Geodesy and Cartography
ISSN 2029-6991 / eISSN 2029-7009
2023 Volume 49 Issue 4: 222–232
https://doi.org/10.3846/gac.2023.17707

UDC 528.2

TESTING THE CONTRIBUTION, ACCURACY AND PERFORMANCE OF MGEX (GNSS (GPS+GLONASS+GALILEO+BEIDOU+QZSS)) POSITIONING IN THE STUDY REGION

Atınç PIRTI*

Department of Surveying Engineering Davutpasa, Yildiz Technical University, Esenler, Istanbul, Turkiye

Received 22 September 2022; accepted 22 November 2023

Abstract. The European Commission (EC) originally proposed ideas for a European Galileo satellite navigation system in 1999. A four-phase development is planned, involving investment from both the public and commercial sectors. Galileo is intended for both public and government use; the system is administered and operated by civil administration. Galileo will consist of a constellation of 30 satellites, a number of globally situated ground stations, and a ground control and monitoring system – all of which are quite similar to the structure, format, and layout of GPS. This document discusses an experiment at the project site that used the static approach to integrate GPS, GLONASS, GALILEO, Beidou, and QZSS signals. This research analyses the possible precision of GPS-only and GPS/GLONASS/GALILEO/Beidou/QZSS. These results suggest that combining a GPS system with GALILEO, GLONASS Beidou, and QZSS is preferable for surveying purposes. Integrating GPS/GLONASS/GALILEO/Beidou/QZSS static measurements in the study region with 0–120 millimetre accuracy looks to be possible in three days.

Keywords: GPS, GLONASS, GALILEO, Beidou, QZSS, Loop Closure, improvement, accuracy.

Introduction

There have been numerous technological advances in the past 50 years, but not one may be more important to the surveying society than the Global Positioning System (GPS). The GPS is a worldwide navigation system that uses information received from 24 or more (currently 32) orbiting satellites. The satellite orbits are filling the South, East and West directions with no satellites in the northern sky. The Galileo positioning system is a satellite navigation system developed by the European Union (EU) to compete with GPS (which is controlled by the US military) and the Russian GLONASS (controlled by the Russian military). The Galileo system is expected to be fully operational by 2023, with 30 more satellites orbiting at a height of 23,222 kilometres. The Europeans claim that the system will provide greater precision to all users than is currently available. It is also intended to improve coverage of satellites at higher latitudes. Although Galileo will be completely interchangeable with the GPS system, it is primarily for the use of European nations in a time of war when the US may turn on selective availability within the GPS system. Commercial service will be available for a fee and will offer positional accuracy of better than 1 meter. The commercial service will be complemented by ground stations for accuracies better than 10 cm. The creators of the Galileo system are predicting that with the increased number of satellites available, users will be able to use satellites for positioning in places that are not feasible with GPS, such as cities with high rise buildings and dense forests. Some have even gone as far as to predict that once Galileo is in place, satellite positioning will be feasible inside buildings. The Galileo space segment will be made up of 27 satellites plus three spares that will orbit in three planes that are 56° inclined to the equator. Six navigation signals will be sent by the satellites: L1F, L1P, E6C, E6P, E5a, and E5b (Montenbruck et al., 2017; Sośnica et al., 2017). In December 2005, the first Galileo experimental satellite was launched. The second launch was postponed until late 2007 due to a problem with the second satellite. With its commercial service delivering meter-level point location, Galileo may provide more precision than GPS. The power of its transmissions, like that of upgraded GPS satellites, should enable it to function in canopy circumstances. The United States and the European Union have agreed to interconnect their networks. Satellites from either system may now be used by receivers (Elmezayen & El-Rabbany, 2019; European Galileo Open Service, 2021;

*Corresponding author. E-mail: *atinc@yildiz.edu.tr*

Guo et al., 2017; Kwasniak, 2018; Li et al., 2015, 2018; Xia et al., 2019; Zhou et al., 2015).

In this study the experiments were performed at three IGS points (ABPO, VACS and REUN) to evaluate the following questions: should surveyors embrace the revived GLONASS system and/or Galileo system; if so is the increase in satellite coverage necessary, and how would these systems affect positional accuracy of surveyed features? This study investigates the GPS-only, GPS/GLONASS/GALILEO8Beidou/QZSS achievable accuracy.

1. Galileo and Galileo signals

Galileo has shown an improvement in the density of the constellation of visible satellites, and thus an improvement in the time needed to obtain centimetre-level accuracy (Figure 1). The nominal values of the main parameters for the Galileo constellation are defined in Table 1 (European Galileo Open Service, 2021).

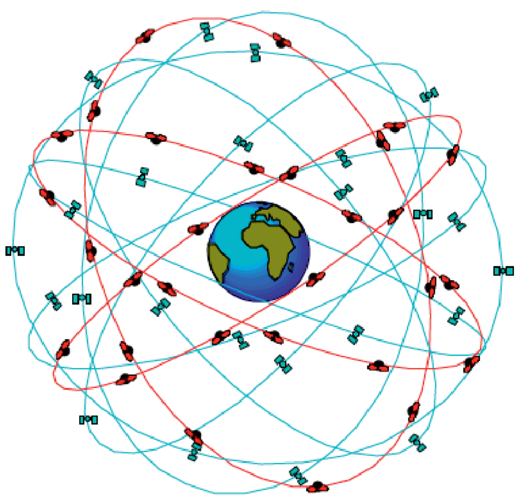


Figure 1. GPS and Galileo will provide around 60 satellites, and more than double the number of available signals for all user segments

Table 1. Main orbit characteristics of the nominal Galileo constellation

Parameter	Explanation	Value
$e_{nominal}$	Nominal orbit eccentricity	0
$i_{nominal}$	Nominal orbit inclination with reference to the equatorial plane	56°
$A_{nominal}$	Nominal orbit semi-major axis	29 600 000 m

Figure 2 specifies the radio-frequency air interface between space and user segments. Three independent CDMA signals, named E5, E6 and E1, are permanently transmitted by all Galileo satellites. The E5 signal is further sub-divided into two signals denoted E5a and E5b (European Galileo Open Service, 2021; Sośnica et al., 2017).

