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1. The sentence ‘Information on the data collected … analyse the collected data’ seems to be incomplete. Please check.

2. Please check whether the deletion a closing parenthesis in the sentence ‘Three Trimble R10 GNSS receivers … one in the afternoon at 4 pm’ is appropriate.

3. Please check the clarity of the sentence ‘It might be because of the … benefits could not be seen’.

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Environmental spatial data within dense tree cover: exploiting multi-frequency GNSS signals to improve positional accuracy

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Received: 31 October 2019 / Accepted: 14 January 2020

Abstract

Environmental monitoring tasks over large spatial coverage often necessitate acquiring sample/reference positions using the global navigation satellite systems in order to optimise operational costs. Often, such tasks occur within dense tree coverage where the navigation signals are blocked. For tasks requiring accurate positions under limited resources, this becomes undesirable, especially if the operation is to be carried out while in motion, i.e. “on the fly” or “real-time kinematic”. Even with this realisation, numerous studies investigating the potential of combining the constellations of these navigation systems mostly focus on their structural aspects, leaving the exploitation of the multi-signal constellation under dense tree cover largely untested. Using a test experiment of a station declared unusable due to dense tree cover at Curtin University (Australia), this study evaluates whether sample positions can be improved using multi-constellation global navigation satellite systems where poor sky visibility exist due to tree coverage. Positioning improvement measures are (1) geometrical gain measured by position dilution of precision, (2) horizontal and vertical uncertainty estimates and (3) positional accuracies determined through the comparison of the obtained control positions and their known values. The results indicate significant positioning improvement when all constellations are utilised in comparison with using Global Positioning System alone in dense tree cover environments, i.e. geometrical gain of as much as 72%, horizontal precisions by about 40%, vertical precisions of up to 50% and 94% accuracy improvement. This study thus opines that utilising full global navigation satellite’s constellation would benefit environmental monitoring tasks carried out under dense tree cover.

Keywords

Environmental sensing
Dense tree coverage

Dense urban
GNSS
Constellation

Communicated by M. Abbaspour.

Introduction

Environmental monitoring tasks within dense forested areas requiring accurate determination of positions using global navigation satellite system (GNSS) observations are on the rise. For example, GNSS is employed to provide ground reference data for accuracy assessment of the land-use–land-cover classified data (Punia et al. 2011), geo-referencing (Goossens et al. 2006), image calibration (Goodman and Ustin 2002), not to mention the location of the sampled data (Sweeney International Management Corp 2009). GNSS suitability in these tasks results mainly from the fact that in recent times, it offers one of the fastest means for positioning on Earth due to the levels of accuracy that can be obtained, the faster solution time achievable in comparison with other traditional positional determination methods (e.g. Schloderer et al. 2011) and the relative ease of use. This has endeared it to environmental monitoring tasks such as coastal shoreline monitoring (Gonçalves et al. 2013), disaster management (Hammond et al. 2010), animal telemetry for conservation (Awange and Kiema 2013), global warming and climate variability/change (Khandu et al. 2010) and land-use/land-cover change (Punia et al. 2011), just to list but a few. A detailed exposition of GNSS environmental sensing is well documented, e.g. in Awange (2012, 2018) and Awange and Kiema (2013, 2019).

Even with a plethora of advantages, GNSS positioning is, however, limited by the inter-visibility between the receivers and the satellites, which are being observed. In order to provide accurate position of an environmental variable, a minimum of four satellites are required to be observed. However, obstructions such as trees and buildings normally prevent observations to the satellites causing what is known as cycle slips [i.e. loss of lock to the satellites, see, for example, Hofman-Wellenhof et al. (2001)] and can also be sources of multi-path (disturbance of unwanted reflected signals), which can degrade results or in some cases prevent positions from being achieved at all if not enough satellites are able to be observed. While the USA's Global Positioning System (GPS) has been designed so that the majority of the time users will have access to a minimum of four satellites at a time, exceptional circumstances such as very poor sky visibility, e.g. from tree cover (e.g. El-naggar

2011) may mean this is not always the case. This situation is undesirable, especially in light of the meagre resources often allocated to GNSS monitoring tasks, especially in the overall budget of an environmental monitoring campaign (Awange and Kiema 2019).

