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Real-time GNSS Positioning: Evolution, Practical Applications and Perspectives for the Future

Posicionamento GNSS em Tempo Real: Evolução, Aplicações Práticas e Perspectivas para o Futuro

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Abstract: Real-time positioning using satellite signals was an advance for air, sea and land navigation with the arise of GPS (Global Positioning System). However, the achievable horizontal and vertical accuracy of 100 m and 150 m (95% probability level), when SA (Selective Availability) technique was activated, became unsatisfactory for many applications and users required other accuracy levels. Efforts were dedicated to the so-called differential positioning, DGPS (Differential GPS), which made it possible to achieve precision about ten times better than that usually obtained throughout absolute positioning. Later, using carrier-phase measurements, it was possible to perform positioning with greater accuracy through the RTK (Real Time Kinematic) method, reaching centimeter quality. Subsequently, there was an evolution towards network-based positioning, using, for example, the VRS (Virtual Reference Station) algorithm. Several errors affecting satellite observables started to be modeled in real time with multi-station solutions. As of 2012, services and products were developed in order to accomplish RT-PPP (Real-Time Precise Point Positioning), a method based on the SSR (State Space Representation) concept. Further, the ambiguity fixing in RT-PPP became possible, and this approach is usually referred as PPP-RTK, which provides a faster convergence to an accurate positioning solution. This article presents the evolution real time positioning, some applications at the national context, as well as the future perspectives.

Keywords: DGPS. RTK. PPP-RT. VRS.

Resumo: O posicionamento em tempo real por meio do emprego dos sinais de satélites foi um avanço nas navegações aérea, marítima e terrestre com o surgimento do GPS (*Global Positioning System*). Contudo as precisões horizontais e verticais de 100 m e 150 m (nível de probabilidade de 95%) alcançadas, estando a SA (*Selective Availability*) ativada, passaram a não ser satisfatórias para muitas aplicações e os usuários buscaram galgar outros níveis de precisões. Esforços foram investidos no chamado posicionamento diferencial DGPS (*Differential* GPS), o qual possibilitou obter precisões em torno de dez vezes melhores do que as do posicionamento absoluto. Posteriormente, usando-se a fase da onda portadora, conseguiu-se realizar posicionamento com maior acurácia por meio do método RTK (*Real Time Kinematic),* atingindo qualidade centimétrica. Na sequência, houve uma evolução para posicionamentos em rede, empregando, por exemplo, o algoritmo de VRS (*Virtual Reference Station*). Vários erros nas observáveis dos satélites passaram a ser modelados com uma solução de multiestações em tempo real. A partir de 2012, surgiram serviços e produtos que favoreceram o desenvolvimento do RT-PPP (*Real-Time Precise Point Positioning*) baseado no conceito SSR (*State Space Representation*). A busca da solução das ambiguidades no RT-PPP deu origem ao PPP-RTK com menor tempo de fixação das ambiguidades e convergência para a solução acurada do posicionamento. Neste artigo apresenta-se como foi a evolução do posicionamento em tempo real, algumas das aplicações no âmbito nacional e as perspectivas desta modalidade de posicionamento para o futuro.

Palavras-chave: DGPS. RTK. PPP-RT. VRS

1 INTRODUCTION

The space age began in 1957, with the launch of the artificial satellite SPUTNIK-1, by the Soviet Union, thus the origins of navigation concept using radio signals sent by satellites. Since 1960 global satellite positioning systems were developed, aiming to provide navigation and positioning on the Earth's surface (SEEBER, 2003; HOFMANN-WELLENHOF; LICHTENEGGER ; WASLE, 2008).

A look at the past shows that when the Global Positioning System (GPS) became operational and complete (FOC - Full Operational Capability) in 1995, users were directly affected by American security policy (USCG, 1995). On this occasion, Selective Availability (SA) and Anti-Spoofing (AS) were introduced, limiting the accuracy of SPS (Standard Positioning Service) users. The SA consisted in the ephemeris data manipulation as well as systematic destabilizing of the satellite clock (LANGLEY; TEUNISSEN; MONTENBRUCK, 2017). The AS was initially part of the system design, which did not allow civilian users to have access to the original P code, thus preventing any type of fraud in the system. At this time, for instantaneous absolute positioning users could achieve horizontal and vertical precision of 100 m and 150 m (95% probability level), respectively (SEEBER, 2003; HEGARTY, 2017). Such precision was insufficient for several applications that demanded better quality for instantaneous positioning, such as precise navigation for air, sea and land environments (GREWAL; WEILL; ANDREWS, 2007). In view of this need, the DGPS (Differential GPS) positioning emerged with the possibility to eliminate a large portion of the SA effect, providing precision values at least ten times better than the values previously mentioned (SEEBER, 2003).

Initially DGPS was performed only for single baseline configuration by code range corrections and carrier smoothed corrections. Later, it was introduced the use of carrier measurements as well as respective differential corrections enabling ambiguity fixing in real time, this approach became known as RTK (Real Time Kinematic).

However, in view of the accuracy degradation of the rover station with the baseline length increase between reference and rover stations another concept emerged, the so-called Network RTK (NRTK) which uses real-time reference stations network (SEEBER, 2003; ALVES, 2008). In this case, systematic errors affecting GNSS signals in the network region (for example, satellite orbit, troposphere and ionosphere) are now modeled and included in the information to be sent to mobile stations located in the region covered by the network, thereby improving the positioning and navigation accuracies. If these network infrastructures are added with geostationary satellites in order to transmit information/data to users, then there are systems augmented by satellites (SBAS - Satellite Based Augmentation System), such as WAAS - Wide Area Augmentation System and EGNOS - European Geostationary Navigation Overlay System (GREWAL; WEILL; ANDREWS, 2007; LANGLEY; TEUNISSEN; MONTENBRUCK, 2017).

