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Multi-GNSS positioning

Posicionamento multi-GNSS

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Abstract: GNSS (Global Navigation Satellite Systems) have gained a lot of visibility in the last two decades, being currently applied in several activities that go far beyond navigation positioning, some of them requiring high precision (centimeter to millimeter), such as structural monitoring and precision agriculture. To meet these requirements, different positioning methods have been developed, such as (standard and precise) point positioning and relative positioning. More recently, the possibility real time positioning with the use of networks has emerged, both for point and relative methods. The launch of new global constellations has enabled the integration of the different systems which, when successful, offers improvements for the positioning regarding the availability of satellites, the geometry between the receiver and the satellites, ambiguity resolution and its performance when compared to the isolated use of systems. In this sense, this paper presents a review and state of the art of the main characteristics of the four global systems and the different positioning methods, highlighting the multi-GNSS integration, trends and challenges in each of them. Results comparing multi-GNSS with the four constellations positioning to GPS-only, using a 25° cutoff angle, simulating an obstructed environment, are also presented. Considering the positioning accuracy, which considers the error and standard deviation in the position estimate, the integration of the systems brought an improvement of up to 44%.
Keywords: Multi-GNSS Positioning. High precision positioning. Standard Point Positioning.

Resumo: Os GNSS (*Global Navigation Satellite Systems*) têm ganhado bastante visibilidade nas últimas duas décadas, sendo atualmente aplicados em diversas atividades, as quais vão muito além do posicionamento e navegação; algumas delas requerem alta acurácia (centimétrica a milimétrica), como o monitoramento de estruturas e a agricultura de precisão. Para atender a estas necessidades, diferentes métodos de posicionamento foram desenvolvidos, como o posicionamento por ponto (simples e preciso) e o posicionamento relativo. Mais recentemente, surgiu a possibilidade do posicionamento em tempo real com uso de redes, tanto para o posicionamento por ponto quanto para o relativo. O lançamento de novas constelações globais de satélites tem permitido a integração dos diferentes sistemas que, quando bem-sucedida, oferece melhorias para o posicionamento quanto à disponibilidade de satélites, à geometria entre o receptor e o satélite, à solução das ambiguidades e o desempenho deste quando comparado ao uso isolado dos sistemas. Nesse sentido, este artigo tem por objetivo apresentar uma revisão e o estado da arte das principais características dos quatro sistemas globais e dos diferentes métodos de posicionamento, dando destaque para a integração multi-GNSS, tendências e desafios em cada um deles. São também apresentados resultados comparando o posicionamento GPS ao posicionamento multi-GNSS com as quatro constelações e uso de uma máscara de elevação de 25°, simulando um ambiente obstruído. Com relação à acurácia do posicionamento, que leva em consideração o erro e desvio-padrão na estimativa da posição, a integração dos sistemas trouxe uma melhoria de até 44%.
Palavras-chave: Posicionamento multi-GNSS. Posicionamento de alta precisão. Posicionamento por ponto simples.

1 INTRODUCTION

Satellite-based positioning has become essential to the modern society life and is used by a large portion of the population. In the last decades, the GPS (Global Positioning System) has been the most known and used system in several applications of Geodesy, Geophysics and navigation. The advent of the GNSS (Global Navigation Satellite Systems), however, has aroused much interest in the scientific community and has been changing this scenario. In addition to the pioneers GPS and GLONASS (GLObal NAtigation Satellite System), both operational, the BDS system (BeiDou System), declared operational in July 2020, and Galileo, which is in the final stages of development, just a few steps away of becoming fully operational, are now available. Currently, GPS and GLONASS are going through modernizations, adding more capacity, more available signals and better accuracy and interoperability with other systems. With these new developments in GNSS, more than 100 satellites with multiple frequencies will be in orbit and a wide range of scientific and commercial applications will benefit, both in the positioning side and in other applications, such as atmospheric modeling and timing-based services.

For GNSS positioning, the most used observables tracked by a receiver are the carrier-phase and the pseudorange (MONICO, 2008). Due to the low precision of the pseudorange and transmitted ephemeris, the accuracy of the Standard Point Positioning (SPP) is of metric level and is commonly used in automobile and maritime navigation in open sea and on smartphones, requiring only one receiver for that (SEEBER, 2003). With the use of two receivers, using only pseudorange data, Differential GNSS (DGNSS) positioning can be performed, which can provide decimetric accuracy (SEEBER, 2003; DALBELO et al., 2007). For this, the receivers must be separated by a not too long distance to reduce errors related to the atmosphere and the satellites orbits. DGNSS is widely used in air navigation applications and for maritime navigation near ports.

For precise positioning, it is necessary to use the carrier-phase observable, which is about one hundred times more accurate than the pseudorange. The positioning methods based on this observable are divided into Real Time Kinematic (RTK) and Precise Point Positioning (PPP) (GOAD; REMONDI, 1984; ZUMBERGE et al., 1997). RTK requires the use of at least two receivers, one of them with a known position, and in PPP a single receiver is required at the user level, requiring robust modeling of errors and the use of precise ephemeris. For long baselines positioning, without requiring a long observation time, the Network-RTK (NRTK) method was developed (FOTOPOULOS; CANNON, 2001). In this method, a network of reference stations is used instead of one single station. From this network, atmospheric errors and orbital parameters can be estimated in real time and transmitted to a user within the network's coverage area. In NRTK the user needs a bidirectional link with the network station that is the data processing center, so that it is possible to receive corrections in real time. To perform the NRTK, regardless of the method used to generate the corrections, it is necessary that the ambiguities between the stations in the network be reliably resolved, which remains a challenging topic in GNSS research and one of the main factors in determining stations maximum baselines. After ambiguity resolution, the errors of the observables in each of these stations must be determined and the corrections generated. The user can use this value to correct its received observables and perform positioning with centimeter accuracy (FOTOPOULOS; CANNON, 2001; ALVES; MONICO, 2011).

In recent years, the PPP has received great attention from the scientific community for its RTK-comparable accuracy. One of the main disadvantages of PPP is the long convergence time for a reliable ambiguity resolution. In order to reduce the convergence time, the NRTK concept was adapted to PPP, giving rise to the PPP-RTK method (TEUNISSEN; KHODABANDEH, 2015). PPP-RTK extends the concept of PPP, providing users of a single receiver with orbital, clocks and hardware errors corrections. The essential difference between PPP and PPP-RTK is that the latter method incorporates additional network corrections, which allow the user's integer ambiguities to be resolved more quickly. Atmospheric corrections generated by the network can also be applied in PPP-RTK and are generally necessary for a shorter convergence time.

The successful integration of GNSS improves the positioning solution regarding the satellites availability, the geometry between the receiver and the satellites, ambiguity resolution and its performance compared to the isolated use of the systems, also allowing a better understanding of possible systematic errors that may not be detected in individual solutions (KOUBA et al., 2017; MONTENBRUCK et al., 2017). In support of this multi-GNSS integration, the International GNSS Service (IGS), a service of the International

Association of Geodesy (IAG) focused on many GNSS-related activities, launched in 2011 the pilot project Multi-GNSS Experiment (MGEX). This project aims to prepare the IGS, which initially provided GPS and GLONASS products, for the advent of multi-GNSS, aiming to generate and make available products for all global satellite systems (MONTENBRUCK et al., 2017).

In this work, a brief introduction to the GNSS systems will be presented, followed by the model of the GNSS observables in their current conception. Then, the positioning methods will be described, emphasizing their main characteristics. Some advantages and problems in investigation on the integration of GNSS systems will be highlighted in this study. The modeling and estimation of parameters resulting from the integrated use of multiple constellations and GNSS signals will be emphasized, such as the Inter System Bias (ISBs) and the Inter Frequency Bias (IFBs). Some comparative results of GPS-only and multi-GNSS positioning are presented and discussed. Additionally, new trends and future challenges in GNSS positioning will be presented.

2 GLOBAL NAVIGATION SATELLITE SYSTEMS

Global navigation satellite systems started in the 1970s, aiming at the instant determination of a user's position, velocity and time, whatever the atmospheric conditions and geographic location (SEEBER, 2003). Developed concomitantly and independently, GPS and GLONASS were the pioneering systems, followed by Galileo and BDS. Table 1 presents the main characteristics of the four global systems, which will be briefly described below.

