Precision of Static GNSS using Multi-Constellation Data as a Function of Session Length

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ABSTRACT

Currently, there are roughly 130 Global Navigation Satellite System (GNSS) satellites in orbit, and it is possible for a user to have a clear view of over 50 satellites at a single epoch. This large number of satellites results in a significant improvement in satellite geometry, visibility and Dilution of Precision (DOP), while also having the potential to improve precision and reliability of GNSS positioning as a whole. Although the factors contributing to a potential benefit have been outlined and some testing has been done using GNSS methods such as Precise Point Positioning (PPP), an analysis of the benefit for various session lengths of static (double-differenced) GNSS is yet to be done. This paper expands on previous works by quantifying the benefit of multi-constellation static GNSS solutions with observation session lengths ranging from 1 to 24 hours using five constellations: GPS (USA), GLONASS (Russia), Galileo (Europe), BeiDou (China) and QZSS (Japan). The results are analysed by computing the Root Mean Square Error (RMSE) for each session length and presented in terms of 2D position and ellipsoidal height. It is demonstrated that significant benefits are gained from using all available GNSS constellations for observation sessions of less than 6 hours in length, including a large decrease in the number of solutions failing to resolve phase ambiguities to an integer value.

KEYWORDS: *GNSS, multi-constellation, session length.*

1 INTRODUCTION

Research in the early 2000s established that a longer Global Navigation Satellite System (GNSS) survey session results in higher precision. Research, such as Eckl et al. (2001), established this relationship and many organisations, such as the Intergovernmental Committee on Surveying and Mapping (ICSM), have gone on to develop standards that relate session length and levels of precision based predominantly on measurements using only Global Positioning System (GPS) satellites.

The investment in GNSS constellations throughout the world in the last two decades has resulted in modern surveyors having the potential to use satellites from multiple GNSS constellations. Although many differences exist between the constellations, such as clock types, carrier phase frequency, the precision of internal clocks and precision of orbit determination, the increased observation data results in greater redundancies and the potential for a more precise solution (Li et al., 2015b; Montenbruck et al., 2017).

If it can be shown that multi-constellation GNSS data can produce measurements of a higher precision with a shorter observation session length, significant survey time could be saved for lower-precision surveys. This time saving would be a benefit to all GNSS users. This paper first outlines relevant literature and gives a brief overview of current GNSS constellations and previous work on the precision of GNSS solutions. It then goes on to quantify the benefit of multi-constellation static GNSS solutions with observation session lengths ranging from 1 to 24 hours using five constellations: GPS (USA), GLONASS (Russia), Galileo (Europe), BeiDou (China) and QZSS (Japan).

1.1 Current GNSS Systems

The five GNSS constellations used in this study are outlined in Table 1. The GPS developed by the United States is the oldest constellation with the most research and development. As such, a number of governmental organisations only use GPS data in their various applications. GPS has also been shown to be the single system with the highest precision (Zheng et al., 2012; Yigit et al., 2014; Li et al., 2015a, 2015b).

Table 1: Summary of GNSS constellations with selected attributes.

GNSS Constellation	Origin	Decade Established	No. of Satellites (2020)	Obit Types
GPS	USA	1980	30	Medium Earth
GLONASS	Russia	1980 (then 2000)	23	Medium Earth
Galileo	Europe	2000	22	Medium Earth
BeiDou	China	2000	50	Medium Earth + Geostationary + Geosynchronous
QZSS	Japan	2010	4	Geostationary + Geosynchronous

1.2 Precision of GNSS as a Function of Session Length

The precision of static GNSS measurements is greatly increased when using longer session lengths as longer occupation times help to average out atmospheric effects (Firuzabadi and King, 2012) and other errors. The following sections outline the relationship between session length and precision for multiple sets of constellations.

