Assessment of the Effects of Combining Multi-GNSS Constellations on the Solution Accuracy and Availability

Hussein Alwan MSAEWE[*] (UK), Craig Matthew HANCOCK (China), Panos PSIMOULIS, Gethin Wyn ROBERTS and Lukasz BONENBERG (UK)

Key words: Multi-GNSS, Noise, Accuracy, DOP Values, Correlation Analysis

SUMMARY

GPS has been proven to achieve high accuracy positioning for many monitoring applications. However, potential weak geometry of the GPS constellation and/or the blockage of the satellite signals by surrounding obstacles may reduce the accuracy, availability and the reliability of GPS monitoring. The development of additional GNSS systems (i.e. GLONASS, BeiDou) broadens the perspective of combining one or more constellations with the GPS constellation in order to resolve cases of weak GPS satellite geometry that may lead to lower accuracy positions and therefore errors in monitoring information.

The aim of this study is to compare the accuracy and the availability of the GPS solution with that of the GNSS solution, by evaluating their correlation with the corresponding satellite constellation. For this purpose, GNSS zero-baseline static measurements were carried out for 12 days simultaneously at two sites in the UK and China.

The GPS/GNSS records were processed in kinematic Double-Difference (DD) mode to assess the accuracy and the availability of the positioning for the two sites, by using various combinations of GPS, GLONASS (GLO) and BeiDou (BDS). The GPS and GNSS time series, expressing mainly noise caused by the satellite constellation and the receiver, were analysed using a moving standard deviation to define the variation of the noise level along the 24-hours of each day and finally were correlated with the corresponding DOP values. It was observed that the periods of high correlation for the GPS solution, corresponded to periods of high noise level and high DOP value, with the latter being above the mean DOP value of the day, while for the corresponding period of the GNSS solution, there was no correlation between noise and GNSS DOP value, indicating that the noise of the GNSS solution was not constellation-dependent.

Thus, it was observed that for periods of weak GPS constellation, which can be defined from the corresponding DOP, the contribution of the GLO and/or BDS will lead to solution of higher accuracy, availability and limit the impact of potential weak satellites.

[*] Nottingham Geospatial Institute, The University of Nottingham, UK
Surveying Department, College of Engineering, University of Baghdad, Iraq

Assessment of the Effects of Combining Multi-GNSS Constellations on the Solution Accuracy and Availability

Hussein Alwan MSAEWE* (UK), Craig Matthew HANCOCK (China), Panos PSIMOULIS, Gethin Wyn ROBERTS and Lukasz BONENBERG (UK)

1. INTRODUCTION

GPS is the positioning tool of choice for a wide variety of applications where high level of accuracy is required, such as structural monitoring in open sky environments. The derived position by GPS can be affected by satellite availability and their geometry, the quality of observations with ability to mitigate most of error sources as well as fixing the integer ambiguity for precise positioning (Hancock et al., 2009, Hancock et al., 2016, Taha et al., 2008).

In the case of poor availability of GPS satellite due to limited valid satellites (weak geometry) or signal obstruction, a possible remedy is integrated GPS data with measurements of other sensor (e.g. accelerometers (Han et al., 2016, Moschas and Stiros, 2015) , Robotic Total Station (Psimoulis et al., 2008, Moschas et al., 2013) or Locata (Bonenberg et al., 2009, Montillet et al., 2009), Inertial Sensors as well as Ultra-Wide Band (Wang et al., 2016, Gao et al., 2014). However, these supplementary sensors have limitations, while the combination of GPS and other GNSS constellation can considered a possible solution (Rabbou and El-Rabbany, 2015). The combination of two or more satellite systems offers more visible satellites to users, and that will enhance the satellite geometry with the expectation of improving the overall positioning solution (Msaewe et al., 2017)

For this study GNSS zero-baseline measurements were carried out with different pairs of similar receivers for 12 consecutive days, simultaneously in the UK and China sites. Zero-baseline with Double-Difference (DD) solution mode, can eliminate most of the common errors of the GNSS measurements (i.e. satellite orbits and clock, atmospheric delay and multipath effect). Thus, the remaining error of the GNSS solution is due to the geometry of the satellite constellations and the noise of the GNSS receiver.

The aim of this study is to assess the contribution of the GLO and BDS satellite systems when they are combined with GPS constellation. The assessment investigated whether the combination of the satellite systems can limit the noise level of the GPS-only solution and assess the improvement of the positional precision with fixed solution availability. The analysis of this study focused on the precision of the GNSS solution using all the possible combinations of the available satellite systems. The precision of each combination of GNSS-solution was correlated with the corresponding DOP values, with the latter expressing the geometry of the satellite constellation.