Galileo provides enhanced distress localisation and call features for the provision of a Search and Rescue (SAR) service interoperable with the COSPAS–SARSAT system (Figure 3). Galileo carrier frequencies are shown in Table 2. The names of the Galileo signals are the same than the corresponding carrier frequencies (European Galileo Open Service, 2021; Kwasniak, 2018; Pan et al., 2017; Sośnica et al., 2017).

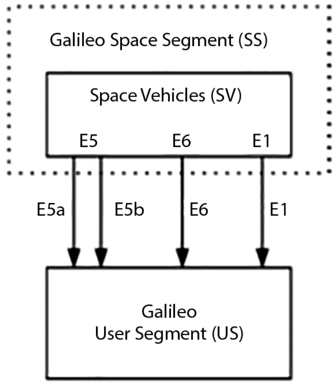


Figure 2. Space vehicle/navigation user interface

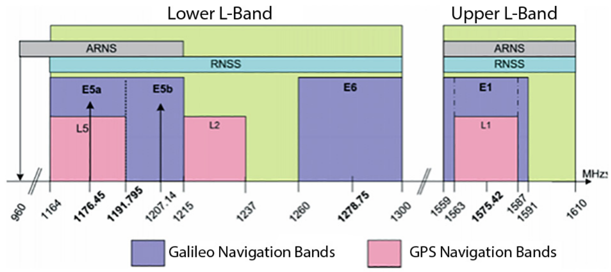


Figure 3. Galileo frequency plan

Table 2. Carrier frequency per signal

Signal	Carrier Frequency [MHz]
E1	1575.420
E6	1278.750
E5	1191.795
E5a	1176.450
E5b	1207.140

Note: the E5a and E5b signals are part of the E5 signal in its full bandwidth.

Galileo E5 signal is composed of signals E5a, E5b (and modulation product signal), and is transmitted in a global homogeneous state in the 1164 215 MHz frequency band allocated to RNSS. (European Galileo Open Service, 2021; Kwasniak, 2018; Sośnica et al., 2017; Xia et al., 2019; Zhou et al., 2015).

As for BeiDou is the Global Navigation Satellite System (GNSS) system developed by China which consists of two separate satellite constellations. The first generation constellation was the BeiDou Satellite Navigation Experimental System and also known as BeiDou-1. It consisted of three satellites which offered limited coverage and navigation services at the beginning of 2000. BeiDou-1 mainly covered users in China and the neighbouring regions. BeiDou-1 was decommissioned at the end of 2012. In December 2011, the second generation constellation, officially called the BeiDou

Navigation Satellite System (BDS) and also known as COMPASS or BeiDou-2 became operational in China. It consisted of a partial constellation of 10 satellites in orbit. Later in December 2012, the constellation expanded its services to customers in the Asia-Pacific region. China launched the third generation constellation (BeiDou-3) in 2015 providing global coverage. The full BeiDou constellation will be completed by 2020 with 35 satellites in three different orbit types, specifically (Septentrio, 2022):

- 5 BeiDou-G satellites in the geostationary orbit (GEO);
- 27 BeiDou-M satellites in medium earth orbit (MEO);
- 3 BeiDou-I satellites in inclined geosynchronous orbits (IGSO).

BeiDou satellites were launched into three different phases: BeiDou-1, BeiDou-2 and BeiDou-3 of which the last two are active (Septentrio, 2022):

BeiDou-2

In the second phase, 16 satellites were launched between 2007–2012 and 3 satellites were launched between 2016 and 2018 of which 15 satellites were operational. The satellites transmitted three different public signals:

- B1I: Frequency below GPS L1 (BPSK modulation);
- B2I: Same frequency as Galileo E5b, but with different signal structure (BPSK modulation);
- B3I: Overlaps with a part of Galileo E6a (BPSK modulation).

BeiDou-3

More satellites were launched of which currently 43 are operational (May 19, 2020). The last phase, BeiDou-3, aims at expanding the global coverage and improving its performance.

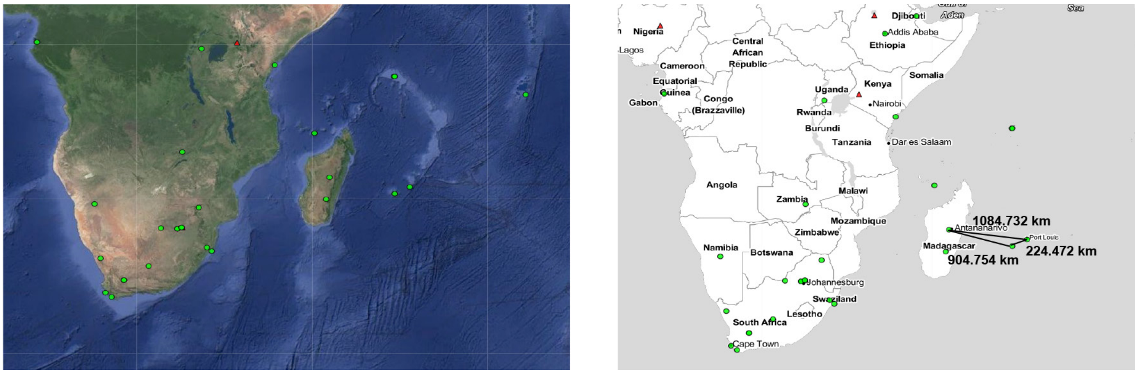
- The same B1I and B3I as in BeiDou-2;
- B1C: Interoperable with GPS L1C and Galileo L1BC (QMBOC modulation);
- B2a: Same as GPS L5 and Galileo E5a (BPSK modulation);
- B2b.