1.2.1 GPS-Only

Using only GPS data and session lengths of 4-24 hours Eckl et al. (2001) found that the improvement in precision can been modelled via the Root Mean Square Error (RMSE) as follows:

$$RMSE = \frac{k}{\sqrt{T}} \tag{1}$$

where k = 9.5 (North), 9.9 (East), 36.5 (Up) [mm/hours$^{0.5}$]
T = time [hours]

Soler et al. (2006) found that this formula does not hold true for session lengths less than 4 hours. Firuzabadi and King (2012) revisited precision as a function of session length for single baseline solutions as well as testing the benefit of minimally constrained multi-baseline solutions translated to fit a network of reference stations using a 3-parameter Helmert (similarity) transformation. Their single baseline results were more precise than previous work, while their results with more than 4 fixed stations were a factor of 2 better than the single baseline results (single baseline results are shown in Figure 3). Due to the limited scope of the present study, only single baseline solutions are used here.

1.2.2 GPS and GLONASS

After the resumption of funding and the launch of new GLONASS satellites in the mid-2000s, the benefits of a combined solution were studied. There was some uncertainty as to whether a GPS + GLONASS solution would be of any benefit due to the accuracy of the GLONASS satellite orbits being around 60 mm (whereas GPS final orbits were around 25 mm) (Zheng et al., 2012). This, combined with issues in the application of Phase Centre Corrections (PCC) for the frequency-modulated signals (FDMA) used by GLONASS satellites, meant that PCC were applied correctly for GPS but not for GLONASS phase measurements, which resulted in systematic errors in the use of GLONASS satellites (Zheng et al., 2012). These limitations meant that at that time any potential benefit of a combined solution was not yet tangible. Zheng et al. (2012) analysed 24-hour periods of data and found there was little to no improvement from using both systems.

In the late 2010s, the accuracy of GLONASS final orbits approached that of GPS. Today, the accuracy of GLONASS final orbits is quoted as 30 mm with GPS final orbits being 25 mm (IGS, 2021). Phase centre corrections for GLONASS satellites are also now applied by software as standard practice. These improvements suggest the potential gain of a combined solution today would be more so than 10 years ago at the time of Zheng et al. (2012).

1.2.3 Multi-Constellation Solutions Using PPP

There is a gap in the literature in assessing the improvement of static GNSS using a multi-constellation solution. As numerous studies assessing the benefit have been undertaken using Precise Point Positioning (PPP), a brief discussion of these results is presented. Although PPP is not directly related to static (double-differenced) GNSS, it is reasonable to expect that some trends would be similar due to both using the same network of satellites. As such, only the trends found from PPP studies are reviewed, as it is not expected that the values found are directly applicable to static GNSS.

Li et al. (2015b) developed a model to attempt to make full use of observations from GPS, GLONASS, Galileo and BeiDou satellites. As well as developing this method, outlining the improved satellite availability, Dilution of Precision (DOP) and PPP convergence time, they briefly documented PPP solutions with session lengths from 15 minutes to 12 hours. The results indicated that significantly better precision was attainable. They found that the precision of a 1-hour multi-GNSS solution is comparable with 2 hours of GPS-only. Similarly, the precision found with 6 hours of combined data achieved a similar precision to 12 hours of GPS-only observations.

2 TESTING METHODOLOGY

2.1 Test Sites and Data Acquisition

7 days of 24-hour GNSS observation data including observations from GPS, GLONASS, Galileo, BeiDou and QZSS satellites was obtained from Geoscience Australia (GA). Three Continuously Operating Reference Stations (CORS) in the Northern Territory (NT), Australia, have been chosen as test sites because these locations make more optimal use of the satellite systems with geosynchronous orbits (both elliptical and stationary orbits). In this region, the full orbit of all QZSS satellites is visible with much of the orbit being almost directly overhead. Almost all BeiDou geosynchronous orbits are also visible. Unlike satellites in medium earth orbits that are positioned to evenly cover the entire earth (except some areas near the poles), these geosynchronous orbits are only visible from select regions in Asia and Oceania. The test network can be considered close to a best-case scenario for the use of multi-constellation data.

Data was obtained from three CORS, operated by GA and the NT Department of Infrastructure, that are part of the Asia-Pacific Reference Frame (APREF – see GA, 2021). Using data obtained from CORS is typical of this kind of study (Eckl et al., 2001; Soler et al, 2006; Firuzabadi and King, 2012) as the antennas are permanently mounted on solid pillars in low multipath environments with a clear sky view. This helps to remove or limit other error sources, such as centring errors and multipath, and provides a consistent sky view. The CORS selected were DARW (Darwin), LKYA (Larrakeyah) and DODA (Douglas Daly). The baselines DARW to LKYA (54 km) and DARW to DODA (110 km) were analysed in this study.