In the last decades, PPP (Precise Point Positioning) and its variant in real time, PPP-RT (PPP in Real Time), appeared, which continue to be improved (GRINTER; ROBERTS, 2011). In PPP method the mobile station is positioned through its data plus precise corrections for orbits and clocks of tracked satellites. An advance is taking place with regard to the determination of the integer values for phase ambiguity parameters, in a few minutes, allowing users to achieve centimeter accuracy in real time. The PPP-RT with an ambiguity solution is usually referred as PPP-RTK (WÜBBENA et al., 2005; TEUNISSEN; KHODABANDEH, 2015). Thus, the PPP-RTK has shown to be quite promising, since its results in the literature indicate that the method can be used with sparser reference networks in comparison to traditional NRTK. However, for users who need results close to RTK results (e.g. instant solutions with 1 ~ 2 cm error), the PPP-RTK method has been considered only a low-cost complementary solution to serve regions where NRTK coverage is not available (ROVIRA -GARCIA; JUAN; GONZALES-CASADO, 2015; OLIVEIRA JR, 2017).

Throughout this article, the positioning evolution for real time purposes is presented, considering its particularities, as well as the existing services available in Brazil. Afterward, some practical applications are described with corresponding results achieved over the past few years. Finally, the future perspectives for real-time positioning methods are presented.

2 REAL-TIME POSITIONING EVOLUTION

As previously stated, satellite positioning has evolved over the past few decades. This evolution is associated with several aspects: the GNSS observable employed, the communication system as well as the corrections format for transference in real-time. These aspects will be addressed below.

2.1 Real-time positioning alternatives

2.1.1 ABSOLUTE POSITIONING

The absolute positioning is one of the possibilities for obtaining instantaneous geodetic coordinates. This solution provides to users the coordinates of the point occupied by the equipment (receiver / antenna) with respect to the geocenter of a geodetic reference system, such as WGS-84 (GPS) and PZ-90 (GLONASS) (MONICO, 2008). Coordinates are computed instantaneously using information from the satellite broadcasted ephemeris and the code measurements in different frequencies (L1, L2, L5) or linear combination of these observables. This positioning alternative provided horizontal and vertical accuracy better than 13 m and 25 m (95% probability level), respectively, with the basic GPS constellation (DIVIS, 2000; SEEBER, 2003). Currently, given the increasing number of GNSS constellations as well as the number of satellites simultaneously observed, better precision is expected for absolute positioning, according to studies carried out, for example, by Euriques, Krueger and Silva (2018). Among the GNSS constellations (Global Navigation Satellite Systems) there are: GPS (31 satellites); GLONASS (29 satellites), BeiDou (27 satellites); GALILEO (not declared operational - currently 22 satellites in operation). As stated by Gao and Enge (2012), by the year 2030, these systems should provide 120 satellites in orbit. However, in view of the current reality, that number of satellites should be reached before that date.

2.1.2 DIFFERENTIAL POSITIONING

Differential positioning (Figure 1) consists of the positioning of a mobile (user) station through the differential corrections generated at a reference station transferred in real time through a communication system (radio transmission, GSM or satellites communication). These corrections must be in appropriate format, defined by the Radio Technical Committee for Maritime Services (RTCM) (SEEBER, 1993; KRUEGER, 1996). The stations must simultaneously observe at least 4 satellites, and the accurate coordinates of the reference station must be known a priori. This positioning alternative makes it possible for short baselines to minimize clock errors, satellite orbits errors, and the systematic errors related to the GNSS signals propagation in the Earth’s atmosphere.

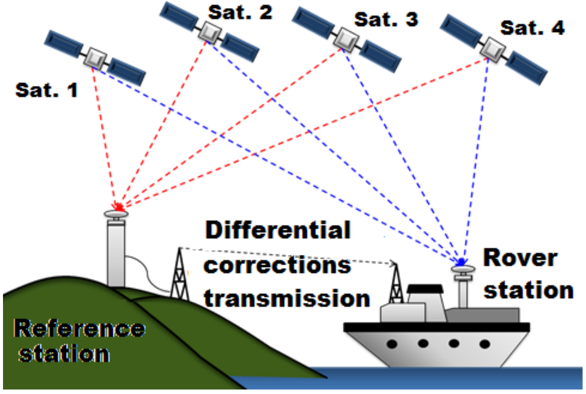
Differential positioning in real time is referred differently in the literature regarding aspects such as: the number of reference stations involved (a single base station or a network of base stations); the used observables (code, code smoothed by carrier phase or carrier phase); the corrections (scalar or vector) used to compute rover station coordinates; and the obtained precision. Considering the used observables there are three different groups:

a) DGNSS (Ordinary DGNSS) using differential corrections based on pseudorange measurements, which can provide precision between 1 to 3 m for mobile station positioning, depending on the baseline length formed between the reference and rover stations;

b) DGNSS (Carrier smoothed DGNSS) using differential corrections based on pseudorange measurements smoothed by carrier phase (e.g. Lachapelle filter), providing positioning precision better than 0.5 m for the rover station;

c) DGNSS (Precise DGNSS) using differential corrections based on carrier phase measurements, well known as precise differential positioning or RTK, which allows precision in the order of centimeter (WILLIGALIS et al., 2002).

Figure 1- Representation of the principle of the differential positioning by GNSS.



Source: Adapted from KRUEGER (1996).

Regarding the differential corrections used by the rover station, we have three other groups of corrections:

a) in the position domain;
b) in the measurements domain; and
c) in the state space domain.

In item a), the accurate coordinates of the reference station are known, thus the differences between them and the coordinates obtained instantly are calculated. These differences are transmitted to the rover station in order to correct its instantaneous position in real time. It is a simple strategy; however, it is efficient only for short baselines where both stations track the same satellites simultaneously.

In case b), differential corrections are obtained in the domain of pseudorange measurements, by computing the difference between the observed (true) pseudorange measurement and the calculated pseudorange for each satellite tracked at the reference station using its known coordinates. This strategy is more flexible, and requires that constellation of satellites observed at the rover station must be a sub constellation of satellites observed at the reference station. In this manner, it is possible to operate with baselines of several kilometers, knowing that the precision achieved for rover station positioning decreases about 1m per 100 km (SEEBER, 2003). This degradation occurs due to the similarity reduction between satellite orbit errors and systematic atmospheric errors (troposphere and ionosphere) with the increase of the formed baseline.

For case c), corrections in the state space domain, networks of reference stations are used. This network-based strategy allows the positioning over greater distances and the modeling of systematic errors. This strategy is based on correction vectors and not on scalar corrections as in the previous case. Thus, rover positioning can be more precise in the reference stations network coverage area.

