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A Retrospective of Global Navigation Satellite System Ionospheric Irregularities Monitoring Networks in Brazil

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ABSTRACT

The use of Global Navigation Satellite System (GNSS) for air and terrestrial navigation and for many applications is increasing in the last decades. However, the Earth's ionosphere causes GNSS signal delay due to the total electron content (TEC) and scintillation in the signal phase and amplitude. This scintillation can give rise to deleterious effects in the GNSS positioning. So, it is important to assess the effects of the ionosphere over the GNSS signal. To achieve this goal, it is necessary to have a large spatial and temporal coverage of data from many different sounders, being the GNSS receivers of great importance due to their global coverage and availability. In this work, we present a retrospective of the scintillation monitoring networks in Brazil and their characteristics. As the RBMC network managed by the IBGE provides TEC and as rate of TEC index (ROTI) is well correlated with ionospheric irregularities, we present also the RBMC network description. These RBMC GNSS receivers provide data in regions with scarcity of scintillation monitors. The description of the Ionospheric Scintillation Monitoring Receivers (ISMR) Query Tool, that is a web software that has been supporting research on the ISMR data, is also presented.

Keywords: Satellite navigation; Equatorial plasma bubbles; Ionospheric scintillation; Space weather monitoring; Geophysical instrumentation.

INTRODUCTION

The use of Global Navigation Satellite Systems (GNSS) for air and terrestrial navigation and for an increasing number of applications is a worldwide trend today. However, when GNSS signals cross the ionosphere deleterious effects are observed. Two of these ionospheric effects are the signal delays due to the total electron content (TEC) and the signal amplitude

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and phase scintillations (Van Dierendonck and Hua 2001). The ionospheric layer presents different behaviors depending on the location (especially with the variation of latitude), the time of day, the period of the year, the geomagnetic activity and the eleven-year cycle of solar activity. The ionosphere over the Brazilian territory, especially in the regions where the Equatorial ionization anomaly occurs, has unique characteristics in relation to the rest of the planet, due to the concentration of phenomena and anomalies that occur there, making the performance of satellite positioning systems in the region worse when compared to middle latitude regions like the United States and Europe, for example (Abdu 2019). For this reason, the application of GNSS-based technologies requires a thorough assessment of the effects of the ionosphere, to support a wide variety of studies with different levels of criticality, including aviation applications (Rodrigues *et al.* 2022). This assessment can be performed using theoretical and semi-empirical ionospheric models; however, the most important contribution comes from ionospheric measurements from different sounders, being the GNSS receivers of utmost importance due to its global coverage and availability. The ionospheric scintillation monitors are GNSS receivers with the capability of measuring the GNSS signal at high rates such as 50 or 100 Hz, what is a requirement for amplitude and phase scintillation calculations which are represented by the S4 and σ_φ indices respectively. The S4 is the standard deviation of signal intensity normalized to the mean value of intensity, while σ_φ is the standard-deviation of the detrended phase in each 60 s interval for both indices (Van Dierendonck *et al.* 1993).

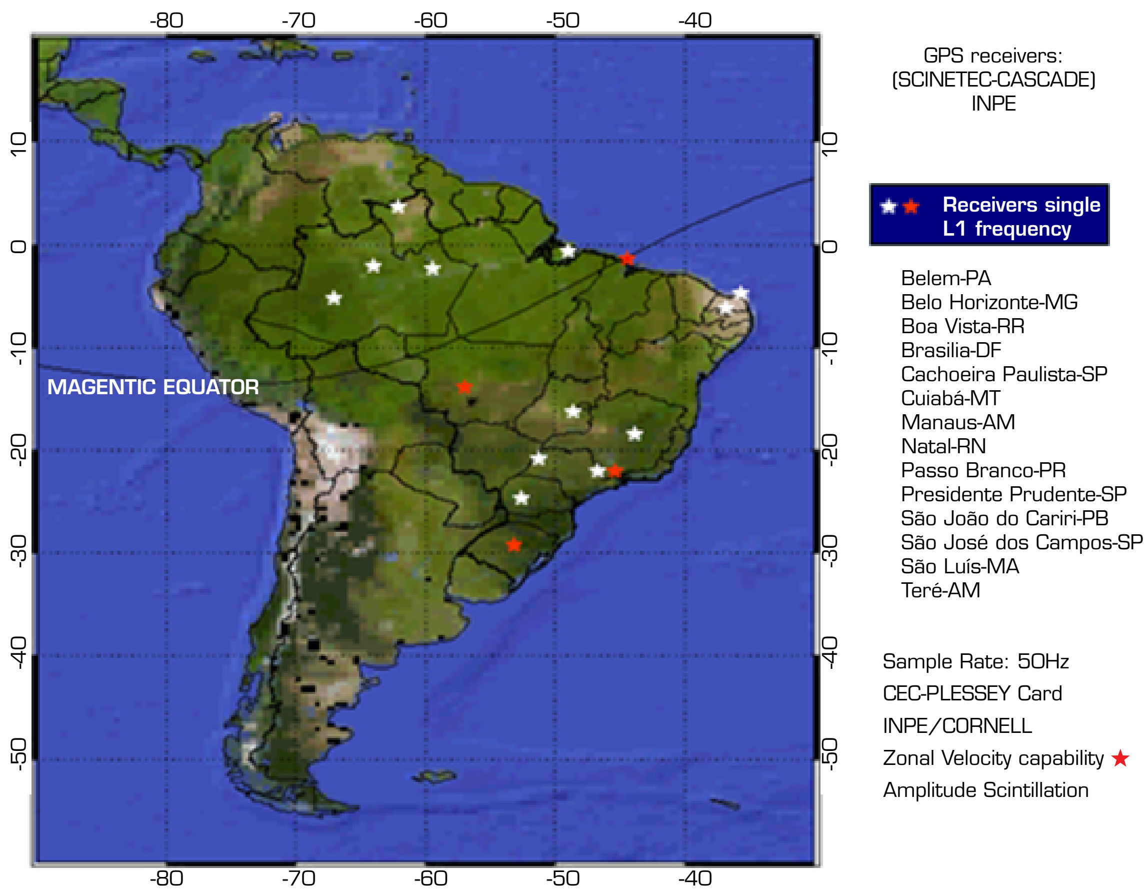
The detailed description of S_4 and σ_φ indices determination is provided at de Paula *et al.* (2020). These scintillations monitors, as they provide the carrier pseudorange and phase besides the signal intensity, the TEC and the parameters rate of TEC (ROT) and ROT index (ROTI) (Pi *et al.* 1997) can also be determined. Jesus *et al.* (2020) and Nguyen *et al.* (2022), among other authors, pointed out that ROTI and S_4 are well correlated. The main aim of this work is to provide the description of the GNSS-based scintillation monitoring networks at the Brazilian territory.