Only two baselines were analysed in this study due to problems encountered with the processing software. Typically, more baselines of varying lengths would need to be analysed to allow more significant conclusions to be drawn.

2.2 'True' Coordinates

Using APREF CORS as test sites also means that the monuments are tied to a well-defined reference frame with established coordinates. GA has published coordinates and uncertainties, called Regulation 13 certificates, calculated from 7 days of data and continually monitored for each of these stations (Hu and Dawson, 2020). These coordinates, expressed in the Geocentric Datum of Australia 2020 (GDA2020 – see ICSM, 2020), were taken as point of truth for this study and confirmed with a minimally constrained network adjustment using 7 days of GPS-only observation data.

In using published values, consideration must be given to the uncertainty of these values. Also, in attempting to assess a method of measurement, consideration must be given whether precision or accuracy is being measured. If the calculated value lies within the range of uncertainty of the 'true' value, it is possible the calculated value could be the true value and therefore use of the term accuracy may be misleading. As a high number of calculated values in these experiments fall within the uncertainty assigned to the GA coordinates, the results obtained will only be referred to as a measure of precision.

Referring to the results of this study as a measure of precision rather than accuracy is consistent with past studies. In fact, although Eckl et al. (2001) used the term accuracy in the title of their paper, they later referred to their results as being a measure of precision. Similarly, Firuzabadi and King (2012) as well as Zheng et al. (2012) referred to their results as a measure of the repeatability (i.e. precision) of an observation rather than accuracy.

2.3 Computation of Baselines

Each baseline was computed using GPS-only, GPS + GLONASS, and a 5-constellation solution (GPS + GLONASS + Galileo + BeiDou + QZSS). GPS has been chosen over GLONASS for the single constellation tests as it has been shown that for a single-constellation solution GPS gives a better result than GLONASS (Zheng et al., 2012; Yigit et al., 2014; Li et al., 2015a, 2015b).

The daily (24-hour) observation files were split into the periods shown in Figure 1. This scheme resulted in processing 171 sets of data for each baseline per day with a total of 399 baselines for each test line. It should be noted that this results in a different number of baselines being used to calculate RMSE for each session length. Although the author is aware of the possible effect that small and varying sample sizes can have on statistics, any method to try and balance the fact that there are a small number of long sessions and a larger number of short sessions would result in further unknowns and error sources needing to be considered. Previous works have implemented a very similar scheme to split data into periods (Eckl et al., 2001; Soler et al., 2006). Section 3 provides more detail on the methods used to process baselines.

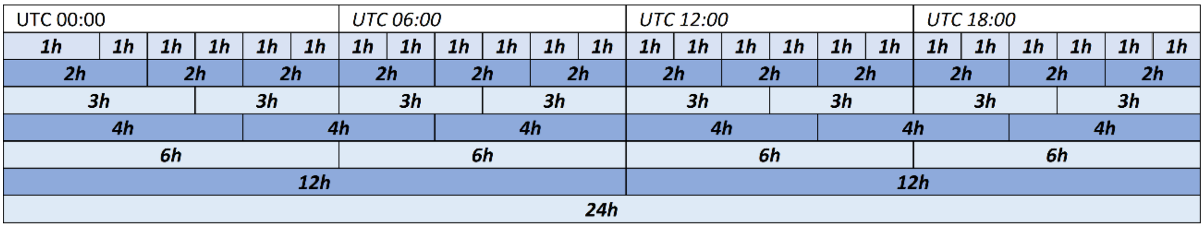

Figure 1: Splitting datasets into session lengths of 1, 2, 3, 4, 6, 12 and 24 hours.

2.4 Calculation of Errors and Statistics

For each set of results and each time period, the RMSE was calculated to measure the uncertainty of each set of solutions for latitude, longitude, 2D position and ellipsoidal height. RMSE is calculated using the residuals obtained from the difference of the calculated coordinates to the GA coordinates. For example, the RMSE for the 1-hour session length using only GPS satellites was determined from 168 GPS-only solutions calculated over the 7-day period. Similarly, the RMSE for the 12-hour session length using GPS and GLONASS was calculated from the 14 GPS + GLONASS solutions that make up the 7-day period. This is consistent with the calculation of RMSE in the literature (Eckl et al., 2001; Soler et al., 2006; Firuzabadi and King, 2012; Zheng et al., 2012; Alcay and Yigit, 2017).