2. EXPERIMENTS DESCRIBTION

Extensive measurements with zero-baselines were carried out with a 1-s sampling rate simultaneously in the UK and China for 12 consecutive days, between the 5th and 16th March, 2015.

At the UK site, a Leica AR10 antenna was mounted on a pillar and connected, via a splitter (GPS RMS18 splitter), to two pairs of multi-GNSS receivers; the Leica-GS10 and Trimble-NET9. For the second zero-baseline in China, a LEIAR25R4 antenna was set up on a pillar and connected, via a splitter (GPS/GNSS RMS18 Splitter 8-way) to four pairs of GNSS receivers consisted of Javad-TRIUMPH, ComNav K508, Unicore UR240 and Septentrio ASTERX2EL. Both antennas were mounted in open sky environments (Figure 1). The specifications of the receivers used are given in Table 1.

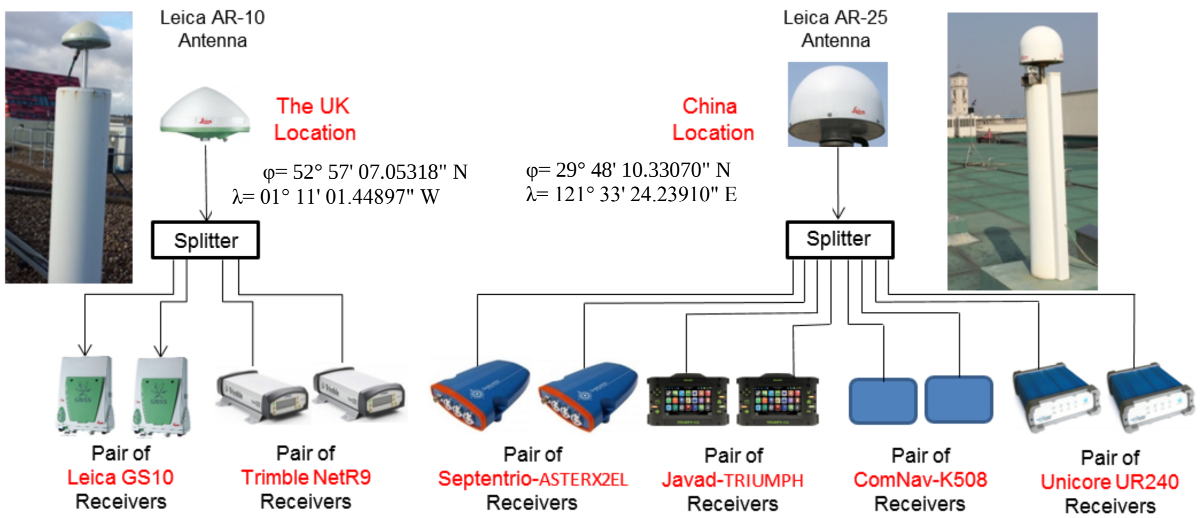

Figure 1, Zero baseline experiment setup. (Msaewe et al., 2017)

Table 1, Specification of the GNSS receivers used in the measurements.

Site	Antenna type	Types of receivers Pairs	Name used	recorded Constellations			
				GPS	GLO	BDS	Gal
UK	Leica AR-10	1) Leica Viva GS10	Rec.UK1	√	√	√	√
		2) Trimble NET9	Rec.UK2	√	√		√
China	Leica AR-25.R4	3) Septentrio ASTERX2EL	Rec.Ch3	√	√	√	√
		4) Javad-TRIUMPH-VS	Rec.Ch4	√	√	√	√
		5) ComNav K508	Rec.Ch5	√	√	√	
		6) Unicore UR240	Rec.Ch6	√		√	

In this study, the contribution of the Galileo constellation is not assessed due to the limited number of available satellites, since there were only three satellites (E11, E12, and E19) functioning reliably at the time of the experiments.

3. DATA ANALYSIS

The GNSS data were converted into RINEX format, and processed using RTKLIB v2.4.2, in kinematic mode to assess the precision of the position for each epoch using DD solutions, with cut-off elevation angle of 15°. In order to define which pair of the available receivers in each site had the most reliable performance and characterised by relatively low receiver noise, a preliminary analysis was achieved. Therefore, among several sessions of 1-hour duration, the 1-hour session from 01:00 to 02:00 (GPS time) of 05/03/2015 was selected. This period was selected as it is free from data gaps and cycle slips, and with the collocated receivers tracking the same satellites, leading to comparable results. The time series of the GPS-only solution, which basically express the deviation of each epoch from the station coordinates, for the different receivers are shown in Figure 2.

