INSTALLATION AND CONFIGURATION OF AN IONOSPHERIC SCINTILLATION MONITORING STATION BASED ON GNSS SDR RECEIVERS IN BRAZIL

Nicola Linty
Politécnico de Torino (POLITO-Itália)
Emilia Correia
Instituto Nacional de Pesquisas Espaciais (INPE-Brazil)
Ingrid Hunstad
Instituto Nacional de Geofisica e Vulcanologia (INGV-Itália)
Amauri S. Kudaka
Universidade Presbiteriana Mackenzie (UPM-Brasil)

Abstract

The use of Global Navigation Satellite Systems (GNSSs) is nowadays very popular, and the positioning service that they provide is becoming the basis of several applications. Due to their wide coverage, GNSS signals can be used at no cost as probing signals to retrieve parameters to characterize the atmosphere, such as ionospheric scintillation indexes. GNSS receivers coupled to the specific algorithm are indeed a valid alternative to large and expensive ad hoc equipment such as ionosondes. In particular, Software Defined Radio (SDR) receivers are characterized by a higher level of flexibility and configurability when compared to commercial receivers, which fits for the purposes of ionospheric monitoring and enable the study of advanced and innovative algorithms, both for scientific purposes (ionospheric monitoring, space weather), and for technological development (robust GNSS receivers design). A GNSS-based ionosphere monitoring station, including an SDR-based receiver and a professional receiver, was installed in the CRAAM laboratory at Mackenzie Presbyterian University (São Paulo, Brazil) on May 2017. Details of the installation and the new approaches for the storage, processing, and transfer of GNSS data, including raw Intermediate Frequency (IF) samples, are described, along with preliminary results related to ionospheric events captured during the first months of its operation.

Keywords: GNSS SDR receiver. Ionospheric scintillation. Space weather.

1 INTRODUCTION

1.1 Navigation Satellite Systems

Global Navigation Satellite Systems (GNSSs), such as the US Global Positioning System (GPS), the European Galileo, the Russian GLONASS and the Chinese Beidou are space-based navigation systems. GNSSs enable a generic user located anywhere on the Earth to determine in real time his/her Position, Velocity and Time (PVT), by processing a Radio Frequency (RF) electromagnetic signal, the Signal-In-Space (SIS), broadcast by satellites. The Position, Navigation, and Time (PNT) solution is determined by GNSS receivers, which continuously process the SIS from the satellites in view, employing trilateration procedures, exploiting the range information computed by the receiver and the information contained in the navigation message (KAPLAN; HEGARTY, 2005).

GNSSs broadcast a variety of different signals, both civilian and military. The most widely known and used is the GPS civilian L1 Coarse Acquisition (C/A) signal, in the L1 band (centered at 1575.42 MHz). Recently, a second (L2C) and a third (L5) civilian signals have been added to the GPS constellation. Galileo, GLONASS and Beidou broadcast similar signals on the same frequency bands. In order to process signals from different constellations and different bands, proper antennas and receivers are required.

1.2 The impact of the ionosphere in GNSS positioning

As GNSS signals propagate through the Earth's atmosphere, they undergo severe propagation nuisances, such as phase shifts, group delays, and amplitude variations. Ionosphere, the ionized layer of the atmosphere, is the most significant and more variable cause of errors in single frequency GNSS receivers (SHANMUGAM et al., 2012). The ionosphere affects the GNSS signals both regarding a temporary delay and of scintillations.

In particular, ionospheric scintillations are amplitude and phase fluctuations caused by non-regular distributions of electron concentration and rapid changes in the electron density. Ionospheric scintillations are frequent at equatorial and polar regions; however, because of the different ionospheric morphology, they manifest in different ways. The amplitude fades are more intense at low latitudes, because of higher ionization levels, while the increased velocity disturbances lead to strong phase scintillations over the poles. Contrary to ionospheric delay, these phenomena cannot be empirically modeled. Both amplitude and phase scintillations can have a serious impact on the receiver performance: the measurements can be heavily corrupted, resulting in positioning errors of tens of meters or, in the most severe cases, in the complete receiver blackout. Scintillation effects on GNSS are particularly harmful for navigation and geodetic applications because they are hard to predict and can challenge the receiver' stability and capability to hold a lock on a signal.