In order to overcome rover positioning accuracy degradation regarding the increase in the length of the baseline, differential network positioning emerged. This positioning method consists of the simultaneous use several reference stations data; such a network can cover a country or even a continent. Therefore, errors are modeled and estimated in the covered region. Corrections are generated and sent rover stations, allowing greater accuracy in their positioning (FOTOPOULOS; CANNON, 2001), (LACHAPELLE; ALVES, 2002), (SEEBER, 2003), (BROWN et. al., 2005). Another advantage of this approach is the increased service reliability and availability. According to Fotopoulos and Cannon (2001), contributions from failing reference stations can be eliminated and the solution is generated using only the remaining reference stations.

In the case of a network-based positioning, the literature indicates that at least three concepts can be applied with respect to the corrections computation and transmission to users: Area Correction Parameters (FKP - *Flächenkorrekturparameter* or ACP - Area Correction Parameter), Virtual Reference Stations (VRS) and Master - Auxiliary Concept - MAC.

In the FKP concept are calculated for each satellite coefficients that represent the effects of ionosphere, troposphere and orbit in the network coverage area and for a certain time interval (WÜBBENA et al., 1996). This calculation is performed by a main station. Corrections and coefficients are sent to the user, in RTCM format, thus user can interpolate the errors and determine his own position with improved accuracy (SEJAS et al., 2002).

According to Alves (2008), in the virtual station concept, the network corrections are used to generate virtual phase and pseudorange measurements for a station that does not exist physically, simulating a reference station in the vicinity of the user. With this VRS station data, located a few meters from user location, it is possible to perform the relative positioning and determine user position.

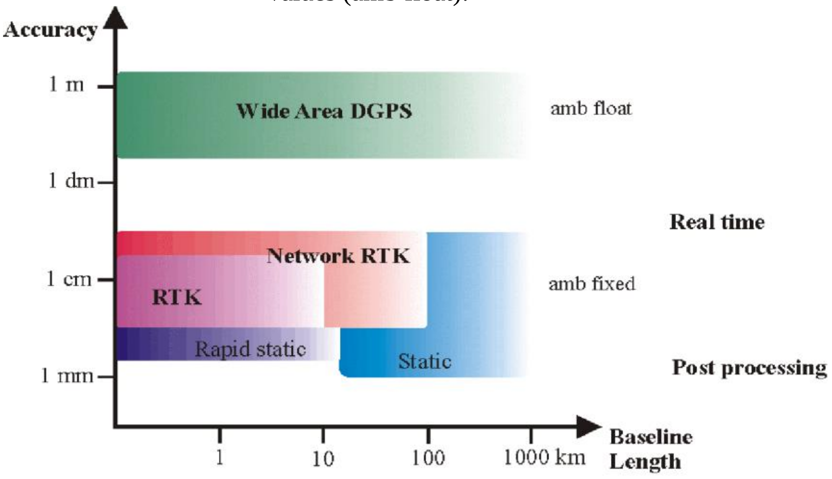
In the third concept (MAC) all relevant data referring to network corrections must be transmitted to the user (BROWN et al., 2005). The RTCM 3.0 format is used to send corrections from the main station (master) as well as corrections differences for auxiliary stations. The precise position of the user will be determined using the information transmitted by the network (SEJAS; KRUEGER, 2007).

According to observables employed to generate corrections as well as the coverage area, the reference networks used for real-time positioning are referred as: Local Area (LADGNSS); Wide Area (WADGNSS); NRTK (SEEBER, 2003). In LADGNSS, to each observed satellite, scalar differential corrections are applied in areas with a radius of up to 1000 km. In this case, only a single value represents the influences of the systematic errors affecting the reference station measurements. Although when more reference stations are used to generate the correction value a weighting process is performed, obtaining an average value. WADGNSS uses a corrections vector for each satellite, derived using observations from several reference stations from a continental or global network. This vector is composed of individual corrections for each satellite clock, satellite position and ionospheric delay model. Usually, this correction vector is valid for large coverage areas. WADGPS was the first to be developed, it used pseudorange measurements from continental reference networks (KEE et al., 1991) and provided differential corrections for maritime, air and land navigation allowing the users to improve positioning accuracy. According to Grewal, Weill and Andrews (2007), corrections are sent in real time by a geostationary communication satellite or through a network of terrestrial transmitters. In Figure 2, it can be seen that when ambiguities remain float (real-valued), the precision obtained is in the order of decimeters and meters, considering baselines up to 1000 km (WILLIGALIS et.al, 2002).

In the NRTK, carrier phase observations can be used and the concepts FKP, VRS or MAC are often applied. Alves (2008) points out that regardless of the method used, some steps must be observed: 1) ambiguities fixing between the reference stations, 2) computation of the network corrections, and 3) transfer of generated data or corrections of to the users.

In Figure 2, it is observed that in NRTK with baselines less than 100 km and ambiguities fixing, the user's positioning precision is about a few centimeters.

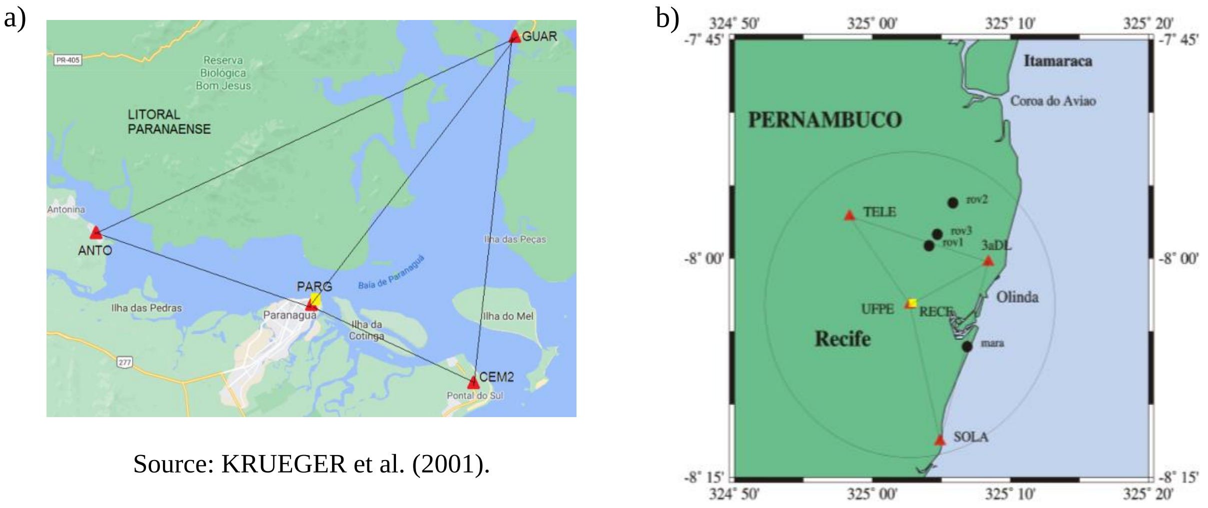
Figure 2 - Baseline-dependent accuracy for different post-processing and real-time positioning methods, taking into account the determination ambiguity cycles as integer values (amb fixed) and the determination of ambiguities as real values (amb float).