GNSS is also composed by regional coverage systems, which include the Regional Navigation Satellite Systems (RNSS), currently composed by the Japanese Quasi-Zenith Satellite System (QZSS), the Indian Regional Navigation Satellite System (IRNSS/NavIC) and the regional component of BDS (KOGURE; GANESHAN; MONTENBRUCK, 2017), and by the augmentation systems based both in satellites (Satellite-Based Augmentation System - SBAS), e.g. the American Wide Area Augmentation System (WAAS) and the European Geostationary Navigation Overlay Service (EGNOS) (WALTER, 2017), and in ground stations (Ground-Based Augmentation System - GBAS) (PULLEN, 2017).

Table 1 – GNSS parameters.

Parameters	GPS	GLONASS	Galileo	BDS (MEO)
Developed by	USA	Russia (Soviet Union)	European Union	China
Nominal constellation	24	24+3	24+6	27
Orbital planes	6	3	3	3
Inclination (°)	55	64,8	56	55
Altitude (km)	20200	19100	23222	21500
Orbital period	11h58min	11h15min	14h04min	12h53min
Repeatability (sidereal days)	1	8	10	7
Frequencies (MHz)	L1: 1575,42 L2: 1227,60 L5: 1176,45	L1: 1597-1617 L2: 1240-1260 L3: 1202,025	E1: 1575,42 E5a: 1176,45 E5b: 1207,14 E5: 1191,795 E6: 1278,75	B1: 1561,098 B2: 1207,14 B3: 1268,52
Satellites identification	CDMA	FDMA/CDMA	CDMA	CDMA
Ephemeris	Keplerian parameters	Position, velocity, and time	Keplerian parameters	Keplerian parameters
Ionospheric model	Klobuchar	-	NeQuick G	-
Reference system	WGS84 (*World Geodetic System 1984*)	PZ-90 (*Parametry Zemli 1990*)	GTRF (*Galileo Terrestrial Reference Frame*)	CGCS2000 (*China Geodetic Coordinate System 2000*)
Time system	GPST (*GPS Time*)	UTC(SU) (*Universal Time Coordinated of Russia*)	GST (*Galileo System Time*)	BDT (*BeiDou Time*)

Source: Adapted from Langley, Teunissen e Montenbruck (2017).

2.1 GPS

Developed and controlled by the United States of America, the GPS was declared operational in 1995. It consists of a nominal constellation of 24 satellites in Medium Earth Orbit (MEO) and ground stations distributed across the globe in order to monitor and control the satellites (SEEBER, 2003); 30 satellites are currently operational (December 2020) (GPS, 2020). Since the launch of the first satellite in 1978 (HEGARTY, 2017), GPS has undergone several modernization projects both in its ground segment and in the satellite blocks. Regarding the signals, the Code Division Multiple Access (CDMA) technique is used, in which all satellites transmit on the same frequency and identification is given by a Pseudo Random Noise (PRN) attributed to each satellite. Initially the system operated in two frequencies, L1 and L2, and only the Precise or Protected code (P-code), reserved for military and authorized users, was transmitted in L2 (SEEBER, 2003). As a result of the modernization projects, from block IIR-M a second civil signal started to be transmitted on L2, called L2C. From 2010, a third frequency, called L5, began to be transmitted in block IIF, with the third civil signal L5C. With three satellites in orbit, a new generation named GPS III has a fourth civil signal in L1 (L1C) (GPS, 2020).

2.2 GLONASS

GLONASS is the global system developed by the former Soviet Union and currently operated by Russia. Similar to GPS, it was created for military purposes and expanded for civilian use (SEEBER, 2003). Although the complete constellation was reached in 1995, the system has gone through a long period of decay, with no new launches required due to the short lifespan of the satellites; in 2001, the constellation had 7 active satellites (FEAIRHELLER; CLARK, 2006). As of 2002, the Russian government established a plan to reestablish global coverage and modernize the system, which today has 28 satellites in orbit, of which 24 are operational (December 2020) (IAC, 2020). Regarding the signals, in the original design, Frequency Division Multiple Access (FDMA) technology was used, in which each satellite transmits and is identified by a different frequency (MONICO, 2008). As in the first GPS satellites, it was transmitted a signal in L1 for the civilian community and authorized users, while a signal in L2 was designated only for authorized users (MONICO, 2008). From the GLONASS-M generation, a new civil signal on the carrier L2 was added to the system (HOFMANN-WELLENHOF; LICHTENEGGER; WASLE, 2008). The GLONASS-K1 satellites started to transmit, in addition to the FDMA signals, a new signal in L3, CDMA. The new generation GLONASS-K2 will also feature CDMA technology in L1 and L2 (REVNIVYKH et al., 2017).

2.3 Galileo

Galileo emerges as the first completely civilian alternative in satellite positioning, developed by the European Union (FALCONE; HAHN; BURGER, 2017). The Galileo constellation, which currently has 28 satellites in orbit, 22 of which are operational (December 2020), is moving towards the Full Operational Capabitily (FOC) phase, when it will have 30 satellites in orbit (ESA, 2020). Each Galileo satellite transmits signals at three frequencies (Table 1) using the CDMA technique, with the E1 signal being transmitted at the same frequency as the GPS L1 signal, and the E5a sub-band using the same frequency as the new GPS L5. The signals are used to offer three types of positioning service: the Open Service (OS), which uses E1 band and E5a and E5b sub-bands for civil positioning; the Public Regulated Service (PRS) on frequencies E1 and E6, a service restricted to users authorized by the government; and the Commercial Service (CS) in a paid service using the encrypted E6 signal. As a fourth service, Galileo satellites support Cospas-Sarsat, an international search and rescue service led by the United States of America, Russia, Canada and France (GSA, 2016; FALCONE; HAHN; BURGER, 2017).

2.4 BDS

China, in the 1980s, decided to develop its own satellite navigation system in three phases. The first phase, called the BeiDou Navigation Satellite Demonstration System (BeiDou-1, or BDS-1), took place with the launch of three geostationary satellites in the years of 2000 to 2003 to demonstrate the system. Such satellites were later replaced by satellites from the BDS-2 phase, the regional phase of the system, which started in 2004 and was declared operational in 2012 (LIU et al., 2014). This phase consists of 14 satellites, 5 of which are in a Geostationary Earth Orbit (GEO), 5 are in an Inclined Geo-Synchronous Orbit (IGSO), and 4 are in a MEO orbit, covering the entire Chinese territory and other parts of Asia and the Pacific (YANG; TANG; MONTENBRUCK, 2017). The third and final phase of the system consists of a global constellation (BDS-3) (SUN et al., 2012; YANG; TANG; MONTENBRUCK, 2017), which was completed in June 2020 (BDS, 2020) with 27 MEO satellites, and the system was declared operational in July 2020. Open and authorized signals are transmitted on three frequencies, called B1, B2, B3 using the CDMA technique (Table 1).

3 GNSS BASIC OBSERVABLES

The basic observables of the GNSS are the pseudorange and the carrier-phase. With metric precision, the pseudodistance is basically a measure of the signal propagation time between the satellite and the receiver, converted to distance and obtained without considering the non-synchronism error between the clocks. Considering a time of observation *t*, frequency *j* and constellation *S*, the pseudorange equation of a satellite *s* tracked by a receiver *r* is given by Eq. (1) (ODJIK, 2017):

$$\begin{aligned} P_r^s(t) = {} & \rho_r^s(t, t-\tau_r^s) + T_r^s + c\left[dt_r(t) + d_{r,j}^S(t) + \Delta \mathrm{d}_{r,j}^s(t)\right] \\ & - c\left[dt^s(t-\tau_r^s) + d_j^s(t-\tau_r^s)\right] + \mu_j^S I_r^s(t) + \varepsilon_{P_{r,j}}^s \end{aligned} \tag{1}$$

in which P_r^s is the pseudorange observable (m), ρ_r^s is the receiver-satellite range (m), τ_r^s is the signal travel time (s), T_r^s is the tropospheric delay (m), *c* is the velocity of light (m/s), dt_r is the receiver clock error (s), $d_{r,j}^S$is the receiver code hardware bias (s), $\Delta \mathrm{d}_{r,j}^s$ is the code interchannel bias (s), dt^s is the satellite clock error (s), d_j^s is the satellite code hardware bias (s), μ_j^S is the ionospheric coefficient, which relates the delay to a certain frequency, I_r^s is the ionospheric delay (m), and $\varepsilon_{P_{r,j}}^s$are the random code noise (m). The receiver hardware bias is different for each constellation, even when signals are tracked in overlapping bands. The difference in the bias between the different systems is called ISB. In the case of the GLONASS FDMA constellation, the pseudorange observations are also contaminated by the code's IFB.