1.3 GNSS-based ionospheric monitoring

If, on the one hand, GNSS receivers' performance is severely affected by scintillation, on the other hand, GNSS receivers can be successfully used as alternative tools for upper atmosphere monitoring at low and high latitudes.

The amount of scintillation affecting a signal can be determined by exploiting the correlation outputs of a GNSS receiver tracking stage. Two indices are considered:

- the S_4 measures the signal amplitude fluctuations and corresponds to the normalized standard deviation of the detrended Signal Intensity (SI) computed from the in-phase and quadrature-phase prompt correlation samples;
- the σ_ϕ measures the phase scintillation and is calculated as the standard deviation of the detrended carrier phase measurements.

Both indices are calculated over a varying observation interval, typically equal to 60 seconds (σ_ϕ is then known as Phi60, DIERENDONCK and HUA, 2001).

Another parameter commonly used to characterize the ionosphere is the Total Electron Content (TEC). The presence of a big number of electrons in the ionosphere results in a higher delay, and thus in more degraded performance. The slant TEC (sTEC) represents the number of free electrons in a cylinder of 1 m diameter along the SIS propagation path, while the vertical TEC (vTEC) represents the same quantity on a vertical cylinder. ROT is the rate of change of the TEC with respect to time; it is a measurement of large-scale irregularities concerning time.

Professional receivers, commercial dual frequency hardware GNSS receivers that are commonly denoted Ionosphere Scintillation Monitoring Receivers (ISMRs), have been successfully exploited for ionosphere monitoring for many years. ISMRs are commercial devices, specifically designed as measurement tools to provide post-correlation data used to model the atmospheric phenomena (ROMANO et al., 2013). Nevertheless, recent works and projects proved that complementary monitoring installations based on Components Off-The-Shelf (COTS) and Software Defined Radio (SDR) technology could provide a valuable alternative to professional receivers (PENG; MORTON, 2013). Linty et al. (2015) give a general overview of the benefits of SDR-based receivers when compared to hardware receivers.

1.4 The Brazilian anomaly

The area of São Paulo represents a region of particular interest in monitoring ionosphere because it is inside the South America Magnetic Anomaly (SAMA), and is near the equatorial ionization anomaly (EIA).

The SAMA is a wide geographic region in which the intensity of geomagnetic field has the lowest value over the Globe. As a result, enhanced atmosphere-magnetosphere interaction occurs leading to the precipitation of inner radiation belt energetic particles that can modify the ionization distribution and hence the conductivity spatial structure in the ionosphere over the SAMA (ABDU et al., 1973; ABDU et al., 2005; MORO et al., 2012; MORO et al., 2013).

An upward vertical E x B drift that lifts the plasma of the ionospheric F-region to higher altitudes over the magnetic equator generates the EIA, which diffuses along magnetic field lines away from the equator, forming two peaks of ionization on both sides at approximately ±15o latitude (e.g., ANDERSON, 1981).