The pioneering L-band scintillation monitoring network in Brazil is no longer in activity but was the Cornell Scintillation Monitor (CSM). The GNSS scintillation monitor networks currently acquiring data in Brazil are the Low-Latitude Ionospheric Sensor Network (LISN), the CIGALA/CALIBRA, the ICEA/DECEA and the GNSS NavAer INCT project (Monico *et al.* 2022). Additionally, the network of geodetic receivers called RBMC/IBGE provides GNSS observables, which allow the estimation of the TEC and consequently the ROTI. These parameters are excellent proxies of scintillation activity. The characteristics and capabilities of the aforementioned networks will be described in the next sections following. Also, a brief visit to the use of low-cost monitors will be shown, once such devices appear as a promising option for ionospheric monitoring. Finally, the Ionospheric Scintillation Monitoring Receivers (ISMR) Query Tool, a web-based software designed to store, explore and analyze the large ISMR GNSS data, is described before the final comments of this report.

RESULTS AND DISCUSSION

The Cornell Scintillation Monitor (CSM) Network

The first scintillation monitor network in Brazil was stablished in 1997 in collaboration with Cornell University, when the first CSM was installed at the National Institute for Space Research (INPE), São José dos Campos, Brazil. A total of 18 monitors were installed during this cooperation in the Brazilian territory. Figure 1 presents the map with the sites. At São Martinho da Serra (RS), Cachoeira Paulista (SP), Cuiabá (MT) and São Luís (MA) scintillation monitors receivers operated in pairs, spaced in the magnetic east-west direction were installed providing the capability to calculate the Global Positioning System (GPS) L1 band zonal drift from 400 m plasma irregularity using the cross-correlation methodology (de Paula *et al.* 2002; Kil *et al.* 2002; Ledvina *et al.* 2004; Muella *et al.* 2008). The first CSM system was the Scintillation Monitor (SCINTMON) (Beach and Kintner 2001) running in the operation system DOS that was latter substituted by the CASCADE system operating in Linux. The CSM uses a modified commercial Plessey GPS Builder-2 card (Beach 1998; Beach and Kintner 2001) to measure the amplitude scintillations in the L1 (1.575 GHz) band, the wide band power (WBP) and the wide band noise at a 50 Hz sampling rate. Even though the scintillation monitor also provides phase data at 10 Hz, it is not advisable to use its carrier phase measurements due to oscillator and tracking loop noise and large background trends. More details about the CSM signal characteristics, its data processing and it is capability to operate during scintillation incidence are provided in de Paula *et al.* (2020).



Source: Elaborated by the authors.

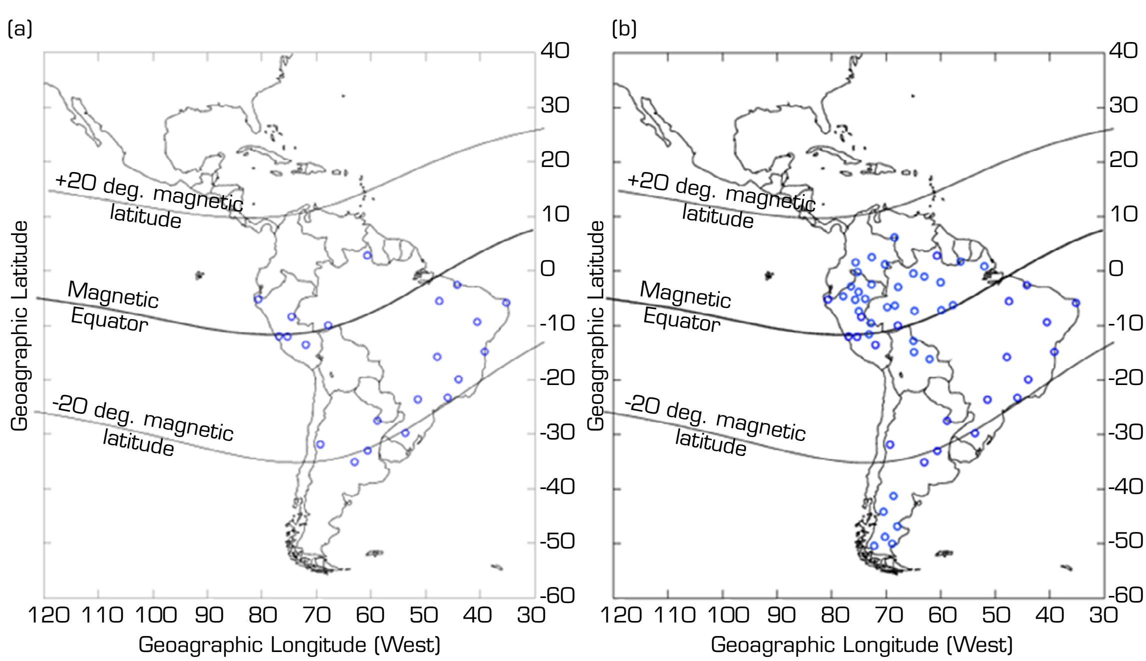
Figure 1. Cornell Scintillation Monitor (CSM) network receivers.

The Low-Latitude Ionospheric Sensor Network (LISN)

The LISN is a scientific project funded by the National Science Foundation (NSF) dedicated to monitoring and studying the low latitude and equatorial ionospheres (Valladares and Chau 2012). The principal goal of the LISN network is to develop a forecasting technique of the electrodynamics and structuring of the plasma environment. LISN performs as a distributed array of small instruments (DASI) in the South American Continent, with a significant part of the receivers installed in Brazil. The present network includes twenty-one Global Positioning System (GPS) receivers, six flux-gate magnetometers, and four Vertical Incidence Pulsed Ionospheric Radar ionosondes. The LISN observatory at Lima, Peru, includes an archival data system to store all the historical data collected with the LISN receivers.

This work will focus only on the GPS receivers that were deployed across the South American continent to fill regions devoid of GPS receivers. The LISN observatory aims to investigate the complex day-to-day variability and the extreme state of disturbance in the equatorial ionosphere nearly every day after sunset. This observatory provides almost real-time measurements (nowcast) to the space weather community. All the LISN instruments upload their real-time observables to a server located at the Instituto Geofísico del Perú headquarters in Lima to receive, process, store and distribute the scientific information. During the last ten years, the LISN project has developed several software codes designed to provide the amplitude scintillation index S_4 and the TEC. Maps of TEC distributions over South and Central America and the Caribbean regions are displayed. In addition, the LISN project has developed programs to identify and study the characteristics of TEC perturbations associated with traveling ionospheric disturbances and TEC depletions. LISN has also advanced new processing methods to investigate the electrodynamics of the ionosphere over South and Central America. Different computer processing and displaying codes are available through a formal request for any member of the Coupling, Energetics, and Dynamics of Atmospheric Regions or the Aeronomy international communities.