While the US-based Global Positioning System (GPS) is the original GNSS constellation, Russia's GLONASS has been in operation since 1993. Since the introduction of GLONASS, studies have been carried out to combine the observations made by both these constellations to assess whether improvements in positioning could be achieved (e.g. Awange and Kiema 2019). More recently, two more GNSS constellations have been introduced: BeiDou, a Chinese developed constellation introduced in its first iteration in 2000 (Tiberius 2011), and Galileo (European Commission and European Space Agency 2002), a constellation developed by the European Union and still in early operation capacity as of 2019 (https://galileognss.eu/). It has been shown in the literature that there may be benefits to using multiple constellations for the processing of GNSS observations where sky visibility is not ideal. For example, Wang et al. (2012) assessed the possibility of using GPS, GLONASS, BeiDou and Galileo looked to improve GNSS positioning within a dense urban environment such as a city using simulation and modelling, and found that they were able to achieve reliable positioning in most scenarios by processing data using all available constellations, whereas they were unable to achieve the same with only GPS or with GPS and GLONASS. While the theory of using multi-constellation was tested using simulation in their study, only GPS and GLONASS observations were taken and compared in practice as Galileo was only available in the early operational stage when they conducted their study. Quan et al. (2016) studied the different signals used by the different constellations GPS, GLONASS, BeiDou, Galileo and Quasi-Zenith Satellite System (QZSS), and the results of using different combinations of constellations for baseline processing (i.e. distance between a known position and the unknown point whose position is desired) and concluded that over very short baselines (10 m), using one constellation alone is enough to achieve very good accuracies, but over long baselines (7 km tested), the accuracies achieved improved when using both dual-constellation combinations and all constellations compared to single constellation. However, it was also found that using dual constellation can actually slightly decrease the precisions achieved in some particular data sets and using all constellations can result in decreased availability of a fixed solution. They concluded that these were likely caused by the magnified effects of multi-path due to the increased number of satellites and signals available. Their study was also conducted before Galileo was officially launched and in the early operational stage, meaning that the results found may not be indicative of Galileo operationality, which would be obtained at the time of this study.

Swann (1999) discussed the limitations of the GPS constellation and the effects of the introduction of a second GNSS constellation and GLONASS on the results in areas where GPS observations by themselves were inadequate for positioning. Only GPS L1 and GLONASS L1 signal observations were taken and analysed due to equipment limitations. The study found that in areas where sky visibility was limited, e.g. due to dense urban environment or tree cover, the increase in available satellites by utilising the additional constellation resulted in improved precision, but did not necessarily result in improved positional accuracy when compared to GPS alone. It is important to note, however, that GLONASS was not fully operational at the time of their study, and GPS was still hindered by selective availability for civilian users. A similar study was conducted more recently by Ferrão (2016) utilising GPS, and GPS and GLONASS combined observations in order to analyse whether using the combined signals proved beneficial to the results of precise point positioning (PPP) (Goncalves and Awange 2017). It was found that numerous improvements to the results were present when using the combined data, such as improved reliability, benefits that were particularly relevant where sky visibility was low and the amount of visible satellites when using a single constellation was not sufficient for good results.

Although numerous studies have been published on the impact of multi-GNSS on positioning and navigation especially after December 2012 (BeiDou) and December 2016 (Galileo), e.g. Lau et al. (2015), Torre and Caporali (2015) and Lou et al. (2016), most of them consider the structural aspects of GNSS such as improving precise point positioning (PPP, for example, Lou et al. 2016). Torre and Caporali (2015) on their part consider the system biases in commercial receivers tracking multiple GNSS satellites. In general, most of these studies target GNSS community and seldom the environmental community whose interest maybe simply to position under dense vegetated areas where GNSS signals are impacted. With many GNSS receivers, such as the Trimble R10 used in this study now having access to signals generated by GNSS constellations such as GLONASS, Galileo and BeiDou, as well as the traditional GPS, the objective of this study is to determine whether by utilising these newer constellations, Galileo and BeiDou, in their current operational capacity in conjunction with GPS, and GPS and GLONASS, improved results in dense vegetation cover that can benefit environmental monitoring tasks that require positioning in such environments.

The remainder of this study is structured as follows. Section 2 presents the test example used to take the GNSS observations required for the analysis. Information on the data collected, the processing applied to the data and the methods used to analyse the collected data. The results are then presented and discussed in Sect. 3 and concluded in Sect. 4.