2.5 Outlier Rejection

All results from each session length were compared against the RMSE and all results greater than 3 times the RMSE were removed and the RMSE recalculated. The removal of outliers helps to avoid a biased results and excludes weaker estimates that would be highly detectable when processing a single baseline due to there being apparent signal loss, high phase noise or failure to solve ambiguities (Firuzabadi and King, 2012).

Eckl et al. (2001) found removing outliers greater than 3 times the RMSE removed 3% of the total solutions. Firuzabadi and King (2012) found that this same scheme removed up to 10% of solutions for session lengths less than 3 hours. Although this difference in the percentage of outliers may seem significant, it can largely be attributed to the fact that Firuzabadi and King (2012) calculated sessions of a shorter length (shorter sessions are more likely to fail to resolve the phase ambiguities to an integer value than longer sessions and therefore are more likely to be outliers).

3 SOFTWARE VERIFICATION

Several tests were undertaken to verify the GNSS processing software used in order to ensure the reliability of this research. The specific software packages used during verification have been anonymised to avoid any legal dispute arising from these comparisons and will be simply referred to as software 1 and software 2. Both packages are commonly used commercial off-the-shelf software marketed as being capable of processing GNSS baselines and least squares network adjustments with both GNSS and terrestrial datasets.

3.1 Data and Methods Used

24 hours of observation data at stations DARW and DODA on three days (6, 10 and 12 January 2020) were used to calculate the baseline in three ways:
1) Software 1 - Method 1
2) Software 1 - Method 2
3) Software 2 - Method 1

Processing method 1 included the following steps:
1) Process baseline with DARW held fixed at the Regulation 13 coordinates within the software.
2) Calculate output coordinates of DODA as geodetic coordinates (latitude, longitude, ellipsoidal height).
3) Use Vincenty's formulae to calculate the difference in distance along the ellipsoid from the Regulation 13 coordinates of DODA.
4) Simple subtraction to determine the difference in ellipsoidal height from the Regulation 13 coordinates of DODA.

Processing method 2 included the following steps:
1) Process baseline with no nodes held fixed in the software.
2) Output baseline in Cartesian components (ΔX, ΔY, ΔZ).
3) Add these components to the Cartesian coordinates of DARW to obtain the Cartesian coordinates of DODA.
4) Convert Cartesian coordinates of DODA to geodetic coordinates, using the formula stated in ICSM (2020).
5) Use Vincenty's formulae to calculate the difference in distance along the ellipsoid from the Regulation 13 coordinates of DODA.
6) Simple subtraction to determine difference in ellipsoidal height from the Regulation 13 coordinates of DODA.

3.2 Verification Results

Table 2 shows the detailed results of the software verification testing, while a summary of the comparison to the Regulation 13 coordinates is given in Table 3.

Table 2: Software comparisons – DARW to DODA with 24-hour session lengths.

Test Case 1 (06/01/2020)		**Diff LAT (m)**	**Diff LON (m)**	**Diff EHGT (m)**
GPS Only	Software 1 - Method 1	0.033	-0.007	0.038
	Software 1 - Method 2	0.007	-0.002	0.044
	Software 2 - Method 1	0.003	-0.001	-0.004
All Constellations	Software 1 - Method 1	0.024	-0.001	0.008
	Software 1 - Method 2	0.005	-0.003	0.006
	Software 2 - Method 1	0.003	-0.003	-0.006
Test Case 2 (10/01/2020)				
GPS Only	Software 1 - Method 1	0.031	-0.001	0.055
	Software 1 - Method 2	0.013	-0.002	0.071
	Software 2 - Method 1	0.000	0.005	-0.006
All Constellations	Software 1 - Method 1	0.025	0.008	0.036
	Software 1 - Method 2	0.006	0.008	0.032
	Software 2 - Method 1	0.001	0.003	-0.005
Test Case 3 (12/01/2020)				
GPS Only	Software 1 - Method 1	0.028	0.007	0.143
	Software 1 - Method 2	0.005	0.006	0.154
	Software 2 - Method 1	-0.005	0.000	0.024
All Constellations	Software 1 - Method 1	0.021	-0.003	0.110
	Software 1 - Method 2	0.006	-0.005	0.109
	Software 2 - Method 1	-0.005	-0.002	0.018

Table 3: Summary of validation results.