The LISN observatory collects (July 2022) real-time observations from 21 GPS receivers (Fig. 2a) that provide real-time TEC and S4 scintillation values. In July 2021, the University of Texas at Dallas was awarded a Grant to deploy thirty-four Septentrio PolaRx5S receivers, mainly in the Amazon region of Colombia, Peru, Brazil, and Bolivia, and the Patagonia region in southern Argentina (Fig. 2b). Such areas are mainly devoid of GPS/GNSS receivers. The new distributed array will increase the real-time probing capability of the LISN network and several other networks in South America. The PolaRx5s is a multifrequency multiconstellation receiver dedicated to ionospheric monitoring and space weather applications. The receiver has been implemented with 544 hardware channels to provide in-phase and quadrature components correlations, phase, code, and carrier-to-noise at up to 100 Hz for all GNSS L-band frequencies. The receiver measures the S4 and phase scintillation using an ultra-low noise oscillator with a phase noise standard deviation as low as 0.03 rad. The PolaRx5s receiver analyzes signals from the principal satellite constellations: GPS, WAAS, GLONASS, Galileo, and BeiDou. This capability makes it possible to investigate how ionospheric irregularities affect radio waves at different frequencies and modulation patterns. These receivers will make it possible to upgrade, augment, and establish a real-time network of ionospheric instruments covering a vast region of the continent. The aim is to nowcast and forecast the ionospheric density variability and its turbulence. This project will also enhance scientific research in the USA and several countries in South America. It will give the American scientific community a unique opportunity to distinguish among competing theories on ESF formation. It will open new avenues of research to assimilate density profiles and TEC data using sophisticated algorithms such as deep neural networks and machine learning and apply them to forecast the onset of plasma instabilities. LISN data can be available under request at: http://lisn.igp.gob.pe/jstations/map/. Part of this data can also be accessed through the ISMR Query Tool that will be described later in this paper.



Source: Elaborated by the authors.

Figure 2. Location of receivers deployed by the LISN network; (a) Scintillation monitors currently active; (b) Monitors planned to be operational by 2023.

THE CIGALA/CALIBRA NETWORK

The Concept for Ionospheric Scintillation Mitigation for Professional GNSS in Latin America (CIGALA) and Countering GNSS high Accuracy applications Limitations due to ionospheric disturbances in Brazil (CALIBRA) projects, together with the Fundação de Amparo à Pesquisa do Estado de São Paulo (Fapesp) Thematic Project so called GNSS-SP provided means to set up the network for monitoring the ionospheric scintillation in the Brazilian sector of the equatorial and low latitude regions. With the CIGALA project, the first Septentrio PolaRxS receivers were deployed in the Brazilian region. The receiver sites were strategically chosen to cover regions with distinguishing ionospheric behavior, such as north and south of the magnetic equator, regions close to the peak of the Equatorial ionization anomaly and low latitudes, therefore supplying research on the dynamics of the plasma irregularities. Initially, receivers were setup to operate at 100 Hz, providing high-rate phase and in-phase and quadrature components correlations. Later, the 50 Hz sample rate was adopted as a standard. After the end of the CIGALA project in 2012, the CALIBRA project were established and provided support to expansion and continuity of the operation of the monitoring network, then characterizing the so-called CIGALA/CALIBRA network.

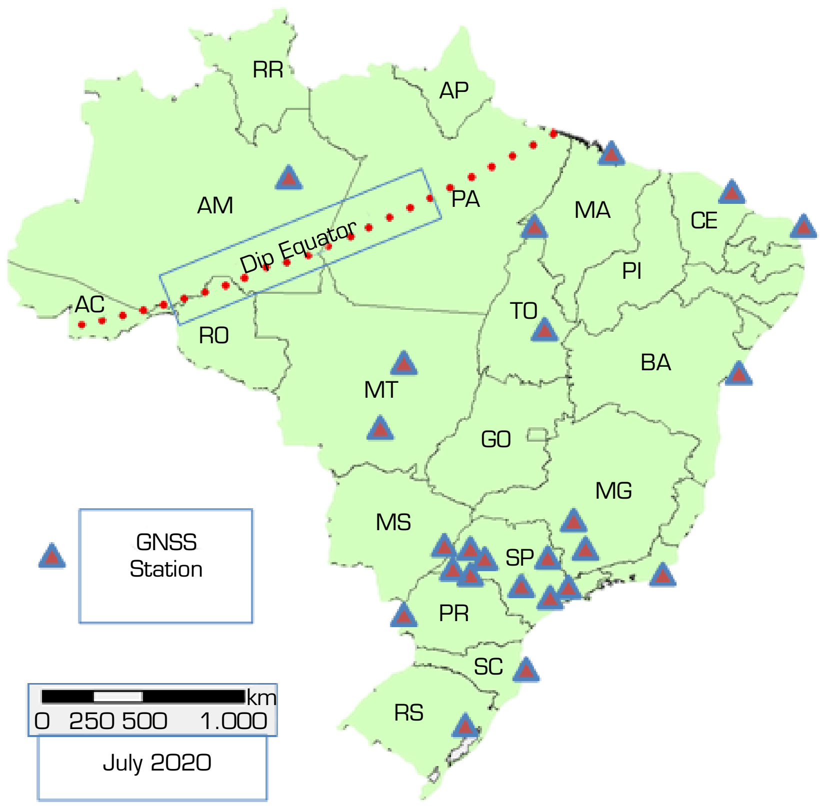
Besides the static data collected with monitoring receivers, several short-term experiments were conducted in real field conditions, such as precision agriculture, surveying, offshore and civil aviation. Within the experiments, performance of applications based on real time kinematic and precise point positioning were assessed in periods characterized by strong scintillation occurrence. The experiments supplied improvement of internal capabilities of the receivers, which received several upgraded firmware with better capabilities to prevent losses of lock associated to strong scintillation.

