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TESTING MULTI-GNSS (GPS/GLONASS/GALILEO/BEIDOU/IRNSS) AND WIDE-LANE PERFORMANCE FOR LONG BASELINES

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Abstract. With the rapid development of multi-constellation global navigation satellite systems (GNSS), the world of satellite navigation has undergone tremendous changes. Once all six systems (IRNSS, BeiDou, QZSS, Galileo, GLONASS, and GPS) are deployed in the next few years, approximately 150 satellites will be available, which will bring huge opportunities and challenges to science and engineering applications. This paper describes an experiment conducted with the static method for the Multi-GNSS about achievable accuracy especially for the long baselines (Wide Lane ambiguity solution). The obtained results indicate that integrating GPS systems with Galileo, GLONASS, BeiDou, QZSS and IRNSS are favoured for surveying applications. It appears that through the integration of GPS/GLONASS/Galileo/BeiDou/QZSS/IRNSS static measurements in the study area, millimetre-centimetre accuracy may be guaranteed on for long baselines by using Wide Lane (WL).

Keywords: GNSS, accuracy, Wide-Lane, IRNSS, QZSS.

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1. Introduction

Ensuring the timely and accurate placement of satellites and creating new opportunities in high-precision dynamic positioning applications with the global navigation satellite system (GNSS) depend greatly on the timely and reliable resolution of carrier phase ambiguities. For an extended period, numerous ambiguity resolution (AR) techniques relied on the least-squares (LS) estimation. This approach allowed for the acquisition of the float solution and variance-covariance, which were then further calibrated to an integer value using specific estimators like rounding, bootstrapping, and integer LS. The development of GNSS real-time and high-precision locating has been substantially aided by these technologies, which have also somewhat increased the dependability of ambiguity resolution. With the upgrading of the GNSS in recent years, end users will have access to more multi-frequency signals. AR will gain from the formation of more useful combinations that can be made with multi-frequency signals. The two most prominent techniques are cascade integer resolution (CIR) and triple-carrier ambiguity resolution (TCAR). The fundamental idea behind both strategies is almost the same. Starting with the easiest-to-fix extra-wide lane (EWL) combination, the method progresses to the narrow-

er wavelength wide-lane (WL) and narrow-lane (NL) combinations in turn. The WL combination is utilized to bridge the longest EWL and the smallest NL wavelength. In the wake of these investigations, a great deal of work has been done on triple-frequency ambiguity resolution using the TCR/CIR or modified TCR/CIR techniques (Cai et al., 2016; Hofmann-Wellenhof et al., 2008; Li et al., 2014; Odijk et al., 2002, 2014; Wolf & Ghilani, 2008). In this study, the baselines of the three selected points are analysed for accuracy by using different satellite configurations and the Wide Lane method for integer ambiguity solution. The effects of IRNSS satellites on this analysis are also investigated.

2. Materials and methods

2.1. Wide Lane

Processing of dual frequency data (L1/L2 GPS GLONASS code and carrier phase measurements) for GPS observation lengths ranging between 30 and 1500 km intervals is done using Wide Lane, Fixed Ionosphere Free. L1-L2 (Wide Lane) combination aids in the first phases of dual frequency survey processing integer ambiguity resolution for L1 and L2 observables. The GPS observations after processing have been classified as “Fixed, Wide Lane/Float, Wide-Lane” in

their final solution type. Broad-Lane Uncertainty Reduction: Once the Melbourne Wübbena Combination is obtained, the double differenced wide-lane ambiguity $\Delta\nabla N_w$ may be calculated by rounding the average in time (Deng et al., 2020; Li et al., 2014).

$$\Delta\nabla N_w = \left\lfloor \frac{\Delta\nabla\phi_w - \Delta\nabla R_N}{\lambda_w} \right\rfloor_{\text{roundoff}}. \quad (1)$$