AQ1

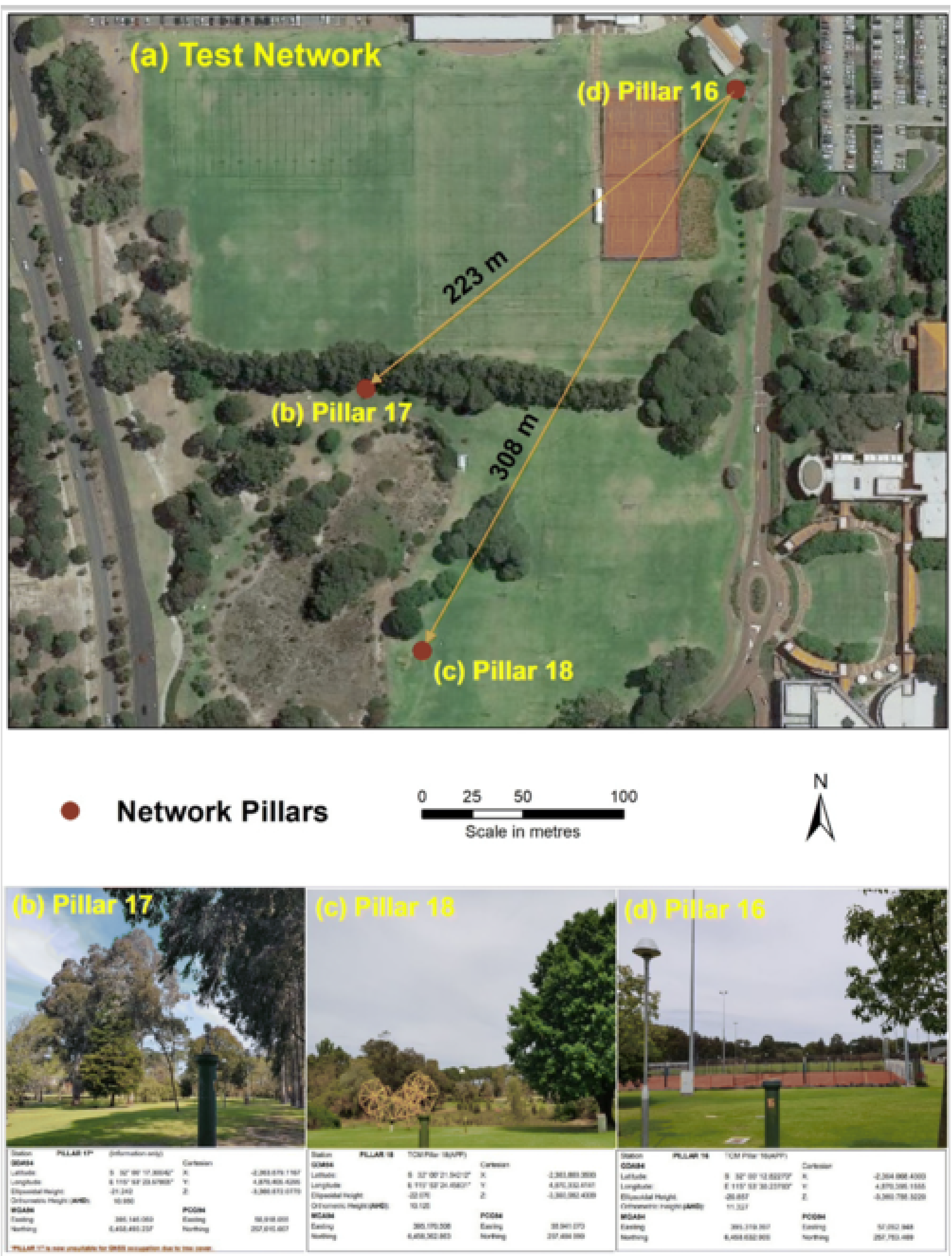
Experimental design

Test network

The experimental setup is placed within the western side of Curtin University (Australia)'s Bentley campus using a network of three GNSS test network. This GNSS test network originally consisted of six concrete pillars with accurately known, and regularly monitored, 3D coordinates. Out of these, pillars (16, 17 and 18) were used, where Pillar 17 has been declared unsuitable due to high level of obstruction caused by dense tree cover (see Fig. 1, which provides an idea of the amount of tree coverage located around this pillar) by the Western Australia's State body in charge, i.e. Landgate. Although Fig. 1a seems to illustrate P18 as more obscured than P17, a closer view of Fig. 1b–d shows the obstruction in Pillar 17. Almost all northern sky visibility of this pillar is blocked, and obstruction is also present partially to the south, meaning only a small window of sky visibility is available. Pillar 17 is thus used as the "*test*", i.e. impacted pillar. Pillar 18 is designated as the "*experimental–control pillar"*, i.e. non-impact impacted pillar, which is largely in the open with small amount of tree obstruction and would be considered mostly ideal for GNSS observations. Although a metal sculpture is located close by, the vast majority of obstruction resulting from it will be removed when the 15° elevation mask is applied during processing. This point is being used in the control baseline. Pillar 16 provides a common base to both test and control pillars, i.e. the positions of Pillars 17 (test) and 18 (control) are obtained relative to those of Pillar 16 whose coordinates are fixed during processing in Trimble Business Centre processing software. Although some obstructions are located nearby Pillar 16, much of it is eliminated by setting the GNSS receiver observation window to 15° elevation mask. Any degradation of results from the obstructions around Pillar 16 will be present in both test and experimental–control pillars, meaning the majority of the differences found between Pillar 17 (test) and Pillar 18 (experimental–control pillar) can be better attributed to being due to very small obstruction (Pillar 18) versus high obstruction (Pillar 17). The Landgate provided coordinates for each of the pillars, which were used in this experiment (see Fig. 1b–d).

Fig. 1

Locations of Pillars 16, 17 and 18 within Curtin University (Australia) that are used for the test experiment. The pillar coordinates are provided by Landgate, which has declared Pillar 17 unsuitable due to dense tree cover. Trimble R10 taking observations on Pillar 17. Although **a** seems to illustrate P18 as more obscured than P17, a closer view of **b**–**d** shows the obstruction in Pillar 17



Field measurements

Three Trimble R10 GNSS receivers were established on top of each pillar (e.g. Figure 1b, Pillar 17) which shows one of the Trimble R10 setups and observing on Pillar 17, and three separate observation sets of 45-min duration were taken: one in the morning at 9 am, one at midday and one in the afternoon at 4 pm. The Trimble R10 receivers are capable of receiving signals from GPS, GLONASS, BeiDou and Galileo, which will be used during the data processing for this experiment. In order to account for any offset between the antenna's physical and phase centre, all the receivers were orientated facing north during observations. These offsets result in small errors being introduced to the distances measured between the baseline points. Orientating all the receivers in the same direction helps to remove these errors.

