ORIGINAL ARTICLE

CrossMark

Software-defined radio technology for GNSS scintillation analysis: bring Antarctica to the lab

Nicola Linty[1] · Fabio Dovis[1] · Lucilla Alfonsi[2]

Abstract

Global navigation satellite systems (GNSSs) are widely used to support logistics, scientific operations, and to monitor the polar ionosphere indirectly, which is a region characterized by strong phase scintillation events that severely affect the quality and reliability of received signals. Professional commercial GNSS receivers are widely used for scintillation monitoring; on the contrary, custom-designed solutions based on data grabbers and software receivers constitute novelty. The latter enables a higher level of flexibility and configurability, which is important when working in remote and severe environments. We describe the scientific, technological, and logistical challenges of installing an ionospheric monitoring station in Antarctica, based on a multi-constellation and multi-frequency GNSS data grabber and a software-defined radio receiver. Having access to the full receiver chain and to intermediate signal processing stages allows a deep analysis of the impact of scintillation and, in turn, a better understanding of the physical phenomenon. The possibility to process high-resolution raw intermediate frequency samples of the signal enables not only the computation of scintillation indexes with the same quality as professional devices but also the design and test of innovative receiver architectures and algorithms. Furthermore, the record and replay approach offers the possibility to process in the lab the signals captured on site, with high fidelity level. It is like being in Antarctica again, but with an unlimited set of receivers and higher computational, storage, and bandwidth resources. The main advantages and disadvantages of this approach are analyzed. Examples of monitoring results are reported, confirming the monitoring capabilities, showing the good agreement with commercial receiver outputs and confirming the validity of post-processing and re-play operations.

Keywords GNSS · SDR · Antarctica · Ionospheric scintillations

Introduction

Global navigation satellite systems (GNSSs) signals have been originally designed and traditionally used to provide users with a position estimate and a timing reference. Additionally, they can be exploited for innovative and advanced scientific applications. For example, as GNSS signals travel through the atmosphere, they can be used as means to investigate the physical phenomena occurring along their path (Lee et al. 2017). This section provides an overview of the use of GNSS receivers for ionospheric monitoring, with a particular focus on the polar ionosphere and on the use of software-defined radio (SDR) receivers.

GNSS and high latitude ionosphere

The earth's upper atmosphere includes a region characterized by a high concentration of free electrons, the ionosphere. Ionospheric propagation degrades the quality of the GNSS-received signal and, in turn, causes significant errors in position estimation. It is, indeed, the major and variable natural error contributor in GNSS signal processing at the receiver level. The ionosphere affects the quality of GNSS-received signals in terms of temporal delay and scintillation (Aarons 1982). Scintillations are fluctuations of the signal amplitude and phase, caused by the irregular electron concentration (Kintner et al. 2007). They are more frequent at equatorial and polar latitudes, although in some instances of severe ionospheric activity they can also be observed at

✉ Nicola Linty
nicola.linty@polito.it

1 Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Turin, Italy

2 Istituto Nazionale di Geofisica e Vulcanologia, Via di Vigna Murata, 605, 00143 Rome, Italy

mid-latitudes. While ionospheric delay can be modeled, and thus compensated, it is very difficult to model the occurrence of scintillations, due to their quasi-random nature. Therefore, they remain to this day as one of the major limiting factors for high-accuracy applications in equatorial and polar regions, which are increasingly required for logistic needs and scientific applications.

Several factors determine the occurrence of ionospheric scintillations, such as solar and geomagnetic activity, geographic location, the season of the year, and local time. Scintillation is generated by diffraction and refraction of the electromagnetic GNSS signal as it passes through plasma bubbles and small-scale spatial irregularities of the electron density. This causes rapid fluctuations in signal intensity and phase jittering, leading, respectively, to amplitude and phase scintillation. Due to the geomagnetic structure of the earth, the high-latitude ionosphere is particularly sensitive to perturbations coming from outer space, solar energetic particles driven by the cusps of the geomagnetic field. The charged particles are the cause of the irregularities in the E-layer of the ionosphere. Since the electron density in the E-layer is low, such irregularities result in phase scintillations, contrarily to what happens in equatorial regions, where amplitude scintillations are more common. Furthermore, while at low latitudes scintillations are commonly observed during the post-sunset hour, at high latitudes there is no direct dependency on the position of the sun (Jiao et al. 2013).

The impact on the receiver tracking performance can be disruptive; scintillations may induce phase errors, cycle slips, increased carrier Doppler jitter, and losses of lock. This can lead to positioning errors of the order of tens of meters or even in the complete receiver outage, in the most severe cases. The modeling of the ionosphere and the prediction of its short-term behavior require a detailed investigation of all these events. At the same time, a good understanding of these effects enables the design of a new generation of robust GNSS receivers.

Use of GNSS in Antarctica

GNSS technology plays a major role in Antarctic sciences. It is widely used to support both logistic and scientific operations, all relying on GNSS and requiring high accuracy and reliability. Logistic needs include, for instance, long ground-based trips for delivery of fuel, airborne operations and air traffic management, or displacements around the base during Antarctic winter. The risk for people and vehicles to fall into a crevasse due to erroneous navigation is high during a snowstorm when visibility is limited and no well-demarcated routes are available. Scientific applications examples are ionospheric monitoring, geodetic survey and prospecting, land, and glaciers monitoring. A better knowledge of the ionospheric behavior in these singular regions could improve

the reliability of global models, thus extending the advantages of this research to GNSS users worldwide.

SDR technology and architecture

The term SDR refers to an ensemble of hardware and software technologies enabling reconfigurable radio communication architectures (Lo Presti et al. 2014). More in detail, SDR receivers are radio communication architectures, made up of configurable hardware and software blocks and performing advanced signal processing operations. SDR technology for implementation in GNSS receivers is emerging as an innovative, flexible, and low-cost alternative to traditional hardware receivers.

The most common architecture of SDR-based data acquisition and monitoring system is composed of an antenna, a radio front-end (RFE), and a software processing unit, as illustrated in Fig. 1. The RFE is in charge of signal conditioning and data grabbing: it first amplifies and filters the analog signal coming from the antenna to minimize out-of-band contributions; then it down-converts the radio frequency (RF) signal to intermediate frequency (IF) or to baseband, in order to allow digital conversion. An automatic gain control (AGC) can be used to adjust the signal dynamics, though it is often not employed for scintillation monitoring. The analog signal is then converted into a stream of digital samples and quantized by an analog-to-digital converter (ADC). This digital signal is commonly referred to as raw IF data or GNSS raw samples. It can be stored in memory as a binary file, for later post-processing, or directly processed in real time by a software receiver running on a general purpose processor (GPP) (Linty et al. 2015).