The benefit of this ambiguity estimate is that, because of the widening of the ambiguity spacing, it can be readily calculated separately for each measurement. A few minutes should be sufficient to resolve the wide-lane ambiguity in the presence of moderate receiver noise and multipath circumstances. L1 ambiguity fixing: The double differenced L1 ambiguity ($\Delta\nabla N_1$) may be corrected from the equation after $\Delta\nabla N_w$ has been fixed.

$$\Delta\nabla N_1 = \left\lfloor \frac{1}{\lambda_N} \left(\Delta\nabla\bar{B}_C - \frac{\lambda_w}{\lambda_2} \Delta\nabla N_w \right) \right\rfloor_{\text{roundoff}}. \quad (2)$$

When a sufficiently precise estimate of the ambiguity $\Delta\nabla\bar{B}_C$ is known. This estimate, $\Delta\nabla\bar{B}_C$, may be calculated by floating the BC ambiguities in the Kalman filter, much as in the preceding section (PPP). Since the ambiguities in BC are ascertained “by floating” them in the navigation filter, it takes some time for the filter to converge—roughly an hour. In fact, approximately speaking, $[RC - \phi]C$ is where the majority of the ambiguity BC is calculated, with RC code noise being nearly three times noisier than the code measurement in the frequency f_1 . More complex approaches, such as the Lambda method or the Null Space, establish the ambiguities “as a set” and then use decorrelation and search (on integers) methods to improve the resolution of the ambiguities. Fixing ionosphere-free bias, $\Delta\nabla N_w$ and $\Delta\nabla N_1$ ambiguities are then resolved, and the double differenced ionosphere-free bias is then resolved by (Deng et al., 2020; Li et al., 2014; Duong et al., 2020):

$$\Delta\nabla\bar{B}_C = \lambda_N \left\lfloor \left(\Delta\nabla N_1 - \frac{\lambda_w}{\lambda_2} \Delta\nabla N_w \right) \right\rfloor_{\text{roundoff}}. \quad (3)$$

Notice that, once the $\Delta\nabla\bar{B}_C$ to converge is to use the following equation, for the ϕ_1 ambiguity fixing

$$\Delta\nabla N_1 = \left\lfloor \frac{\Delta\nabla\phi_1 - \Delta\nabla\phi_2 - \Delta\nabla I - \lambda_2 \Delta\nabla N_w}{\lambda_2 - \lambda_1} \right\rfloor_{\text{roundoff}}. \quad (4)$$

For short baselines (up to 10–15 kilometres, depending on the ionospheric condition), the primary issue here is the ionospheric refraction term $\Delta\nabla I$. It may be assumed that the double-differenced ionospheric refraction coefficients, that is, $\Delta\nabla I \approx 0$, can be rounded from the following formula to resolve the $\Delta\nabla N_1$ ambiguity:

$$\Delta\nabla N_1 = \left\lfloor \frac{\Delta\nabla\phi_1 - \Delta\nabla\phi_2 - \lambda_2 \Delta\nabla N_w}{\lambda_2 - \lambda_1} \right\rfloor_{\text{roundoff}}. \quad (5)$$

A precise estimate of the ionospheric adjustment, $\Delta\nabla I$, is required for long baselines in order to enable the user to resolve any ambiguity by rounding from (4). Observe that, when the ambiguity N_w —carrier measurement noise of a few millimetres—is resolved, the $\Delta\nabla I$ term accounts for the majority of the rounding error. Notice also that its accuracy must be better than $\frac{\lambda_1 - \lambda_2}{2}$ to allow the integer rounding in the case of the Galileo E1 and E5b signals, this accuracy threshold is $\frac{\lambda_2 - \lambda_1}{2} = 2.9$ cm (Carrier phase ambiguity fixing with three frequencies). For the of L1 and L2 GPS signals, it is $\frac{\lambda_2 - \lambda_1}{2} = 2.7$ cm (Combination of GNSS surveys) (Cai et al., 2016; Deng et al., 2020; Li et al., 2014; Odijk et al., 2014).