QZSS

QZSS is a Japanese satellite positioning system made up mostly of satellites in quasi-zenith orbits (QZO). However, the name "Quasi-Zenith Satellite (QZS)" may apply to both satellites in QZO and geostationary orbits (GEO). As a result, the term "QZO satellite" is used when referring to satellites in QZO. Satellite positioning systems employ satellite signals to compute location information. The American Global Positioning System (GPS) is one well-known example; the QZSS is frequently referred to as the "Japanese GPS." QZSS (Michibiki) has been operational as a four-satellite constellation since November 2018, with three satellites visible at all times from Asia-Oceania locales. QZSS may be used in conjunction with GPS to ensure a sufficient number of satellites for consistent, high-precision positioning. Because QZS are GPS-compatible and receivers are inexpensive, it is envisaged that location information companies based on geographical and spatial data would emerge. In recent years, many nations have developed and established their own satellite positioning systems. QZSS, on the other hand, outperforms these systems. While several nations launch positioning satellites, only Japan's QZSS is extremely compatible with GPS and may be used in conjunction with GPS; QZSS and GPS can be used as a single set of satellites. Simply said, QZSS increases the number of GPS satellites. Because QZSS may be used in conjunction with GPS, the number of satellites that can broadcast satellite signals at the same time is increased, allowing for very accurate and steady placement. This also reduces the placement mistakes mentioned above. QZS transmits the same location signals as GPS (L1C/A, L2C, and L5) and has clocks that are synced with GPS, allowing them to be utilized as extra GPS satellites. QZS spends around 16 hours at elevation angles of 20° or more from the region near Japan. With a four-satellite constellation, additional satellites will be seen in conjunction with GPS, resolving multipath and satellite placement issues. This will help increase positioning stability in hilly and urban settings with restricted fields of view owing to buildings, trees, and so on (Quasi-Zenith Satellite System [QZSS], 2022).

2. Description of the experiment

To investigate MGEX; the impact of Galileo, Beidou and QZSS positioning, the experiments were conducted in the project area. For this aim, three IGS points (ABPO, REUN, VACS in Madagascar and Indian Ocean) were selected in the project area because of the lengths (between 225 km and 1085 km) (see Figure 4). All three IGS points were recorded with the data of GPS, GLONASS, Galileo, Beidou and QZSS satellites. Static GNSS surveys on 17.07.2022, 18.07.2022 and 19.07.2022 for these three points was downloaded by using IGS web-site to compute the coordinates of these three points. Three points of static measurements were taken during an observation period of at 24 hours. Use Topcon Magnet TOOLS Software (version 7.3.0-Commercial software) to perform data processing and network adjustments. During the adjustment process, the ITRF 2014 (Epoch 2022.55) coordinates of ABPO (IGS station) is fixed. The GNSS receivers were used for three IGS points measurement includes two SEPT POLARX5 (ABPO Antenna: ASH701945G_M], SEPTPOLARX5 (VACS Antenna: AVRINGANT_DM) and SEPT POLARX5 (REUN Antenna: TRM55971.00). For static GNSS measurements of these three points, the data receiving and processing rate is set to 30 seconds, and the cut-off elevation mask angle is set to 10 degrees. On the other hand, two processing tests (GPS-only, GPS/GLONASS/GALILEO/Beidou/QZSS satellites) for the static survey were conducted at the three days. During these two tests, the number of GPS, GPS/GLONASS/GALILEO/Beidou/QZSS satellites tracked and their distribution are usually "normal", from 22 to 43 satellites observed, and the Precision Position Dilution (PDOP) is between 0.75 and 1.58 (see Figures 5, 6, and 7).



a) b)

Figure 4. Study area (a) and GNSS network by using three IGS points in Madagascar and Indian Ocean (b)

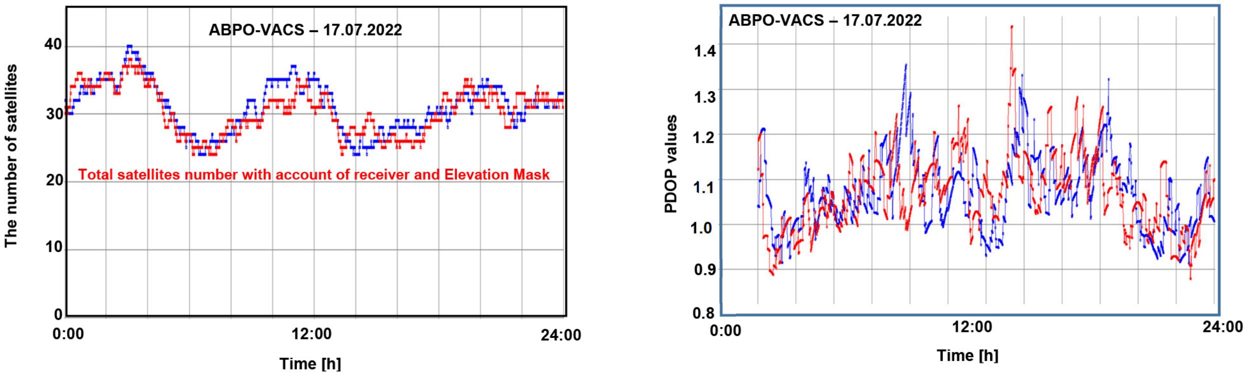


Figure 5. The charts of number of GPS/GLONASS/GALILEO/Beidou/QZSS satellites and Dilution of Precision (DoP) for ABPO-VACS baseline on 17 July 2022