The carrier-phase observation equation is given by Eq. (2) (ODJIK, 2017):

$$\begin{aligned} \varphi_r^s(t) = {} & \rho_r^s(t, t-\tau_r^s) + T_r^s + c\left[dt_r(t) + \delta_{r,j}^S(t) + \Delta\delta_{r,j}^s(t)\right] \\ & - c\left[dt^s(t-\tau_r^s) + \delta_j^s(t-\tau_r^s)\right] - \mu_j^S I_r^s(t) + \lambda_j^S N_r^s + \varepsilon_{\varphi_{r,j}}^s \end{aligned} \tag{2}$$

in which φ_r^s is the carrier-phase observable (m), $\delta_{r,j}^S$ is the receiver phase hardware bias (s), $\Delta\delta_{r,j}^s$is the phase interchannel bias (s), δ_j^s is the satellite phase hardware bias (s), λ_j^S is the wavelength (m), N_r^s is the carrier-phase ambiguity (cycles), and $\varepsilon_{\varphi_{r,j}}^s$ is the random carrier-phase noise (m).

4 MULTI-GNSS POSITIONING

Different positioning methods using the GNSS have been developed in the last decades, with different degrees of complexity and accuracy, from positioning using pseudorange and single frequency, the method most used by the civilian community, to highly accurate methods that use carrier-phase observations, combination of frequencies and constellations and information from networks. This section presents the concept of Dilution of Precision (DOP), which indicates the expected positioning quality from the geometry of the tracked satellites. In the next sections, the particularities introduced in each positioning method when using combined systems will be detailed, highlighting their applications, limitations and trends, as well as results and analyzes comparing GPS-only positioning to multi-GNSS positioning, using quad-constellation. For processing, PPTE station (-22°07'12 "; -51°24'31"), located in Presidente Prudente, SP, was selected. The station is part of the Brazilian Network for Continuous Monitoring of the GNSS Systems (*Rede Brasileira de Monitoramento Contínuo dos Sistemas GNSS* - RBMC) (IBGE, 2020). The date 01/06/2020 was selected, from 10h to 12h UTC, and a 25° elevation mask was used. The 25° value was selected to simulate an environment with a high degree of obstructions, such as urban canyons, where multi-GNSS positioning is very advantageous compared to GPS positioning with a 5° or 10° elevation mask, as commonly performed.

For the processing it was used the open source RTKLib 2.4.3 software (TAKASU, 2013), except for the PPP-RTK, in which the PPP-WIZARD software was used (LAURICHESSE; PRIVAT, 2015), and the GPS-only positioning was compared to the GPS+GLONASS solution. The estimated position is compared to the official coordinates of the station, updated to the processing epoch. The results are presented considering the bias (difference between the station true coordinates and those estimated) and from the accuracy, which considers the bias and the standard deviation of the coordinates estimated in the adjustment.

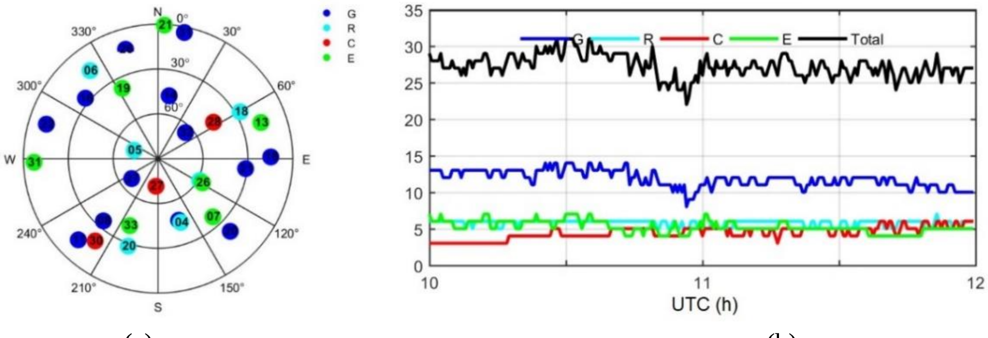
4.1 Dilution of Precision

The positioning quality is directly affected by the geometric distribution of the satellites in the sky. The accuracy of the solution will be proportional to the precision of the observations multiplied by the DOP, which will be calculated from the position of the receiver and the satellites it tracks. When the satellites are very close together or closer to a plane with the receiver, a high DOP value is obtained due to the weak geometry. The volume of the geometric figure formed by the unit vectors that join the receiver to the satellites is inversely proportional to the DOP; the best geometry occurs when the volume is maximized, which implies a minimum DOP (LANGLEY, 1999). The concept of DOP can also be derived from the variance-covariance matrix of the parameters in the least squares adjustment of the GNSS observations in the Point Positioning (MONICO, 2008), propagated to the local system (JEKELI, 2002; MARQUES, 2012).

To exemplify the concept of DOP, Figure 1 shows the sky plot of PPTE station at 10h00min00s UTC on 01/06/2020, as well as the number of satellites tracked during the period from 10h to 12h UTC. On average, 27 satellites were tracked. From the sky plot, which shows the position of the 13 GPS, 6 GLONASS, 7 Galileo and 3 BDS-2 tracked satellites, it is noted that the combination of systems improves the geometry of the satellites, with a better spatial distribution. The better distribution of the satellites is more evident in Figure 2, which shows the Position DOP (PDOP) of the station, also during the period from 10 am to 12 pm UTC, considering the GPS and multi-GNSS (quad-) constellations, and an elevation mask of 10° and 25°, the latter to simulate an obstructed environment, in which the line of sight between the receiver and satellites close to the horizon is compromised.

Considering that the ideal geometry is achieved when the PDOP value is less than 5 or 6 (LANGLEY, 1999; BORRE et al., 2007), it is possible to observe that the best results are expected for multi-GNSS positioning, with the 10° elevation mask and an average PDOP of 1.1. When the elevation mask is increased to 25°, the PDOP averages increases to 1.8 and, in most of the time, is comparable to GPS with a 10° elevation mask, which presented an average of 1.7. The worst scenario is in the GPS constellation with a 25° elevation mask, which presented an average PDOP of 4.2, being greater than 6 at certain times of the day.

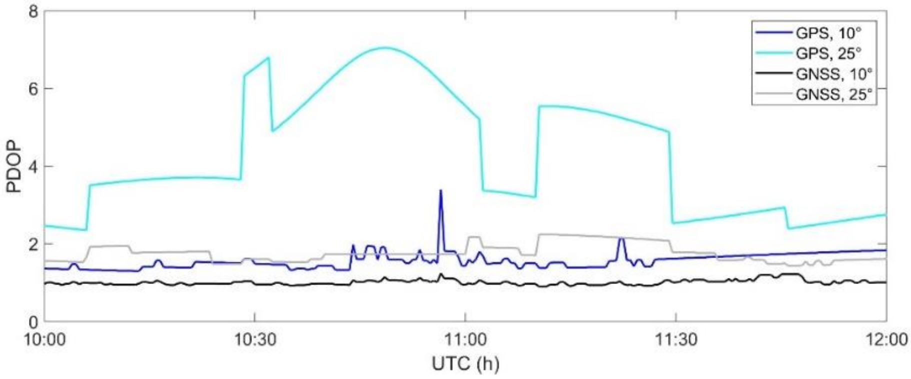
Figure 1 – (a) Sky plot (10h UTC) and (b) number of tracked satellites, PPTE station in 01/06/2020; G – GPS, R – GLONASS, C – BDS, E – Galileo.