1.5 The novelty of the work and literature review

SDR-based GNSS data recording systems have been successfully used in various regions of the world. For instance, in the frame of the DemoGRAPE project (ROMERO et al., 2017) an SDR-based ionospheric monitoring system has been installed in two Antarctica research stations (LINTY et al., 2016a, 2016b). Some results are reported in (ALFONSI et al., 2016). Similarly, monitoring stations have been installed in Equatorial regions, such as in Vietnam (POVERO et al., 2017). In the frame of the MIMOSA project, a first experimental and provisional installation was done in Presidente Prudente in 2015 (CESARONI et al., 2015). However, the SDR receiver installed was experimental, and it was only able to grab signals in the L1 bandwidth. To the best of the authors' knowledge, there are no SDR-based permanent, multi-constellation and multi-frequency ionospheric monitoring stations in Brazil other than the one presented in this work. The possibility to access and process GNSS data captured using a GNSS SDR acquisition system in the SAMA area represents a novelty indeed and enables a deeper and more complete assessment of the effects of equatorial scintillations on GNSS signals in this region. Furthermore, most of the works (e.g., DE PAULA et al., 2007; AKALA et al., 2011; SREEJA et al., 2011; MUELLA et al., 2013) are based on the observation of GPS signals only, while this installation gives focus also to GLONASS and Galileo signals.

The rest of the paper is organized as follow: Section 2 provides a general overview of the architecture and advantages of the SDR approach for ionospheric monitoring. In Section 3, the details of the installation at Mackenzie University in São Paulo are provided. Section 4 reports some preliminary results of the installation. Finally, conclusions are provided in Section 5.

2 METHODOLOGY: THE SOFTWARE-DEFINED RADIO APPROACH

SDR refers to an ensemble of hardware and software technologies that enable reconfigurable radio communication architectures (LO PRESTI et al., 2014). Generally speaking, dedicated hardware components are implemented in software, either on programmable platforms or reconfigurable hardware. In the particular case of receivers for GNSS, all the typical signal processing operations, such as acquisition (signal correlation), tracking (phase and delay lock loops), data demodulation and position computation, are entirely performed in software exploiting programmable platforms, such as high-performance general purpose processors (PC). Concerning commercial hardware tools, SDR receivers allow to access intermediate and low-level signal processing stages; therefore, they offer the user a larger subset of observables. This fact yields higher flexibility and reconfigurability and, in turn, enables the possibility to design and implement innovative ionosphere monitoring techniques.

2.1 SDR architecture

The most common architecture of a GNSS SDR receiver is depicted in **Figure 1** and is based on a two-step signal analysis:

– *GNSS data grabber*. It includes a GNSS multi-frequency antenna and a Radio Frequency (RF) front-end; the raw GNSS signal is received, amplified, band-pass filtered, down-converted to Intermediate Frequency (IF), represented into a stream of digital samples exploiting an Analog-to-Digital Converter (ADC). Finally, raw GNSS IF samples are stored on mass memories for further processing.

– *SDR-based GNSS receiver*. Post-processing of the stored raw IF samples is performed through a receiver entirely developed in software (fully software receiver), either in real time or in a post-processing phase, to produce standard GNSS observables and scintillation indices.

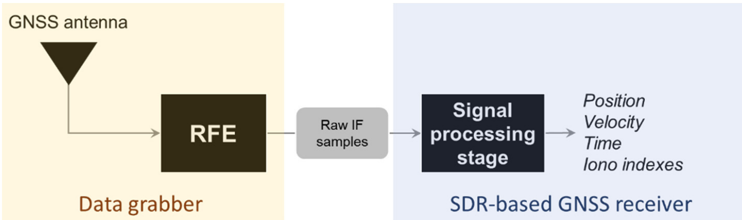


Figure 1 The architecture of an SDR-based GNSS receiver.

Source: The authors (2017).

2.2 The concept of raw IF data

The concept of GNSS raw IF data is of paramount importance when dealing with SDR receivers. GNSS raw data, or IF data, is the output of the RF front-end. They consisted of a sequence of digital samples, at a specific sampling frequency f_s (up to 30 MHz) and represented on a certain number of bits (from 1 bit up to 2 bytes). Raw data can be stored as binary files in memories, transferred, shared, and then used for post-processing. It is important not to confuse raw IF data with GNSS observables, such as the IQ (In-phase and Quadrature) correlation outputs, the Carrier-to-Noise power density ratio (C/N_0), the pseudo-ranges and the PVT solution, which correspond to the output of GNSS commercial receivers.