The lifetime of the CIGALA and CALIBRA projects allowed to cover a period of ascension and peak of the solar cycle number 23 (2012–2015). After the end of the projects, receivers were kept in operation by the Universidade Estadual Paulista (Unesp) and research partners. Access to data were made widely available with the support of the ISMR Query Tool (Vani *et al.* 2017), later described. As the first CIGALA stations were deployed in 2011 and with the continuity on the operation of legacy stations, the mark of ten years of continuous monitoring data were achieved in 2021. Several works are presented in the literature relying on CIGALA/CALIBRA monitoring data over this period. The works refer to monitor and modeling the ionosphere and its effects on GNSS under different perspectives, such as receiver design, performance and potential vulnerabilities (Moraes *et al.* 2014; Salles *et al.* 2021; Veettil *et al.* 2011; 2012), effects on GNSS positioning and mitigation (Marques *et al.* 2016; 2018; Park *et al.* 2017; Vani *et al.* 2019; Veettil *et al.* 2020), climatology and monitoring the ionosphere (Pereira *et al.* 2017; Spogli *et al.* 2013; Vani *et al.* 2021), among others.

The INCT GNSS-NavAer Network

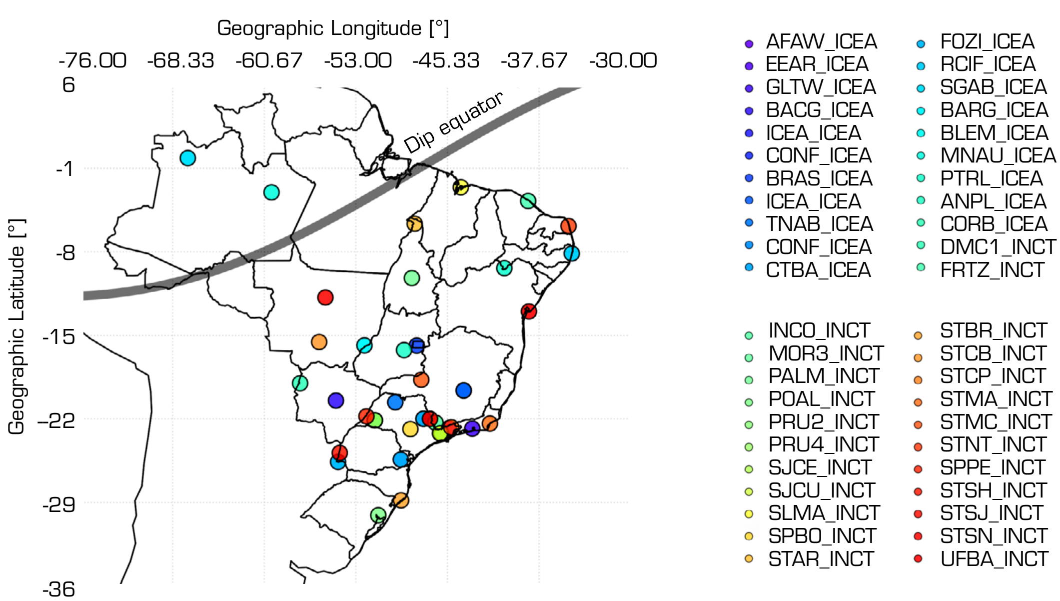
The GNSS-NavAer (https://inct-gnss-navaer.fct.unesp.br/) is a follow-on of the CIGALA/CALIBRA network, which is located inside the Brazilian territory (for more details see Monico *et al.* 2022). New GNSS receivers, Septentrio PolaRx5S, were deployed in some new sites and most of the older receivers PolaRxS–PRO were replaced. On July 2021, 13 new PolaRx5S receivers were acquired and they will be installed at regions with scarcity of receivers. Data are stored since 2011 at 50 Hz. Therefore, a huge amount of data is available and a deeply insight on them would be very important to see what we have learned and what could we do in the future to help minimize the problems resulting from ionospheric scintillation. This network provides data and very important parameters for understanding the scintillation occurrence and to assess the influence in the quality of positioning and navigation. The INCT GNSS NavAer data can be accessed at http://ismrquerytool.fct.unesp.br/is/. Figure 3 presents their location map in July 2020, including the legacy stations from CIGALA-CALIBRA.

To display the evolution of INCT stations, Fig. 4 presents their sites updated to July 2022. As stated above new installations are underway, some of them in the Amazon region, such as Manaus (AM) and Carajás (PA). Figure 4 also displays the ICEA network stations that will be described in the next section. It is worth noting that some circles are overlapped on the map in cities where there is more than one scintillation monitor, such as São José dos Campos and Presidente Prudente.



Source: Elaborated by the authors.

Figure 3. GNSS NavAer stations – Status July 2020.



Source: Elaborated by the authors.

Figure 4. INCT GNSS NavAer and ICEA Network – status July 2022.

Table 1 shows the INCT GNSS NAVAER sites, their identifications (4 letters) and their positioning.

Table 1. INCT GNSS NavAer sites, their identifications (4 letters), locations, geographic coordinates and altitudes, status July 2022.

Station ID	City	State	Latitude	Longitude	Height (m)
DMC1	Presidente Prudente	SP	22°07'23.1"S	51°24'28.8"W	444.8
FRTZ	Fortaleza	CE	3°44'40.3"S	38°34'39.5"W	24.8
INCO	Inconfidentes	MG	22°19'06.6"S	46°19'41.2"W	889.8
MOR3	Presidente Prudente	SP	22°07'39.7"S	51°24'47.9"W	454.0
PALM	Palmas	TO	10°11'58.7"S	48°18'40.7"W	275.0
POAL	Porto Alegre	RS	30°04'26.0"S	51°07'10.8"W	81.2
PRU2	Presidente Prudente	SP	22°07'19.4"S	51°24'25.5"W	441.9
PRU4	Presidente Prudente	SP	22°07'12.3"S	51°24'30.7"W	431.4
SJCE	São José dos Campos	SP	23°12'27.1"S	45°51'35.0"W	615.1
SJCU	São José dos Campos	SP	23°12'38.2"S	45°57'23.7"W	606.2
SLMA	São Luís	MA	2°35'36.3"S	44°12'44.2"W	28.1
SPBO	Botucatu	SP	22°51'08.9"S	48°25'56.3"W	803.1
STAR	Araguatins	TO	5°39'04.2"S	48°04'24.0"W	101.0
STBR	Balneário Rincão	SC	28°49'36.1"S	49°12'50.1"W	14.0
STCB	Cuiabá	MT	15°33'18.8"S	56°04'11.4"W	234.2
STCP	Cachoeira Paulista	SP	22°42'08.1"S	45°00'49.7"W	588.7
STMA	Macaé	RJ	22°23'19.3"S	41°46'34.4"W	38.5
STMC	Monte Carmelo	MG	18°43'26.4"S	47°31'25.6"W	913.9
STNT	Natal	RN	5°50'26.1"S	35°11'46.3"W	60.8
SPPE	Presidente Epitácio	SP	21°47'06.8"S	52°06'41.8"W	317.2
STSH	Santa Helena	PR	24°50'49.2"S	54°20'39.7"W	256.5
STSJ	São João da Boa Vista	SP	21°59'49.5"S	46°47'32.0"W	769.9
STSN	Sinop	MT	11°49'45.8"S	55°32'40.8"W	365.1
UFBA	Salvador	BA	12°59'59.3"S	38°30'38.3"W	69.7

Source: Elaborated by the authors.