(a) (b)

Source: The authors (2020).

Figure 2 – PDOP (PPTE, 01/06/2020) for GPS-only and multi-GNSS, elevation mask of 10° and 25°.



Source: The authors (2020).

5 STANDARD POINT POSITIONING

In SPP, the method most used by the civilian community in navigation activities, the coordinates of the receiver are estimated directly in relation to the geocenter, with only one receiver at the user level and the use of pseudorange usually in single frequency (ODIJK, 2017). It is necessary to know the GNSS satellites positions and clock errors, obtained from the navigation messages.

Due to the metric accuracy of the method, it is not necessary to use a robust model that considers all the differences between the systems, but some biases cannot be overlooked. When using transmitted ephemeris, information related to satellites is obtained in the time and reference systems of each system (Table 1). To solve the receiver's position, however, a common time and reference systems should be adopted or transformation parameters added. The reference systems associated with GPS, GLONASS, Galileo and BDS are aligned to the International Terrestrial Reference Frame (ITRF) at the centimeter level (YANG, 2009; FALCONE; HAHN; BURGER, 2017; JEKELI; MONTENBRUCK, 2017); given the expected accuracy of the SPP, the transformation between reference systems can be neglected. The adoption of a single time frame, however, must be considered, since a difference of only 10 ns would result in an error of almost 3 m; the time difference between GPST and GST, for example, is tens of nanoseconds (DEFRAINGNE et al., 2013).

Let X and Y be two different constellations. The time recorded at receiver t_r tr in which observations of the X system were collected relates to the time of X t^X through the receiver clock error dt_r in Eq. (3):

$$t_r(t^X) = t^X + dt_r(t^X). \tag{3}$$

Observations of the system Y that are collected at the same epoch t_r recorded by the receiver are associated with another time system, which uses different physical clocks for its realization. However, t_r can be expressed by the receiver clock error in relation to the time system of X in Eq. (4):

$$t_r(t^Y) = t^Y + dt_r(t^Y) = t^Y + dt_r(t^X) - t^{XY} \tag{4}$$

with $t^{XY} = t^Y - t^X$.

The same principle can be used to estimate the receiver code hardware bias of observations from constellation Y, being the ISB defined by Eq. (5):

$$ISB_r^{XY}(t^X, t^Y) = [d_r^Y(t^Y) - d_r^X(t^X)]. \tag{5}$$

If the constellation in Eq. (5) referred to GLONASS, a term referring to the IFB could be added and the ISB would be dependent on each satellite, and not just on the receiver. In SPP, however, the IFB is often overlooked. In practice, if the ISB is not previously known or calibrated, it is not possible to disassociate it from the time difference between two constellations, and the two parameters are estimated as one in Eq. (6):

$$ISB_r^{XY} = [d_r^Y - d_r^X(t^X)] - t^{XY}. \tag{6}$$

In this case, the receiver clock error is given as a function of system X, and the Y-related clock error becomes dependent of the ISB between X and Y, as shown in Eq. (7):

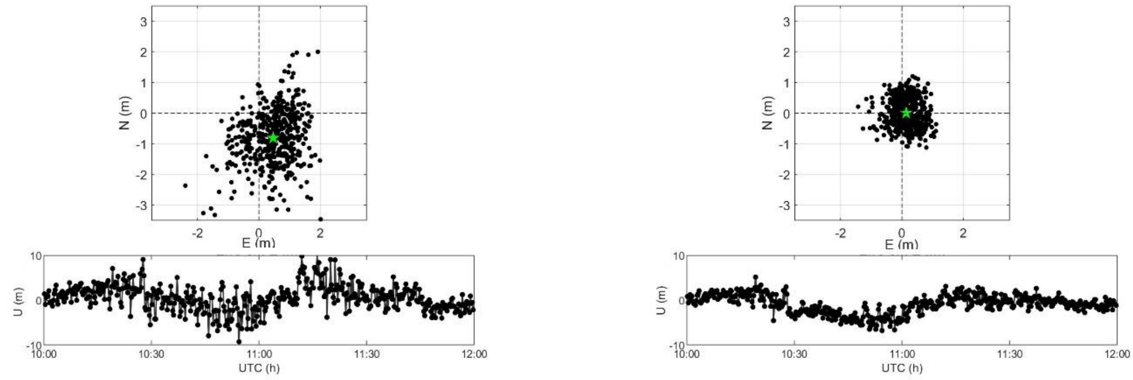
$$dt_r^Y(t) = dt_r^X(t) + ISB_r^{XY} . \tag{7}$$

In this way, the number of parameters to be estimated in the adjustment is equal to $3 + i$, with i being the number of systems used (3 receiver coordinates, $dt_r^X(t)$ and ISB_r between X and the other tracked systems).

To achieve better accuracy atmospheric errors must be corrected, usually by models. For the ionospheric delay, the Klobuchar (KLOBUCHAR, 1987) and NeQuick G (RADICELLA, 2009) models can be mentioned; for the tropospheric delay, Hopfield and Saastamoinen models can be cited (SEEBER, 2003). The receiver position is estimated epoch by epoch, with static and kinematic modes being processed in a similar way.

Figure 3 shows the GPS and multi-GNSS SPP bias for PPTE station, with GPS and GLONASS L1, Galileo E1 and BDS B1 pseudorange observations, Saastamoinen tropospheric model and Klobuchar ionospheric model. Considering the two hours of processing, the GPS solution presented an average bias of 0.9 m in the east component, 0.8 m in the north component and 0.9 m in the up component. In the multi-GNSS solution, the average error was of 0.1 m in the east and north components and 0.5 m in the up component. The improvement of the multi-GNSS combination is more evident in the standard deviation of the adjustment, which went from 5.9 m, 6.6 m and 7.5 m in the east, north and up components, respectively, of the GPS positioning to 3.7 m, 3.4 m and 4.9 m in multi-GNSS positioning. Considering the three-dimensional accuracy, the position estimate had an improvement of 40% in the multi-GNSS solution compared to GPS-only.

Figure 3 – (a) GPS and (b) multi-GNSS SPP horizontal and vertical bias. In green, horizontal bias average.



(a) (b)

Source: The authors (2020).

6 DGNSS

In DGNSS, a continuous tracking base station with known coordinates and a second receiver which position is to be determined are used. In these conditions, if the two receivers are not too far apart, a high correlation of the errors involved in the observations collected by both is assumed (SEEBER, 2003). Once the coordinates of the base station are known, it is possible to calculate, from its observations, corrections that should be applied to the positioning of the station of unknown position. Corrections to pseudoranges or positions can be estimated, the first being the most commonly used method (DALBELO et al., 2007).

Let i be the base station and x a satellite of constellation X. The pseudorange correction ΔP_i^x will be, from Eq. (1), given by Eq. (8) (LIU et al., 2017a):

$$\Delta P_i^x = c(dt_i + d_r^X + t^X) - c[dt^x + d^x] + T_i^x + I_i^x + \varepsilon_{P_i}^x \tag{8}$$

in which t^X is the time offset between constellation X and another system adopted as reference, with $t = 0$ for the satellites of the constellation with the time system adopted as reference.

The correction ΔP_i^x is then sent to the receiver ii, with unknown position. Errors in the assumedly correlated pseudoranges are eliminated or reduced, such as the atmospheric error and errors related to satellites. The corrected observations are given by Eq. (9):

$$P_{ii}^x - \Delta P_i^x = \rho_{ii}^x + c\, dT^X + \varepsilon_{P_{i,ii}}^x \tag{9}$$

with $dT^X = dt_{ii} - dt_i + d_{ii}^X - d_i^X$.