2.3 Advantages of the SDR approach

On one side, the software approach enables the possibility to design and implement innovative algorithms (e.g., different acquisition or tracking loops structures) and advanced signal processing techniques, for example for multipath and interference removal or ionosphere monitoring (CURRAN; BAVARO; FORTUNY, 2014).

On the other side, having access to the full receiver chain, SDR receivers offer the user any intermediate and low-level measure and elaboration of the signal. On the contrary, when using commercial GNSS receivers, only the storage of post-processed data is possible, such as ionospheric data and outputs of the correlation stages. In addition, the two different blocks of Figure 1 can operate independently during monitoring operations. Raw IF signal samples collected on site can be transferred exploiting external memories and then post-processed, by using different configurations and architectures of the receivers, including those yet to be developed. Disposing of raw IF data also allows replaying GNSS signals back to RF, thus recreating in the lab the original data collection scenario. This signal can be fed to different commercial receivers, for instance, to test and compare their performance. This feature makes the approach equivalent to a plethora of receivers.

Finally, even considering the hardware costs for the front-end section, the solution is cost-effective, especially when considering the possibility to mimic the behavior of different receiver architectures and the possibility to replay scenarios for significant atmospheric events.

The effectiveness of the architecture has been proved in several installations at equatorial and polar regions. Significant ionospheric events have been observed, and the software processing has been able to provide values for the scintillation indexes S_4 and σ_ϕ with the quality and reliability of a SeptentrioPolaRxS PRO ISMR (ROMERO et al., 2017; LINTY et al., 2016a, 2016b).

2.4 From "moving data" to "moving software"

The main drawback of SDR-based installations is indeed the vast dimension of raw IF data files. While the typical output data of a commercial receiver, such as Rinex files, amounts of about few MBs per day, GNSS raw data can grow up to about 1 GB per minute. Network and bandwidth are, in general, precious resources, and the transfer of such amount of data is often not affordable.

Nevertheless, the flexibility of the SDR implementation of the GNSS receivers provides a solution. The full software implementation offers, in fact, the possibility to move the processing engine, enabling the new paradigm of *moving the software to the data* rather than *moving the data to the software*. This approach consists in transferring pieces of code on the machine hosting the raw data in the *Data Collection Site*, rather than moving the data itself to the *Research Lab*.

This paradigm is applied to the installation at Mackenzie University. In this case, the SDR receiver is configured to have a proper robust architecture for the tracking loops and optimized to provide as outputs the typical indexes used for scintillation monitoring, such as amplitude and phase scintillation indexes. The presence of additional nuisances such as multipath, in some data collections, requires the tuning of the software receiver, for example changing the spacing of the early-late correlators, or the activation of a signal processing unit to mitigate the multipath effect. In this way, more reliable results for the assessment of the intensity of the scintillation event can be obtained.

This operation is facilitated by the exploitation of GNSS SDR metadata files, initially proposed by the ION GNSS SDR Metadata Group. SDR metadata describe the content of the data collections to help the automated interpretation process through a processing software. Based on this standard, an SDR receiver can automatically configure internal parameters (i.e., RF and IF center frequencies, sample rate, quantization bits, among others) enabling the playback and post-processing of the collected data. The standard is designed to promote the interoperability of GNSS SDR data collection systems and processors and includes a formal XML Schema Definition (XSD, ION GNSS SDR, 2017).

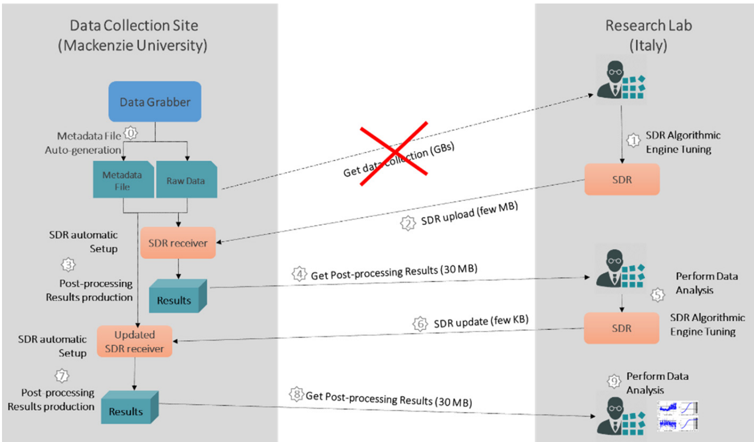


Figure 2 Data flow of the *moving software* approach.