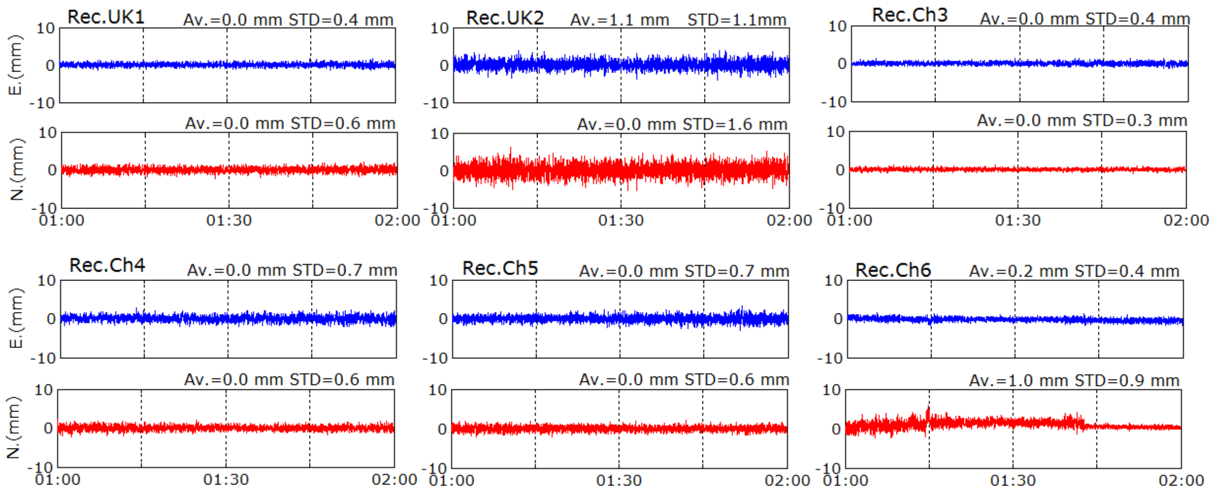

Figure 2, GPS time series of the zero-baseline records of the six types of receivers for the UK and China sites.

For each set, the average and standard deviation (STD) of every component was computed. From the analysis of the two pairs of receivers in the UK, it is clear that the noise level of the Rec.UK2 is larger than that of Rec.UK1. On the other hand, comparisons between the receivers in China indicate that Rec.Ch3 receivers show the least noisy behaviour, from all the receivers in China, with the minimum STD relative to the other receivers in China along E, N and U components. Similar results were found by comparing these receivers for the constellations of GLO and BDS.
Rec.UK1 seemed to be more accurate than the Rec.UK2 for all the available constellations. In China, the Rec.Ch3 receivers characterised by the lowest noise level (i.e. smallest STD) for GPS-only solution, followed by the Rec.Ch4.

Furthermore in order to evaluate the quality of the GNSS data, auto-correlation analysis was applied, which expresses potential correlation of the time series data and reveals whether the time series are contaminated only by white noise. The results of the auto-correlation of the GNSS time series of the preliminary analysis are presented, where it is obvious that the GPS data are uncorrelated and express mainly white noise for most of the receivers, as the auto-correlation coefficient is ranging randomly around zero, for all the time lag values.

Finally, the results of this analysis indicate that the receivers Rec.UK1 and Rec.Ch3 can be adopted for the investigation of the study, as they proved to be the receivers fulfilling the criteria of (i) reliable performance, (ii) low noise level and (iii) the least correlated data noise.

3.1 Availability and precision in the UK site

To investigate the precision and availability in the UK dataset, there are three different GNSS solutions: (i) GPS-only, (ii) GLO-only and (iii) a combined GPS/GLO. The availability represents the percentage of epochs with fixed solution compared to the total number of observed epochs. When the daily solution is analysed, the time series of the GPS-only solution has an availability of 97.4% fixed solution, while GLO-only solution shows fewer gaps with availability of 99.1% as illustrated in Figure 3. By using the GPS+GLO combined solution the availability increases up to 100%, proving that the combined GNSS solution, due to the increased number of satellites, can overcome problematic periods, where the GPS-only or GLO-only solutions are characterised by gaps.