AQ2

Data processing

Once all data had been collected, Trimble Business Centre (TBC) was used for the baseline processing. A set of baselines from Pillar 16 to Pillar 17 and Pillar 16 to Pillar 18 were processed for each set of data obtained. Each baseline was trimmed so that exactly 45 min of overlapping observations was processed for each (at a 5 s sampling rate, i.e. 12 observations per minute or 540 observations over the 45-min period), to ensure that the baselines were directly comparable.

Each of the three observation sets were processed using only one GPS signal (L1), two GPS signals (L1 and L2), a combination of GPS L1 and GLONASS L1, a combination of GPS L1 + L2 and GLONASS L1 + L2 and a combined GPS, GLONASS, BeiDou and Galileo signals. A summary of the GNSS signal combinations tested is given in Table 1. TBC outputs baseline processing reports, which are used to analyse the precision and accuracy measures, amounts of satellites tracked and the quality of observations to each satellite.

Table 1

GNSS signal structure and the possible combinations

Signal	Employment
GPS L1	Only one US-based GPS signal is used
GPS L1 + L2	A combination of both US-based L1 and L2 signals used to mitigate ionospheric effects

Signal	Employment
GPS L1 and GLONASS L1	A combination of both US-based L1 and Russian-based L1 signals
GPS L1 + L2 and GLONASS L1 + L2	A combination of both US-based L1 + L2 and Russian-based L1 + L2 signals used to mitigate ionospheric effects
All constellations	Use of all available US-based GPS, Russian-based GLONASS, EU-based Galileo and Chinese-based BeiDou signals

Analysis method

The quality of results is defined by their precision and accuracy. The ability for ambiguity resolution to provide a fixed solution for integer ambiguities is essential for a high level of accuracy and precision to be obtained using this method of positioning. Whether a fixed or float solution is obtained using the different signal combinations is assessed, and the effects this has on accuracy are determined.

The precision, which describes the repeatability of the results obtained, is estimated in terms of horizontal and vertical precisions. They are provided once a baseline has been processed, where they are determined using redundant observations, satellite geometry and estimated error sources. The estimated precisions for each set of data are then compared. In addition, positional dilution of precision (PDOP) values are expressed as single numbers that describe the positional uncertainties, which are a result of the amount of satellites that are being observed, on the one hand, and the geometry between the satellites, on the other hand. The higher the PDOP values, the lower the precision obtained. The changes in the PDOP which is found by adding GNSS constellations are also analysed as a way of estimating any improvements in precision.

Finally, accuracies defined by the difference between calculated results and the known values are utilised to analyse the results since the pillar coordinates are already known. The coordinate differences between the known and calculated easting, northing and heights for the two points are examined, and the positional errors for each tested option (see Table 1) are expressed in RMSE form so that they are easily compared.