Source: The authors (2017).

A pictorial representation of this approach, summarizing the concepts, is reported in Figure 2.

3 INSTALLATION OVERVIEW

A permanent GNSS-based ionosphere monitoring station, including a SDR-based GNSS receiver and a professional ISMR, was installed from May 29 to June 02, 2017, at the CRAAM laboratory of the Mackenzie Presbyterian University, in São

Paulo, Brazil (Lat: 23.5474825 S, Long: 46.6523133 E, height: 809.5 m AMSL). The activity has been carried on in the frame of a scientific collaboration between the Mackenzie Astronomy and Astrophysics Radio Center (Centro de Rádio Astronomia e Astrofísica Mackenzie – CRAAM), the National Institute of Space Research (cInstituto Nacional de Pesquisas Espaciais – INPE), and the Italian National Institute of Geophysics and Vulcanology (Instituto Nazionale di Geofisica e Vulcanologia, INGV, Rome, Italy) and the Politecnico di Torino (Torino, Italy).

Although other GNSS-based monitoring systems are already present in the same lab and have been successfully used for years, the novelty of this installation is the presence, in parallel to a professional commercial scintillation monitoring receiver, of an innovative GNSS data acquisition system, based on a radio frequency front-end and an SDR GNSS receiver. Even though the paper refers to the installation at the Mackenzie University, the procedures described can be easily generalized for future installations.

a) GNSS antenna on the rooftop   b) Receivers in the CRAAM lab

Figure 3 Installation of the monitoring system at Mackenzie Presbyterian University.

Source: The authors (2017).

3.1 Description and block diagram of the installation

The ionospheric monitoring station installed at Mackenzie University includes a GNSS choke ring multi-frequency and multi-constellation antenna (*AeroAntenna Technology Inc., Sepchoke_MC*), installed on the building rooftop, as depicted in **Figure 3**a. An RF cable connects the antenna to a four ways splitter, thus sharing the signal with other GNSS systems operating in the lab (Figure 3b).

The ionospheric monitoring station also includes two GNSS receivers:

– A *SeptentrioPolaRxS PRO professional ISMR*, specifically developed for ionospheric monitoring (upper-left frame of Figure 4). It can process GPS, Galileo and GLONASS signals in the L1, L2, and L5 bandwidths. The receiver is connected to a workstation that is used for the receiver configuration and data storage

– an experimental GNSS raw data acquisition system based on a four-band RF front-end, called *4tuNe*, developed by the Joint Research Centre (JRC) of the European Commission (https://ec.europa.eu/jrc/en/about/jrc-site/ispra) (upper-right frame of Figure 4). It is connected to a computer, for grabbing raw GNSS data and post-processing them using an SDR-based receiver.

Both systems transmit data to a local server installed at CRAAM lab (bottom block of Figure 4). In addition to the local storage, a selection of data of reduced size is transferred to a server in Italy. This fact allows on one side to monitor the status of the receivers and, possibly to tune their configuration, and on the other side to work on the data and to share results.