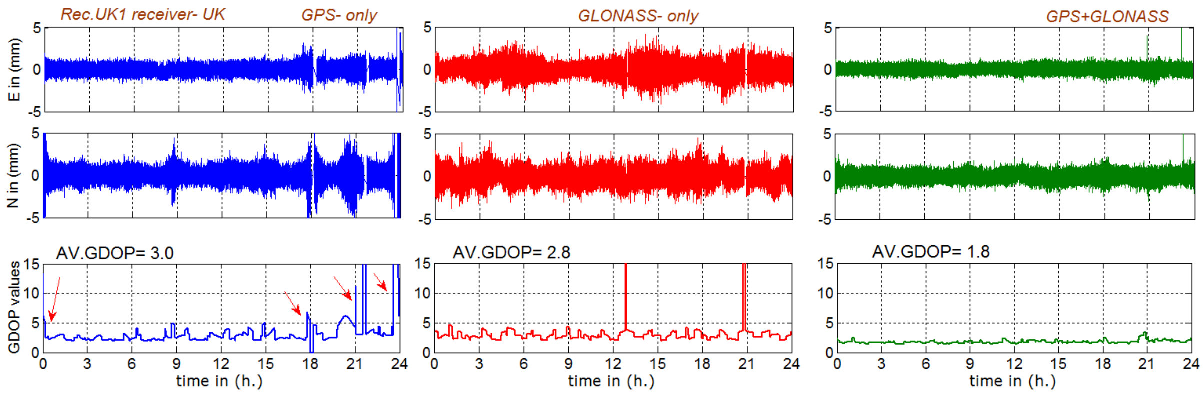

Figure 3, Daily time series showing GPS-only (left), GLO-only (centre) and combined GPS+GLO (right) with Rec. UK1 receiver (UK site) on 05/03/2015.

By analysing the whole 12-day period, it is clear that the GLO-only solution has, slightly better availability than the GPS-only solution as illustrated in Figure 4a, due to a few data gaps in the GPS-only solution. These gaps are the result of weak geometry when the solution corresponds to extremely high DOP values (i.e. GDOP>30), or fundamentally there is no solution due to limited number of satellites (<4) at these intervals. These gap intervals lead to the minimising of the GPS availability corresponding to loss ~50 min during a day (i.e. 12th March). Therefore, the combination of GPS+GLO solution increases the number of valid satellites and gives the highest availability reaching up to 100% for the entire examined period.

Regarding the precision of the positioning, it is observed that the GPS-only solution is more accurate than the GLO-only solution in the E and U components, while the GLO-only solution proved to be more accurate for the N component. However, the GPS+GLO combination gives the more accurate solution for all components as expressed in Figure 4b. The improvement in N component of GLO is related to its constellation design with 64.8° inclination, which leads to better coverage at higher latitudes.

The combination of GPS and GLO leads to enhanced satellite geometry, which is expressed through the reduction of the DOP values (Odolinski and Teunissen, 2016), improving the achieved precision. Furthermore, all outliers in the individual solutions due to poor satellite coverage are removed, with the mean of the GDOP being improved by 60%; (e.g. the GPS+GLO solution provides mean GDOP of 1.8, while for GPS- only and GLO-only solution are 3.0 and 2.8, respectively).