	Latitude	**Longitude**	**Ellipsoidal Height**
Software 1 - Method 1	Significantly outside Reg 13 uncertainty	Within Reg 13 uncertainty	Significantly outside Reg 13 uncertainty
Software 1 - Method 2	Mostly within Reg 13 uncertainty	Within Reg 13 uncertainty	Significantly outside Reg 13 uncertainty
Software 2 - Method 1	Within Reg 13 uncertainty	Within Reg 13 uncertainty	Mostly within Reg 13 uncertainty

It is interesting to note that irrespective of calculation method and software used, the longitude was always within the uncertainty of the Regulation 13 values whereas the latitude and ellipsoidal height (particularly for Software 1 - Method 1) was well outside the uncertainty. As ellipsoidal parameters are used only to calculate latitude and ellipsoidal height, it is theorised that software 1 may be incorrectly handling ellipsoidal parameters at some point within the application. Further tests were conducted with different ellipsoidal models selected within software 1, but the error remained. However, in the absence of access to the source code or processes used internally by software 1, it is not possible to confirm this interpretation.

Although this verification has shown that Software 2 - Method 1 appears to be the best option for this study, the data presented in this paper uses Software 1 - Method 2 for all calculations. This is due to software 2 not being available during the entire time this research was conducted. As the calculation of ellipsoidal height has shown to be well outside the expected values for this method, it has been excluded from the results presented in section 4. Instead, the remainder of this paper focuses on the longitude and 2D results.

4 RESULTS

4.1 Combined GPS and GLONASS

For both test cases and all session lengths the difference between the results of GPS-only and GPS + GLONASS processing is negligible (Table 4). In all test cases the GPS-only and GPS + GLONASS results were within 0.1 mm. From these results, it can be concluded that a combined GPS + GLONASS solution yields no real benefit. As such, the RMSE values for the GPS + GLONASS solutions are not shown on any figures in the remainder of this paper.

Table 4: RMSE values of each satellite combination for each session length.

		Session Length						
Baseline	**Constellations**	**1 hr**	**2 hr**	**3 hr**	**4 hr**	**6 hr**	**12 hr**	**24 hr**
DARW to LKYA 2D	GPS only	0.050	0.030	0.028	0.017	0.015	0.016	0.009
	GPS+GLO	0.050	0.030	0.028	0.017	0.015	0.016	0.009
	ALL	0.024	0.020	0.018	0.015	0.015	0.016	0.012
DARW to DODA 2D	GPS only	0.117	0.087	0.058	0.038	0.036	0.019	0.014
	GPS+GLO	0.117	0.087	0.058	0.038	0.036	0.019	0.014
	ALL	0.071	0.049	0.036	0.020	0.019	0.014	0.014

Although these results show no benefit of combining GPS with GLONASS for the data investigated, further research is needed to confirm this result as previous work has indicated that some benefit exists. Alcay and Yigit (2017), like Zheng et al. (2012), concluded that there was no measurable benefit for 24-hour session lengths but showed a benefit for session lengths of 4 hours. This is not consistent with the results presented here and not the expected result (see section 1.2.2).

4.2 Benefit of GPS + GLONASS + Galileo + BeiDou + QZSS

Using a 5-constellation solution by combining GPS with GLONASS, Galileo, BeiDou and QZSS showed a significant increase in precision for longitude and 2D positioning (see Table 4). Figure 2 shows the longitude RMSE values for the GPS-only and the 5-constellation solutions for each session length. It can be seen that the benefit of the additional satellites is significant for shorter sessions but that the different solution types converge at some session length between 12 and 24 hours. Further study is needed to quantify the point of convergence more precisely.