In a GNSS SDR receiver, all the baseband signal processing stages, such as signal acquisition, tracking, navigation solutions, and ionospheric indexes computation, are implemented in software, unlike in hardware receiver where most of the operations are performed by dedicated hardware components. Indeed, SDR receivers grant full access to low-level and intermediate signal processing stages, offering a wider subset of observables. This yields higher flexibility and reconfigurability and, in turn, enables the possibility to design and implement innovative and ad hoc ionospheric monitoring techniques. In addition, SDR receivers feature lower development costs, shorter development times, easier maintainability, and upgradability when compared to traditional GNSS hardware monitoring receivers (Linty et al. 2015).

Advantages of SDR receivers for ionospheric monitoring

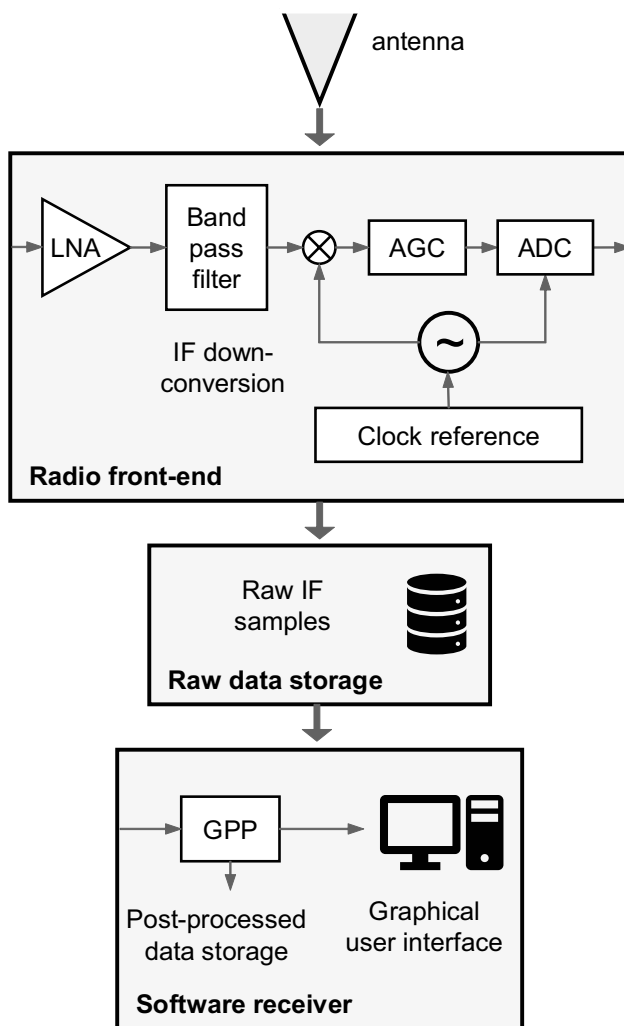The traditional way of monitoring ionosphere envisages the use of professional commercial hardware devices. In

Fig. 1 Common architecture of an SDR-based GNSS data acquisition and processing system, including the analog radio front-end, the storage of the raw IF samples, and the post-processing by means of a software receiver

particular, ionospheric scintillation monitoring receivers (ISMRs) are commercial devices specifically designed for monitoring ionospheric events affecting GNSS signals. ISMRs have been successfully used for many years (Van Dierendonck 1993; Shanmugam et al. 2012; Romano et al. 2013). Nonetheless, recent trends in ionospheric monitoring stations installations also consider SDR as a flexible, competitive, and cost-effective alternative. The assessment of the ionospheric behavior and the study and mitigation of scintillations employing SDR GNSS receivers is a valuable solution, and all existing installations have shown consistent and reliable results (Linty et al. 2015; Skone et al. 2005; Peng and Morton 2013; Povero et al. 2015). This approach is valuable only if the data acquisition system does not mask or alter any important signal feature, especially those related to ionospheric disturbances. The SDR receiver must

indeed grant the same quality offered by today state-of-the-art installations, in terms of scintillation observation capabilities.

The advantages of the SDR approach can then be summarized as

- *accessibility*, the possibility to enter any intermediate receiver stage, and thus to access unconventional measures and observables;
- *configurability*, the possibility to modify any parameter of the receiver, from the digital signal sampling rate or bit resolution to the acquisition and tracking architecture, to improve the performance of the signal processing blocks;
- *modularity* and block structure, enabling the capability to replace, improve, delete functions without affecting the overall architecture;
- *flexibility*, which summarizes all the previous concepts: an SDR receiver allows any user with enough expertise to do any modification, improvement, or extension.

The DemoGRAPE project

DemoGRAPE is a project funded by the Italian National Antarctic Research Program (Programma Nazionale di Ricerche in Antartide, PNRA), led by the Italian National Institute of Geophysics and Volcanology (Istituto Nazionale di Geofisica e Vulcanologia, INGV), with the collaboration of Politecnico di Torino and Istituto Superiore Mario Boella (ISMB), the partnership of the South African National Space Agency (SANSA), and of the Brazilian Institute of Space Research (INPE) (Alfonsi et al. 2016). The objective of the project is to improve the quality of the GNSS position solution in polar regions. In particular, two ionospheric monitoring stations, including a professional ionospheric monitoring receiver and a prototype of GNSS data collection system based on a GNSS raw data grabber and a software receiver, have been installed in Antarctica.

Ionospheric scintillation monitoring in Antarctica using GNSS signals has been a valuable research topic for many years (De Franceschi et al. 2006). The novelty introduced by DemoGRAPE is the use of a GNSS data acquisition system based on non-conventional radio front-ends and on SDR receivers, thus exploiting their features and advantages outlined before for installations in remote and severe environments.

Installation summary

The first monitoring station was installed in November 2015, in the Brazilian Antarctic station Estação Antártica Comandante Ferraz (EACF). The station is located on King George

Fig. 2 Main module of the EACF station in Antarctica, and the GNSS antenna used for the DemoGRAPE project

Fig. 3 Geometrical field of view from EACF and SANAE IV stations in Antarctica, at 30° and 20° elevation

Island, South Shetland Islands, in the Antarctic Peninsula, at 62°05′07″S and 58°23′29″W. The system was installed as part of the XXXI Italian Expedition in Antarctica of the PNRA, with the collaboration of INPE. Figure 2 reports a picture of the main module of the EACF station and of the GNSS antenna installed for the DemoGRAPE project.

A second monitoring station was installed in the South African station SANAE IV in January 2016, with the support of SANSA. The station is located in the Queen Maud Land region of Eastern Antarctica and is managed by the South African National Antarctic Expedition (Linty et al. 2016).

Since the installation, both systems have been almost continuously monitoring the ionosphere. From a first analysis, the receivers detected mostly phase scintillation rather than amplitude scintillations, as expected for polar regions (Doherty et al. 2000). Furthermore, it is evident that the ionospheric activity is much more intense at SANAE than at EACF, because of the more poleward geomagnetic position of the SANAE: geomagnetic dipole latitude of SANAE is 66°45′S and of EACF is 52°95′S. The sky field of view from EACF and SANAE IV stations is reported in Fig. 3. The areas enclosed by the red and blue lines correspond to the portion of ionosphere monitored when applying a 30° and 20° elevation mask, respectively.