Source: WILLIGALIS et al. (2002).

Figure 3 shows two local RTK reference networks that were implemented in Brazil, for 15 days, within an international cooperation project between Brazil (UFPR and UFPE) and Germany (IfE / UH) from 1998 to 2001. The main station received the corrections generated by the other reference stations and calculated surface correction parameters (FKP) for the area, in order to allow ambiguity fixing (GNRT / GNNET) and generated new differential corrections to be sent to the rover station, through UHF (Ultra High Frequency) radios. Currently, in Brazil, there are scientific studies related to NRTK in continuity to the system developed by Alves (2008). But in terms of operational services, only commercial systems are available.

Figure 3 - Examples of RTK Local Networks in Brazil: a) RTK Network on the coast of Paraná (1999) formed by 4 reference stations, CEM2 (main station); PARG; GUAR and ANTO. The distance between the main station and the reference stations was less than 27 km; b) RTK network in Pernambuco (2000) formed by 4 reference stations, RECF (main station); 3aDL; SOLA and TELE. The distance between the main station and the reference stations was less than 20km.

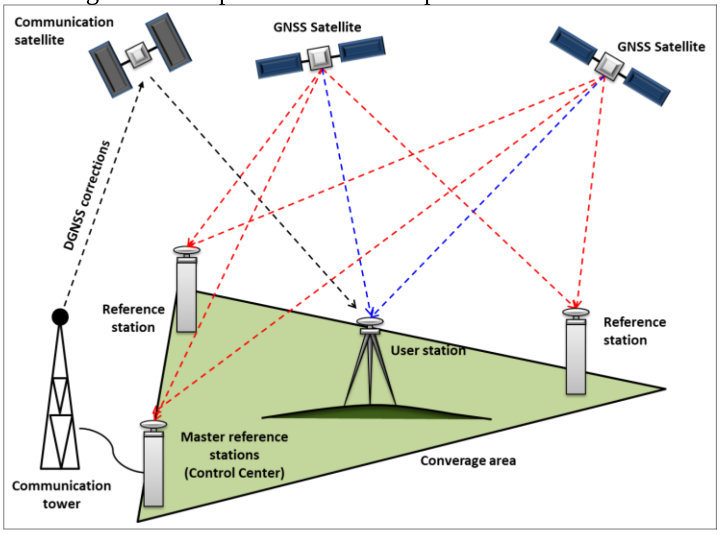


Source: KRUEGER et al. (2001).

Source: WILLGALIS et al. (2002).

In the context of real-time positioning, SBAS (Satellite Based Augmentation System) services also stand out. These systems are composed of reference stations and main stations, as well as terrestrial transmission antennas that send differential corrections to geostationary satellites, communicating to users (Figure 4). SBAS were designed to improve the quality of a GNSS system, such as: accuracy, robustness and signal availability. Among the main characteristics of SBAS are: integrity, accuracy, availability and continuity of service to users.

Figure 4 - Simplified scheme of operation of an SBAS.



Source: Adapted from TEUNISSEN and MONTEBRUCK (2017).

WAAS - Wide Area Augmentation System (USA), EGNOS - European Geostationary Navigation Overlay System (Europe) and MSAS - Satellite Based Augmentation System (Japan) are examples of SBAS. According to Flament, Thompson and Ahmad (2020), the SBAS working group (SBAS IWG) started in 1997 with 4 members and now has more than 10 members. Figure 5 shows the SBAS in operation and those that are being defined or being developed. Brazil does not have an SBAS service and, although it may receive differential corrections from the SBAS geostationary satellites in operation, they are not satisfactory, since Brazil is not within any of the definition areas of existing services.

Figure 5 - SBAS systems. The systems in operation are indicated by the rectangles in blue, containing the year of operation, being: CWAAS from Canada, WAAS from the United States, EGNOS from Europe, GAGAN from India and MSAS from Japan. The yellow rectangles show the systems that are in definition or development, indicating the expected year of operation: BDSBAS from China, KASS from South Korea, ASECNA from East Africa and Indian Ocean, SDCM from Russia, SPAN from Australia and New Zealand.

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Source: FLAMENT, THOMPSON and AHMAD (2020).

2.1.3 PPP IN REAL TIME

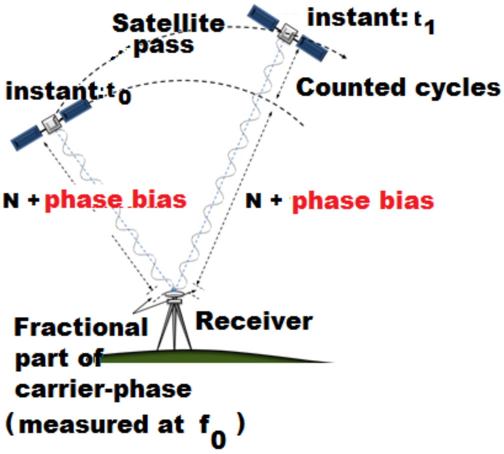
PPP-RT consists of a single station positioning, which needs to receive orbit and satellites clocks corrections in real time. In this context, in 2007 IGS started a pilot project using real-time GNSS observations obtained from a global network. In 2010 this institution created the RTWG (Real Time Working Group) working group, and in April 2013, it officially launched the RTS (Real Time Service) service whose official products include corrections for PPP-RT. With the use of products obtained using global GNSS networks, centimeter accuracy became feasible in PPP-RT (GRINTER; ROBERTS, 2011; RIZOS et al., 2012). In this method, the time required for the convergence of the positioning solution is still a limiting factor. In Brazil, the contributions of Marques (2012) stands with the implementation of the estimation and application of the satellite clock corrections for PPP-RT purposes. In this study, several experiments were carried out with results of centimetric and decimetric quality, for static and kinematic modes of PPP-RT, respectively.