From the corrected observations in Eq. (9), the receiver estimates its coordinates by SPP. As in SPP, a constellation is chosen to have its time system as a reference, and the clock error of the other systems is divided into two components. Let X be the system adopted as a reference. The observation equation for a satellite *y*, from the constellation Y, will be given by Eq. (10) (LIU et al., 2017a):

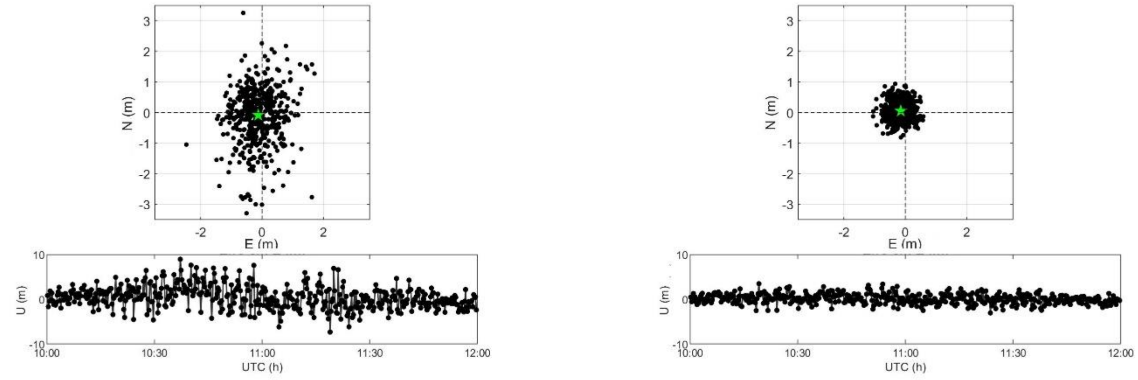
$$P_{ii}^y - \Delta P_i^x = \rho_{ii}^y + c\left(dT^X + ISB_{i,ii}^{XY}\right) + \varepsilon_{P_{i,ii}}^x \tag{10}$$

with $ISB_{i,ii}^{XY} = d_{ii}^Y - d_i^Y - (d_{ii}^X - d_i^X)$. The parameter $ISB_{i,ii}^{XY}$ refers to the ISB difference between two different constellations in the DGNSS model, which can be called Differential ISB (DISB) (ODIJK; TEUNISSEN, 2013). Such parameter, as in the SPP, can be calibrated a priori or estimated together with the other parameters in the adjustment. As soon as a new epoch of data is available, the process is repeated and variations in corrections are calculated to be also made available to the users.

When a network of stations is used to generate corrections, there is the concept of network DGNSS (NDGNSS) or Wide-area DGNSS (WADGNSS). Using NDGNSS, it is possible to minimize the problem of spatial correlation of errors involved in the DGNSS. In the method, corrections are calculated individually at each network station by Eq. (8). A single correction for each satellite is sent to the user, which is done by using some interpolation method, usually based on the distance between stations in relation to the user's position (BAKULA, 2010; ALVES et al., 2012). WADGNSS is the method used by SBAS, usually with continental coverage. In this method, a network over the coverage area continuously sends its observations to a central control station. This station then calculates corrections for the orbits and clocks parameters transmitted in the navigation messages, in addition to information related to the state of the atmosphere (ionosphere and troposphere). The corrections are sent to the geostationary satellites of the augmentation system, and then sent to users, who apply such corrections in their position estimation (KEE; PARKINSON; AXELRAD, 1991; ASHKENAZI et al., 1993).

Figure 4 presents the Differential GPS (DGPS) and quad-constellation DGNSS positioning bias for PPTE station. RBMC station SPAR (-21°11'05"; -50°26'23"), located in Araçatuba, SP, was used as base station. The baseline formed was of 144 km. As with SPP, GPS and GLONASS L1, Galileo E1 and BDS B1 pseudorange observations were used. The Figure shows the advantage of the combined use of GNSS constellations. Considering the two hours of processing, the GPS position presented an average bias of 0.21 m in the east component, 0.10 m in the north component and 0.43 m in the up component. With quad-constellation, the error was of 0.15 m in the east component, 0.05 m in the north component and 0.11 m in the up component. The standard deviation of the GPS adjustment was of 1.27 m for the east component, 1.44 m for the north component and 2.54 m for the up component. For the multi-GNSS case, the standard deviation was of 0.50 m, 0.42 m and 1.69 m for the east, north and up components, respectively. Considering the three-dimensional accuracy, the station's estimated position had an improvement of 44% in the multi-GNSS solution compared to GPS-only. It is worth noting that the resulting errors are of a metric order due to the length of the baseline; even so, the results are more accurate when compared to the SPP results (for the multi-GNSS case, the three-dimensional accuracy was 7.0 m in the SPP and 1.82 m in the DGNSS).

Figure 4 – (a) DGPS and (b) DGNSS horizontal and vertical bias. In green, horizontal bias average.



(a) (b)

Source: The authors (2020).

7 RELATIVE POSITIONING

Relative positioning, like DGNSS, requires the use of two receivers, which are used to eliminate or significantly reduce systematic errors. One of the receivers is known as the reference (or base) receiver so that it is possible to differentiate the observations from the other receiver(s), known as rover(s). This is also applied to satellites, where the satellite with the highest elevation angle is assigned as a reference (or base) satellite. One of the differences between the DGNSS and the relative positioning is that the latter uses the carrier-phase observable, which depends on the Ambiguity Resolution (AR) to estimate the position of the rover receiver accurately.

The multi-GNSS combination has several benefits. In the case of a small number of satellites of each system observed, it is possible to realize the double difference (DD) between the systems and, thus, make it possible to resolve the ambiguities quickly, or even instantaneously. Another important advantage is not only the use of multi-GNSS, but also of multi-frequency observations, which can be beneficial for AR and consequently for positioning (CELLMER; PAZIEWSKI; WIELGOSZ, 2013; HE et al., 2014; TEUNISSEN; ODOLINSKI; ODIJK, 2014; ODOLINSKI; TEUNISSEN; ODIJK, 2015; GAO; GAO; PAN, 2017; PAZIEWSKI; SIERADZKI, 2017; LI et al., 2018; ZHANG et al., 2020). On the other hand, the use of multi-frequency observations and systems can increase the computational need for AR due to the large number of observables and parameters to be estimated. Studies have been carried out to solve this problem and the Partial Ambiguity Resolution (PAR) has been developed (CAO; O'KEEFE; CANNON, 2007; PARKINS, 2011; LI et al., 2015; GAO; GAO; PAN, 2017).

The ideal approach for combining these observations is still an open problem. The integration of multiple systems can be performed in two different ways: the loose combination (LC) or the tight combination (TC) (ZHANG et al., 2003; JULIEN et al., 2004). In LC, each system has its own base satellite, while in TC the base satellite of one system can be used to form the differences to the other systems. Systems with equal frequencies allow differentiation between systems. This approach is called TC and considers the DISB (MONTENBRUCK; HAUSCHILD; HESSELS, 2011; ODIJK; TEUNISSEN, 2013; PAZIEWSKI; WIELGOSZ, 2015; ODIJK et al., 2017; PAZIEWSKI; SIERADZKI, 2017).

The DD equation for the pseudorange and carrier-phase, considering two receivers, *i* and *ii*, and two satellites *x* and *v*, belonging to constellation X, is given by Eq. (11) (ODIJK; WANNINGER, 2017):

$$\begin{gathered}\Delta\nabla P_{i,ii}^{xv} = \Delta\nabla\rho_{i,ii}^{xv} + \Delta\nabla cd_{i,ii}^{xv} + \Delta\nabla\xi_{i,ii}^{xv} + \Delta\nabla \mathrm{I}_{i,ii}^{xv} + \Delta\nabla \mathrm{T}_{i,ii}^{xv} + e_{P_{DD}} \\ \nabla\Delta\varphi_{i,ii}^{xv} = \Delta\rho_{i,ii}^{xv} + c\nabla\Delta\delta_{i,ii}^{xv} + \nabla\Delta\zeta_{i,ii}^{xv} - \nabla\Delta I_{i,ii}^{xv} + \nabla\Delta T_{i,ii}^{xv} + +\lambda(\nabla\Delta N_{i,ii}^{xv} + \nabla\Delta\omega_{i,ii}^{xv}) + \epsilon_{\Phi_{DD}}\end{gathered} \tag{11}$$

in which $\Delta\nabla$ is the symbol adopted for DD, which represents $\Delta\nabla(\cdot)_{i,ii}^{xv} = (\cdot)_{i,ii}^{v} - (\cdot)_{i,ii}^{x} = (\cdot)_{i}^{xv} - (\cdot)_{ii}^{xv}$.