The increased precision for session lengths less than 4 hours can also be attributed to the fact that the number of solutions that failed to resolve to a fixed solution is significantly reduced when combining the five GNSS constellations. Table 5 shows the number of solutions that failed to resolve phase ambiguities to integer values for test series of 1 to 3 hours. For both baselines the number of 1- and 2-hour float solutions is decreased by a factor of 4.

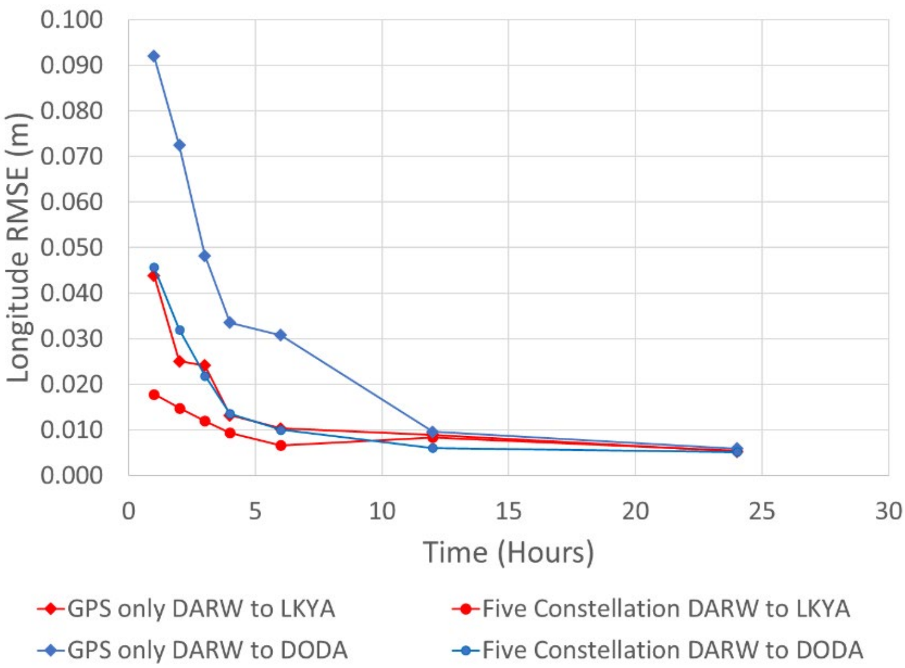

Figure 2: Comparison of longitude RMSE for GPS-only and 5-constellation solutions as a function of session length for baselines of 54 km (red) and 110 km (blue).

Table 5: Number of baseline solutions failing to resolve phase ambiguities to integer values.

Baseline	Constellations	Session Length 1 hr	2 hr	3 hr
DARW to LKYA	GPS only	26	5	1
	GPS+GLO	26	5	1
	ALL	6	1	1
DARW to DODA	GPS only	65	25	13
	GPS+GLO	65	25	13
	ALL	14	4	5

5 DISCUSSION OF RESULTS

Although the magnitude of these results needs further verification due to software issues encountered, resulting in the RMSE values being higher than expected, the trends found and the relationship between each set of constellations is worthy of note as it indicates that significant advantages are possible when using multi-GNSS solutions.

From the two test cases analysed, it has been shown that:

1) A combined GPS + GLONASS solution gives no significant benefit over GPS-only for any session length.
2) A 5-constellation solution is beneficial for horizontal position for session lengths less than 4-6 hours.
3) The number of float solutions is significantly reduced for 1- and 2-hour session lengths when using five constellations.

5.1 Comparison to Past Results

Although the results presented show significant improvements in precision for short sessions, when they are considered in the context of previous work, it is clear that the magnitude of the RMSE values are significantly higher than in previous work. Figure 3 compares the results for the baseline DARW to LKYA with the single-baseline, GPS-only result from Firuzabadi and King (2012).