The standard PPP-RT strategy requires the estimation of state parameters (for example, tropospheric delays) along with float ambiguities, which requires considerable initialization time (at least 30 min) to achieve appropriate adjustment convergence and ambiguities values, even under good satellite geometry conditions (ROVIRA-GARCIA; JUAN; GONZALES-CASADO, 2015). Thus, the possibility of accelerating the solution convergence in PPP-RT by using SSR corrections (State Space Representation) from reference stations networks has been extensively explored. In this case, the advantage over NRTK is the use of mono-directional communication with users and the possibility of adopting a sparser network of reference stations (OLIVEIRA JR et al., 2017).

According to Teunissen and Khodabandeh (2015), the possibility of fixing ambiguities to integer values in PPP-RT has been explored, usually called PPP-RTK. The products of the network of reference stations for the PPP-RTK may include corrections of satellite instrumental biases for phase measurements (Figure 6) which can facilitate the ambiguities parameter (N) fixing (LAURICHESSE; PRIVAT, 2015;

OLIVEIRA JR et al., 2020). In the absence of ionospheric anomalies and high multipath effects the standard convergence time for PPP-RTK is about a few minutes (2 ~ 10 min). This required time also depends on several factors, i.e. implementation, applied corrections, network topology, among others. In Brazil, the research studies of Lima (2015) contributed with an implementation of PPP-RTK.

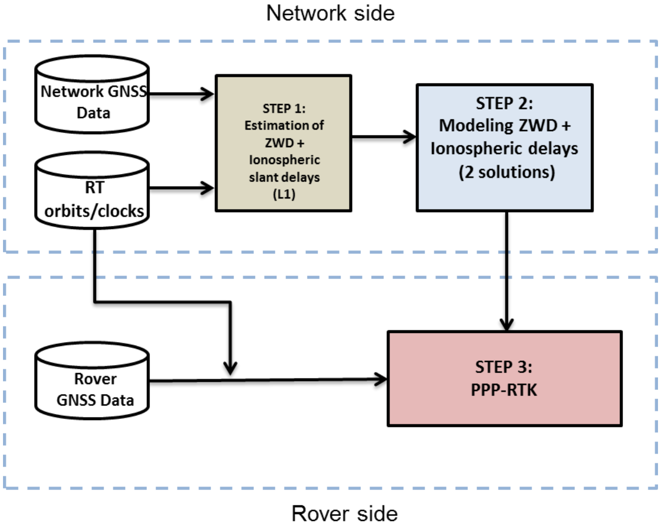
Figure 6 - Geometric interpretation of ambiguities and instrumental biases in phase measurements for a tracked satellite arc.



Source: Adapted from LIMA (2015).

PPP-RTK results including the application of SSR corrections for atmospheric parameters, such as ionospheric and tropospheric delays, have shown improvements with convergence at the centimeter level in the first minutes or even seconds (LI et al., 2014; ROVIRA-GARCIA ; JUAN; GONZALES-CASADO, 2015). These studies show the positioning based on SSR corrections as an independent or complementary solution to the RTK or NRTK methods. It is important to point that for applications requiring instant convergence with centimeter accuracy, NRTK still imposes itself as the most reliable alternative for network services. PPP-RTK has been presented as a less expensive solution, capable of serving users who need accuracy results better than 10 cm and with a convergence time of a few minutes. However, atmospheric modeling performances for generation of SSR corrections depend on the network topology and atmospheric conditions. In the case of Brazil, the modeling of the ionosphere is a challenge in itself, given the equatorial anomaly and the occurrence of irregularities due to ionospheric scintillation. Figure 7 illustrates an example of data flow and steps for performing PPP-RTK with atmospheric corrections (OLIVEIRA JR, 2017).

Figure 7 - Scheme for performing the PPP-RTK, with the generation of SSR atmospheric corrections and their application for the user positioning.



Source: OLIVEIRA JR. (2017).

2.2 Format for Transference of Data and Differential Corrections

As explained above, differential corrections and data are sent in real time through a communication system and in an appropriate format. With the development of DGPS, the U.S. Institute of Navigation (ION), in 1983, asked RTCM to develop recommendations for the transmission of differential corrections to users of the system (KRUEGER, 1996). This service founded the Special Committee 104 (SC - 104), which is responsible for the dissemination and definition of standards for GNSS differential systems, which are used worldwide for satellite navigation (sea or land). In 1985 the first version of these standards was published, which has been continuously improved. An overview of this evolution is shown in Table 1, highlighting the version, the year of publication, the main messages and other specifications (RTCM, 2006).

Table 1 – Overview of the RTCM-SC104 evolution.