When the baseline between the receivers is short enough (typically less than 10 km), it can be assumed that tropospheric and ionospheric errors are canceled out. For longer baselines, these errors are not canceled, as they are spatially correlated. For tropospheric delays, it is possible to estimate a parameter for the residual wet delay, while the hydrostatic component can be corrected using an empirical model. In relation to ionospheric delays, one can estimate the DD of the ionospheric parameters in the processing or eliminate them using combinations of two or more frequencies.

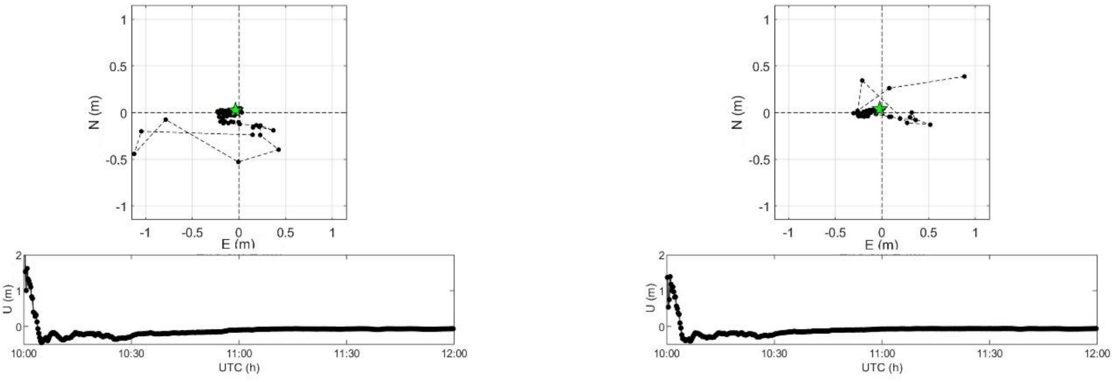
There are some ways to perform relative positioning: static, semi-kinematic and kinematic. In static mode, the data is collected by stationary receivers and for the position to be obtained with high precision, a long observation time is necessary, so that the geometry of the satellite changes and it is possible to obtain the AR, something in the order of half an hour to a few hours in case of long baselines (GOAD; REMONDI, 1984). The semi-kinematic mode was developed so that this long period of observation is not necessary. For this, some methods have been proposed in order to obtain the position with high accuracy, with a shorter observation time than the conventional static method. These methods are based on the continuous tracking of the receiver between points of interest, i.e., the receiver collects data for a short period at one point and then visits another point to collect data for a short time, continuously tracking satellites during the way between the points. Among the semi-kinematic strategies, we can highlight the antenna exchange (HOFMANN-WELLENHOF; REMONDI, 1988; ODIJK; WANNINGER, 2017), relative positioning with revisiting of stations (CANNON, 1990; ODIJK; WANNINGER, 2017) and the stop and go (REMONDI, 1985; ODIJK; WANNINGER, 2017) methods.

When the second receiver is in kinematic mode and it is necessary to obtain instantaneous positions in real time, the method is called RTK. It is used in applications that require high accuracy, such as agricultural machinery control. In the RTK, to obtain the position of the rover in real time, the corrections determined in the base receiver are transmitted to the rover via a data communication link. In the RTK, it is not necessary for the reference receiver to remain static, it can also be in motion. RTK is limited to baselines up to 10 km, if radio communication links are used or, if longer baselines are used, atmospheric delays should be estimated based on observations from at least two frequencies. Due to its high productivity, RTK is commonly used in cadastral surveys and precision engineering and agriculture.

If BDS observations are used, another type of bias arises, if the baseline is formed by different receivers. This bias is called the Differential Inter-Satellite-Type Bias (DISTB) and appears when differentiations are made, at the same frequency, between satellites of different BDS types (GEO, IGSO and MEO) (NADARAJAH et al., 2013; NADARAJAH et al., 2015). Receiver manufacturers have updated their firmware to eliminate DISTB when using different receivers to perform RTK with BDS. However, users with old firmware receivers should consider the DISTB when processing BDS data (NADARAJAH et al., 2015).

Figure 5 presents the PPTE station processing bias, in RTK mode and using SPAR as the base station (144 km baseline). Observations were used in the ionosphere-free combination for the GPS and GLONASS L1 and L2, Galileo E1 and E5 and BDS B1 and B2 frequencies. Analyzing the Figure, the centimetric accuracy of the method is evident. At the end of processing, the three-dimensional GPS bias was of 9.4 cm, with a standard deviation of 3.6 cm, against a 7.1 cm bias and 2.9 cm standard deviation in multi-GNSS processing, which represents a 24% improvement in three-dimensional accuracy.

Figure 5 – (a) GPS and (b) multi-GNSS RTK horizontal and vertical bias. In green, horizontal bias average.



(a) (b)

Source: The authors (2020).

8 NETWORK REAL TIME KINEMATIC

In the last few years, a positioning method that has been widely used is network-based positioning, also known as Network RTK (NRTK). This method was developed to end the spatial limitation of RTK, introducing the use of a network of reference stations. In NRTK the number of reference stations can vary from three to dozens and the distance between them can vary from a few kilometers to hundreds of kilometers.

A very important step in NRTK is the process of AR for each of the independent baselines of this network. Once the ambiguities have been resolved, it is possible to determine the errors of the observables at each of these stations and, using an appropriate method, correction for any position in the network coverage area can be obtained. Several methods have been developed in recent years to formulate corrections based on the observations from the stations of a network. There are some possibilities such as partial derivative algorithms (WÜBBENA et al., 1996), interpolation algorithms (GAO; LI; MCLELLAN, 1997) and conditional adjustment algorithm (RAQUET, 1998). The corrections can also be used to generate data from a Virtual Reference Station (VRS) close to the user or the Master-Auxiliary Concept (MAC) (EULER et al., 2001; VOLLATH et al., 2002, LACHAPELLE; ALVES, 2002). Further details on this positioning method can be found in Alves and Monico (2011), Alves et al. (2016) and Jerez and Alves (2019).

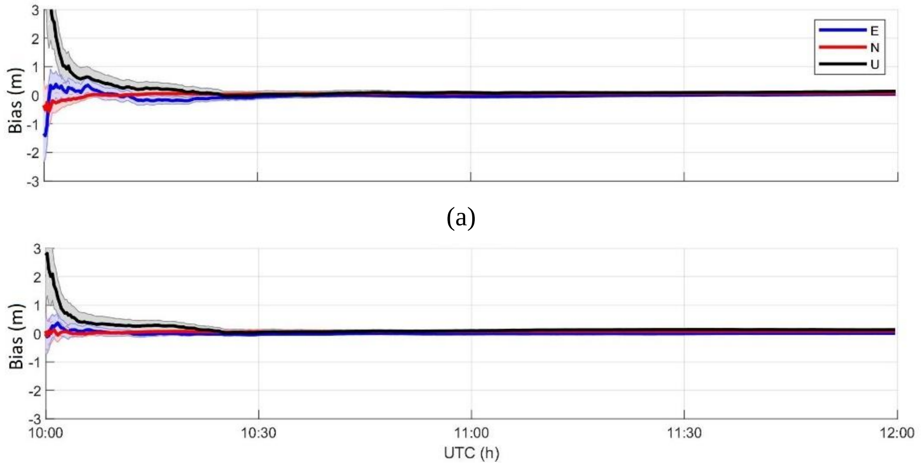
9 PRECISE POINT POSITIONING

The PPP emerges as an alternative to RTK (ODIJK, 2017), with the main advantage of not needing a base station to differentiate observations, thus requiring the use of only one receiver at the user level (ZUMBERGE et al., 1997; KOUBA; HÉROUX, 2001). Because of this, the method has been increasingly used in high accuracy activities, such as topographic and geodetic surveys and monitoring of structures and movement of the earth's crust (AN; MENG; JIANG, 2020). In its original conception, the method requires the use of carrier-phase and pseudorange observations in GPS dual frequency, precise orbits and clocks and robust errors modeling. The ambiguities of the carrier-phase observations are treated as float, being a combination of their integer values added to the hardware biases originated in the satellites and in the receiver (KOUBA et al., 2017).