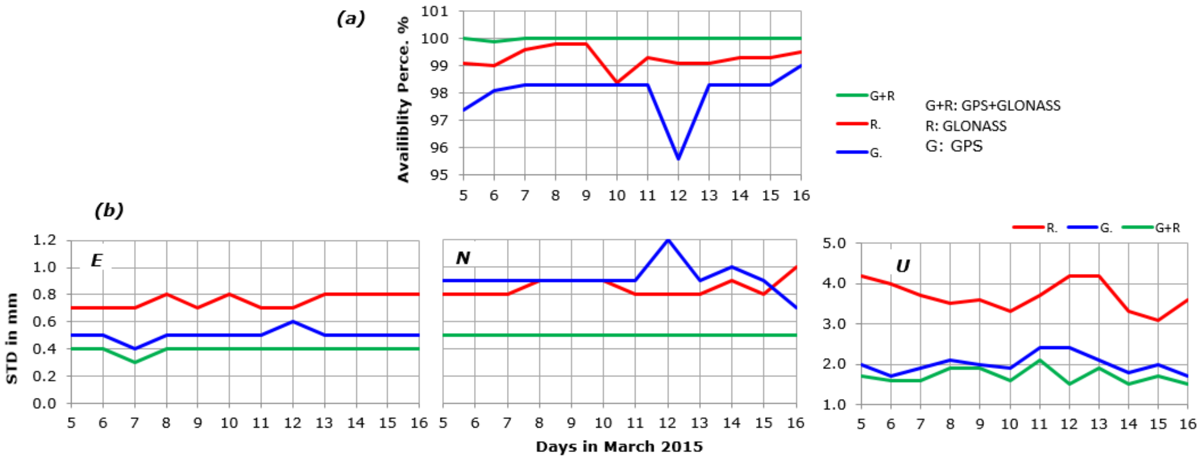

Figure 4, (a) Availability and (b) precision expressed as STD at the UK site with Rec.UK1 over the 12 days period of the measurements.

3.2 Availability and precision at the China site

Regarding the GNSS records of the dataset in China, the same approach was followed for the analysis of the GNSS records, with the only difference being the additional constellation of BDS and all the possible combination of it with GPS and GLO. The daily solution on 5th March showing that the individual solution of either GPS or BeiDou has an optimum availability of 100% fixed solution, which indicates a perfect coverage due to the adequate number of satellites. Whereas the availability of GLO-only fixed solution is slightly lower (i.e. 98.2%) as a result of few periods with weak geometry. These periods have extremely high DOP values, when the elevation of the reference GLO satellite is lower than 50°. A similar trend of the availability can be repeated along 12 days for individual solution of three systems, while combination between any two systems can achieve optimum availability of 100%, as illustrated in Figure 5a.

To assess the precision, the two sites can be compared. The GPS-only solution in China is similar to that of UK site, with significant improvement of STD though in the N component (~0.4mm in China versus 0.8-0.9mm in the UK), due to the improved constellation (Fig. 5b). The precision of GLO-only solution at the two sites showing similar precision in N component, while the E and mainly U components in China site have significantly worse accuracy than that of UK site, especially in U component reaching up to 23-mm.

The achieved precision of the BDS-only solution proved to be receiver dependent. Although, the main focus is concentrated on GPS solution and how the other constellation can help degraded GPS solution, the comparison between different receivers led to the selection of receiver Rec.Ch3, as it achieved the minimum level of noise for the combined GPS and GLO solution, however the corresponding BDS solution was very noisy. On the contrary, the Chinese receiver (Rec.Ch5) led to less noisy BDS solution, while the corresponding GPS solution was very noisy. Therefore, the positional precision of GPS-only, BDS-only were investigated using these two receivers. The corresponding results related to improvement along all components and reduce the noise level of GPS when combined with BDS consistent to low level of noise.