Version	**Year**	**Main messages**	**Differential positioning users/system**
1.0	1985	Implementation. There were operational problems	DGPS (code) / GPS.
2.0	1990	1 - Differential GPS corrections. 2 – Delta differential corrections. 3 – GPS Reference station parameters.	DGPS (code and code smoothed by carrier) / GPS.
2.1	1994	Version 2.0 + Messages 18 to 21. 18 – RTK uncorrected carrier phases. 19 – RTK uncorrected pseudoranges. 20 – RTK carrier phase corrections. 21 – RTK high accuracy pseudorange corrections.	DGPS e RTK (code and code smoothed by carrier and carrier phase)/ GPS.
2.2	1998	Version 2.1 + Messages 31 to 36 (GLONASS) +37. 31 - Differential GLONASS corrections. 32 - Differential GLONASS reference station parameters. 33 – GLONASS constellation health. 34 – GLONASS partial differential correction set 37 – GNSS system time offset.	DGPS e RTK (code and code smoothed by carrier and carrier phase)/ GPS and GLONASS.
2.3	2001	Version 2.2 + Messages 23 to 24. 23 – Antenna type definition record. 24 – Antenna reference point.	DGPS e (code and code smoothed by carrier and carrier phase)/ GPS and GLONASS.
3.0 (RTCM Paper 30-2004 / SC104-STD)	2004	Version 2.3 + Reformulated messages. 13 reformulated messages (1001,1002... 1013). Messages to support real-time services including code and carrier phase, antenna description and auxiliary operation information.	RTK (carrier phase) / GPS and GLONASS.
3.1 ou RTCM Standard 10403.1	2006	Version 3.0 + GPS Network RTK Corrections (conceito *Master-Auxiliary*) + GPS Ephemeris message +GLONASS Ephemeris message. UNICODE message, which provides textual information. A set of message types reserved for proprietary use by sellers who wish to broadcast special information to their users.	Network RTK (carrier phase) / GPS and GLONASS.
3.2 ou RTCM 10403.2	2013	Verson 3.1 + 5 amendments 3.0 + Multiple Signal Messages (MSM) + integration with other constellations + Ephemeris of GLONASS and QZSS.	*Network* RTK (carrier phase) / GPS, GLONASS (GNSS)beyond integration as Galileo, BeiDou, QZSS.
3.3	2016	Support to satellite-based augmentation systems (SBAS). Adds ephemeris of BeiDou.	
10.1 ou RTCM 10410.1	2004	Standardizes the protocol used for transmitting GNSS messages over the Internet, called NTRIP, that can be accessed through mobile protocol transmission services IP.	Carrier phase / NTRIP/ GNSS.

Source: Adapted from RTCM (2006) and SEEBER (2003).

2.3 Communication systems

The communication system directly influences the quality of the differential positioning in real time. The transmission of corrections or data from the reference station to the rover station should be properly performed in order to guarantee the integrity of this information and follow the rules established by the Special Committee SC 104. According to Heimberg (1994), high frequencies allow a better solution, so leading to precision results. The shorter the wavelength, the higher the data transmission rate, but the lower the range. Table 2 shows some communication systems with some characteristics for different types of real-time positioning. In this table it can be seen, for example, that for NRTK the transmission by Radio 70 cm, Cellular phone or Internet are recommended enabling the transmission of data with the rate of 9600 bit/s.

Among these communication alternatives, it can be highlighted that the VHF and UHF transmissions have simple and lower cost installations; however the system reliability can be affected by the multi-path effect. Several companies currently offer radios with multiple channels, which should be used in communication. The satellite communication systems have the disadvantages of the high cost for data transmission and the need for a connection (for example, a telephone line) for each reference station. A global system is very complex, since neither the sender nor the receiver are portable systems. Transmission via cell phone is currently promising mainly due to the drop in prices for data transmission. It has the disadvantage that the number of simultaneous users is limited by the number of modems in the reference station. The most robust way to send differential corrections is the Internet. This information is sent via the NTRIP protocol (Network Transport of RTCM via Internet Protocol) which is capable of transmitting data via the internet, including via wireless devices, managed by software that convert the RTCM protocol to the Internet language in an IP. The user must select his IP and configure his mobile receiver for RTK/GSM using the NTRIP service.

Table 2 – Examples of communication systems for real-time positioning.

Transmission	**Frequency**	**coverage/transmission capability**	**User**	**Positioning type/differential**
Radio *Low Frequency* (LF)	< 300 KHz	Hundreds of km / 300 bps	Unlimited	DGPS
Radio *Medium Frequency* (MF)	300 KHz - 3 MHz	Hundreds of km / 100 bps	Unlimited	DGPS (*beacons*)
Radio *Very High Frequency* (VHF)	30 - 300 MHz	2400 bps	Unlimited	RTK
Radio RDS (*Radio Data System*)	65 MHz - 108 MHz	Dozens of km / 100 bps	Unlimited	DGPS
Radio 2m	144 MHz – 148 MHz	Dozens of km / 2400 bps	Unlimited	DGPS, RTK
Radio UHF	300 - 3000 MHz	2400 bps	Unlimited	RTK
Radio 70 cm (*Mobile* UHF)	428 MHz	Few km / 9600 bps	Unlimited	DGPS, RTK, *Network* RTK
Communication satellite (Inmarsat)	1545 MHz - 3687 MHz	Global / >2400 bps	Unlimited	DGPS
Cellular phone	3 a 4 GHz	Variable / 9600 bps	One per channel	DGPS, RTK, *Network* RTK
Internet	2.4 GHz - 5 Ghz	Global / > 9600 bps	Unlimited	DGPS, RTK, Network RTK

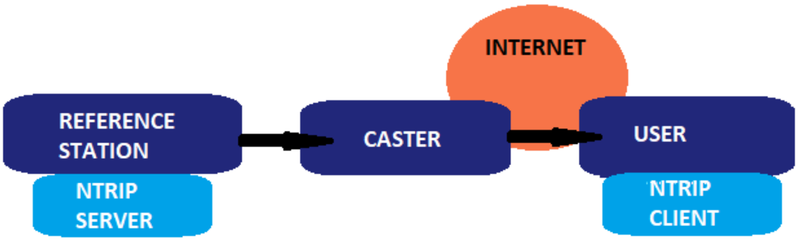
Source: Adapted from SEEBER (2003).

2.4 Real time positioning services in Brazil

One of the real time positioning services was implemented by the Brazilian Navy, the ERDGPS (DGPS Reference Stations) (BRIONES, 1999). According to Moreira (2011), the main objective was to improve the accuracy of maritime navigation in ports and access channels. Eleven reference stations were installed next to some radio beacons on the Brazilian coast. Differential corrections were generated at these stations and sent in RTCM format by MF radio, with a range of 200 to 300 miles, enabling transmission of 100 bps. This service is currently deactivated, but it significantly contributed to the positioning of vessels at the time when SA was activated, as it had an accuracy better than 3 m + 2 ppm of the separation distance between stations.

Since 2009, the Brazilian Institute of Geography and Statistics (IBGE – *Instituto Brasileiro de Geografia e Estatística*) has provided a free national service called RBMC-IP (Brazilian Network for Continuous Monitoring of GNSS Systems in real time) (Figure 8). This service serves users who use the RTK or DGPS technique for their surveys, using the NTRIP protocol to disseminate differential corrections (SOUZA; GARNÉS; MARQUES, 2014). In this service, the user selects which RBMC-IP station to obtain corrections/data information in real time (COSTA et al., 2009).