Results and discussion

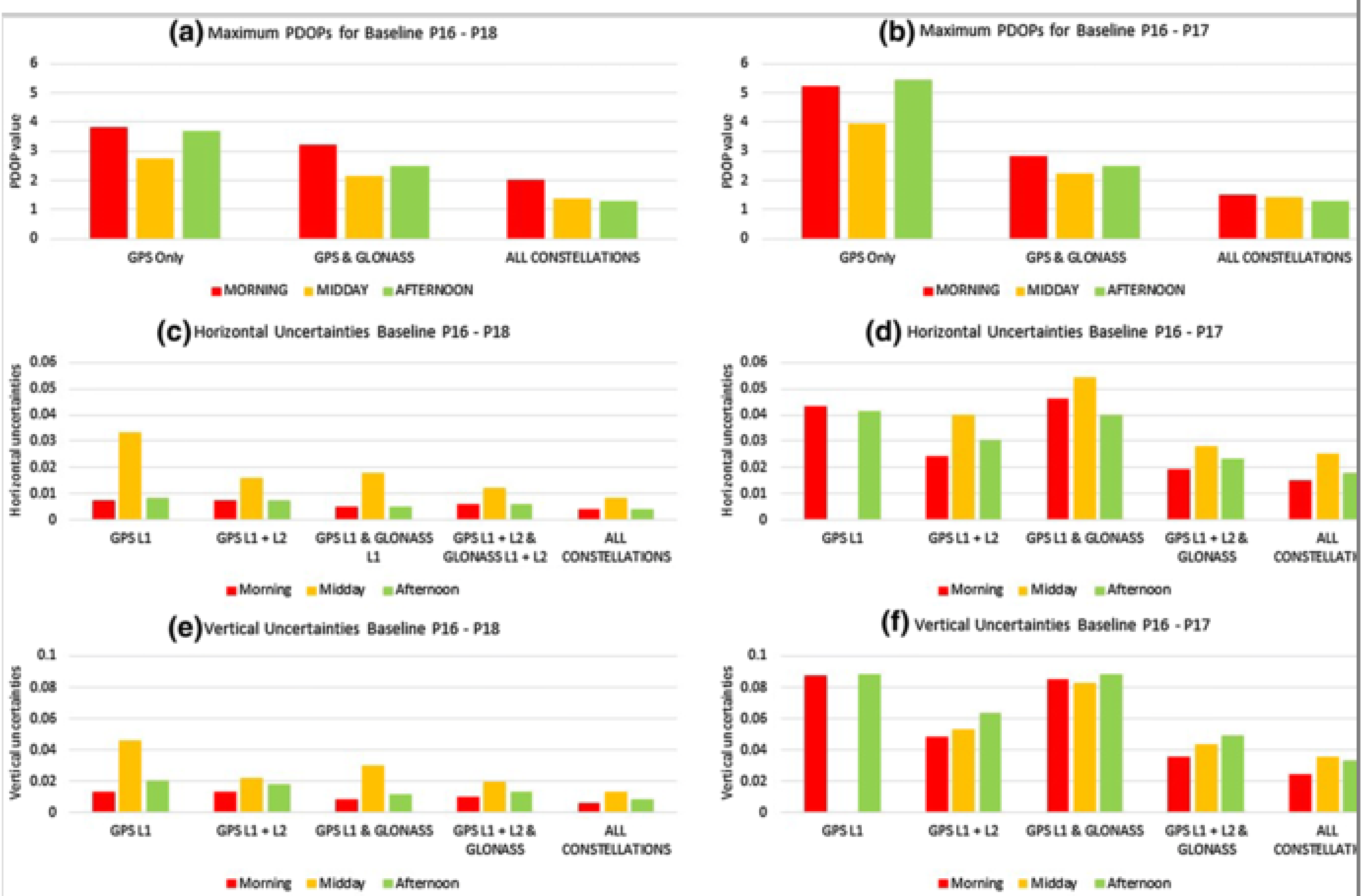
Precision measures

Maximum PDOPs

The maximum positional dilution of precision reached during the observation times can indicate the optimality of the geometry between the receiver and the satellites that are being observed. A higher PDOP will reduce precisions determined. It is generally considered that a PDOP of less than 4 indicates good satellite geometry, and anything higher than 7 is less than ideal (Awange 2018; Awange and Kiema 2019). Figure 2 shows the maximum PDOP values experienced for (a) the baseline from Pillar 16 (hereafter P16) to Pillar 18 (hereafter P18), i.e. our experimental–control baseline, and (b) the baseline from P16 to P17, i.e., our test baseline, when employing only GPS, GPS and GLONASS, and all constellations (see Table 1) at the different times of day when observations were taken.

Fig. 2

a Maximum PDOPs for the control baseline P16–P18, **b** maximum PDOPs for the test baseline P16–P17, **c** horizontal uncertainties produced for the control baseline P16–P18, **d** horizontal uncertainties produced for the test baseline P16–P17, **e** vertical uncertainties produced for the control baseline P16–P18 and **f** vertical uncertainties produced for the test baseline P16–P18



The maximum PDOP values experienced for the experimental–control baseline (P16–P18), even when using only the GPS constellation, are always below 4 (Fig. 2a). This would be due to the good sky visibility present at Pillar 18, which allows a good spread of satellites to be observed. Small improvements can be seen when GLONASS is included and again when all constellations are employed. For the test baseline involving Pillar 17, however, higher PDOPs are experienced when only GPS satellites are used, with both the morning and afternoon observations having maximum PDOP values of above 5 (Fig. 2b). This indicates that the presence of trees contributed to degradation of the GPS satellite geometry; hence, there are the higher PDOP values compared to the control Pillar 18 with less tree cover. When GLONASS constellation was utilised alongside that of GPS, however, as with the experimental–control baseline, the test baseline saw improvements, more so when the all constellations were used. The improvements were more evident for the test baseline, as the increased satellite availability would have had a larger influence on the observation geometry. Using the afternoon observations as an example, the control baseline saw a reduction in the largest PDOP experienced by 32% when GLONASS was included in the processing, whereas the test baseline saw a much larger improvement of almost 55% reduced PDOP. Including GLONASS, BeiDou and Galileo as well as GPS saw a reduction in maximum PDOP in the control baseline of just under 65%, while the experimental baseline saw a reduction of a significant 72%. This highlights the GNSS geometrical gain that would be achieved for environmental monitoring tasks in forested areas if all the available constellations are used.

Precision estimates

Precisions are calculated by the Trimble Business Centre software during the data processing stage. The obtained precisions for the test baseline (P16–P17) and the control baseline (P16–P18) processed using the different combinations in Table 1 are presented in Table 2.