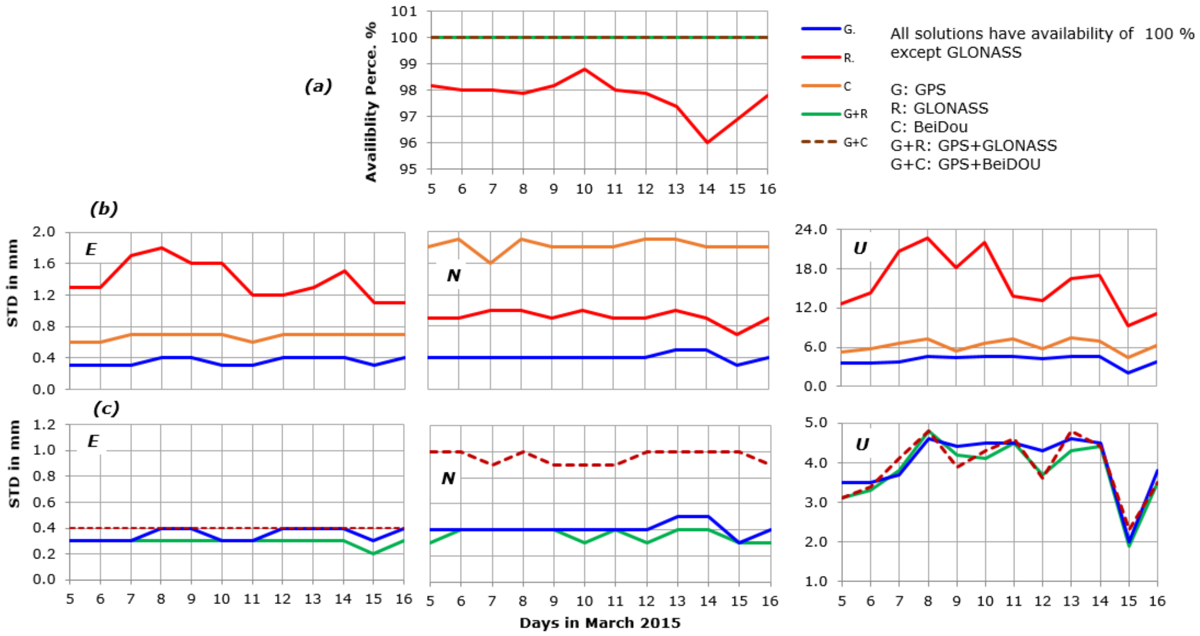

Figure 5, a) Availability of fixed solution and (b) comparison between precision expressed as STD of individual GPS, GLO and BDS solutions and c) GPS-only, combined GPS/GLO and combined GPS/BDS at the China site with Rec.Ch3, during the 12 days period of the measurements.

4. NOISE AND GEOMETRY CORRELATION

To quantify the impact of the geometry of different GNSS systems combinations on the precision of the GNSS positioning, a linear-correlation analysis was made between the DOP values and the standard deviation (STD) of the GNSS solutions, with the latter expressing the precision of the results. The horizontal component of the GNSS measurements, derived from E and N components, corresponds to the HDOP (Horizontal DOP), while the vertical component U corresponds to the VDOP (Vertical DOP). The correlations were assessed for consequent segments of the time series using a moving window, and computed the correlation coefficients (R^2), to assess whether the precision of the GPS solution is strongly correlated with the satellite constellation. Furthermore, to examine whether an additional satellite constellation can improve the noise level of GPS-only solution.

For the daily time series of GPS-only on 5th March, the correlation of the moving STD and the moving average of DOP values for UK time series related to R^2 of 0.93 and 0.86 for the horizontal and vertical components, respectively. The corresponding correlation for China GPS time series resulted in R^2 of 0.85 and 0.51 for the horizontal and vertical components, respectively. However, the correlation of daily results between the noise and satellite geometry gives a representative picture, a better identification of high correlated intervals can be achieved for hourly segments. Therefore, the correlation is computed for GPS-only and compared with combined GPS/GLO for both data sets in the UK and China as shown in Figure 6.

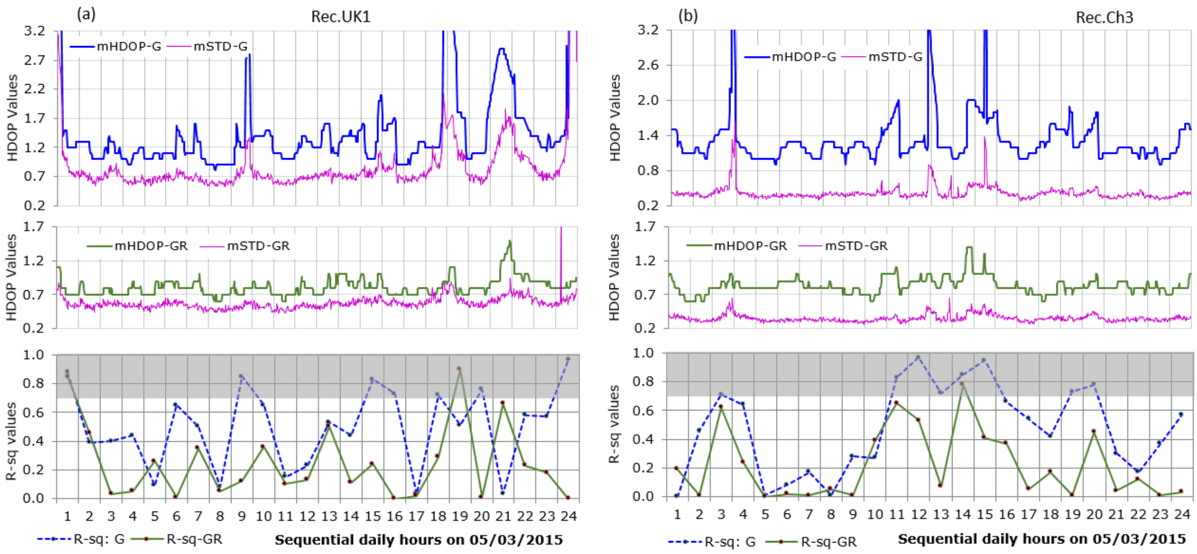

Figure 6, Linear correlation between moving average of the HDOP values and the moving STD of the corresponding horizontal component for GPS-only and combined GPS/GLO solutions for (a) the UK site (b) China site.