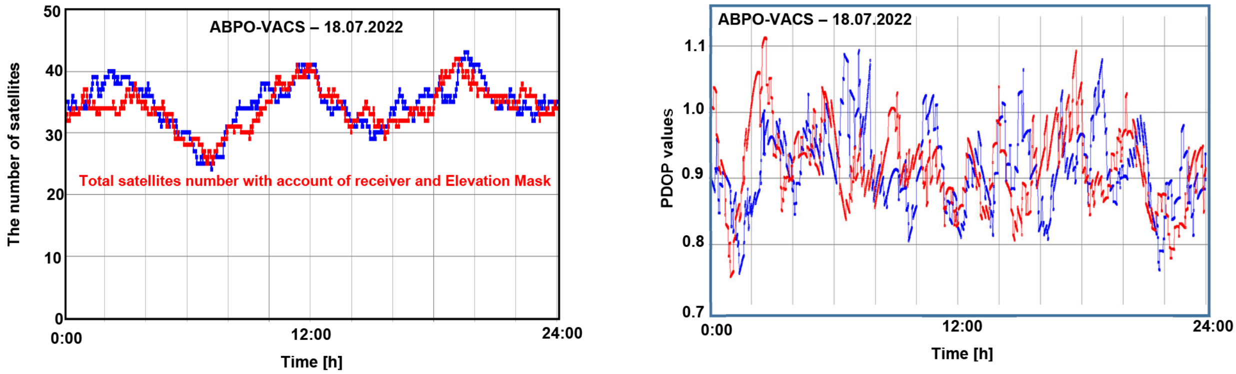


Figure 6. The Dilution of Precision (DoP) and quantity of GPS, GLONASS, Galileo, Beidou, and QZSS satellites for the ABPO-VACS baseline on July 18, 2022

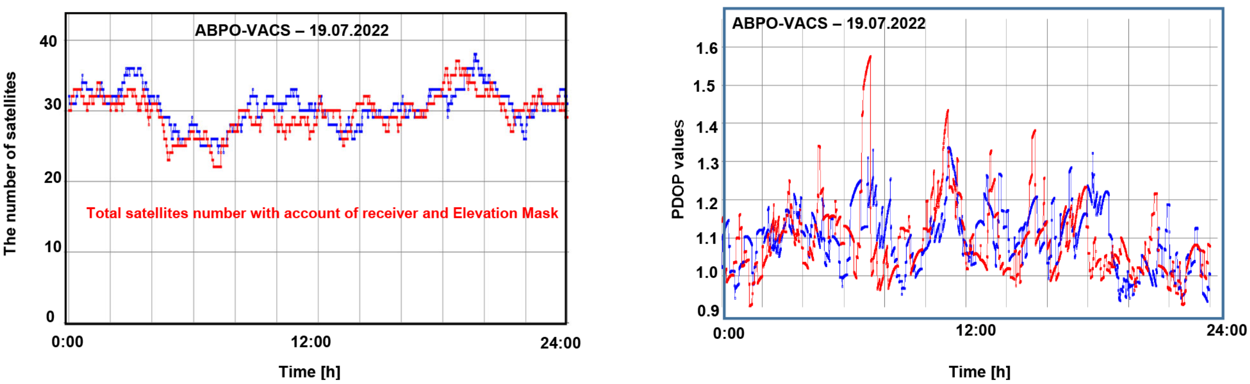


Figure 7. The amount of GPS, GLONASS, Galileo, Beidou, QZSS, and Dilution of Precision (DoP) charts for the ABPO-VACS baseline on July 19, 2022

During the first test (GPS-only, 17.07.2022), the number of GPS satellites tracked and their distribution are usually "normal" ranging from 8 to 13 satellites observed, and the Dilution of Precision (DoP) values are between 2.1 and 3.0. During the first test (GPS/GLONASS/GALILEO/BEİDOU/QZSS satellites, 17.07.2022), the number of GPS/GLONASS/GALILEO/BEİDOU/QZSS satellites tracked and their distribution are usually "normal", from 23 to 40 satellites observed, and the Dilution of Precision (DoP) values are between 0.88 and 1.43 (see Figure 5).

The number of GPS satellites monitored and their distribution are typically "normal" during the second test (GPS-only, 18.07.2022), with 8 to 13 satellites detected, and the Dilution of Precision (DoP) values range from 2.1 to 3.0. There were 25 to 43 GPS/GLONASS/GALILEO/Beidou/QZSS satellites tracked and spread out evenly during the second test (GPS/GLONASS/GALILEO/Beidou/QZSS satellites, 18.07.2022). This is a "normal" number of satellites, and the Dilution of Precision (DoP) values were between 0.75 and 1.1 (see Figure 6).

In the third test (GPS only, 19.07.2022), the Dilution of Precision (DoP) values range from 2.1 to 3.0, and the number of monitored GPS satellites and their distribution are typically "normal," with 8 to 13 satellites detected. In the initial test (GPS/GLONASS/GALILEO/Beidou/QZSS satellites, 19.07.2022), the distribution and number of tracked GPS/GLONASS/GALILEO/Beidou/QZSS satellites are typically "normal," with 22–38 satellites observed and Dilution of Precision (DoP) values ranging from 0.92 to 1.58 (Figure 7).

3. Results

3.1. Web-Online GNSS processing results (CSRS-PPP and Trimble RTX)

CSRS-PPP and Trimble RTX web online processing Software were used to process all of the static GNSS measurements. CSRS-PPP is an internet program for post-processing data from global navigation satellite systems (GNSS). It determines exact user locations everywhere on the world, independent of proximity to reference stations, by using precise satellite orbit, time, and bias adjustments extracted from a global network of receivers. Send over the Internet observation data in Receiver INdependent Exchange (RINEX) format from single or dual-frequency receivers operating in static or kinematic mode, and recover enhanced positioning precisions in the North American Datum of 1983 of the Canadian Spatial Reference System (NAD83 (CSRS)) or the International Terrestrial Reference Frame (ITRF) (CSRS-PPP, 2022; Trimble, 2022).