Table 2

(a) Horizontal, vertical and RMS precisions for baseline from Pillar 16 to Pillar 17. Note the midday baseline using GPS L1 only was not able to achieve a fixed solution, meaning estimated precisions could not be produced. (b) Horizontal, vertical and RMS precisions for the baselines between Pillar 16 and Pillar 18

(a) Pillar 16–17				**(b) Pillar 16–18**		
GPS L1 Only	**Horizontal (m)**	**Vertical (m)**	**RMS (m)**	**Horizontal (m)**	**Vertical (m)**	**RMS (m)**

(a) Pillar 16–17				(b) Pillar 16–18		
GPS L1 Only	**Horizontal (m)**	**Vertical (m)**	**RMS (m)**	**Horizontal (m)**	**Vertical (m)**	**RMS (m)**
Morning	0.032	0.087	0.012	0.007	0.013	0.006
Midday	Float***			0.033	0.046	0.011
Afternoon	0.041	0.088	0.015	0.008	0.02	0.006
GPS L1 + L2						
Morning	0.024	0.048	0.013	0.007	0.013	0.008
Midday	0.04	0.053	0.021	0.016	0.022	0.012
Afternoon	0.03	0.063	0.015	0.007	0.018	0.01
GPS L1 and GLONASS L1						
Morning	0.046	0.085	0.014	0.005	0.008	0.006
Midday	0.054	0.082	0.02	0.018	0.03	0.01
Afternoon	0.04	0.088	0.015	0.005	0.011	0.007
GPS L1 + L2 and GLONASS L1 + L2						
Morning	0.019	0.035	0.015	0.006	0.01	0.008
Midday	0.028	0.043	0.024	0.012	0.019	0.013
Afternoon	0.023	0.049	0.018	0.006	0.013	0.011
All constellations						
Morning	0.016	0.025	0.015	0.004	0.007	0.009
Midday	0.025	0.035	0.021	0.008	0.013	0.011
Afternoon	0.018	0.033	0.018	0.004	0.008	0.009

As expected, the horizontal uncertainties experienced for the test baseline are much higher than those of the control baseline (Fig. 2). While the control baseline was able to resolve the integer ambiguities and obtain a fixed solution (i.e. more accurate positions) using GPS L1 alone during the midday observation (Fig. 2c), the test baseline with Pillar 17 hindered by trees was not, resulting in a float solution (i.e. less accurate positions with ambiguities unresolved; Fig. 2d). This meant precision estimates could not be determined due to the tree cover around Pillar 17. Even though a fixed solution was obtained for the control baseline, the uncertainty was still rather high. Around midday is when ionospheric errors are highest (El-naggar 2011), so this would likely explain the larger estimated precision, especially considering the PDOP at this time for GPS only was lower in comparison with the morning and afternoon.

Adding GLONASS L1 to the GPS L1 signal did not significantly affect the morning and afternoon observations for the test baseline; however, the extra satellites did allow a fixed solution to be established for the midday observation, which greatly improved the positioning results (Fig. 2c). The control baseline saw an improvement of 45% in the afternoon observation when the GLONASS L1 was introduced, while the morning and afternoon observations also saw small improvements, which can likely be attributed to higher redundancy thanks to the GLONASS satellite observations.

The ionosphere-free combination of GPS L1 + L2 is meant to greatly reduce the effects of ionospheric delay (Odijk 2003; Awange 2018; Awange and Kiema 2019). This combination showed promising improvements for the test baseline from Pillar 16 to Pillar 17 for all observations. Introducing the GPS L2 signal to GPS L1 also allowed a fixed solution to be obtained for the midday baseline and saw a reduction of 26% in the horizontal uncertainty in comparison with the GPS L1 and GLONASS L1 combination. The GPS L1 + L2 combination resulted in the horizontal uncertainty of the morning observation by 44% and the afternoon observation by 27% in comparison with GPS L1 alone. While the control baseline saw practically no change in the uncertainties of the morning and afternoon observations (Fig. 2c), the midday observation saw an improvement of 51.5% in comparison with using GPS L1 only. As Pillar 18 of the control baseline is located in a much more open area, with better sky visibility in comparison with Pillar 17 of the test baseline, it would appear that the effects of errors such as ionospheric delay are less prevalent; hence, the only improvement found by using the ionosphere-free combination was during the midday observation when the ionosphere delay is at its highest. The test baseline showed improvements during all three observations, however (Fig. 2d), which may indicate that errors such as ionospheric delay are magnified when blockages from tree are present.

Introducing the GLONASS L1 + L2 signals to GPS' L1 + L2 further improved upon the results of the GPS L1 + L2 combination. The test baseline saw a reduction in the horizontal uncertainty in the midday observation of 30% in comparison with the GPS L1 + L2 combination, while the morning and afternoon observations saw improvements of 21% and 23%, respectively. These improvements are again likely caused by the increased redundancy provided by the extra satellite observations from GLONASS. The control baseline saw only small improvements (~ 1 mm) in the morning and afternoon baselines, but an improvement of 25% (4 mm) was found for the midday baseline.