Challenges of remote installations

The installation and maintenance of a monitoring station in Antarctica require months of preparation and logistics organization. In most of the cases, once installed, the set-up is left unattended for several months, during which nobody is present at the station to operate on the devices. Accessibility, space, and energy resources are indeed extremely limited in environments such as a research station in Antarctica. Fi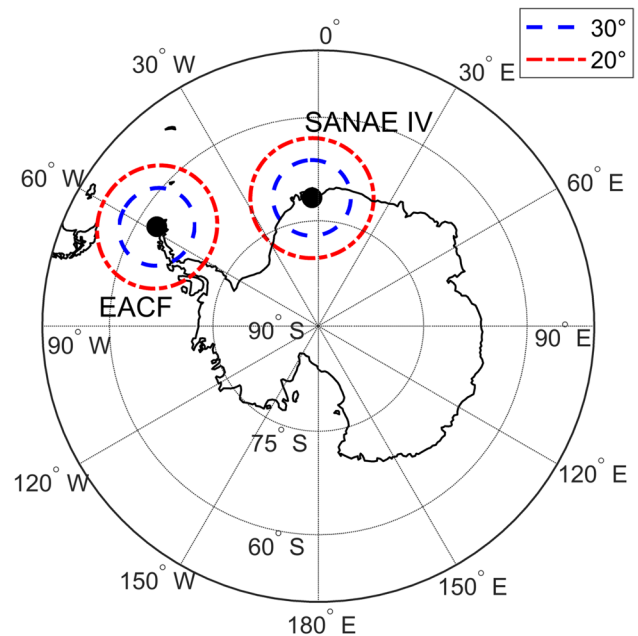nally, network and bandwidth resources are slow, unreliable, and expensive. Therefore, a well-planned strategy for data management and sharing is mandatory.

Cold weather and isolation are not the only difficulties when tacking on an expedition at the Pole. It can take up to 1 month to reach the research station, due to unpredictable and hazardous weather conditions. The installation of the GNSS antenna, depicted in Fig. 4, strictly depends on the availability of the qualified staff and on the wind, visibility, and humidity conditions.

Station design and implementation

This section summarizes the technological challenges and solutions adopted for the installation and maintenance of the monitoring system. First, the complete set-up is described, with a particular focus on the SDR-based receivers. The two main drawbacks of the SDR approach, data storage, and data transfer, are examined. At the same time, the benefits of IF data storing are explained by describing IF post-processing and RF re-play techniques that allow bringing the Antarctic environment to the lab.

Installation set-up

The complete installation set-up includes three independent monitoring receivers. A block scheme is depicted in Fig. 5 (Linty et al. 2015).
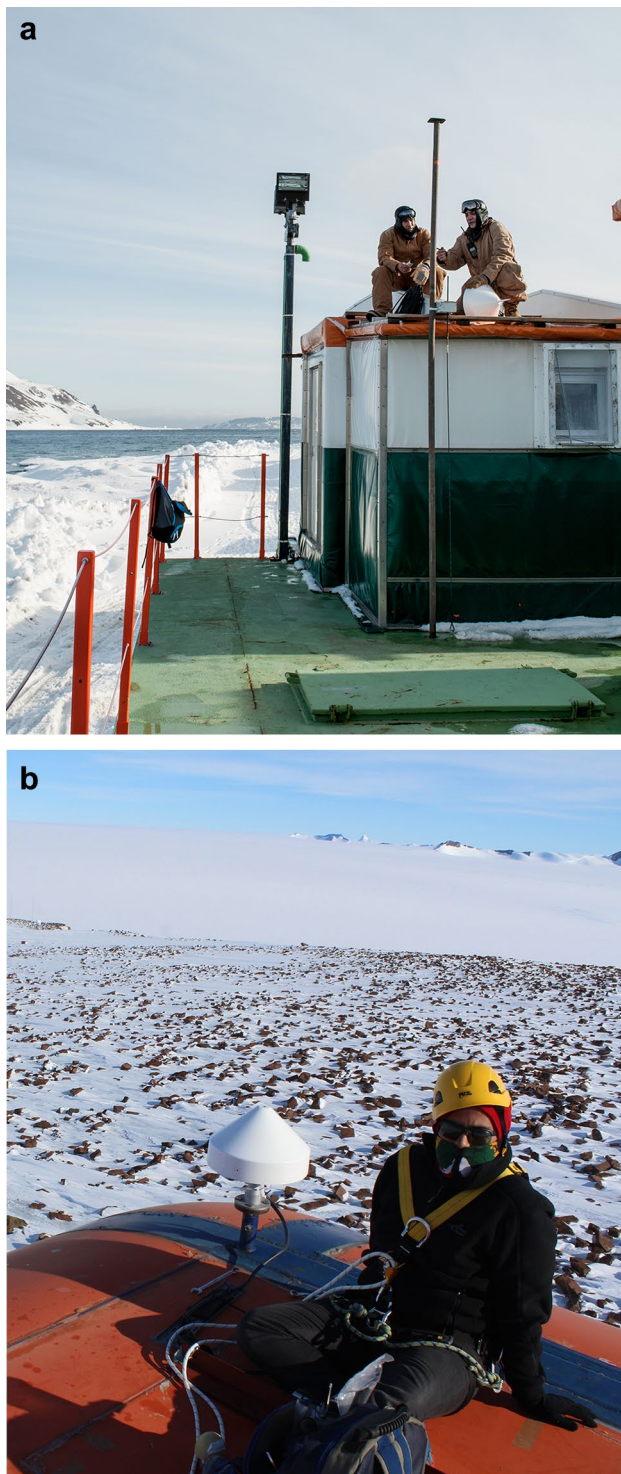
Fig. 4 Installation of the DemoGRAPE GNSS antenna at EACF station (top) and at SANAE IV station (bottom)

- A Septentrio PolaRxS PRO ISMR, providing scintillation and Total Electron Content (TEC) measurements, together with common GNSS observables stored in RINEX files.

- A GNSS data acquisition system based on N210 Universal Software Radio Peripherals (USRPs), specifically developed by the NavSAS group at Politecnico di Torino for ionospheric monitoring (Linty et al. 2015). The USRPs are low-IF architecture radio peripherals allowing GPPs to function as high bandwidth communication devices (Peng and Morton 2013). Two USRPs have been used, to capture both L1/E1 and L2 streams, and configured to store I and Q baseband samples at a 5 MHz sampling frequency and exploiting up to 14 quantization bits. A rubidium atomic oscillator provides a stable and accurate reference to the ADC and is especially important for reducing noise in phase scintillation estimation.
- 4tuNe, a four-band automatic Galileo/GPS bit grabber, developed by the Joint Research Centre (JRC) of the European Commission (EC) (Curran et al. 2014b). In the present configuration, it is able to save three streams, centered on the L1/E1, L2, and L5/E5a bands, at a sampling frequency of 5 and 30 MHz.