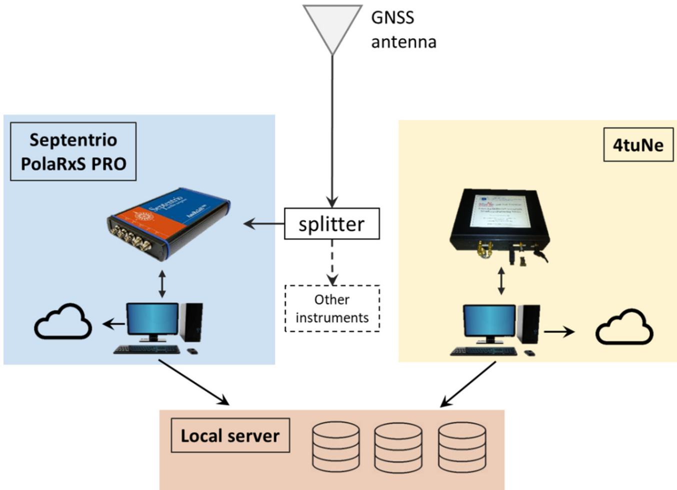


Figure 4 Block diagram of the ionosphere monitoring station and data storage.

Source: The authors (2017).

3.2 Data acquisition set-up

The Septentrio receiver is configured to provide as output proprietary SBF files, proprietary ISMR files, and Rinex files. In addition to the configuration of the receiver software, the computer has been specifically configured and tuned to account for the needs of the remote installation (automatically restart in case of power outage and automatically launch the software for data logging after a reboot).

SDR-based fully software receivers do not have a strict configuration scheme, as they are a research tool rather a final commercial product. Besides, the philosophy behind the SDR approach makes it very flexible regarding configuration. Having access to the raw data represents indeed the possibility to post-process them with any possible configuration. For these reasons, the configuration parameters of the software receiver are considered free and not included in this paper. Suggested parameters for the data acquisition related to the front-end are listed in TABLE 1; however, all of them can be modified according to the needs and purposes of the users.

TABLE 1

Configuration suggested for the SDR-based GNSS data collection.

Sampling frequency (L1, L2)	5 MHz
Sampling frequency (L5)	30 MHz
Quantization (L1. L2, L5)	1 bit
Sampling format	IQ
Intermediate frequency	around 4 kHz
Data chunk duration	50 minutes

Source: The authors (2017).

The high configurability and flexibility of the SDR approach results in the huge raw IF data files. With the configuration reported in Table 1, 50 minutes of data, properly compacted, gives about 30 GB of data, making the continuous storage of all data not affordable. Therefore, a well-planned strategy for data management and sharing is mandatory. For ionospheric scintillation analysis, a rule has been established to automatically detect interesting scintillation events and, in turn, to keep the IF data. The software routine controlling the front-end is configured to perform the following cyclic operations:

1. grab a chunk of raw GNSSIF data, e.g., 1 hour;
2. quickly post-process (acquisition and tracking) L1data fully exploiting a software receiver and save the observables (including C/N_0, S_4, and σ_ϕ) in a log file;
3. compare the averaged values of $C/N0$, S_4, and σ_ϕ with predefined thresholds ($\mathcal{T}_{C/N_0}$, $\mathcal{T}_{S_4}$, and $\mathcal{T}_{\sigma_\phi}$) and decide whether scintillation has occurred.
4. If a scintillation event has been detected, keep the IF data; otherwise, keep the log files and discard the IF data.

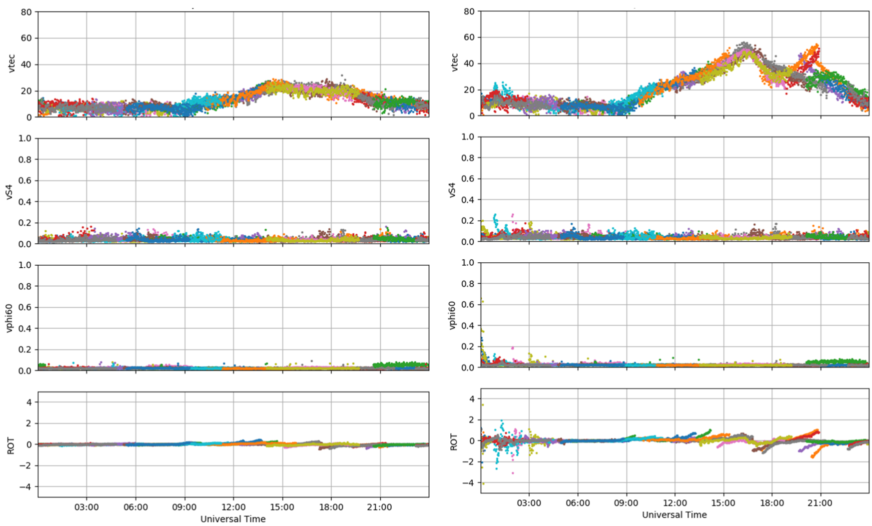
The configuration can be properly modified and tuned according to the needs and the constraints, to improve missed detection and false alarm rates.