Trimble RTX technology computes and relays satellite orbit, satellite clock, and other system modifications to the receiver in real-time using data from an infrastructure of Trimble-owned worldwide reference stations. As a consequence, positions at the centimeter level are produced that consistently provide high precision locations around the globe. The user receives the post-processed findings via email or a client interface, while the modifications are conveyed to the recipient by satellite, Internet Protocol (IP) or cellular. The CenterPoint RTX post-processing service can achieve an accuracy level of at least 2 cm in the horizontal and around 6 cm in the vertical. Based on a minimum observation file of one hour, this is this. The precision may reach 1 cm in the horizontal direction and 3 cm in the vertical direction when the data session draws near, but not beyond 24 hours. Less than an hour's worth of data will provide less precise location findings. Even more precision may be obtained with data sets longer than an hour, perhaps approaching 1 cm (Trimble, 2022).

The standard deviation values of the latitudes and longitudes of the three IGS points by processing CSRS-PPP and Trimble RTX-Post processing Software shown in Table 3 was obtained between 2 mm and 6 mm. The standard deviation values of the ellipsoidal heights of the three IGS points shown in Table 3 were obtained between 7 mm and 9 mm. All of the tables list the coordinates and standard deviations of the three IGS points.

The obtained coordinates from CSRS-PPP and Trimble RTX Software for three days were compared. The coordinate differences were calculated in the range of 0 mm to 7 mm. The differences between the coordinates obtained from both software and the length values found were obtained in the range of 0 mm to 7 mm. The obtained coordinates of the two software for three days are consistent with each other (Table 3).

3.2. Commercial software (Magnet Tools v.7.3.0) results

Magnet Tools provides customizable processing and adjustment options for data collected using optical total station systems and GNSS hardware. Process of field surveys of combined methods of GNSS and total stations.

In Table 4, the coordinate and standard deviation values obtained by processing GPS-only satellite data of the three days are shown. The differences between the coordinates are calculated between 3 mm and 22 mm with each other. The obtained latitude, longitude and ellipsoidal height values of ABPO station by using CSRS-PPP Software were taken as fixed. The Cartesian coordinate differences of the three IGS stations were computed by using geographic coordinates of these three IGS stations. Cartesian coordinate differences were computed between CSRS-PPP and Topcon Magnet Tools Software v. 7.3.0 (GPS-only and GPS/GLONASS/Galileo/Beidou/QZSS) was calculated between 0 mm and 120 mm, see Tables 4 and 5 (Topcon, 2022).

Table 5 shows the coordinates and standard deviation values obtained by processing GPS/GLONASS/Galileo/Beidou/QZSS satellite data in the three days. The differences between the coordinates are calculated between 3 mm and 39 mm.

Table 6 shows the selection of ambiguity solution type, orbit and tropospheric mapping function model for Topcon Magnet Tools Software v. 7.3.0, as well as the date

Table 3. The values (ITRF 2014, 2021.1658) of the coordinate differences between Trimble RTX Software results and CSRS-PPP results for the three tests in the study site

St.	CSRS-PPP Software (GPS/GLONASS)-17.07.2022						Trimble RTX Software (GPS/GLOSASS)17.07.2022					
	φ_{ITRF} (°)	λ_{ITRF} (°)	h_{ITRF} (m)	Std (φ) [mm]	Std (λ) [mm]	Std (h) [mm]	φ_{ITRF} (°)	λ_{ITRF} (°)	h_{ITRF} (m)	Std (φ) [mm]	Std (λ) [mm]	Std (h) [mm]
ABPO	19°01'05,89434"S	47°13'45,17136"W	1552,966	2	2	9	19°01'05,89422"S	47°13'45,17140"W	1552,963	2	6	8
REUN	21°12'29,60584"S	55°34'18,20252"W	1558,340	2	2	9	21°12'29,60584"S	55°34'18,20252"W	1558,340	2	2	8
VACS	20°17'49,46694"S	57°29'49,34070"W	421,147	2	2	9	20°17'49,46694"S	57°29'49,34070"W	421,147	2	5	8
	X_{ITRF} (m)	Y_{ITRF} (m)	Z_{ITRF} (m)	S [km]			X_{ITRF} (m)	Y_{ITRF} (m)	Z_{ITRF} (m)	dX [m]	dY [m]	dZ [m]
ABPO	4097216,515	4429119,248	–2065771,145	$S_{ABPO-VACS}$= 1084732.107 $S_{ABPO-VACS}$= 1084732.106			4097216,513	4429119,248	–2065771,141	0.002	0	–0.004
REUN	3364098,887	4907944,685	–2293466,659	$S_{ABPO-REUN}$= 904754.388 $S_{ABPO-REUN}$= 904754.387			3364098,887	4907944,685	–2293466,659	0	0	0
VACS	3215946,87	5047449,787	–2198718,129	$S_{REUN-VACS}$= 224472.666 $S_{REUN-VACS}$= 224472.666			3215946,87	5047449,787	–2198718,129	0	0	0
	CSRSPPP Software (GPS/GLOSASS)18.07.2022						Trimble RTX Software (GPS/GLOSASS)18.07.2022					
ABPO	19°01'05,89435"S	47°13'45,17138"W	1552,964	2	2	9	19°01'05,89420"S	47°13'45,17144"W	1552,957	2	5	7
REUN	21°12'29,60579"S	55°34'18,20265"W	1558,340	2	2	8	21°12'29,60570"S	55°34'18,20271"W	1558,335	2	5	7
VACS	20°17'49,46687"S	57°29'49,34062"W	421,155	2	2	9	20°17'49,46679"S	57°29'49,34079"W	421,160	2	5	7
	X_{ITRF} (m)	Y_{ITRF} (m)	Z_{ITRF} (m)	S [km]			X_{ITRF} (m)	Y_{ITRF} (m)	Z_{ITRF} (m)	dX [m]	dY [m]	dZ [m]
ABPO	4097216,513	4429119,247	–2065771,145	$S_{ABPO-VACS}$= 1084732.104 $S_{ABPO-VACS}$= 1084732.102			4097216,508	4429119,245	–2065771,138	0.005	0.002	–0.007
REUN	3364098,884	4907944,688	–2293466,657	$S_{ABPO-REUN}$= 904754.391 $S_{ABPO-REUN}$= 904754.390			–2293466,653	3364098,88	4907944,686	0.004	0.002	–0.004
VACS	3215946,876	5047449,793	–2198718,13	$S_{REUN-VACS}$= 224472.660 $S_{REUN-VACS}$= 224472.657			–2198718,13	3215946,876	5047449,793	0	0	0
	CSRSPPP Software (GPS/GLOSASS)19.07.2022						Trimble RTX Software (GPS/GLOSASS)19.07.2022					
ABPO	19°01'05,89441"S	47°13'45,17140"W	1552,959	2	2	9	19°01'05,89425"S	47°13'45,17139"W	1552,966	2	5	7
REUN	21°12'29,60577"S	55°34'18,20264"W	1558,331	2	2	8	21°12'29,60563"S	55°34'18,20267"W	1558,334	2	5	7
VACS	20°17'49,46694"S	57°29'49,34072"W	421,151	2	2	9	20°17'49,46682"S	57°29'49,34067"W	421,157	2	5	7
	X_{ITRF} (m)	Y_{ITRF} (m)	Z_{ITRF} (m)	S [km]			X_{ITRF} (m)	Y_{ITRF} (m)	Z_{ITRF} (m)	dX [m]	dY [m]	dZ [m]
ABPO	4097216,509	4429119,244	–2065771,145	$S_{ABPO-VACS}$= 1084732.106 $S_{ABPO-VACS}$= 1084732.106			4097216,515	4429119,25	–2065771,143	–0.006	–0.006	–0.002
REUN	3364098,88	4907944,681	–2293466,653	$S_{ABPO-REUN}$= 904754.387 $S_{ABPO-REUN}$= 904754.390			–2293466,65	3364098,881	4907944,685	–0.001	–0.004	–0.003
VACS	3215946,871	5047449,791	–2198718,131	$S_{REUN-VACS}$= 224472.662 $S_{REUN-VACS}$= 224472.659			–2198718,129	3215946,876	5047449,796	–0.005	–0.005	–0.002