The full monitoring system has been installed at EACF station, while the SANAE installation does not include the USRP-based acquisition system.

Figure 6 shows a picture of the system installed at the EACF station. The USRPs and the 4tuNe front-end are used to pre-condition, amplify, and analog-to-digital convert the analog signal. Raw IF samples are saved in the external storage. The SDR software receiver, running on the PC, is based on the NGene software receiver, developed by the NavSAS group (Molino et al. 2009).

The bottleneck of data storage

While the typical output data of an ISMR receiver, such as Rinex files, amount to a few MB per day, GNSS raw IF data can grow up to more than 1 GB per minute. As a consequence, a large data repository is required for their storage. As an example, with the configuration parameters used in the Antarctica installation for the USRP configuration, 1 h of double frequency raw data amounts to about 144 GB, and a 2 TB external hard drive would be full after only 14 h.

As there is no correlation between scintillation occurrence and time of the day, it is not convenient to limit the observation to post-sunset hours, as it is often done at equatorial latitudes (Peng and Morton 2013). On the contrary, continuous monitoring over time is required. However, continuous storage of the raw IF samples is not possible. A smart strategy for automatic storage of the raw signal consists in the use of a basic software routine to automatically grab a portion of raw data, rapidly process only GPS L1 C/A signals computing scintillation indexes and compare

Fig. 5 Block scheme of the set-up of the ionospheric scintillations monitoring installation, including a professional ionospheric monitoring receiver and two experimental SDR-based data acquisition systems
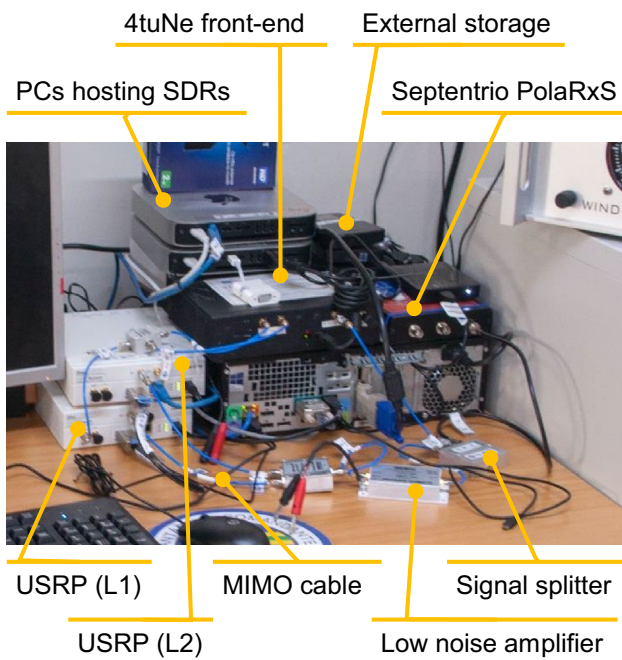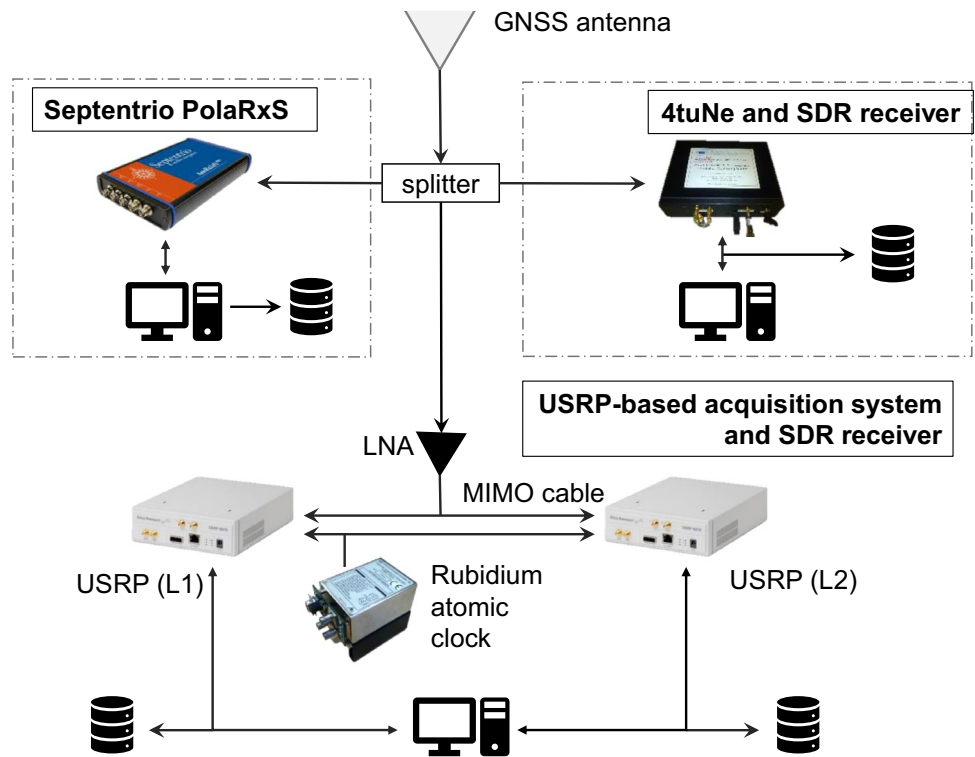

Fig. 6 Picture of the set-up of the monitoring station installed at EACF

them to configurable predefined thresholds, thus declaring or no scintillation. Hence, only IF data relative to relevant ionospheric events are saved, while other data are discarded.

Raw IF data potentialities: multiple receivers at the price of one

Commercial receivers only allow saving post-processed data, such as correlation outputs and ionospheric indexes, at 50 Hz or even at a lower rate. On the contrary, having access to an extremely faithful digital representation of the received GNSS signal enables a deeper analysis of scintillation and on its impact on radio signals. Furthermore, the possibility to use a software receiver enables access to the complete receiver chain and to intermediate measures. This, in turn, can offer tools to understand better the physical phenomenon characterizing polar ionosphere.

The bigger advantage of an SDR-based installation is indeed the availability of raw IF samples. Raw IF data are sequences of digital samples recorded at the output of the ADC of the RF front-end, as depicted in Fig. 1. They are sampled at a high sampling rate, up to 30 MHz, and represented over a number of bits ranging from 1 bit up to 2 bytes. Higher sampling frequency and high quantization level guarantee a better signal digital representation, at the expenses of a higher computational and storage complexity.