4 RESULTS

4.1 Septentrio receiver

This section reports some results obtained processing data acquired with the Septentrio receiver. The plots reported in Figure 5 show a daily overview of vTEC, vertical S_4 (vS4), vertical σ_ϕ (vphi60) and ROT. Each colour is related to the L1 C/A signal from a different GPS satellite.

The plots on the left are relative to a quiet day (September 1st, 2017): no relevant scintillation activity can be reported. The amplitude and phase scintillation indexes are always below the value 0.2, while the vTEC and ROT show no significant changes. On the contrary, the plots on the right (September 8, 2017) report moderate scintillation activity. While on September 1st the ROT values are most of the time bounded in the interval [–1TECu/min; +1 TECu/min], on September 8th several satellites exhibit higher values, between 00:00 and 03:00 UT in the night and around 20:00 UT (local sunset time), during a moderately intense geomagnetic activity, occurred from 7 to 10 September. This fact is confirmed by higher values of the S_4 and σ_ϕ indexes, especially between 00:00 and 03:00.



a) September 1, 2017 b) September 8, 2017

Figure 5 Comparison of ionospheric parameters derived from Septentrio GNSS receiver data on two different days.

Source: The authors (2017).

4.2 Comparison of SDR and Septentrio receivers

Figure 6 shows the scintillation indexes for GPS L1 C/A signals as computed by the two receivers with an elevation mask of 30° applied to the data. The dashed line is related to the results of the Septentrio PolaRxS PRO professional receiver, while the continuous line shows the indices as computed by the software receiver post-processing raw GNSS data grabbed with the 4tuNe. The good match, especially for moderate and high values of the indexes, is a confirmation of the good quality of the SDR-based acquisition systems and software receiver measurements for ionospheric scintillation monitoring. Both receivers identified amplitude and phase scintillation on the signals of GPS PRNs 2 and 24.

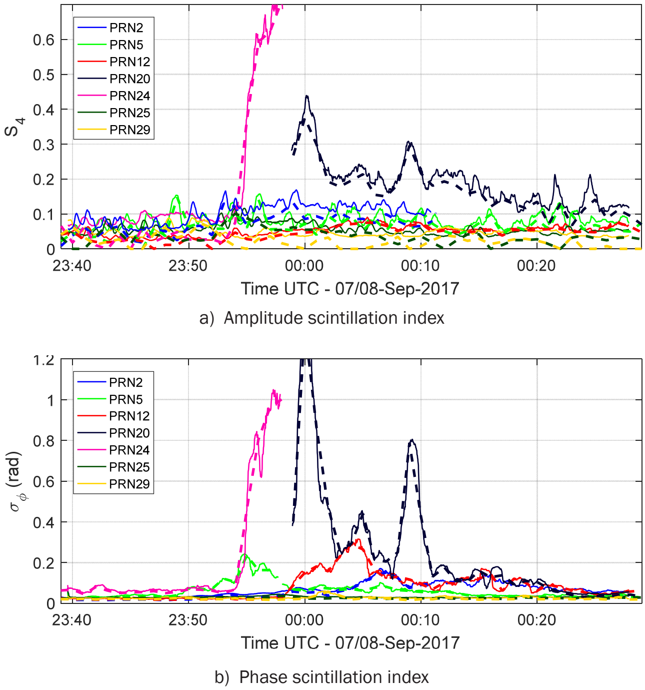


Figure 6 Comparison of scintillation indexes for GPS L1 C/A signals – Septentrio PolaRxS receiver (dashed line) vs. software receiver (continuous line).