Table 4. Standard deviation and coordinate values (ITRF 2014, Epoch 2021.1658) of the three IGS points by processing static GPS satellites (Topcon Magnet TOOLS Software version 7.3.0) (Topcon, 2022)

GPS-only/ 17.07.2022						
Name	Latitude (°)	Longitude (°)	Ell. Height (m)	Std (Lat)	Std (Lon)	Std (h)
ABPO	19°01'05,89441"S	47°13'45,17140"W	1552,959	0	0	0
REUN	21°12'29,60609"S	55°34'18,20419"W	1558,264	0.033	0.042	0.096
VACS	20°17'49,46692"S	57°29'49,34268"W	421,027	0.033	0.043	0.098
	X_{ITRF} (m)	Y_{ITRF} (m)	Z_{ITRF} (m)			
ABPO	4 097 216,509	4 429 119,244	–2 065 771,145			
REUN	3 364 098,805	4 907 944,652	–2 293 466,638			
VACS	3 215 946,761	5 047 449,723	–2 198 718,087			
GPS-only/ 18.07.2022						
Name	Latitude (°)	Longitude (°)	Ell. Height (m)	Std (Lat)	Std (Lon)	Std (h)
ABPO	19°01'05,89441"S	47°13'45,17140"W	1552,959	0	0	0
REUN	21°12'29,60613"S	55°34'18,20438"W	1558,269	0.029	0.050	0.088
VACS	20°17'49,46695"S	57°29'49,34257"W	421,054	0.027	0.055	0.086
	X_{ITRF} (m)	Y_{ITRF} (m)	Z_{ITRF} (m)			
ABPO	4 097 216,509	4 429 119,244	–2 065 771,145			
REUN	3 364 098,803	4 907 944,658	–2 293 466,641			
VACS	3 215 946,777	5 047 449,743	–2 198 718,097			
GPS-only/ 19.07.2022						
Name	Latitude (°)	Longitude (°)	Ell. Height (m)	Std (Lat)	Std (Lon)	Std (h)
ABPO	19°01'05,89441"S	47°13'45,17140"W	1552,959	0	0	0
REUN	21°12'29,60596"S	55°34'18,20448"W	1558,280	0.030	0.040	0.097
VACS	20°17'49,46680"S	57°29'49,34278"W	421,068	0.031	0.041	0.099
	X_{ITRF} (m)	Y_{ITRF} (m)	Z_{ITRF} (m)			
ABPO	4 097 216,509	4 429 119,244	–2 065 771,145			
REUN	3 364 098,808	4 907 944,67	–2 293 466,64			
VACS	3 215 946,78	5 047 449,759	–2 198 718,098			

Table 5. Standard deviation and coordinate values (ITRF 2014, Epoch 2021.1658) of the three IGS points by processing static GPS/GLONASS/Galileo/Beidou/QZSS satellites (Topcon Magnet TOOLS Software version 7.3.0)