Raw data are typically stored as binary files in memories, transferred and possibly shared. Hence, at the end of each summer expedition, hard drives full of raw data are manually shipped back. This allows to reproduce the Antarctic situation in the lab, but with a plethora of receivers and processing tools that can rely on much larger computational,

storage, and bandwidth resources. IF data can be either post-processed at IF or re-played at RF, as described in the following subsections.

Recent research works showed the importance of unique and rare raw IF samples of polar scintillation events. On one side, they can enable advanced scintillation monitoring solutions (Romero et al. 2016), to enhance the observation of ionospheric phenomena. On the other side, they foster the design of novel receiver architectures (Vilà-Valls et al. 2017), which are more robust to such impairments.

IF post-processing

On one side, raw IF data can be post-processed, exploiting software receivers. This approach is reported on the left side of the scheme of Fig. 7. The advantage is the possibility to use different configurations of the receiver, to test new algorithms specifically designed to improve the receiver robustness in the case of scintillation events, or to develop advanced techniques for monitoring the ionosphere and for mitigating its impact on the GNSS signal (Lachapelle and Ali 2016; Lee et al. 2017). As an example, the performance

Fig. 7 Key aspect of raw IF GNSS samples recording: IF post-processing and RF replay

of different tracking loop discriminators has been evaluated by Humphreys et al. (2005). Open-loop/based software receivers were investigated by Curran et al. (2014a).

RF re-play

USRPs can also be used as modulating devices. Thanks to the availability of stored baseband digital samples, it is possible to replay the original environment, recreating the analog signals at RF (Cristodaro et al. 2017). Such signal can then be fed to a generic receiver in order to test the performance in an extremely realistic test case. This allows, as an example, to have a comparative analysis of different commercial receivers as if they were all tested in Antarctica, or in regions where the installation of monitoring stations or the organization of live test campaigns might not be cost-effective. This approach is shown in the right part of Fig. 7. Furthermore, the availability of the raw samples data allows modifying the test emulating the presence of impairments. External nuisances, such as RF interference, can be added to evaluate its impact on the computation of scintillation indexes (Cesaroni et al. 2015).

One of the parameters which affect the fidelity of the recorded signal to the physical one is the quantization level. One or two bits are enough for the computation of scintillation indexes using a—software receiver (Cristodaro et al. 2018). However, a strong reduction of the number of quantization bits reduces the fidelity of the re-played test case to the original one. At least 8 bits are required to properly perform RF up-conversion and signal re-play (Cristodaro et al. 2017).

Remote monitoring by exploiting raw samples metadata

Similarly, the problem of data transfer is relevant for installation in Antarctica. The limited resources available in remote stations in terms of network reliability, bandwidth, and speed impose severe rules, and indeed forbid the transfer of such large amounts of data. Binary files can only be physically moved by moving the hard drives in which they are stored. As a consequence, they are only available for post-processing at the end of each summer expedition, typically once a year. Nevertheless, SDR technology offers the possibility to configure and run a software receiver directly on the PC of the remote station, by exploiting the slow network connection. Only the compact post-processed results are transferred, respecting the bandwidth limitation. This approach is known as "moving the software," opposed to the traditional concept of "moving the data" (Favenza et al. 2016).

Particular attention has been given to work conducted by the ION GNSS SDR Metadata Group, which is proposing a standard for an XML-based GNSS SDR metadata file
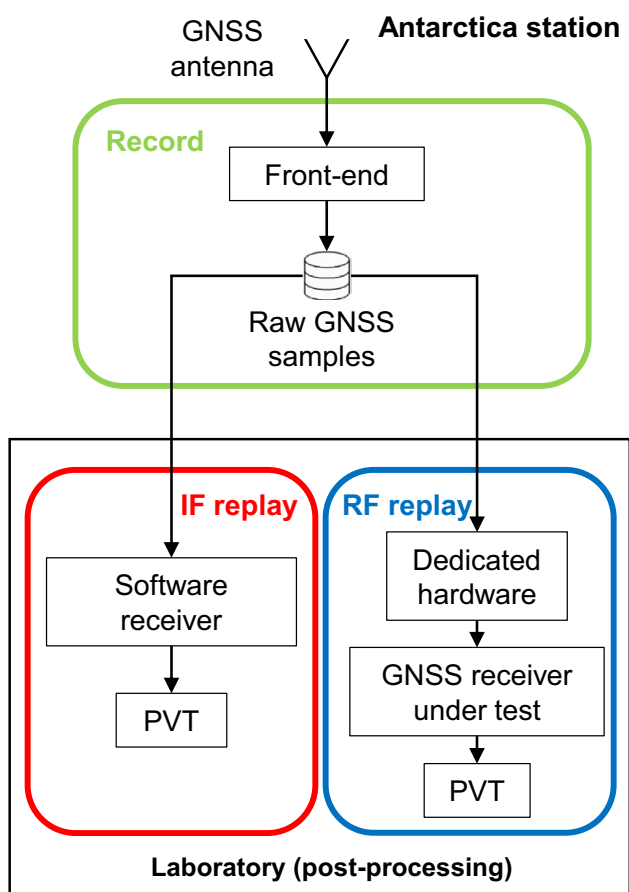
format to describe the content of the data collections to help the automated interpretation process by processing software. Based on this standard, an SDR receiver installed in the Antarctica remote station can automatically configure internal parameters, as for instance RF and IF center frequencies, sample rate, or quantization level, enabling the playback and post-processing of the collected data.

Monitoring results

In order to confirm the validity of the installation, in this section, some results are provided. In particular, two of the strongest ionospheric events affecting the ionosphere in the regions observed are reported: January 20–21, 2016 and May 28, 2017. To conclude, the benefits of multi-constellation and multi-frequency analysis are outlined, with further examples.

Receivers measure the amount of amplitude and phase scintillation affecting a signal by making use of 50 Hz rate data at the output of the tracking stage. Two indexes are employed to this end. Amplitude scintillation is monitored by computing the S4 index, corresponding to the standard deviation of detrended signal intensity, computed from the prompt correlator samples. Phase scintillation monitoring is achieved by computing the σ_ϕ index, corresponding to the standard deviation of the detrended carrier phase measurements. The most widely used σ_ϕ index is Phi60, which is calculated over the same 60 s interval as S4 (Van Dierendonck et al. 1993). The detection is performed by comparing such indexes to predefined thresholds, the values of which are set to roughly classify the presence of moderate and strong events. Linear plots show the trend of S4 and σ_ϕ versus time. For moderate to strong scintillations, typical threshold values are 0.25 radians for σ_ϕ and 0.25 for S4 (Alfonsi et al. 2011).

The TEC is another parameter used to characterize ionosphere. In particular, the vertical TEC (vTEC) is defined as the number of free electrons in a vertical cylinder of 1 m diameter perpendicular to the ground. The rate of change of the TEC with respect to time is called ROT. vTEC and ROT can, therefore, be used to measure the irregularities of the electrons distribution.