The Institute of Airspace Control (ICEA) Network

GNSS are widely used in air navigation. In the future, such technology is currently becoming the main means for air navigation in all phases of flight. GNSS has several advantages over traditional radio navigation aids resulting in considerable ground infrastructure, fuel consumption, air route optimization, among others. In this context, the Ground-Based Augmentation System (GBAS) was designed to provide corrections and integrity for GNSS measurements to support more stringent air navigation procedures, as precision approaches (Pullen, 2017).

However, as pointed out by Marini-Pereira *et al.* (2021) and Sousasantos *et al.* (2021), the ionosphere strongly affects GNSS positioning integrity for more string aviation applications, which is the case of GBAS. The ionosphere in low latitudes regions, such as Brazil, has strong dynamics and intense variability, especially when compared to regions like Europe and the United States where GBAS, for example is well established.

For this reason, the use of GNSS-based technologies for more stringent applications in air navigation over Brazilian territory requires a thorough assessment regarding the effects of the ionosphere. Hence, research in this area is necessary to provide the basis to ensure safety of such applications. A better comprehension of the ionospheric dynamics in low latitudes in the terms required to support GBAS operations in Brazil was the main motivation for the Institute of Airspace Control (ICEA, which is the DECEA organization responsible for research and training) to establish a GNSS network to monitoring the ionosphere.

The focus of the ICEA network is the ionospheric scintillation for supporting air navigation in Brazil. For this reason, receivers with scintillation capability, i.e., with a high sample rate are used for this purpose. ICEA adopts the PolaRxS–Pro model receivers currently surpassed by the PolaRx5S model from the Belgian manufacturer Septentrio.

The stations were deployed in sites with existing Brazilian Air Force infrastructure, mostly, Military Organizations part of the Brazilian Department of Airspace Control (DECEA). The first deployment campaign occurred in 2013 and had the support of INPE and FCT/Unesp of Presidente Prudente.

After the 2013 campaign, three other deployment campaigns were carried out. One in 2015 to deploy four new stations, another in 2017 to six more stations and the last one in 2019 adding four new stations to the network. Currently, the ICEA network has 17 receivers capable of measuring scintillation, being distributed in the locations described in Table 2, respectively with the name of the military organization that hosts each station.

Table 2. ICEA monitoring stations deployed in each campaign.

1st Campaign (2013)	2nd Campaign (2015)	3rd Campaign (2017)	4th Campaign (2019)
		Recife (CINDACTA III)	
Pirassununga (AFA) Decommissioned	Brasília (CINDACTA I)	Manaus (CINDACTA IV)	Anápolis (DTCEA-AN)
Campo Grande (DTCEA-CG)	Curitiba (CINDACTA II)	Belém (DTCEA-BE)	Corumbá (DTCEA-CR)
Guaratinguetá (EEAR) Decommissioned	Confins (DTCEA-CF)	São Gabriel da Cachoeira (DTCEA-UA)	Cuiabá (DTCEA-CY)
Rio de Janeiro (DTCEA-GL)	Tanabi (DTCEA-TNB)	Foz do Iguaçu (DTCEA-FI)	Petrolina (DTCEA-PL)
São José dos Campos (ICEA)		Barra do Garças (DTCEA-BW)	

Source: Elaborated by the authors.

Table 3 presents the geographic coordinates of these ICEA stations and their identification and Fig. 5 shows the location of the reference stations.

Table 3. ICEA monitoring network sites, their identifications (4 letters), location and geographic coordinates – status July 2022.

Station ID	Location	State	Latitude (°)	Longitude (°)
GLTW	Rio de Janeiro	RJ	–22.809860	–43.250365
BACG	Campo Grande	MS	–20.466205	–54.661880
ICEA	S. J. dos Campos	SP	–23.208124	–45.869630
BRAS	Brasília	DF	–15.857693	–47.904351
TNAB	Tanabi	SP	–20.613772	–49.698078
CONF	Confins	MG	–19.624137	–43.971906
CTBA	Curitiba	PR	–25.400743	–49.237133
FOZI	Foz do Iguaçu	PR	–25.600255	–54.485044
RCIF	Recife	PE	–8.138391	–34.925202
SGAB	São Gabriel da Cachoeira	AM	–0.144629	–67.061335
BARG	Barra do Garças	MT	–15.840342	–52.277983
BLEM	Belém	PA	–1.388447	–48.480090
MNAU	Manaus	AM	–3.023598	–60.054070
PTRL	Petrolina	PE	–9.368163	–40.569403
ANPL	Anápolis	GO	–16.232672	–48.962938
CORB	Corumbá	MS	–19.015231	–57.665338
CUIA	Cuiabá	MT	–15.652052	–56.119578

Source: Elaborated by the authors.

Source: Elaborated by the authors.

Figure 5. ICEA monitoring stations as of 2022.

The larger concentration of stations in the southern region parallel to the dip equator is justified by the fact that the most intense phenomena occur in this area, due to the so-called equatorial ionization anomaly (Batista *et al.* 2011). In the last years, ICEA has made efforts into keeping the receiver network working and collecting data. Currently, the network has several stations close to the end of their lifespan. For this reason, ICEA has already prepared a plan for the revitalization of the network, which involves the gradual replacement of the receivers, antennas and computers that make up each one of the stations. They will be gradually replaced by new receivers between the years 2022 and 2025. Also, the real time health monitoring of the stations will not be performed by ICEA, but by the organization responsible to maintain the navigation aids and communication infrastructure managed by DECEA. Currently the Institute has started efforts to provide the data upon user registration and approval of the managers.