Studies carried out in the last two decades (HÉROUX; KOUBA, 2001; SEEPERSAD; BISNATH, 2014) have demonstrated the millimeter to centimeter level accuracy potential of the method in its original conception in both static and kinematic modes, using dual frequency GPS data in the ionosphere-free combination and a long period of observation. The main disadvantage of PPP, however, lies in the solution's convergence time, defined as the time elapsed from the beginning of the positioning until the time when the receiver's position estimate reaches a certain level of accuracy, no more deviating from it (KOUBA et al., 2017). This convergence time is directly linked to the pseudorange noise level at the receiver and the location where the positioning is being carried out (e.g. multipath, ionosphere, antenna, satellite geometry). With adequate modeling, the multi-GNSS PPP presents better accuracy and a shorter convergence time in relation to the GPS PPP (TEGEDOR; OVSTEDAL; VIGEN, 2014; LI et al., 2015; LIU et al., 2017b).

Figure 6 presents the bias and standard deviation in the three local components for the PPP. The ionosphere-free combination was used for the L1 and L2 GPS and GLONASS frequencies, Galileo E1 and E5 and BDS B1 and B2. The standard deviation of the GPS solution took 25 min to converge to 10 cm in the east component, 7 min for the north component and 45 min for the up component. In the multi-GNSS solution, the convergence time was reduced to 12 min in the east, 5 min in the north and 31 min in the up component. At the end of the two hours of processing, the three-dimensional GPS bias was of 16.5 cm, with a standard deviation of 3.8 cm, against a bias of 15.1 cm and 2.5 cm of standard deviation in the multi-GNSS processing, which represents a 9% improvement in the three-dimensional accuracy, and a 14 min reduction in convergence time.

Figure 6 – Bias (solid lines) and standard deviation (shadow) of (a) GPS and (b) multi-GNSS PPP in the three local components.



(a)

(b)

Source: The authors (2020).

10 PPP-RTK

In recent years, the Geodesy community has directed a large amount of studies towards real or near real time PPP solutions. It was in this sense that the IGS Real-Time Working Group (IGS RTWG) was established in 2001 with a view to investigating precise products aimed at real-time applications (CAISSY; AGROTIS, 2011); results with centimeter-level accuracy were presented by Gao and Chen (2004). In this context, the Real-Time Pilot Project (RTPP) was started by IGS in 2007. In this project, GNSS observations in real time obtained from a global network are used. The Real Time Service (RTS) was officially launched only in 2013. The products included corrections for the GPS satellites transmitted orbits and clocks (http://www.rtigs.net). Thus, for users of the service, centimeter accuracy becomes possible with PPP in real time based on products obtained with global GNSS networks (RIZOS et al., 2012; GRINTER; ROBERTS, 2013; OLIVERA JR et al., 2017). The trend of researches focusing on real-time PPP is also seen in GNSS events held annually. In these sessions, the potential of PPP for real-time applications was systematically highlighted (WÜBBENA et al. 2005; LAURICHESSE; MERCIER, 2007; LAURICHESSE et al., 2009).

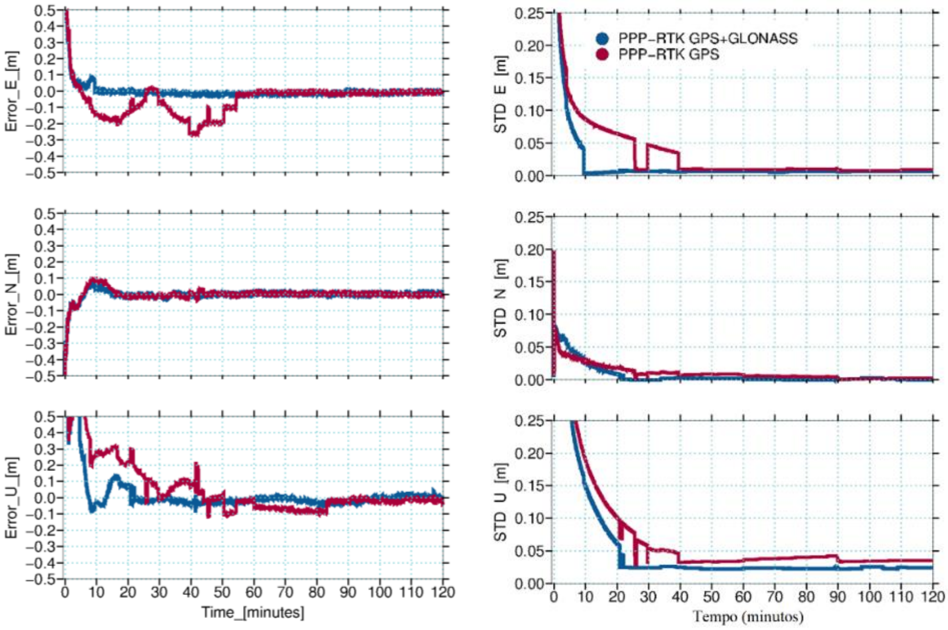
Similarly to what happens in post-processed mode, one of the biggest challenges for real-time PPP is the solution convergence time, which occurs because traditional PPP estimates state parameters (such as tropospheric delay) together with float ambiguities, which requires a considerable observation period. In the literature, there is a need for at least ~ 30 min for proper convergence of the float values of the ambiguities, even when there are good conditions of satellite geometry and reduced effect of multipath (GE et al. 2012; ROVIRA-GARCIA et al., 2015).

The practicality and profitability in terms of the cost of PPP, as well as the availability of accurate products in real time, have driven researches that seek algorithms for resolving phase ambiguities to integer values (MERVART et al., 2008; COLLINS et al. , 2010; LAURICHESSE et al., 2010; GE et al., 2012). It is observed that significant improvements are achieved when, in addition to orbit corrections and clocks, products related to instrumental biases in carrier-phase measurements are provided, which allow a reliable ambiguity resolution as integer values (SHI & GAO 2014; TEUNISSEN and KHODABANDEH, 2015). These and other advances have strengthened the concept known as State Space Representation (SSR), with the aim of isolating all physical errors that affect the GNSS observables (WÜBBENA et al. 2005; MERVART et al. 2013). In this sense, results that include the application of SSR corrections for the ionospheric effect and/or tropospheric delay have shown advances and tend to show convergence at the centimeter level in the first minutes or even seconds (LEANDRO et al. 2011; ROVIRA-GARCIA et al. 2015; OLIVEIRA JR 2017; OLIVEIRA JR et al. 2020). Thus, the improvement in the convergence time of the solution is promoted jointly by corrections of hardware biases and atmospheric corrections provided by networks of permanent GNSS stations, leading to the so-called PPP-RTK (WÜBBENA et al., 2005; 2014; STÜRZE et al 2012; OLIVEIRA JR, 2017).

PPP-RTK presents itself as a positioning solution based on SSR corrections and as a potential rival or complementary solution to traditional RTK or NRTK methods. This proves to be feasible especially if SSR corrections are generated from sparse GNSS networks than those required for generating NRTK corrections, with a less expensive infrastructure. However, the atmospheric modeling performances for generating SSR corrections depend on the network topology and atmospheric conditions and advances are still needed to guarantee the reliability and integrity of the solutions in a way equivalent to that found in NRTK. Advances in multi-GNSS positioning will certainly bring more improvements and perspectives to PPP-RTK algorithms.

Figure 7 presents the results of an experiment with 2 hours of data, using the PPP-WIZARD software and the products made available by CNES (*Centre Nationale d'Etudes Spatiales*) in real time for orbit, clock and phase bias that allow to perform PPP-RTK. In the first solution, only the GPS constellation is used and in the second, GPS + GLONASS is used. Positioning is performed in kinematic mode with the first attempt to fix the ambiguities after 1h of initialization. Considering the coordinates bias (Figure 7a), the GPS solution took around 50 min to reach 10 cm considering the three-dimensional positioning; the GPS + GLONASS solution reached that mark in 19 min. The biggest improvement was in the up and east components. Similar behavior is verified for the formal standard deviation of the solution (Figure 7b), where the improvements of using a larger number of observations from two constellations are even clearer.