GPS/GLONASS/Galileo/Beidou/QZSS 17.07.2022						
Name	Latitude (°)	Longitude (°)	Ell. Height (m)	Std (Lat)	Std (Lon)	Std (h)
ABPO	19°01'05,89441"S	47°13'45,17140"W	1552,959	0	0	0
REUN	21°12'29,60601"S	55°34'18,20417"W	1558,276	0.026	0.072	0.084
VACS	20°17'49,46693"S	57°29'49,34279"W	421,038	0.026	0.073	0.086
	X_{ITRF} (m)	Y_{ITRF} (m)	Z_{ITRF} (m)			
ABPO	4 097 216,509	4 429 119,244	–2 065 771,145			
REUN	3 364 098,813	4 907 944,661	–2 293 466,64			
VACS	3 215 946,764	5 047 449,734	–2 198 718,091			
GPS/GLONASS/Galileo/Beidou/QZSS 18.07.2022						
Name	Latitude (°)	Longitude (°)	Ell. Height (m)	Std (Lat)	Std (Lon)	Std (h)
ABPO	19°01'05,89441"S	47°13'45,17140"W	1552,959	0	0	0
REUN	21°12'29,60606"S	55°34'18,20477"W	1558,238	0.027	0.071	0.087
VACS	20°17'49,46690"S	57°29'49,34292"W	421,032	0.027	0.071	0.090
	X_{ITRF} (m)	Y_{ITRF} (m)	Z_{ITRF} (m)			
ABPO	4 097 216,509	4 429 119,244	–2 065 771,145			
REUN	3 364 098,778	4 907 944,641	–2 293 466,628			
VACS	3 215 946,758	5 047 449,731	–2 198 718,088			

End of Table 5

GPS/GLONASS/Galileo/Beidou/QZSS 19.07.2022						
Name	Latitude (°)	Longitude (°)	Ell. Height (m)	Std (Lat)	Std (Lon)	Std (h)
ABPO	19°01'05,89441"S	47°13'45,17140"W	1552,959	0	0	0
REUN	21°12'29,60597"S	55°34'18,20397"W	1558,293	0.026	0.065	0.090
VACS	20°17'49,46695"S	57°29'49,34216"W	421,074	0.026	0.066	0.091
	X_{ITRF} (m)	Y_{ITRF} (m)	Z_{ITRF} (m)			
ABPO	4 097 216,509	4 429 119,244	–2 065 771,145			
REUN	3 364 098,827	4 907 944,671	–2 293 466,645			
VACS	3 215 946,797	5 047 449,752	–2 198 718,104			

Table 6. The obtained three baseline values by using Topcon Magnet Tools Software v. 7.3.0 in the three tests in the study site (GPS-only)

GPS-only (17.07.2022)											
Point From	Point To	Horizontal Std (m)	Vertical Std (m)	Solution Type	Orbit	Elevation Mask	Mapping functions	Meteo Model	GPS	Distance (m)	PDOP
ABPO	VACS	0.073	0.138	Fixed, Wide Lane	Precise	15	Niell	GPT	32	1084732.154	1.581
ABPO	REUN	0.069	0.125	Fixed, Wide Lane	Precise	15	Niell	GPT	31	904754.426	1.642
REUN	VACS	0.032	0.063	Fixed, Wide Lane	Precise	15	Niell	GPT	31	224472,673	1.588
GPS-only (18.07.2022)											
Point From	Point To	Horizontal Std (m)	Vertical Std (m)	Solution Type	Orbit	Elevation Mask	Mapping functions	Meteo Model	GPS	Distance (m)	PDOP
ABPO	VACS	0.111	0.111	Float, Wide Lane	Precise	15	Niell	GPT	32	1084732.157	1.581
ABPO	REUN	0.071	0.124	Fixed, Wide Lane	Precise	15	Niell	GPT	31	904754.433	1.642
REUN	VACS	0.035	0.062	Fixed, Wide Lane	Precise	15	Niell	GPT	31	224472.666	1.605
GPS-only (19.07.2022)											
Point From	Point To	Horizontal Std (m)	Vertical Std (m)	Solution Type	Orbit	Elevation Mask	Mapping functions	Meteo Model	GPS	Distance (m)	PDOP
ABPO	VACS	0.072	0.139	Fixed, Wide Lane	Precise	15	Niell	GPT	32	1084732.153	1.550
ABPO	REUN	0.064	0.128	Fixed, Wide Lane	Precise	15	Niell	GPT	31	904754.440	1.622
REUN	VACS	0.031	0.064	Fixed, Wide Lane	Precise	15	Niell	GPT	31	224472.671	1.591

and time of their observations. The difference among the three baselines obtained between Topcon Magnet Tools Software v.7.3.0 (using GPS-only and GPS/GLONASS/Galileo/Beidou/QZSS satellites) remained in the range of 1–17 mm (Table 6). However, the obtained difference among the three baselines by processing Topcon Magnet Tools Software (using GPS/GLONASS/Galileo/Beidou/QZSS satellites satellites) and CSRS-PPP and Trimble RTX web online processing Software (GPS/GLONASS satellites) remained in the range of 3–49 mm (Tables 3 and 7).

The GNSS Loop Closure of the adjustment group allows to perform a loop closures test for the post-processed GNSS observations that form a closed loop. You can configure tolerance of GNSS observations and then analyse a quality of network by calculating the residuals of the closed figures that form loops in the network. If the analysis results in some residuals that exceed the tolerance values you can change your observation values by re-measure them in field or correct the erroneous observations by rejecting suspicious occupations, satellites or changing elevation mask, etc.