THE LOW-COST SCINTILLATION MONITORS

In the past few years, the use of low-cost receivers to monitor scintillation has become a possibility to introduce undergraduate and high school students to Science, Technology, Engineering and Mathematics education. Examples of this type of monitors are the ScintPi by Rodrigues and Moraes (2019) and the pioneering project that was Ionik, reported by Vani *et al.* (2021). Both prototypes were based on the Adafruit Ultimate GPS Breakout receiver (Fig. 6), with a sampling rate of 10 Hz. These efforts validated the use of this type of hardware for scintillation research. Taking ScintPi as a platform, Freitas *et al.* (2022) performed a proof-of-concept of a low-cost receiver network temporarily. This network was implemented with Internet of Things (IoT) features where data is stored in a cloud service and mobile phone users can access this data, including in real time S4 measurements through the ScintApp Android application. This network is still working under experimental conditions. Figure 6 shows an example of the app where the data can be accessed.

Source: Elaborated by the authors.

Figure 6. Future instrumentation trend, low-cost scintillation monitors. Left panel: GPS module Adafruit Ultimate GPS Breakout. Right panel: ScintApp screen showing the Brazilian map with the available stations during a proof-of-concept experiment and their respective ionospheric pierce points. The bar indicating the strength of scintillation is shown at the bottom of the app screen.

The purpose of this receiver is not to compete with professional scintillation monitors but to make ionospheric studies more accessible. In addition, this type of receiver can eventually add up a more extensive multi-instrumentation analysis. Due to its low cost, along with the possibility of training students in the areas of science, telecommunications and programming, this kind of platform has a promising future, particularly for the development of networks in technical schools and universities. As mentioned in Monico *et al.* (2022), low-cost monitors have been used by undergraduate students from IFSP in Brazil, to introduce them to IoT and computer science concepts, allowing the students to develop their skills in these areas. Another interesting example of this kind of low-cost of monitors is the work of Fagundes *et al.* (2021) where a system similar to those described in this section was developed dedicated to SNR-based GNSS reflectometry.

Recently, Socola and Rodrigues (2022) developed ScintPi 3.0 monitor with a more sophisticated hardware platform which is able to estimate the TEC. This advance expands the possibility of studies with this type of geophysical instrumentation, the evolution of electronic systems nowadays, more complex versions of this type of system are expected soon. Mobile phones that currently record GNSS observables and real time kinematic cards should be two possibilities for the next generations of this type of monitors. Multifrequency and multiconstellation monitors are another demand that should be addressed in similar developments in the near future. Finally, an open topic that deserves attention for the developers of these monitors is the design of low-cost antennas with the ability to reject multipath and protocol design for safety connections.

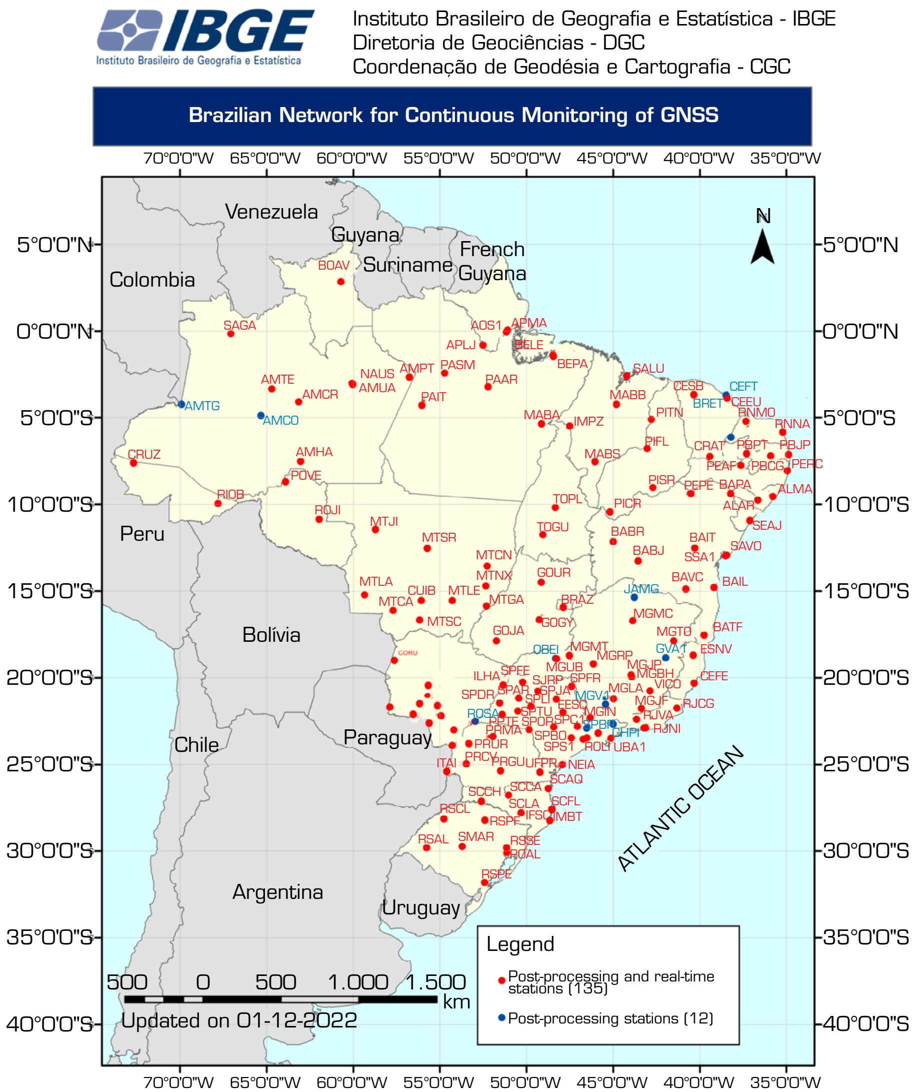
The Brazilian Network for Continuous Monitoring of GNSS RBMC

RBMC is a national network of continuously operating reference GNSS stations. Since its establishment in December 1996, it has been playing an essential role for the maintenance and user access of the fundamental geodetic frame in the country. It provides to the users a direct connection to the Brazilian Geodetic System (SGB) for postprocessing and real-time applications. At the moment, RBMC has 147 stations in operation, 136 of them for post and real time missions. Data provided by RBMC stations are important for scientific research related to Earth system, for example, space weather and geodynamics. Considering the continental dimensions and adversities of country, the maintenance and network operations are tasks shared under the collaboration with more than 50 national institutions, mainly universities. The partnership between three federal institutions, the Brazilian Institute of Geography and Statistics (IBGE), the National Institute of Colonization and Land Reform (INCRA) and INPE is strategic for the network expansion and modernization.

GNSS data is open in the IBGE and INCRA portals. INCRA is providing hourly and IBGE providing daily files with different sampling rates, 5 and 15 seconds respectively. For real-time operations, a NTRIPcaster was set up, providing real-time corrections and data. The RBMC real-time service called "RBMC-IP" is open for all users through a login and password that need real-time corrections for their surveys. The national and international research institutions have real-time data access for all stations.