January 20–21, 2016

The first GNSS scintillations from DemoGRAPE have been captured in January 2016 from SANAE station (Alfonsi et al. 2016). One of the events occurred during a moderate geomagnetic storm that started on January 19 and peaked on January 20, 2016, as shown by the Disturbance Storm Time (DST) index in Fig. 8.
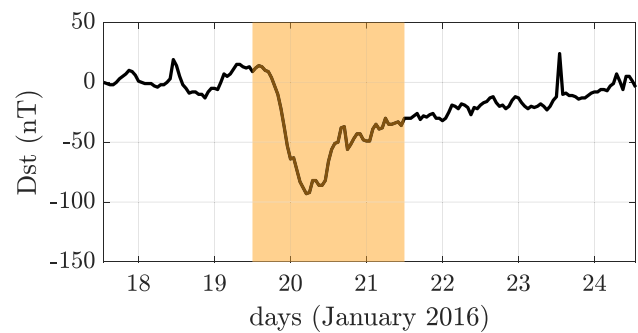

Fig. 8 DST index variation on January 18–24, 2016. The orange box identifies the day recording phase scintillations at SANAE (January 20)

The storm was caused by a transit of a coronal mass ejection erupting filament recorded on January 14 (IPS Daily Report—14 January 16). Phase scintillations occurred in the coordinated universal time (UTC) afternoon and evening of January 20. Moderate to severe scintillations maximized between 20 and 22 UTC, at the beginning of the storm recovery phase, as shown in Fig. 8.

Figure 9 shows amplitude and phase scintillation indexes on GPS L1 C/A signals, during a strong scintillation event in the night between January 20 and 21. Raw IF data, captured by the 4tuNe front-end, were post-processed by the software receiver. Many satellites exhibit high values of σ_ϕ between 00:40 and 00:55 UTC. As expected, S4 reaches values above the scintillation threshold 0.25 only for one satellite, while σ_ϕ exceeds the detection threshold of 0.25 rad on many signals.

Similarly, Fig. 10 depicts in detail the trend of the phase scintillation index on GPS L1 C/A PRN 14, for the same event. The trend of σ_ϕ as computed by the software receiver post-processing raw IF data captured by the 4tuNe front-end (red continuous line) is benchmarked to the results of the Septentrio receiver (green dashed line). The figure illustrates the capability of the system to detect ionospheric scintillation and reveals the excellent correspondence between the data from the SDR-based and the Septentrio receiver, thus validating the SDR approach to monitor scintillations.

Furthermore, it is interesting to focus on the resolution of the σ_ϕ values. While the commercial receiver logs phase scintillation index values every 60 s, the software receiver is able to obtain σ_ϕ values at a higher rate. In the example reported in Fig. 10, the phase scintillation values computed by the software receiver are drawn at a rate of one second, improving the event observation capabilities. For instance, the higher rate σ_ϕ points out different phase dynamics and higher peaks, which are not visible in the solution provided by the commercial receiver.
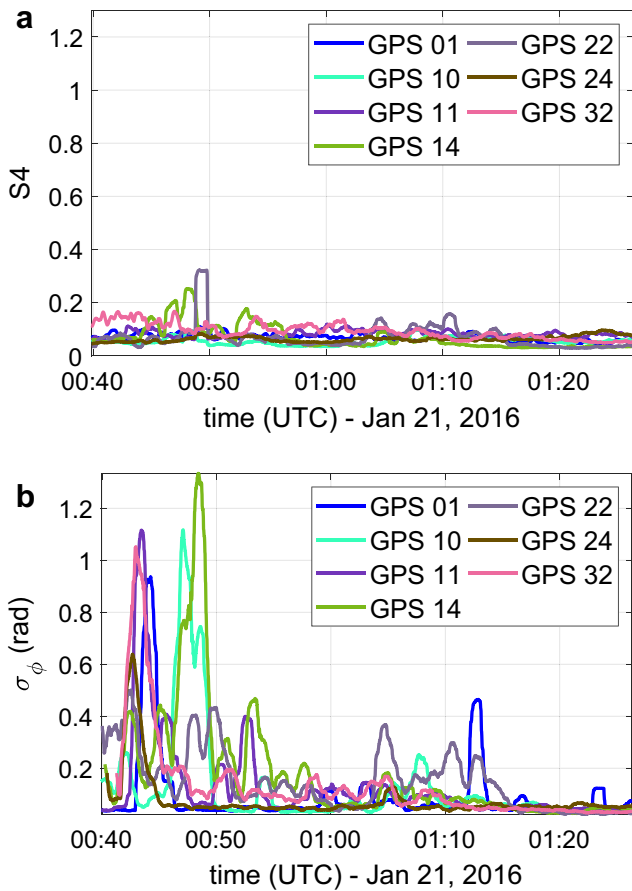
Fig. 9 Amplitude (top panel) and phase (bottom panel) scintillation indexes, obtained by post-processing raw IF samples of GPS L1 C/A signals captured by the 4tuNe front-end at SANAE IV on January 21, 2016
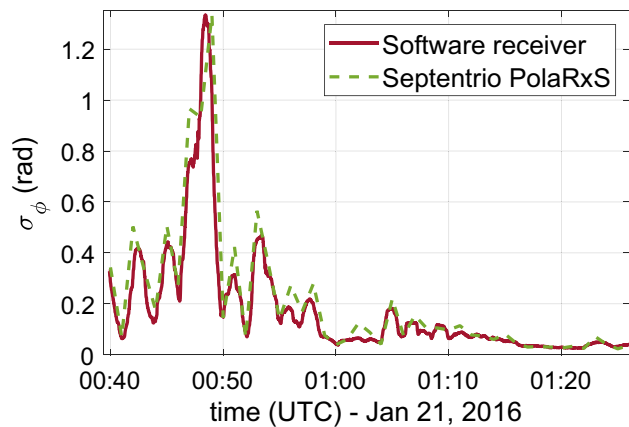

Fig. 10 Comparison of phase scintillation index, computed by a commercial hardware receiver and by a software receiver. GPS PRN 14, January 21, 2016, SANAE IV
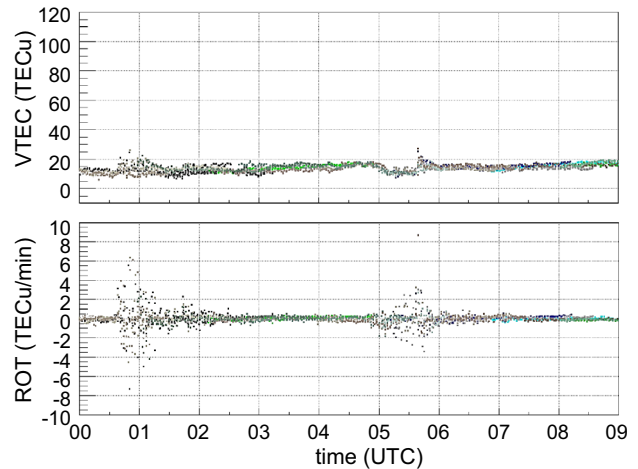