Figure 7 – Example of PPP-RTK convergence in terms of (a) bias in relation to the true coordinates and (b) formal standard deviation in the three local components.


(a) (b)

Source: The authors (2020).

11 TRENDS AND CHALLENGES IN MULTI-GNSS POSITIONING

The four global GNSS will be fully operational by 2021. With the launch of the modernized GPS III satellites, the GPS system will improve its robustness in the coming years. GLONASS has similar modernization plans. GLONASS-B satellites will transmit new CDMA signals in the three GLONASS frequency bands, scheduled to launch in 2023, with six satellites by 2025. Galileo foresees better robustness than GPS, and has been studied, as an evolution for the system, a regional aspect of IGSO satellites over Europe. BDS is currently the only one that has a regional component, which should be extended, in the coming years, by a component of Low Earth Orbit (LEO) satellites, called Centispace-1 (HEIN, 2020). When the four global systems reach their full constellations, we will have more than 120 operational satellites transmitting signals at different frequencies. This will contribute significantly to the positioning activities, in which dual-frequency GPS data is normally adopted. It can be expected for the coming years, therefore, improvements in the positioning methods both in the accuracy of the position estimate and in the observation period, more robust modeling of the errors that affect the GNSS observables, as well as the emergence of new applications for the signals, as in geodetic remote sensing and real-time applications. Among the challenges and trends in this topic, we can highlight the multi-GNSS stochastic modeling, atmospheric modeling, the use of low-cost receivers and antennas and the application of GNSS in civil aviation.

5G network can be considered a trend in GNSS positioning, since the network can provide centimetric positioning, on a local scale, with the help of a dense network of base stations. An interesting point is the integration of 5G with GNSS in urban areas, since GNSS positioning has its accuracy deteriorated due to the limited availability of signals and multipath. Thus, such integration can result in more accurate positioning (PERAL-ROSADO et al., 2018), but, still, compatibility and interoperability between 5G and GNSS is necessary.

Stochastic modeling involves determining the variance information from the observables tracked by multi-GNSS receivers. This is important to obtain accurate estimates of the unknown parameters and, once the stochastic models are realistically determined, the uncertainty of the estimated parameters will be minimized. By combining systems and signals, the reliability and redundancy of the positioning models can be improved. In addition, by using multiple frequencies and more precise atmospheric delay information, precise positioning can be achieved more quickly when compared to single or double frequency approaches.

An important point that has an impact especially on the convergence of PPP is atmospheric modeling. In Brazil, this becomes even more relevant due to the peculiar conditions of the region, which makes this topic a challenge for accurate GNSS positioning. The behavior of the troposphere is extremely variable due to the country's territorial extension: some regions under the influence of the Amazon rainforest are extremely wet while others in the interior are extremely dry, in addition to the existence of coastal regions. In the case of the ionosphere, the country has regions with strong ionospheric activity and irregularities due to its location in relation to the geomagnetic equator (CAMARGO, 1999), which requires the development of robust models that are adequate to this reality. Regarding the treatment of the troposphere in positioning, studies have shown that the use of a priori Zenith Wet Delay (ZWD) information, coming from a regional network, can contribute to the reduction of convergence period, especially when few measurements are available (ZHENG et al., 2018). Alves et al. (2016) also showed that the use of Numerical Weather Prediction (NWP) models in the Brazilian region can improve the accuracy of PPP by up to 3 times in relation to that of empirical models.

Research carried out in regions of ionospheric activity more regular than Brazil has shown that the best approach for fast PPP convergence is to abandon the ionosphere-free combination and incorporate accurate ionosphere information derived from some external source, normally interpolated from the local or regional (BANVILLE et al., 2014; ABDELAZEEM; ÇELIK; EL-RABBANY, 2017; OLIVEIRA JR., 2017; ZHAO et al., 2018). The injunction of a priori information from the ionosphere makes the estimates of the ionospheric delay robust and prevents the amplification of noise from linear combinations (LOU et al., 2016). When abandoning the ionospheric-free combination, one must rethink the PPP models, algorithms and processing strategies, since both the determination of the user's position and the generation of precise orbits and clocks are based on this combination. Thus, research of this nature is also a trend in Brazil, which has peculiar ionospheric conditions, as already mentioned.

In recent years, the use of low-cost receivers has been gaining ground in high-accuracy positioning activities. Among such receivers, there is the use of smartphones capable of tracking multiple constellations and frequencies. The collected observations, however, are up to 90% noisier than those obtained by geodetic receivers, with very low Signal to Noise Ratio (SNR) values due to the sensitivity to multipath and other factors such as antenna polarization (CHEN et al., 2019; WU et al., 2019; PAZIEWSKI, 2020). It is necessary to develop methods to mitigate such effects.

In the coming years, among the main challenges of satellite navigation, space cyber security, space junk and the global crisis of 2020 can also be highlighted. With the evolution of artificial intelligence, more cyber risks may arise, making those responsible for the systems and receiver manufacturers present new cybersecurity solutions, aiming to develop defense for counterfeiting signals (PSIAKI; HUYMPHREYS, 2016). As highlighted earlier, many satellites will be launched in the coming years, which makes space junk management of paramount importance. Our planet is surrounded by thousands of artificial satellites, which bring Internet connectivity and location services, among others, to people from all over the world. Because of this, there is an immense number of space junk, which makes space around the Earth a dangerous place and which, without actions, will be totally off limits for future missions and launch of satellites and technology (ESAb, 2020). The crisis caused by the SARS-CoV-2 virus ("coronavirus") is creating disruptions in all sectors of the world economy. It is necessary to assess the extent to which this crisis will have an impact on the economy of the space sector and, consequently, on the GNSS. As far as we can see, there have been satellite launches postponed, supply chains being interrupted, access to financial issues that threaten the survival of startups and scientific events being canceled (SPACENEWS, 2020).

As a trend, there is also the use of GNSS in air navigation. For many years, so-called traditional technologies have been used for this purpose (PAMPLONA, 2014). In recent years, however, there has been an increasing demand for the use of airspace. The use of new technologies aims to provide a more economical and optimized use of this space, replacing radio aids installed on the ground (FELUX et al., 2013). GNSS presents itself as a more economical technology, which would dispense much of the ground infrastructure, facilitate the precise aircraft landings in degraded visual conditions and provide greater flexibility in landing procedures. Globally, GNSS has been used for route navigation and non-precision approaches. For precise procedures, it is possible to use GBAS and SBAS, capable of providing additional information on error correction, integrity, continuity and availability of signals. In Brazilian territory, the Department of Airspace Control (*Departamento de Controle do Espaço Aéreo* - DECEA) studies the feasibility of using GNSS in precise air navigation activities. The biggest challenge in this regard is the influence of the ionospheric layer on GNSS signals (FEUERLE et al., 2017; YOON et al., 2017; 2019; PEREIRA, 2018; SILVA, 2020).

Since the launch of the first navigation satellites in the late 1970s to the present day, many advances have been made in the use of GNSS. From GPS and GLONASS, initially launched for military purposes, four nearly complete global systems are now available, with the possibility of another system launching by the United Kingdom due to its withdrawal from the European Union's economic bloc (GPS WORLD, 2019), in addition to the various regional augmentation systems already launched and under development. From the initial metric accuracy of the system, it is possible today to perform positioning with high accuracy, in real time, and with a relatively short period of observation. The advancement in the use of GNSS has also enabled activities that go far beyond positioning to become possible, such as modeling the Earth's atmosphere. Although much is known about the GNSS and a huge progress has been made, several researches still need to be carried out in order to improve the systems technology, and new applications for the signals are expected to emerge in the coming years and decades.

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Author Contributions

PTSJ e CMS were responsible for the conception and the conceptualization of the paper, and for the revision of the manuscript. PTSJ and PSOJ participated in curating the data and carrying out the experiments. The authors PTSJ, CMS and PSOJ wrote the first draft of the manuscript. DBMA and JFGM helped to conceptualize, review and supervise the development of the paper.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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