It is obvious that for the GPS-only solution, the well-correlated intervals (i.e. $R^2 > 0.7$; in the grey-shaded area of Fig.6) occur for periods of high DOP values, larger than 1.4, and noisy data, where the STD is more than 0.8mm and follows the waveform of the DOP value. For the low-correlated intervals (R^2 <0.7), the DOP value is below 1.4 and the GPS solution of high precision, since the STD fluctuates below 0.8mm. The impact of the poor constellation in the GPS-only solution is more well-defined in China, where the GPS-only solution is of high precision apart from some weak intervals, while in the UK the relatively worse constellation leads in generally less accurate GPS-only solution. Therefore, the highly correlated intervals indicate the significant impact on precision, which means the improvement in constellation geometry would improve the precision, while low correlated values (i.e. R^2 <0.7) the precision is practically independent from the satellite constellation (i.e. DOP values).

For combined GPS/GLO solution, it is clear that the correlation of DOP values with the standard deviation is weaker than the GPS-only solution, as the R^2 is usually smaller than the corresponding of the GPS-only solution. Consequently, this indicates that the addition of GLO constellation reduces significantly the impact of the satellite constellation in the final solution, as a result of reduced DOP values (i.e. <1.5) and the STD ranging below 0.8mm for both data sets in the UK and China (Fig. 6). A Similar effect can be achieved when adding BDS to GPS with for the Chinese collected dataset. The noise level was reduced in combined solution with improvement in DOP values, which also reduced the correlation coefficients.

5. CONCLUSIONS

The results show that the combination of GPS with other GNSS constellations can overcome problematic periods occurred in the time series of GPS-only solution, and increase the availability of fixed solution. Furthermore, the ability of combined solution to reduce the noise level and improved the positioning precision. The results illustrate that there is a correlation between GNSS geometry expressed by DOP values and the precision of noise characterised by STD. The high correlated intervals can identified when the DOP values and STD are larger than the limit of daily mean of the corresponding DOP and STD, while lower correlation occurred in periods lower than this limit. The latter case means the precision is practically independent from the satellite constellation. The impact of this correlation can be applied when analyse the noise of GNSS constellations, and contributes in analysis of errors in structural monitoring.

AKNOWLEDGEMENTS

The work in this paper is sponsored by the Iraqi Ministry of Higher Education and scientific Research (MOHESR), and partially supported by the Ningbo Science and Technology Bureau as part of the International Academy for the Marine Economy and Technology (IAMET) project ‘Structural Health Monitoring of Infrastructure in the Logistics Cycle (2014A35008)’.

REFERENCES

BONENBERG, L. K., ROBERTS, G. W., HANCOCK, C. M., OGUNDIPE, O. & LEE, J. K. Feasibility of integrated Locata and GNSS for Engineering Work Application. Proceedings of the 2009 International Symposium on GPS/GNSS, Korea, 2009.

GAO, Y., MENG, X., HANCOCK, C. M., STEPHENSON, S. & ZHANG, Q. UWB/GNSS-based Cooperative Positioning Method for V2X Applications. 27th International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS+ 2014), Tampa, Florida, 2014.

HAN, H. Z., WANG, J., MENG, X. L. & LIU, H. 2016. Analysis of the dynamic response of a long span bridge using GPS/accelerometer/anemometer under typhoon loading. *Engineering Structures*, 122**,** 238-250.

HANCOCK, C., ROBERTS, G. & TAHA, A. 2009. Satellite mapping in cities: How good can it get. *Proceedings of the Institution of Civil Engineers: Civil Engineering,* 162**,** 122-128.

HANCOCK, C., ZHANG, P., LAU, L., ROBERTS, G. & LIGT, H. D. Satellite mapping in cities and below cities: how good is it now? Proceedings of the Institution of Civil Engineers-Civil Engineering, 2016. Thomas Telford Ltd, 1-6.

MONTILLET, J. P., ROBERTS, G. W., HANCOCK, C., MENG, X., OGUNDIPE, O. & BARNES, J. 2009. Deploying a Locata network to enable precise positioning in urban canyons. *Journal of Geodesy,* 83**,** 91-103.

MOSCHAS, F., PSIMOULIS, P. A. & STIROS, S. C. 2013. GPS/RTS data fusion to overcome signal deficiencies in certain bridge dynamic monitoring projects. *Smart Structures and Systems,* 12**,** 251-269.