Combining all constellations saw the lowest uncertainties for all observations for both the control and experimental baselines. The extra satellites provided by the Galileo and BeiDou constellations allow more observations and thus redundancy, but also an improved observation geometry as the satellites observed will be better spread throughout the sky. The comparison of GPS L1 + L2 to the results of combining all constellations showed a largest improvement of 40% for the test baseline during the afternoon observation, while both the morning and midday observations saw reductions in uncertainty of 37.5%. The control baseline saw improvements of 50% for the midday observation and 43% for the morning and afternoon observations when compared to the GPS L1 + L2 results. It is important to note, however, that the magnitude of the improvements was much larger for the test baseline, with a 15 mm reduction in uncertainty for the midday baseline in the test baseline, while the control baseline only saw an 8 mm improvement.

The results for the vertical uncertainties are similar to those of the horizontal uncertainties, except the magnitude of the uncertainties is larger. This is due to the nature of GNSS positioning, with the limitation of the Earth's surface only allowing satellites above the horizon to be observed, meaning the geometry of the observations is not ideal for determining vertical heights. The same trend of improving uncertainties when more satellites are introduced can be seen in both the control and test baselines. When GLONASS L1 + L2 is introduced to the GPS L1 + L2 signals, the test baseline saw a largest relative improvement of 22% (13 mm) in the morning observation (Fig. 2f), while the control baseline saw the largest relative improvement in the afternoon observation of 28% (5 mm) (Fig. 2e).

When all constellations were utilised, the largest improvement in the vertical uncertainty for the test baseline was found during the morning observation with the uncertainty half that of the uncertainty found using only GPS L1 + L2 (24 mm reduction), while the control baseline saw the largest improvement in the afternoon baseline with a 55.5% (0.01) reduction in the vertical uncertainty.

Accuracy assessment

Table 3 shows the calculated coordinates for each processing combination, and the differences of each of these to the Landgate provided coordinates of Pillars 17 and

18, respectively. To give a clearer depiction of the overall positional accuracy achieved, the RMS of the coordinate differences (easting, northing and height) found for each of the signal combinations in Table 1 is calculated. Figure 3 shows the coordinate difference RMS calculated for Pillar 17.

Table 3

(a) Calculated coordinates for Pillar 17 using the different signal combinations and t differences of these to the known coordinates. Pillar 17 known coordinates, easting 395,146.069, northing = 6,458,493.237 and AHD height = 10.950. (b) Calculated coordinates f Pillar 18 using the different signal combinations and the differences of these to the knov coordinates. Pillar 18 known coordinates, easting = 395,170.506, northing = 6,458,362.863 a AHD height = 10.125

(a) Pillar 17				**(b) Pillar 18**		
GPS L1 only	**Easting**	**Northing**	**AHD height**	**Easting**	**Northing**	**AHD heigh**
Morning	395,146.065	6,458,493.211	10.951	395,170.503	6,458,362.861	10.11
	−0.004	−0.026	0.001	−0.003	−0.002	−0.00
Midday	395,146.438	6,458,493.144	11.106	395,170.505	6,458,362.863	10.11
	0.369	−0.093	0.156	−0.001	0.000	−0.00
Afternoon	395,146.065	6,458,493.212	10.943	395,170.503	6,458,362.864	10.11
	−0.004	−0.025	−0.007	−0.003	0.001	−0.00
GPS L1 + L2						
Morning	395,146.065	6,458,493.212	10.953	395,170.503	6,458,362.862	10.11
	−0.004	−0.025	0.003	−0.003	−0.001	−0.00
Midday	395,146.067	6,458,493.234	10.924	395,170.507	6,458,362.862	10.12
	−0.002	−0.003	−0.026	0.001	−0.001	−0.00
Afternoon	395,146.063	458,493.211	10.942	395,170.505	6,458,362.866	10.11
	−0.006	−0.026	−0.008	−0.001	0.003	−0.00
GPS L1 and GLONASS L1						
Morning	395,146.064	6,458,493.212	10.958	395,170.503	6,458,362.861	10.11
	−0.005	−0.025	0.008	−0.003	−0.002	−0.00
Midday	395,146.065	6,458,493.237	10.922	395,170.505	6,458,362.864	10.12
	−0.004	0.000	−0.028	−0.001	0.001	−0.00

(a) Pillar 17				(b) Pillar 18		
GPS L1 only	**Easting**	**Northing**	**AHD height**	**Easting**	**Northing**	**AHD height**
Afternoon	395,146.064	6,458,493.213	10.938	395,170.503	6,458,362.864	10.118
	−0.005	−0.024	−0.012	−0.003	0.001	−0.007
GPS L1 + L2 and GLONASS L1 + L2						
Morning	395,146.064	6,458,493.213	10.959	395,146.064	6,458,493.213	10.959
	−0.005	−0.024	0.009	−0.003	−0.001	−0.009
Midday	395,146.062	6,458,493.235	10.930	395,146.062	6,458,493.235	10.930
	−0.007	−0.002	−0.020	0.000	0.001	−0.004
Afternoon	395,146.062	6,458,493.212	10.936	395,146.062	6,458,493.212	10.936
	−0.007	−0.025	−0.014	−0.001	0.004	−0.003
All constellations						
Morning	395,146.058	6,458,493.218	10.952	395,170.504	6,458,362.863	10.117
	−0.011	−0.019	0.002	−0.002	0.000	−0.008
Midday	395,146.067	6,458,493.232	10.923	395,170.506	6,458,362.864	10.124
	−0.002	−0.005	−0.027	0.000	0.001	−0.00
Afternoon	395,146.061	6,458,493.212	10.933	395,170.505	6,458,362.866	10.12
	−0.008	−0.025	−0.017	−0.001	0.003	−0.003