Figure 8 - Positioning scheme in real time through NTRIP.



Source: The authors (2020).

There are also other global commercial services available to Brazil. These services include RTG (Real Time Gipsy) and RTX (Real-Time eXtended). The first is also called GDGPS (Global Differential GPS) and has 53 reference stations that form the C-Nav GcGPS network (MOREIRA, 2016). According to Ramos (2007), the continental WADGPS RTG system uses correction algorithms (WCT - Wide Area Correction Transform) that provide a single set of corrections for an entire continental area. Corrections for orbits and clocks of the GPS or GPS/GLONASS satellites are applied. Some of these stations analyze and monitor the latency and real reliability of data transfer at a JPL (Jet Propulsion Laboratory) processing center. Differential corrections are sent via terrestrial communications links to geostationary satellite control centers for retransmission to system users.

In 2011 Trimble launched RTX technology, the service does not require local reference stations and combines the advantages of RTK with PPP, being similar to the PPP-RTK method. It employs global satellite corrections extending the coverage area of the RTK and provides real-time centimeter accuracy all over the world (LEANDRO et al., 2012). This new technique is based on the generation and delivery of accurate satellite corrections (ie, orbit, clocks and others) on a global scale, via a satellite Internet communication link.

3 RESEARCHES ASSOCIATED WITH PRACTICAL APPLICATIONS

A great expansion of the use of positioning systems worldwide in different applications occurred with the evolution of GNSS receivers providing positioning for real time purposes, at more accessible cost, as well as, the evolution of the RTCM format for the differential corrections and the communication solutions available for data/corrections transmission. It is notable that, although some of these applications can also be carried out using other methods, real time is desired, as it presents some advantages, for example, obtaining precise coordinates, without the need to carry out post-processing.

The following sections describe some researches that involve different practical applications with real-time positioning, among the numerous existing possibilities, which were developed at the national level. In Brazil, these applications occur mainly from a single reference station, even if the user is using the RBMC-IP service. However, the positioning of a rover station based on corrections generated by a network of reference stations is becoming possible with the use of global private services such as RTG and RTX.

3.1 Air, sea and land navigation

Navigation covers a range of applications that require different precision levels. In maritime navigation, for example, positioning on the high seas can be accomplished with absolute positioning. However, this method does not achieve the precision required for navigation in shallow water, where navigation safety is required.

The first works developed in Brazil with real-time positioning date back to 1994, when the positioning of trains was carried out through DGPS using code differential corrections sent by means of VHF radio (KRUEGER, 1994). Results reached accuracy 10 times better than the absolute positioning provided at the time. The positioning of vehicles in real time was carried out, for example, by Saatkamp (2003). In this research, DGPS differential corrections (code smoothed by the carrier phase) sent by a broadcasting station via RDS were used. The accuracy obtained in this research was between 0.31 and 3.88 m involving different classes of GPS receivers and baselines.

In maritime navigation for hydrographic surveys, Krueger (1996) used differential corrections applying the code smoothed by the carrier phase, obtaining accuracy better than 5 meters for vessel positioning. Within this application context, Briones (1999) used ERDGPS. The results achieved showed accuracy better than 10 m. Differential RTG positioning was used by Ramos et al. (2007), and Leandro et al. (2008), who indicated the suitability of the RTG system to the required specifications for horizontal positioning recommended by the IHO (International Hydrographic Organization) for Special or Lower Hydrographic Surveys. Also, in the context of vessel positioning, Nakao (2015) used the RTK in bathymetric surveys and the results achieved satisfied the ANEEL/ANA joint resolution of 2010 (NAKAO; KRUEGER, 2017).

A relevant application is the use of GNSS in air navigation, being used routinely for route navigation. Several traditional and costly methods have been used for many years. With the advances in technology and seeking lower costs, GNSS systems have become usual for this application. Another possibility is the use of GNSS positioning for aircraft landing and takeoff using the GBAS (Ground Based Augmentation System) concept. However, in Brazil, none of these systems is operational. One of the great barriers that exist is the strong interference imposed by the ionospheric layer affecting the GNSS signals (PEREIRA, 2018).

Precision agriculture involves a set of technologies in order to improve management of agricultural production systems (MOLIN; AMARAL; COLAÇO, 2015). This is one of the first applications that used real-time positioning. An example of this application was carried out by Castro and Lopes (2000), where an RTK system was installed on board an agricultural machine on the Canguiri farm of the Federal University of Paraná. Metric positioning accuracy was obtained by these authors. Currently the companies that produce these machines offer RTK solutions using, for example, cellular networks and RTK transmission towers.

Currently, remotely piloted aerial vehicles (Remotely Piloted Aircraft - RPA) have been widely used in mapping. In general, the positioning of these vehicles is carried out in real time through RTK. A reference station is implanted in the vicinity of the area to be mapped, transmitting the differential corrections through a radio transmitter. As this telemetry signal may suffer interference during the flight, the consolidation of the PPP-RTK in Brazil is promising in this area.

3.2 Environmental monitoring

Monitoring consists of the systematic observation of parameters for a specific purpose, defining quantitative and qualitative information in a considered time interval, aiming to investigate a problem. According to Spellerberg (2005), monitoring can be defined as the measurement of items that change over time and space. Therefore, the GNSS positioning is relevant and meets these requirements, since it enables positioning, navigation and time continuously (HOFMANN-WELLENHOF; LICHTENEGGER; COLLINS, 2001). In the environment area, some applications require positioning in real time. In others, this positioning can simply provide more agility in obtaining solutions.

The control and monitoring of marine biodiversity evolution, such as artificial reefs, is important with regard to sustainable fishing and tourism corridors. It also contributes to the understanding of ecological and hydrological processes on the continental shelf. Artificial reefs were launched on the coast of Paraná and their monitoring started to be made by DGPS with corrections sent by VHF radios and later by RTK (KRUEGER et al., 1999). In this research, real-time positioning allowed divers to be closer to the reefs, about 1 to 5 meters, facilitating the return visit.