2.2. Study region

The three points were selected for this study (JOG2, XMIS, COCO, see Figure 1) are located in Indonesia and Australia. The reason for the selection of these three points is that they have satellite configurations (GPS/GLONASS/Galileo/BeiDou/QZSS/IRNSS) and their base lengths are between 594 km and 1560 km. The GNSS data for these three stations were downloaded with recording interval of 30 seconds on January 1, 2024.

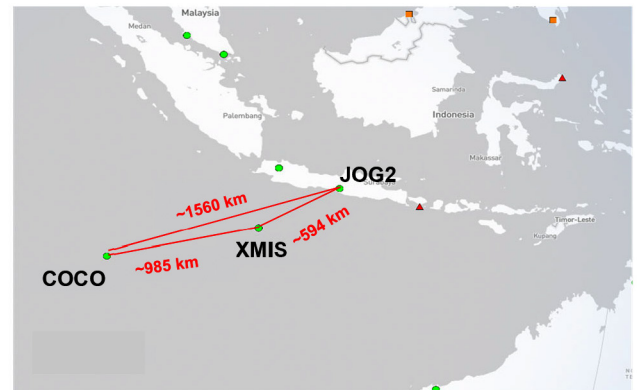


Figure 1. Three IGS stations in the study region

3. Results

As explained before, all of the static GNSS measurements were processed by using Topcon Magnet Tools version 8.1.0 and Bernese 5.2 Software. The latitude, longitude and ellipsoidal height values of JOG2, XMIS and COCO points were obtained by using Bernese Software on 01.01.2024 (Table 1). The standard deviation values of the latitudes and longitudes of the three IGS points shown in Table 1 were obtained as 2–3 mm. The standard deviation values of the ellipsoidal heights of the three IGS points were obtained between 8 mm and 9 mm.

As shown in Table 2, the satellite configurations for which the integer ambiguity (Wide-Lane and Fixed) is solved at three baseline lengths are GPS, GPS/Galileo,

GPS/Galileo/QZSS, GLONASS, Galileo, GLONASS/QZSS, and Galileo/QZSS. The differences between the baselines were obtained by using Bernese and Magnet Tools v 8.1.0; firstly baseline (JOG2-XMIS, ~594 km) ranged from 5.8 cm (BeiDou/QZSS) to 10.7 cm. For the other two baselines (COCO-XMIS, ~985 km), the differences are calculated as 9.3 cm (Galileo/QZSS/BeiDou) – 22.9 cm (GLONASS/QZSS)

and for the baseline (COCO-JOG2, ~1559 km) the differences are calculated as 11.7 cm (Galileo/QZSS) – 60.9 cm. As can be seen, the Galileo/BeiDou/QZSS satellite configurations seem to be quite effective in solving the Fixed-Wide Lane integer ambiguity for the long baselines. Especially for the signals used by Galileo satellites show both strong and robust characteristics.

Table 1. Standard deviation, coordinates (ITRF 20, Epoch 2024.1) values of the three IGS points by processing static GPS/GLONASS satellites

Name	Latitude (°)	Longitude (°)	h (m)	Std Lat (m)	Std Lon (m)	Std h (m)
XMIS	–10°26'59.84563"	105°41' 18.62104"	261,511	0.002	0.003	0.009
COCO	–12°11'18.01729"	96°50' 2.31673"	–35,314	0.002	0.002	0.008
JOG2	–7°45'49.73247"	110°22' 20.87240"	174,250	0.002	0.002	0.009

Table 2. Comparison of satellite configuration, type of integer ambiguity solution, number of satellites and baseline length values