MOSCHAS, F. & STIROS, S. 2015. Dynamic Deflections of a Stiff Footbridge Using 100-Hz GNSS and Accelerometer Data. *Journal of Surveying Engineering,* 141**,** 04015003.

MSAEWE, H. A., HANCOCK, C. M., PSIMOULIS, P. A., ROBERTS, G. W., BONENBERG, L. & DE LIGT, H. 2017. Investigating multi-GNSS performance in the UK and China based on a zero-baseline measurement approach. *Measurement,* 102**,** 186-199.

ODOLINSKI, R. & TEUNISSEN, P. J. G. 2016. Single-frequency, dual-GNSS versus dual-frequency, single-GNSS: a low-cost and high-grade receivers GPS-BDS RTK analysis. *Journal of Geodesy,* 90**,** 1255-1278.

PSIMOULIS, P., PYTHAROULI, S., KARAMBALIS, D. & STIROS, S. 2008. Potential of Global Positioning System (GPS) to measure frequencies of oscillations of engineering structures. *Journal of Sound and Vibration,* 318**,** 606-623.

RABBOU, M. A. & EL-RABBANY, A. 2015. Precise Point Positioning using Multi-Constellation GNSS Observations for Kinematic Applications. *Journal of Applied Geodesy,* 9**,** 15-26.

TAHA, A., KOKKAS, N., HANCOCK, C., ROBERTS, G., MENG, X. & UFF, J. A GIS Approach to GNSS Simulation in Urban Canyons. In Proc of ENC-GNSS 2008, 2008.

WANG, J., GAO, Y., LI, Z., MENG, X. & HANCOCK, C. M. 2016. A Tightly-Coupled GPS/INS/UWB Cooperative Positioning Sensors System Supported by V2I Communication. *Sensors,* 16**,** 944.

BIOGRAPHICAL NOTES

Hussein Msaewe is Assistant Professor of Surveying Engineering at the College of Engineering, University of Baghdad, Iraq. He is currently enrolled as a full-time PhD student with the Nottingham Geospatial Institute (NGI), the University of Nottingham, UK. His current research interests are concentrated around structural monitoring by multi-GNSS.

Dr. Hancock is Acting Head of the Department of Civil Engineering and Head of the Geospatial and Geohazards research group at The University of Nottingham, Ningbo, China. He is a member of the Editorial Board of the Journal "Survey Review" and has been involved with the International Federation of Surveyors (FIG) and has been a Vice Chair for communications on Commission 6 (Engineering Surveys) from 2010 – 2013.

Dr. Panagiotis Psimoulis is Assistant Professor in Geospatial Engineering at The University of Nottingham and member of Nottingham Geospatial Institute. His research activities, started in University of Patra leading to a PhD degree, continued in ETH Zurich, Switzerland, and now in University of Nottingham, focus on structural monitoring using advanced geodetic techniques and GPS applications in Geohazards. His research has led to 25 published international journal papers and more than 60 conference papers.

Gethin Wyn Roberts has worked and studied at the University of Nottingham for over 26 years. He has a degree in Mining Engineering and a PhD in Engineering Surveying and Geodesy. He has co-authored over 250 publications, and supervised 25 PhD students. Gethin is a Fellow of the Chartered Institution of Civil Engineering Surveyors, and past Chairman of FIG's Commission 6 "Engineering Surveys". Gethin is also Co-Editor in Chief of the Springer Journal of Applied Geomatics.

Dr Lukasz K Bonenberg is a Senior Experimental Officer at the University of Nottingham with over ten years of experience in academia and industry. Lukasz holds PhD from the University of Nottingham. His main research focus is positioning, navigation, sensor fusion and data science. His previous research included augmentation of GNSS with ground transmitters for engineering applications, low-cost IMU and UWB indoor positioning and GNSS interference including jamming. His industrial experience includes large commercial and governmental GIS, engineering and monitoring projects in the UK, USA and Poland. He is a Corporate Member of Chartered Institute of Civil Engineering Surveyors, Association for Geoinformatics, GeoIT and Navigation e.V. and the Institute of Navigation.

CONTACTS

Hussein Alwan Msaewe
Nottingham Geospatial Institute (NGI), the University of Nottingham, UK
The University of Nottingham, Jubilee Campus, Triumph Rd, Nottingham NG7 2TU
Nottingham
UK
Tel. +44 7784488545
Fax +
Email:isxhm1@nottingham.ac.uk
Web site: www.nottingham.ac.uk