With the expansion of GNSS, mainly for Beidou and Galileo systems, stations are receiving new multi-constellation equipment, increasing GNSS data availability and sampling rate to 1 second.

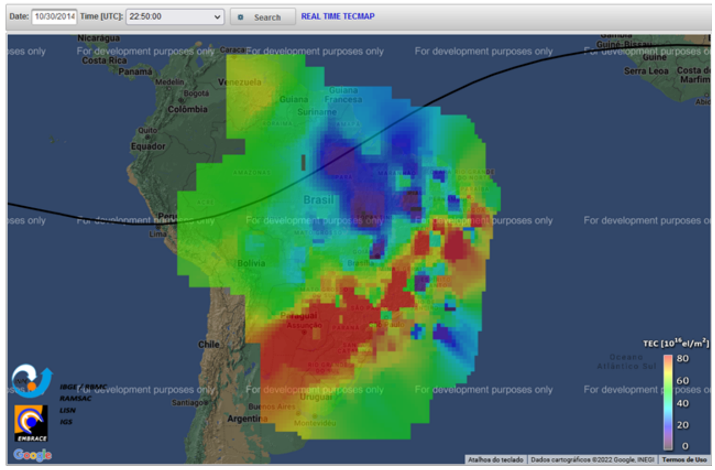
The network maintenance and operation improved in the last years with only 6 % of outages per month and consequently the number of users increased in the last years due to service credibility. More than 400,000 GNSS 24-hour observation files are downloaded per month. RBMC data can be accessed directly at ftp://geoftp.ibge.gov.br/informacoes_sobre_posicionamento_geodesico/rbmc/. Figure 7 presents map with the current status of RBMC network for post-processing and real-time services.



Source: Elaborated by the authors.

Figure 7. Current status of RBMC for post-processing and real-time services.

The Space Weather Information and Prediction Center (EMBRACE) - INPE, has been producing daily and near real time maps of TEC using RBMC real-time and post-processing data since 2013. Figure 8 shows one example of these maps. The TEC maps are designed to estimate the signal delay for single and dual frequency GNSS applications. As stated in the Item 2 the ROTI, that has a good correlation with the scintillation index S_4, can be calculated from TEC. So, ROTI can be a proxy for ionospheric scintillation with a large Brazilian territorial coverage due to the large number of RBMC stations. EMBRACE also provides GNSS scintillation maps (S_4 index) over Brazil. EMBRACE data can be accessed in the site http://www2.inpe.br/climaespacial/portal/pt/.

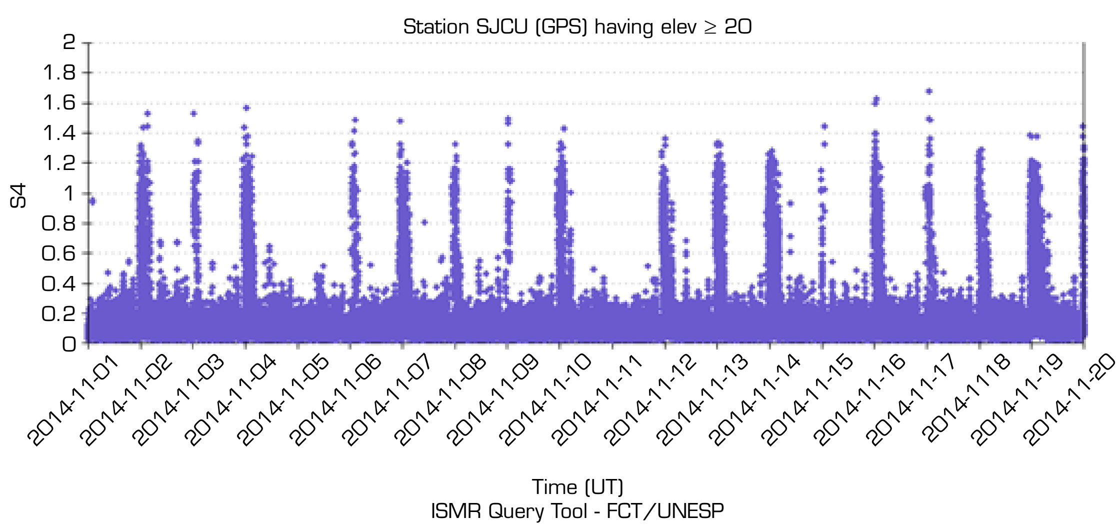


Source: https://www2.inpe.br/climaespacial/portal/tec-map-home/

Figure 8. Example of TEC map provided by EMBRACE using RBMC geodetic receivers for the night of October 30, 2014.

ISMR Query Tool

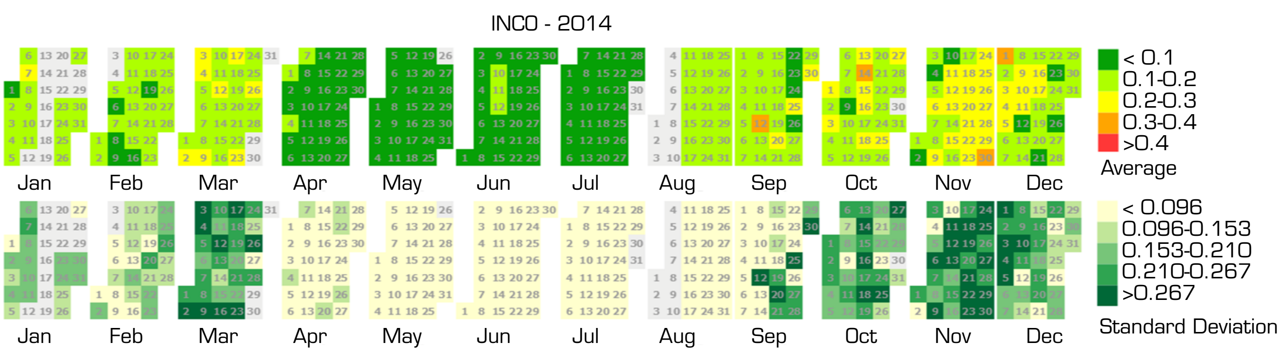
The ISMR Query Tool is a web software that has been supporting research on ISMR data. This web-based software has been designed and developed aiming to ensure insights over the huge amount of ISMR data that is fetched every day on an integrated platform. The software applies and adapts time series mining and information visualization techniques to extend the possibilities of exploring and analyzing ISMR data. The tool provides several resources on data visualization and data mining via web (available at ismrquerytool.fct.unesp.br) and contributes to several research on ionospheric scintillation all over the world (Vani et al. 2017). One of the most used resources of the tool is the query and view data facility with scatter (xy) plots, which allows the users to quickly check scintillation index for a given period by selecting station(s) and applying Boolean filters. A sample output of this feature is presents in Fig. 9, in which scintillation index S_4 is presented for a period of 20 days during November 2014. Besides to show the typical daily peaks of scintillation occurrence after sunset in a typical month during a period of high solar cycle activity, the plot also illustrates some challenging behavior related to absence of scintillation occurrence when it was expected to occur.