The determination of coastlines can be carried out through different GNSS positioning methods, both real time and post-processing approaches. The choice will depend on the application purpose, for example, when aiming to update a nautical chart, this element can be represented with an imprecision of up to 10 meters (MARINHA DO BRASIL, 2017). However, when the user intends to analyze the advance or shorter setback a better accuracy is required. In the context of real-time positioning, researches carried out by Moreira (2016), RTG and NTRIP were used. Analyzing the planimetric precision obtained using phase/code solutions, RTG presented better results. However, when analyzing only the phase fixed solutions, the NTRIP proved to be more efficient. Regarding the accuracy analysis, the author indicates that the RTG (<0.35m) presented a better result in comparison to RTK/NTRIP (<0.50m)

In hydrographic surveys, several environmental parameters are measured. In these surveys, the instantaneous water level is essential and can be determined by real-time positioning. In 2006, RTK OTF (On the Fly) was used to monitor variations in sea level associated with ellipsoidal altitudes variations of a GNSS antenna installed on a vessel, reaching centimeter accuracy (RAMOS; KRUEGER, 2006).

Monitoring of risk areas is necessary; as it allows actions to be taken that make it possible to mitigate the destructive effects to which these areas are susceptible. Burity (2016) used the RTK/NTRIP in an area at risk of mass landslide, in the city of Recife - PE, in order to determine physical vulnerability. Errors of a few centimeters were obtained and RTK/NTRIP proved to be an effective alternative that can be applied in the calculation of landslides.

3.3 Surveys related to territorial management.

In some survey applications, such as rural and urban registry, georeferencing of rural properties, real-time positioning brought great advantages with fast and accurate solutions. In Willgalis et al. (2002), the real-time positioning networks presented in section 2.1.2 (Figure 3) were used in the registry of the cities of Paranaguá - PR and Olinda - PE. The authors indicated that the results were affected by ionospheric effects. In 2002, a portion of the *Centro Politécnico* campus of the Federal University of Paraná was registered using the RTK method and the precision achieved was in the order of centimeters (SEJAS; KRUEGER, 2002).

The RTK has been used to determine the coordinates of building vertices, as authorized by the INCRA georeferencing standards. Coelho (2013) found that the method allowed the coordinates of vertices to be determined in short time. However, limitations, such as multipath effect and signal losses, influenced accuracy.

Euriques, Krueger and da Silva (2018) used low cost receivers in positioning points without obstructions by the absolute method and obtained planimetric accuracy of around 2 m and three-dimensional accuracy in the order of 3.5 m. The authors emphasize that such results indicate the feasibility to perform, for example, the georeferencing of images with resolution of about 3 m. With this positioning quality, the boundary marks georeferencing of a rural property could be surveyed with this method, although, the surroundings of these marks must be evaluated.

Prado (2001) performed positioning using DGPS and RTK methods in an urban environment, therefore, susceptible to multipath effects and interferences that difficult reception of differential corrections by the rover station. Baselines ranged from 0.2 km to 29 km were assessed. DGPS horizontal and heigh errors were less than 3.5 m and 4 m, respectively. With the use of RTK, these errors were about 6 and 15 cm, respectively. In similar study, Freiberger Junior (2002) detected a shadow area when sending differential corrections from the reference station, which compromised the positioning quality. The author indicated in this case the need to change the location of the reference station.

Souza et al. (2013) evaluated urban cinematic trajectories in multipath environments in the city of Recife, using PPP-RT via BKG BNC 2.6 software (*Bundesamt für Kartographie und Geodäsie*), and RTK using data transmitted via NTRIP from RBMC-IP. Results of the average precision and the accuracy of the surveys were for the PPP-RT of 0.47 m and 10.46 m, respectively. For RTK/NTRIP a precision mean of 1.23 m and an accuracy of 2.85 m were obtained. Also, in urban environment, Garnés et al. (2018) performed surveys for land regularization purposes, using a 4-meter extension pole. In this study the RTK method was used to define property boundaries, achieving positional accuracy results between 3 to 8 cm.

4 FUTURE PERSPECTIVE

The PPP-RT method continues to evolve, especially with regard to fast ambiguity fixing (few minutes), allowing users to achieve centimeter accuracy. As explained earlier, this version of the method has been called PPP-RTK, and it presents itself as complementary solution to NRTK. Several services have been developed to respond mass market needs, regarding commercial and operational advantages of this method. Thus, PPP-RTK alternative is particularly interesting for the Brazilian region, considering that PPP-RTK usually requires sparser networks than NRTK. In view of PPP-RTK consolidation it is worth mentioning that several details of this method still need to be carefully investigated in the coming years. Most of these challenges are related to atmospheric effects modeling, ambiguities validation or outliers elimination (ROVIRA GARCIA; JUAN; GONZALES-CASADO, 2015; OLIVEIRA JR, 2017).

It would be of great importance for Brazil, the development of a SBAS to serve the national territory, later joining the working group (SBAS IWG). Such advances would result in the formation of an aviation support system in the Brazilian region. In this sense, efforts have been made at FCT/Unesp through INCT - GNSS NavAer (National Institute of Sciences and Technology - GNSS in Support of Air Navigation) to develop and improve GBAS - (Ground Based Augmentation System) in Brazil, this system plays a similar role using ground stations near airports that support the system (PEREIRA, 2018).

According to Darugna et. al. (2019), the possibility of RTK positioning with low-cost sensors available on smartphones is notable, since they achieved results with instant ambiguity fixing for zero baseline configuration. The authors also indicate that positioning with PPP-RTK or NRTK is more challenging in view of the additional residual atmospheric noise. These are challenges to be overcome.

According to Hein (2020), 5G technology could represent a new revolution on the internet through mobile devices. The main targets include the Internet of Things (IoT) and ultra-fast mobile broadband, which can contribute to the transmission of differential corrections, and as result, with real-time positioning. The combination of 5G with GNSS may result in improved accuracy, especially in urban environments, however, the compatibility and interoperability of 5G and GNSS will be necessary.

Finally, it is important to add that the GNSS is in a continuous process of expansion and modernization. In this direction, substantial advances have been achieved with the inclusion of new signals and the previous mentioned constellations, in operation and under development. It is important to highlight the L5 signal, which brings more possibilities for ambiguities fixing and ionospheric effects. This will directly benefit real-time GNSS positioning applications.

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Conflicts of Interest

The authors declare no conflicts of interest

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