Fig. 3

Accuracies of **a** Pillar 17 expressed as RMS of the coordinate differences, **b** Pillar 17 with the float solution removed and **c** Pillar 18 expressed as RMS of coordinate differences

The effect of not being able to fix the integer ambiguities and thus only achieve a float solution can be clearly seen through the midday GPS L1 baseline to Pillar 17. The position determined through the baseline processing was nearly 0.37 m off in the easting, over 0.09 m in the northing and 0.15 m in height from the given coordinates of Pillar 17, resulting in an RMS of 0.237 m. This is compared to the RMS of just 0.015 m for the same baseline when the GPS L2 signal is introduced and a fixed solution is obtained (improvement of 94%). The float solution from the midday GPS L1 baseline is removed in Fig. 3 so that the graph scale does not prevent the results from being easily examined and compared. The results found when combining GPS and GLONASS reflect those found by Swann (1999) and Ferrão (2016), whereby the precisions and reliability improved when using both constellations, but the accuracies did not. Quan et al. (2016) looked at combining all of the constellations (GPS, GLONASS, BeiDou and Galileo), although not testing in areas hindered by tree coverage, and found that over short baselines a single constellation was enough to achieve good accuracies, but over longer baselines combining the constellations significantly improved the accuracies. It might be because of the relatively short baseline lengths that were observed the full benefits could not be seen.

AQ3

Conclusion

This study sought to assess the positional accuracy gained by the use of multi-constellation for environmental monitoring tasks under dense tree cover. It was found that:

1. The positional accuracy measures were greatly influenced by the introduction of more constellations, with the satellite geometry through the PDOPs, estimated horizontal and vertical precisions all greatly improving both for the test baseline from Pillars 16 to 17 and for the control baseline from Pillars 16 to 18. This is to be expected with the increased satellite availability, allowing more redundant observations to be taken.

2. The accuracies obtained on the test Pillar 17 covered by dense trees were heavily degraded in the afternoon when the effect of the ionosphere is high. This was the case for the midday baseline when only GPS L1 was used and the solution of the position of Pillar 17 failed, leading to a float solution. However, when the GPS L2 signal was introduced, the solution (known as fixed solution) was obtained leading to 94% improvement in root mean square. This indicates that using more than one signal not only improves the situation in a densely vegetated area but also helps to mitigate against ionospheric errors.

3. The 94% improvement above (i.e. from a RMS error of 0.237 m to 0.015 m) provides significant gain for environmental monitoring tasks requiring accurate position determination, e.g. it pushes the uncertainty in position from sub-metre level to centimetre level. From environmental point of view therefore, Pillar 17 would be useful given that the use of multi-constellation pushed the boundary from a failed (float solution) to a successful fixed solution. For non-environmental tasks such as the establishment of control network, the caution by the Landgate still stands as the accuracies desired are generally to millimetre level.

4. Using multi-constellation processing improved the accuracy for the control

Pillar 18, which would indicate that while benefits may be found using the extra signals in areas which do not have poor visibility, when blockages caused by tree cover are introduced these benefits are nullified.

Environmental monitoring in dense tree cover areas therefore would benefit by exploiting all the possible GNSS satellites available. This would ensure fixed solutions (i.e. more accurate positions with ambiguities resolved) are obtained and avoid float solutions (i.e. less accurate positions with unresolved ambiguities resolved). Future tests will consider the effects of utilising multi-constellation GNSS in areas hindered by tree cover when the baselines observed are long (e.g. more than 5 km typical of short baselines). Also, as other methods of GNSS positioning are also subject to blockages, it would be interesting to conduct similar studies using these methods of positioning to see what results are found. The method of real-time kinematic (known as RTK) that delivers positions in real time, for example, which might benefit environmental tasks that require positions in real time, uses much shorter occupation time. This predisposes it to greater influence of tree cover, and as such, different combinations may result in higher rates of successful ambiguity resolution, thereby giving either fixed or float solutions.

AQ4

Acknowledgment

J.L. Awange would like to thank the financial support of the Alexander von Humboldt Foundation that supported his time at Karlsruhe Institute of Technology. He is grateful to the good working atmosphere provided by his hosts Prof. Hansjörg Kutterer and Prof Bernhard Heck. Ashty Saleem is grateful for the opportunity offered to him by Curtin University, School of Earth and Planetary Sciences to carry out his postdoctoral studies.

Compliance with ethical standards

Conflict of interest The authors declared that they have no conflict of interest.

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