Source: Elaborated by the authors.

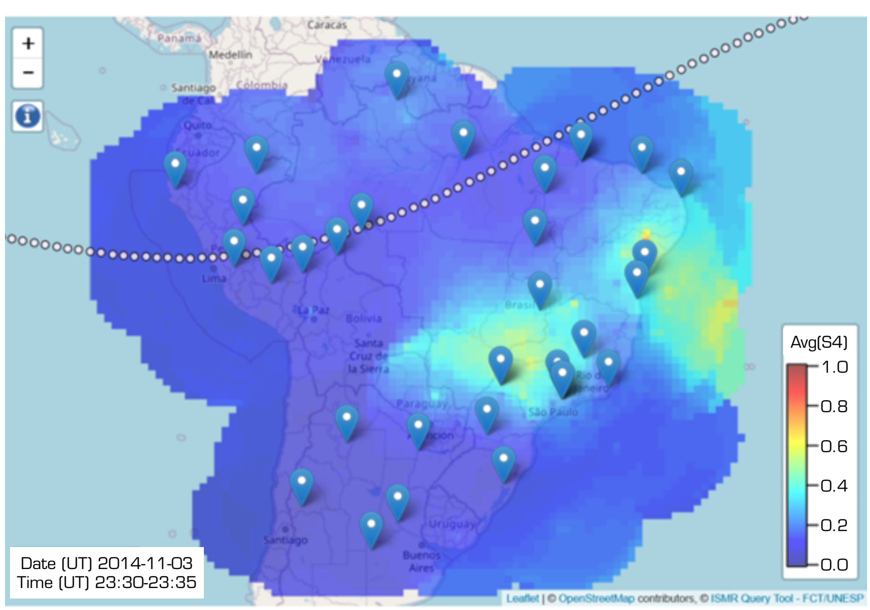
Figure 9. Sample plot obtained via query and view facility of the ISMR Query Tool. The plot shows the S_4 index for a period of 20 days (cut-off elevation 20°).

A new facility that allows the data analyses in the form of calendar with the possibility of hourly analyses, differently from the previous one that was daily, was made available. Improvements in the calendar showing average scintillation values, allowing to choose the time of day, and providing in addition to the average values, the standard deviation and the maximum value are underway. Example is presented in Fig. 10, in which the calendar-based visualization shows the average and standard deviation of the S4 index in the 22-24 (UT) interval for the station located in Inconfidentes (INCO). The implementation and usage specification of the previously created 50 Hz webservice for data exchange was adapted to function as an Application Programming Interface (API). These features allow researchers to get access to the data via third-part software and/or programming languages, such as MATLAB, R and Python. An example of output generated on third-part software is presented in Fig. 11. The data was obtained via the ISMR Query Tool API, and a map of S_4 was generated via the R language; after that, the generated map was made available online through a web interface. Data from different monitoring stations mentioned earlier (LISN, CIGALA/CALIBRA, INCT GNSS-NavAer and ICEA/DCTA) were suitable arranged and stored with the Database Management System (DBMS) PostgreSQL. Currently, more than 1.2 billion of one-minute ISMR records are stored in the DBMS, coming from more than 100 stations with different lifetime ranging from 2011 to 2022 (and still operating at the time of writing this paper).



Source: Elaborated by the authors.

Figure 10. Example of visualization based on calendar-view demonstrating the average and the standard deviation of scintillation index S_4 in the post-sunset nights of 2014 (time interval of 22-24 UT).



Source: Elaborated by the authors.

Figure 11. Example of scintillation map: the data was retrieved via the API of the ISMR Query Tool, processed in R language and made available through a web interface.

CONCLUSION

Nearly two and a half decades of ionospheric GNSS monitoring over Brazil have brought many advances in geophysical research as well as in technological development related to positioning and navigation applications. The growth in the number of GNSS monitoring stations over the years has enabled not only single station analyzes but also the macroscopic visualization of the ionosphere over all of Brazil. Investigations involving GNSS monitor arrays should be a major demand in the near future for both geophysical studies of ionosphere and for providing monitoring and alert services of ionospheric threats, especially for critical users, such as those of safety-of-life applications. The large amount of data from these networks is a challenge for the managing and storage. Modern instrumentation with high resolution acquisition rates, IoT and 5G connectivity will also be a strong trend for the next generations of GNSS monitoring stations. The large databases will also bring new possibilities with data mining research and the use of this data for the development of models based on machine learning, that is the framework for the next decades of space weather monitoring.

AUTHORS' CONTRIBUTION

Conceptualization: de Paula ER, Monico JFG and Moraes AO; **Resources:** de Paula ER, Monico JFG, Valladares CE, Costa SMA and Marini-Pereira L; **Data Curation:** de Paula ER, Monico JFG, Tsuchiya ÍH, Vani BC, Valladares CE, Costa SMA and Marini-Pereira L; **Writing – Original Draft:** de Paula ER, Monico JFG, Moraes AO, Marini-Pereira L, Valladares CE and Costa SMA; **Writing – Review & Editing:** de Paula ER, Marini-Pereira L, Vani BC, Monico JFG and Moraes AO; **Visualization:** BV and Tsuchiya ÍH; **Project administration:** de Paula ER, Monico JFG, Valladares CE, Costa SMA, Vani BC, Marini-Pereira L and Tsuchiya ÍH; **Funding acquisition:** de Paula ER, Monico JFG, Valladares CE and Costa SMA.

DATA AVAILABILITY STATEMENT

The data are available in a data repositories:
[https://www.ibge.gov.br/geociencias/informacoes-sobre-posicionamento-geodesico/rede-geodesica/16258-rede-brasileira-de-monitoramento-continuo-dos-sistemas-gnss-rbmc.html?=&t=downloads]
[https://www2.inpe.br/climaespacial/portal/sci-home/]
[http://lisn.igp.gob.pe/jdata/database/]
[https://zenodo.org/record/5763076#.Y7P6yezMI1I]
[https://ismrquerytool.fct.unesp.br/is/]

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