Satellite configuration	Solution type	S_{TMTS} (m)	GPS	GLO.	QZSS	GAL.	BDS	IRNSS	$S_{BERNESE}$ (m)	Diff. (m)	ppm
GPS	Fixed, Wide Lane	1558676,673	32	24	4	24	47	8	1558676,497	0.176	0.113
	Fixed, Wide Lane	984535,567	31	24	3	23	23	0	984535,442	0.125	0.127
	Fixed, Wide Lane	594209,387	31	24	3	23	23	0	594209,307	0.080	0.135
GPS/GLONASS	Fixed, Wide Lane	1558677,106	32	24	4	24	47	8	1558676,497	0.609	0.391
	Float, Wide Lane	984535,575	31	24	3	23	23	0	984535,442	0.133	0.135
	Float, Wide Lane	594209,392	31	24	3	23	23	0	594209,307	0.085	0.143
GPS/GLONASS/Galileo	Float, Wide Lane	1558676,738	32	24	4	24	47	8	1558676,497	0.241	0.155
	Float, Wide Lane	984535,550	31	24	3	23	23	0	984535,442	0.108	0.110
	Fixed, Wide Lane	594209,392	31	24	3	23	23	0	594209,307	0.085	0.143
GPS/GLONASS/Galileo/QZSS	Float, Wide Lane	1558676,650	32	24	4	24	47	8	1558676,497	0.153	0.098
	Float, Wide Lane	984535,554	31	24	3	23	23	0	984535,442	0.112	0.114
	Float, Wide Lane	594209,389	31	24	3	23	23	0	594209,307	0.082	0.138
GPS/GLONASS/Galileo/QZSS/BeiDou	Float, Wide Lane	1558676,643	32	24	4	24	47	8	1558676,497	0.146	0.094
	Float, Wide Lane	984535,546	31	24	3	23	23	0	984535,442	0.104	0.106
	Float, Wide Lane	594209,378	31	24	3	23	23	0	594209,307	0.071	0.120
GPS/Galileo	Fixed, Wide Lane	1558676,651	32	24	4	24	47	8	1558676,497	0.154	0.099
	Fixed, Wide Lane	984535,537	31	24	3	23	23	0	984535,442	0.095	0.097
	Fixed, Wide Lane	594209,391	31	24	3	23	23	0	594209,307	0.084	0.141
GPS/Galileo/QZSS	Fixed, Wide Lane	1558676,633	32	24	4	24	47	8	1558676,497	0.136	0.087
	Fixed, Wide Lane	984535,545	31	24	3	23	23	0	984535,442	0.103	0.105
	Fixed, Wide Lane	594209,386	31	24	3	23	23	0	594209,307	0.079	0.133
GPS/Galileo/QZSS/BeiDou	Float, Wide Lane	1558676,641	32	24	4	24	47	8	1558676,497	0.144	0.092
	Float, Wide Lane	984535,542	31	24	3	23	23	0	984535,442	0.100	0.102
	Float, Wide Lane	594209,375	31	24	3	23	23	0	594209,307	0.068	0.114
GLONASS/Galileo	Fixed, Wide Lane	1558676,676	32	24	4	24	47	8	1558676,497	0.179	0.115
	Fixed, Wide Lane	984535,554	31	24	3	23	23	0	984535,442	0.112	0.114
	Fixed, Wide Lane	594209,404	31	24	3	23	23	0	594209,307	0.097	0.163
GLONASS/QZSS	Fixed, Wide Lane	1558676,716	32	24	4	24	47	8	1558676,497	0.219	0.140
	Fixed, Wide Lane	984535,671	31	24	3	23	23	0	984535,442	0.229	0.233
	Fixed, Wide Lane	594209,414	31	24	3	23	23	0	594209,307	0.107	0.180