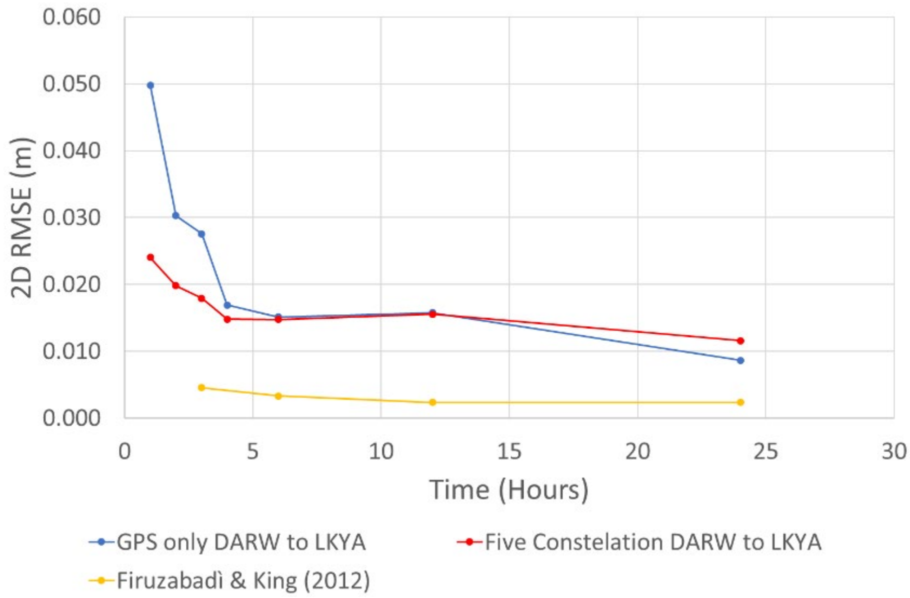

Figure 3: Comparison of the 2D results from the baseline DODA to LKYA against the GPS-only results from Firuzabadi and King (2012).

Although the software issues encountered may have contributed to the differences seen, there is also reason to question how valid this comparison is due to the possibility of systematic processing errors. As such, the validity of this comparison and possible bias in previous results requires discussion.

Comparison with Firuzabadi and King (2012) is not exactly a like-for-like comparison because Figure 3 compares a single 54 km baseline to the average of 7 baselines computed using baseline lengths ranging from 26 to 585 km. Nevertheless, the results of the present study would still be expected to be more similar to Firuzabadi and King (2012), particularly for session lengths of 4-24 hours, as they found that precision was not dependent on baseline length for session lengths greater than 4 hours.

Although Figure 3 only shows comparison to the results from Firuzabadi and King (2012), the results of the present study have also been compared to the results from Eckl et al. (2001) and Soler et al. (2006). As the results of these three previous studies do not differ significantly, not all shown in Figure 3.

All of these three studies calculated the 'true' coordinates using the same software as that used in the study. Soler et al. (2006) took values published by the U.S. National Geodetic Survey (NGS) as point of truth but used NGS's Online Positioning User Service (OPUS) to calculate their results. At the time, OPUS was merely an online version of a software called PAGES (which was used to calculate the coordinates published by NGS) and did not report or note any validation process in using these calculated values. Using the same software, and in the case of Eckl et al. (2001) the exact same data, to calculate 'true' and test values does not allow systematic errors or biases within the software to be detected. This was acknowledged by Eckl et al. (2001) at the time.

Jamieson and Gillins (2018), as part of a comparative analysis of online post-processing services, analysed the systematic error of various online solutions by comparing RMSE and the variance of subsets of their data and found that over 25% of the subsets (38% of the subsets calculated using OPUS) contained statistically significant systematic errors. If these systematic errors were found in software tests undertaken in 2018, it can be assumed they were present in 2001-2010 when these early studies were undertaken (and possibly of greater magnitude). As these systematic errors were not accounted for in those early studies, it can be expected that the RMSE values from the present study should be larger in comparison.

6 CONCLUDING REMARKS

This paper has sought to quantify the benefit of multi-constellation static GNSS solutions with observation session lengths ranging from 1 to 24 hours. It has been shown that significant benefits can be gained from using all available GNSS constellations for observation sessions of less than 6 hours in length. Although the analysis undertaken has been limited due to software availability issues, it has shown the relationship between GPS-only, GPS + GLONASS and 5-constellation solutions. This study has also highlighted the need for further research on this topic.

In summary, the results have shown:

- The likelihood of short solutions failing to resolve phase ambiguity to an integer value is greatly decreased when using multiple constellations.
- There is little benefit gained from combining constellations if using more than 12 hours of data.
- The benefit is significant for session lengths less than 6 hours.

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