed on 21st June, 2017).
[24] M.Z.H. Bhuiyan, S. Söderholm, S. Thombre, L. Ruotsalainen, H. Kuusniemi, Overcoming the challenges of BeiDou receiver implementation, Sensors 14 (11) (2014) 22082–22098.
[25] R. Zou, Y. Chen, H. Koivalu, S. Lahtinen, M. Poutanen, J. Tang, C. Shi, The Performance of BeiDou Signals in High Latitude Area in Nordic Countries. 2016, European Navigation Conference, 2016, https://doi.org/10.1109/EURONAV.2016.7530556.
[26] P. Dabove, A.M. Manzino, GPS & GLONASS mass-market receivers: positioning performances and peculiarities, Sensors 14 (2014) 22159–22179, https://doi.org/10.3390/s141222159.
[27] D. Odijk, P.J. Teunissen, A. Khodabandeh, Single-frequency PPP-RTK: theory and experimental results, in: Earth on the Edge: Science for a Sustainable Planet, Springer, Berlin, Heidelberg, 2014, pp. 571–578.
[28] T. Takasu, A. Yasuda, Evaluation of RTK-GPS performance with low-cost single-frequency GPS receivers, in: Proceedings of International Symposium on GPS/GNSS, 2008, November, pp. 852–861.

[29] C.N. Nguyen, N.T. Tran, C.N. Nguyen, Evaluation of low-cost RTK-GPS accuracy for applications in the mekong delta, in: The 7th Vietnam Conference on Mechatronics (VCM-2014), 2014, pp. 608–613.
[30] S. Zhao, X. Cui, F. Guan, M. Lu, A Kalman filter-based short baseline RTK algorithm for single-frequency combination of GPS and BDS, Sensors 14 (8) (2014) 15415–15433.
[31] R. Odolinski, P.J.G. Teunissen, D. Odijk, Combined GPS+ BDS for short to long baseline RTK positioning, Meas. Sci. Technol. 26 (4) (2015) 045801.
[32] G.W. Roberts, Xu. Tang, Analysis and Comparison of GPS/BeiDou GNSS Signal Performance, FIG Working Week 2015, Sofia, Bulgaria, 17-21 May 2015, 2015. Available online: https://www.fig.net/resources/proceedings/fig_proceedings/fig2015/papers/ts05g/TS05G_roberts_tang_7620.pdf (Accessed on 21st June, 2017).
[33] u-center GNSS evaluation software for Windows, UBX-13005250-R16. Available online: https://www.u-blox.com/sites/default/files/u-center_UserGuide_%28UBX-13005250%29.pdf (Accessed on 2nd September, 2018).
[34] M. Barbarella, S. Gandolfi, A. Burchi, Improvement of an MMS trajectory, in presence of GPS outage, using virtual positions, in: 24th International Technical Meeting of the Satellite Division of the Institute of Navigation 2011, 2011, pp. 1012–1018. ION GNSS 2011.

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