End of Table 2

Satellite configuration	Solution type	S_{TMTS} (m)	GPS	GLO.	QZSS	GAL.	BDS	IRNSS	$S_{BERNESE}$ (m)	Diff. (m)	ppm
GLONASS/BeiDou	Float, Wide Lane	1558676,637	32	24	4	24	47	8	1558676,497	0.140	0.090
	Float, Wide Lane	984535,547	31	24	3	23	23	0	984535,442	0.105	0.107
	Float, Wide Lane	594209,371	31	24	3	23	23	0	594209,307	0.064	0.108
GLONASS/Galileo/BeiDou	Float, Wide Lane	1558676,640	32	24	4	24	47	8	1558676,497	0.143	0.092
	Float, Wide Lane	984535,541	31	24	3	23	23	0	984535,442	0.099	0.101
	Float, Wide Lane	594209,380	31	24	3	23	23	0	594209,307	0.073	0.123
GLONASS/Galileo/BeiDou/QZSS	Float, Wide Lane	1558676,643	32	24	4	24	47	8	1558676,497	0.146	0.094
	Float, Wide Lane	984535,546	31	24	3	23	23	0	984535,442	0.104	0.106
	Float, Wide Lane	594209,378	31	24	3	23	23	0	594209,307	0.071	0.120
Galileo/QZSS	Fixed, Wide Lane	1558676,614	32	24	4	24	47	8	1558676,497	0.117	0.075
	Fixed, Wide Lane	984535,546	31	24	3	23	23	0	984535,442	0.104	0.106
	Fixed, Wide Lane	594209,385	31	24	3	23	23	0	594209,307	0.078	0.131
Galileo/QZSS/BeiDou	Float, Wide Lane	1558676,633	32	24	4	24	47	8	1558676,497	0.136	0.087
	Fixed, Wide Lane	984535,535	31	24	3	23	23	0	984535,442	0.093	0.094
	Float, Wide Lane	594209,375	31	24	3	23	23	0	594209,307	0.068	0.114
Galileo/BeiDou	Float, Wide Lane	1558676,636	32	24	4	24	47	8	1558676,497	0.139	0.089
	Float, Wide Lane	984535,535	31	24	3	23	23	0	984535,442	0.093	0.095
	Float, Wide Lane	594209,377	31	24	3	23	23	0	594209,307	0.070	0.118
BeiDou/QZSS	Float, Wide Lane	1558676,626	32	24	4	24	47	8	1558676,497	0.129	0.083
	Fixed, Wide Lane	984535,552	31	24	3	23	23	0	984535,442	0.110	0.112
	Fixed, Wide Lane	594209,365	31	24	3	23	23	0	594209,307	0.058	0.098
BeiDou	Float, Wide Lane	1558676,631	32	24	4	24	47	8	1558676,497	0.134	0.086
	Fixed, Wide Lane	984535,548	31	24	3	23	23	0	984535,442	0.106	0.108
	Float, Wide Lane	594209,374	31	24	3	23	23	0	594209,307	0.067	0.113

3.1. Impact of IRNSS satellites for long baseline solution

Since IRNSS satellites are observed and effective only in the COCO-JOG2 baseline, this baseline was analysed. When the COCO-JOG2 baseline solution (Fixed-Wide Lane) and the

obtained differences are analysed, the differences between the Galileo/QZSS/IRNSS satellite configuration and the baseline length obtained from Bernese is 17.3 cm (Table 3). As explained above, the effect of the Galileo satellites on the solution of the integer ambiguity is clearly visible.

Table 3. Comparison of satellite configuration, type of integer ambiguity solution, number of satellites and baseline length values

Satellite configuration	Solution type	Distance (m)	GPS	GLO.	QZSS	GAL	BDS	IRNSS	$S_{BERNESE}$ (m)	Diff. (m)	ppm
GPS/IRNSS	Fixed, Wide Lane	1558677,623	32	24	4	24	47	8	1558676,497	1.126	0.722
GPS/GLONASS/IRNSS	Float, Wide Lane	1558679,212	32	24	4	24	47	8	1558676,497	2.715	1.742
GPS/GLONASS/Galileo/IRNSS	Fixed, Wide Lane	1558678,285	32	24	4	24	47	8	1558676,497	1.788	1.147
GPS/GLONASS/Galileo/QZSS/IRNSS	Float, Wide Lane	1558677,371	32	24	4	24	47	8	1558676,497	0.874	0.561
GPS/GLONASS/Galileo/QZSS/IRNSS/BeiDou	Float, Wide Lane	1558676,742	32	24	4	24	47	8	1558676,497	0.245	0.157
GLONASS/IRNSS	Fixed, Wide Lane	1558678,071	32	24	4	24	47	8	1558676,497	1.574	1.010