Source: The authors (2017).

4.3 Example of remote re-configuration

In this section, an example of remote re-configuration of the SDR-based acquisition system based on the *moving software* paradigm is reported to prove the advantages and the functionalities of the approach. The example refers to the setting of the threshold for scintillation detection within the SDR receiver. As explained in Section 3.2, the raw IF data are kept only if the average scintillation indexes are above a certain threshold. During the configuration of the station, due to lack of time, the thresholds have been set to common values: $\mathcal{T}_{C/N_0} = 40$ dBHz, $\mathcal{T}_{S_4} = 0.4$ and $\mathcal{T}_{\sigma_\phi} = 0.4$ rad. After a few months of continuous monitoring, the value of the threshold was reduced, to improve the scintillation detection performance: $\mathcal{T}_{C/N_0} = 38$ dBHz, $\mathcal{T}_{S_4} = 0.3$ and $\mathcal{T}_{\sigma_\phi} = 0.3$ rad. An updated version of the software receiver was properly modified and tested in the authors' premises, in Italy. Afterward, the updated executables files were remotely transferred to the monitoring station in Brazil. Due to the flexibility of the software approach and to the access to low-level receiver functions, this operation was performed remotely from Italy.

5 CONCLUSIONS

This paper described the installation and configuration of a station for ionospheric monitoring in the SAMA region, based on the processing of GNSS signals captured through a professional receiver and an SDR-based acquisition system. The SDR approach is described in detail, outlining its advantages and criticalities. The results showed that SDR acquisition systems coupled to fully software GNSS receivers provide high-quality scintillation indexes. Furthermore, this paradigm enables a new level of remote data management and processing.

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INSTALAÇÃO E CONFIGURAÇÃO DE UMA ESTAÇÃO DE MONITORAMENTO DE CINTILAÇÃO IONOSFÉRICA BASEADA EM RECEPTORES GNSS SDR NO BRASIL

Resumo

O uso de sistemas de navegação via satélite (GNSS) é hoje em dia muito popular, e o serviço de posicionamento que eles fornecem tem sido utilizado por muitas aplicações. Devido à sua larga cobertura, os sinais GNSS podem ser utilizados sem custo para a obtenção de parâmetros da atmosfera, tais como os índices de cintilação ionosférica. Os receptores GNSS e os algoritmos específicos são uma alternativa frente aos equipamentos específicos de alto custo, tais como as ionossondas. Particularmente, os receptores rádio de programação definida (SDR) são caracterizados por seu alto nível de flexibilidade e configurabilidade quando comparados com os receptores comerciais, sendo mais apropriados para estudos avançados da ionosfera (monitoramento da ionosfera e clima espacial) e elaboração de algoritmos inovadores com finalidade de desenvolvimento tecnológico (projetos de receptores GNSS robustos). Uma estação para monitoramento da ionosfera do tipo GNSS, incluindo um receptor tipo SDR e um receptor profissional, foi instalada no Centro de Rádio Astronomia e Astrofísica Mackenzie (Craam) na Universidade Presbiteriana Mackenzie (São Paulo, Brasil) em maio de 2017. Detalhes da instalação e os novos mecanismos para armazenamento, processamento e transferência de dados, incluindo amostras de dados brutos da Frequência Intermediária (IF), são descritos, e são apresentados alguns resultados preliminares dos eventos ionosféricos detectados.

Palavras-chave: Receptor GNSS SDR. Cintilação ionosférica. Clima espacial.

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Contact

Emilia Correia
ecorreia@craam.mackenzie.br

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