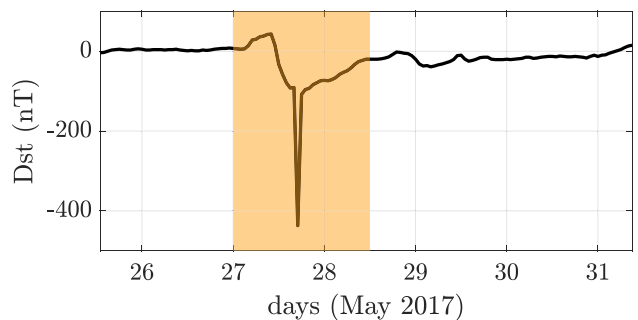**Fig. 11** TEC and ROT values on January 21, 2016 at SANAE IV station

Fig. 12 DST index variation on May 26–31, 2017. The orange box identifies the day recording phase scintillations at SANAE (28 May)

Figure 11 reports the vTEC and the ROT for the same day as computed by the Septentrio receiver at SANAE. The high variability of both values confirms that a scintillation event started around 00:40 UTC.

May 28, 2017

The most recent noteworthy event was captured on May 28, 2017. The DST index is reported in Fig. 12. Strong phase scintillation was detected by the monitoring system, starting from 02:15 UTC, for about 7 h.

The plots of the C/N_0, S4, and σ_ϕ on GPS L1 C/A signals are reported in Fig. 13. The gaps in the data collection correspond to the time taken by the software receiver to post-process the previous block of IF data captured by the grabber. The figures were automatically generated by the software receiver post-processing data acquired by the 4tuNe front-end. The plots are related to the time slots in which scintillation events are automatically detected. The figure shows high phase scintillation values for most of the PRNs

Fig. 13 Phase scintillation events on May 28, 2017, from 02:15 to 09:00 UTC
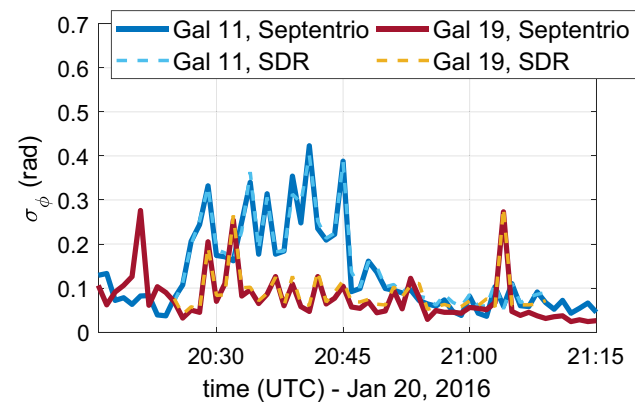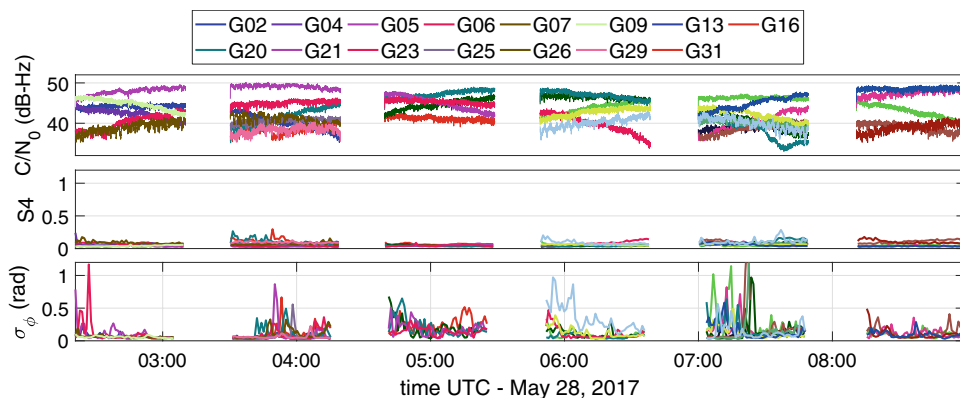

Fig. 14 Phase scintillation event, Galileo PRN 11 and 19, on January 20, 2016 at SANAE IV

in view ($\sigma_\phi > 0.25$), while the S4 index is generally close to the noise floor (S4 < 0.25). Triple-frequency raw GNSS files relative to those time slots, grabbed by the front-end, were automatically saved and are available on external memories in Antarctica stations, and will be post-processed when the disk will be brought back at the end of the campaign.

Multi-constellation monitoring

Galileo signals in the E1 bandwidth can be used, along with legacy GPS L1 C/A signals, to detect ionospheric events. The availability of more satellites from more constellations enables, in principle, denser monitoring of ionosphere. In addition, since one of the features of Galileo is to provide better coverage at high latitudes, the usage of these signals could allow improved monitoring, especially in polar regions (Romero et al. 2017).

Figure 14 shows the detection of phase scintillation from Galileo E1 satellites 11 and 19, as detected by the Septentrio ISMR and the SDR-based system at SANAE, on January 20, 2016. Also, in this case, a good match is observed between Septentrio and SDR results. In detail, the dashed line shows

the σ_ϕ index computed by the software receiver post-processing raw IF signals captured by the 4tuNe front-end. The software receiver has been configured to acquire and track the Galileo pilot signal E1c, using a coherent integration time equal to 20 ms, in analogy to what has been done in the case of GPS L1 C/A signals.

Multi-frequency monitoring

With the completion of new GNSS systems and with the modernization of GPS and GLONASS, a greater number of signals will be available for monitoring purposes. The systems installed in Antarctica stations are indeed multi-constellation and multi-frequency. The new civilian signals, such as GPS L2C, GPS L5, Galileo E1bc or Galileo E5a, can be successfully used for scintillation monitoring. Romero et al. (2017) showed how ionospheric measurements from Galileo signals could be used and integrated with GPS.

The influence of ionospheric perturbations is different for each frequency band, due to the dispersive nature of ionosphere and the employment of different code structures to generate the different satellite signals. Also, within the receiver, different bands may be tracked by different tracking architectures that could potentially be more susceptible to errors in the presence of scintillations, as it is the case with scintillation monitoring on the GPS L2 band with the encrypted precise code P(Y) by receivers that are not updated to track the new L2C signal. Nevertheless, signals with carrier frequency lower than L1 will in general experience larger signal fluctuations. Such difference is minimal during unperturbed conditions, but it is noticeable in the presence of events. Figure 15 shows a comparison of σ_ϕ calculated on the L1 band versus its counterpart on L5/E5a for selected GPS and Galileo satellites, confirming this fact.