End of Table 3

Satellite configuration	Solution type	Distance (m)	GPS	GLO.	QZSS	GAL	BDS	IRNSS	S _{BERNESE} (m)	Diff. (m)	ppm
GLONASS/Galileo/IRNSS	Fixed, Wide Lane	1558678,477	32	24	4	24	47	8	1558676,497	1.980	1.270
GLONASS/Galileo/QZSS/IRNSS	Fixed, Wide Lane	1558677,161	32	24	4	24	47	8	1558676,497	0.664	0.426
GLONASS/Galileo/QZSS/BeiDou/IRNSS	Float, Wide Lane	1558676,733	32	24	4	24	47	8	1558676,497	0.236	0.151
Galileo/BeiDou/QZSS/IRNSS	Float, Wide Lane	1558676,709	32	24	4	24	47	8	1558676,497	0.212	0.136
Galileo/BeiDou/IRNSS	Float, Wide Lane	1558676,764	32	24	4	24	47	8	1558676,497	0.267	0.171
Galileo/QZSS/IRNSS	Fixed, Wide Lane	1558676,670	32	24	4	24	47	8	1558676,497	0.173	0.111
QZSS/BeiDou/IRNSS	Float, Wide Lane	1558676,599	32	24	4	24	47	8	1558676,497	0.102	0.065
QZSS/IRNSS	Fixed, Wide Lane	1558676,133	32	24	4	24	47	8	1558676,497	-0.364	0.234
BeiDou/IRNSS	Float, Wide Lane	1558676,698	32	24	4	24	47	8	1558676,497	0.201	0.129
Galileo/IRNSS	Fixed, Wide Lane	1558677,610	32	24	4	24	47	8	1558676,497	1.113	0.714

3.2. Analysis of fixed baseline surveys

The Federal Geodetic Control Subcommittee (FGCS) has developed a document titled "Geometric Geodetic Accuracy Standards and Specifications for Using GPS Relative Positioning Techniques." It is intended to serve as a guideline for planning, executing, and classifying geodetic surveys performed by GNSS relative positioning methods. This document may be consulted to determine whether or not the ppm values of column (Tables 2 and 3) are acceptable for the required order of accuracy for the survey. Besides ppm requirements, the FGCS guidelines specify other criteria that must be met for the different orders of accuracy in connection with repeat baseline observations. Again the acceptability of the line can be computed based on the FGCS guidelines or by comparing the baseline against the manufacturer's specified accuracies. Another procedure employed in evaluating the consistency of the observed data and in weeding out blunders is to make repeat observations of certain baselines. These repeat measurements are taken in different observing sessions and the results compared. Significant differences in repeat baselines indicate problems with field procedures or hardware (Wolf & Ghilani, 2008).

In this study, GPS/GLONASS/Galileo/BeiDou/QZSS and IRNSS satellite configurations and Fixed-Wide Lane integer ambiguity solution for long baseline and ppm values were computed by using the FGCS guidelines. Thus, a statistical check was also performed in this study. Another remarkable effect of this study is that the 8 visible IRNSS satellites were able to compute the COCO-JOG2 baseline (Galileo/QZSS/IRNSS configuration) with a difference of around 6 cm (Fixed-Wide Lane, see Tables 2 and 3).

4. Conclusions

In this study, the Wide-Lane method, which is particularly effective in solving integer ambiguity in long bases, is investigated. The results obtained with different satellite configurations for the Fixed-Wide-Lane integer uncertainty solution are compared. In the statistical test-based investigations, the differences obtained were calculated in ppm values. In this study, the effectiveness of Galileo satellites (Six navigation signals-designated as L1F, L1P, E6C, E6P, E6P, E5a, and E5b) in the long baselines solution is obvious.

The large wavelength of the Wide-lane combination (~86 cm) is useful for ambiguity resolution algorithms, as well as cycle-slip and outliers detection. But it is important to emphasize that noises present in the original observables are also amplified.

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