On the other hand, the loop closures for static processing (GPS-only and GPS/GLONASS/GALILEO/Beidou/QZSS satellites) are compared with each other. The value of the loop closure of GPS–only for static processing is 4 mm and 11 mm in Table 8. However, the value of the

Table 7. The obtained three baseline values by using Topcon Magnet Tools Software v. 7.3.0 in the three tests in the study site (GPS/GLONASS/Galileo/Beidou/QZSS)

GPS/GLONASS/Galileo/Beidou/QZSS (17.07.2022)															
Point From	Point To	Horizontal Std (m)	Vertical Std (m)	Solution Type	Orbit	Elevation Mask	Mapping functions	Meteo Model	GPS	GLONASS	QZSS	Galileo	BDS	Distance (m)	PDOP
ABPO	VACS	0.108	0.121	Float, Wide Lane	Precise	15	Niell	GPT	32	22	4	27	31	1084732.156	1.581
ABPO	REUN	0.098	0.109	Fixed, Wide Lane	Precise	15	Niell	GPT	31	21	3	21	31	904754.428	1.642
REUN	VACS	0.052	0.056	Float, Wide Lane	Precise	15	Niell	GPT	31	21	3	21	31	224472.676	1.588
GPS/GLONASS/Galileo/Beidou/QZSS (18.07.2022)															
Point From	Point To	Horizontal Std (m)	Vertical Std (m)	Solution Type	Orbit	Elevation Mask	Mapping functions	Meteo Model	GPS	GLONASS	QZSS	Galileo	BDS	Distance (m)	PDOP
ABPO	VACS	0.103	0.127	Float, Wide Lane	Precise	15	Niell	GPT	32	22	4	27	31	1084732.158	1.581
ABPO	REUN	0.103	0.112	Float, Wide Lane	Precise	15	Niell	GPT	31	21	3	21	31	904754.443	1.642
REUN	VACS	0.049	0.059	Fixed, Wide Lane	Precise	15	Niell	GPT	31	21	3	21	31	224472.664	1.605
GPS/GLONASS/Galileo/Beidou/QZSS (19.07.2022)															
Point From	Point To	Horizontal Std (m)	Vertical Std (m)	Solution Type	Orbit	Elevation Mask	Mapping functions	Meteo Model	GPS	GLONASS	QZSS	Galileo	BDS	Distance (m)	PDOP
ABPO	VACS	0.099	0.126	Float, Wide Lane	Precise	15	Niell	GPT	32	22	4	27	31	1084732.141	1.550
ABPO	REUN	0.091	0.118	Float, Wide Lane	Precise	15	Niell	GPT	31	21	3	21	31	904754.423	1.622
REUN	VACS	0.046	0.062	Float, Wide Lane	Precise	15	Niell	GPT	31	21	3	21	31	224472.665	1.591

Table 8. The loop closure for static processing of the network by using GPS and GNSS satellites (Topcon Magnet Tools Software v. 7.3.0)

Loop	dN (mm)	dE (mm)	dHZ (mm)	dU (mm)	Hozizontal Tolerance (m)	Vertical Tolerance (m)	Length (km)	dHz (ppm)	dU (ppm)	dHZ relative	dU relative
GPS-only (17.07.2022)											
ABPO-VACS ABPO-REUN REUN-VACS	4	7	8	10	11.100	11.130	2213.959253	0	0	1:27435298	1:217658072
GPS/GLONASS/ Galileo/Beidou/QZSS (17.07.2022)											
ABPO-VACS ABPO-REUN REUN-VACS	2	1	2	0	11.100	11.130	2213.959260	0	0	1:1172550185	1:23794303785
GPS-only (18.07.2022)											
ABPO-VACS ABPO-REUN REUN-VACS	0	9	9	9	11.100	11.130	2213.959256	0	0	1:260196555	1:241764307
GPS/GLONASS/ Galileo/Beidou/QZSS (18.07.2022)											
ABPO-VACS ABPO-REUN REUN-VACS	2	0	2	0	11.100	11.130	2213.959265	0	0	1:1102728218	1:4981940770
GPS-only (19.07.2022)											
ABPO-VACS ABPO-REUN REUN-VACS	4	11	11	8	11.100	11.130	2213.959264	0.01	0	1:197662612	1:290703106
GPS/GLONASS/ Galileo/Beidou/QZSS (19.07.2022)											
ABPO-VACS ABPO-REUN REUN-VACS	2	2	3	11	11.100	11.130	2213.959229	0	0	1:779502632	1:202081650

The Loops Table displays the following information:

Loop – a set of GNSS observations that form a closed loop.

dN / dE – an absolute value of N and E coordinates misclosures for the given loop.

dHz – an absolute value of horizontal misclosures for the given loop.

dU – an absolute value of vertical misclosures for the given loop.

Horz Tolerance / Vert Tolerance (m) – threshold values. Formulas used for calculating these parameters for the selected GNSS observations are shown in the Loop Closure Precisions upper part of the dialog.

Length (m) – a length of the loop.

dHz (ppm) / dU(ppm) – tolerance of the accuracy of the loop in parts per million.

dHz relative / dU relative – tolerance of the relative accuracy of the loop considering the loop length.

The threshold value (horizontal and vertical) for the test is computed by a formula:

Tolerance = Absolute Tolerance + Relative Tolerance $\times 10^{-6}$,

where Length is the length of the loop in kilometers.

loop closure static processing (GPS/GLONASS/GALILEO/Beidou/QZSS) is 0 mm and 2 mm in Table 8. These results show that the accurate coordinates are obtained by using static processing (GPS/GLONASS/GALILEO/Beidou/QZSS satellites) in this study.

Conclusions

The obtained results have been made concerning increased positional accuracy with the addition of the Galileo, Beidou and QZSS system. The Galileo system developer assert that users will be able to use a GNSS in dense forest, near high rise buildings, and inside buildings, but even with more satellites available for use, the problem of multi-path must first be addressed. When three base lengths are compared in this study, GPS-only and GPS/GLONASS/GALILEO/Beidou/QZSS static processing, and the baseline differences are 1–17 mm (ABPO-VACS), 3–20 mm (ABPO-REUN), 1–9 mm (REUN-VACS). It is obvious that these smallest differences were computed by processing the GPS/GLONASS/GALILEO/Beidou/QZSS satellite data.

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