A further advantage of SDR technology is the possibility to process modernized multi-frequency and multi-constellation GNSS signals, such as Galileo commercial service, or GPS L5, right after they have been enabled. A software receiver update and, when needed, the reconfiguration of
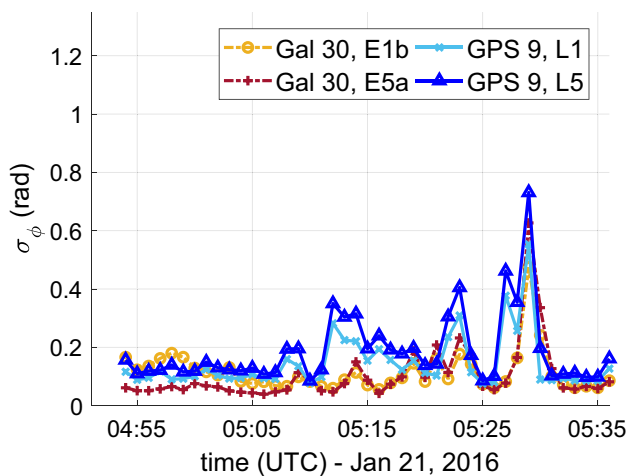
Fig. 15 Phase scintillation event, GPS and Galileo in L1 and L5 bands, on January 21, 2016 at SANAE IV

the front-end are enough to enable the processing of the new signal, without the need to physically install a new receiver. In addition, the availability of recorded raw IF data gives the possibility to replay new signals after they were broadcast, with receiver technologies which were not available at the time of grabbing.

Conclusions

Installation of an ionospheric monitoring station based on data grabber and SDR GNSS receivers is at the same time a novelty and a challenge. The technological choices taken during the design and installation of such system as part of the DemoGRAPE project, in two Antarctica remote research stations, between the end of 2015 and the beginning of 2016, were discussed. In particular, the advantages of using an SDR-based monitoring system and the benefits of repositories of raw IF data samples recording have been outlined. Thanks to the record and replay approach, it is possible to reproduce the original Antarctic electromagnetic environment in the lab, enabling advanced monitoring solutions and development of algorithms tailored to positioning in situations affected by scintillation.

References

Aarons J (1982) Global morphology of ionospheric scintillations. Proc IEEE 70(4):360–378
Alfonsi L, Spogli L, De Franceschi G, Romano V, Aquino M, Dodson A, Mitchell CN (2011) Bipolar climatology of GPS ionospheric scintillation at solar minimum. Radio Sci 46(3):1–21
Alfonsi L, Cilliers PJ, Romano V, Hunstad I, Correia E, Linty N, Dovis F, Terzo O, Ruiu P, Ward J, Riley P (2016) First observations of GNSS ionospheric scintillations from DemoGRAPE project. Sp Weather 14(10):704–709
Cesaroni C, Alfonsi L, Romero R, Linty N, Dovis F, Vaddake Veettil S, Park J, Barroca D, Ortega MC, Orus Perez R (2015) Monitoring Ionosphere Over South America: the MImOSA and MImOSA2 projects. Proc IEEE IAIN World Congress 20:1–7
Cristodaro C, Dovis F, Ruotsalainen L (2017) The record and replay approach for GNSS receiver performance assessment in road environment. In: Proceedings of ION ITM 2017, Institute of Navigation, Monterey, California, USA, January 30–1, pp 1369–1375
Cristodaro C, Dovis F, Linty N, Romero R (2018) Design of a configurable monitoring station for scintillations by means of a GNSS software radio receiver. IEEE Geosci Remote Sens Lett 15(3):325–329
Curran JT, Bavaro M, Fortuny-Guasch J, Hein G (2014a) An open-loop vector receiver architecture for GNSS-based scintillation monitoring. In: Proceedings of IEEE ENC
Curran JT, Bavaro M, Morrison A, Fortuny-Guasch J, Hein G (2014b) Developing an ionospheric scintillation monitoring receiver. Inside GNSS 9(5):60–72
De Franceschi G, Alfonsi L, Romano V (2006) ISACCO: an Italian project to monitor the high latitudes ionosphere by means of GPS receivers. GPS Solut 10(4):263–267
Doherty PH, Delay SH, Valladares CE, Klobuchar JA (2000) Ionospheric scintillation effects in the equatorial and auroral regions. In: Proceedings of ION GPS 2000, Institute of Navigation, Salt Lake City, Utah, USA, September 19–22, pp 662–671
Favenza A, Linty N, Dovis F (2016) Exploiting standardized metadata for GNSS SDR remote processing: a case study. In: Proceedings of ION GNSS + 2016, Institute of Navigation, Portland, Oregon, USA, September 12–16, pp 77–85
Humphreys TE, Psiaki ML, Kintner PM (2005) GPS carrier tracking loop performance in the presence of ionospheric scintillations. In: Proceedings of ION GNSS 2005, Institute of Navigation, Long Beach, California, USA, September 13–16, pp 156–167
Jiao Y, Morton YT, Taylor S, Pelgrum W (2013) Characterization of high-latitude ionospheric scintillation of GPS signals. Radio Sci 48(6):698–708
Kintner PM, Ledvina BM, De Paula ER (2007) GPS and ionospheric scintillations. Sp Weather 5(9):1–23
Lachapelle G, Ali B (2016) Benefits of GNSS IF data recording. In: Proceedings of IEEE ENC, pp 1–6

Lee J, Morton YJ, Lee J, Moon HS, Seo J (2017) Monitoring and mitigation of ionospheric anomalies for GNSS-based safety critical systems: a review of up-to-date signal processing techniques. IEEE Signal Process Mag 34(5):96–110

Linty N, Romero R, Dovis F, Alfonsi L (2015) Benefits of GNSS software receivers for ionospheric monitoring at high latitudes. In: Proceedings of radio science conference (URSI AT-RASC), pp 1–6

Linty N, Romero R, Cristodaro C, Dovis F, Bavaro M, Curran JT, Fortuny-Guasch J, Ward J, Lamprecht G, Riley P, Cilliers P, Correia E, Alfonsi L (2016) Ionospheric scintillation threats to GNSS in polar regions: the DemoGRAPE case study in Antarctica. In: Proceedings of IEEE ENC, pp 1–7

Lo Presti L, Falletti E, Nicola M, Troglia Gamba M (2014) Software defined radio technology for GNSS receivers. In: Proceedings of metrology for aerospace (IEEE MetroAeroSpace), pp 314–319

Molino A, Nicola M, Pini M, Fantino M (2009) N-GENE GNSS software receiver for acquisition and tracking algorithms validation. In: Proceedings of IEEE European Signal Processing Conference, pp 2171–2175

Peng S, Morton Y (2013) A USRP2-based reconfigurable multi-constellation multi-frequency GNSS software receiver front end. GPS Solut 17(1):89–102

Povero G, Pini M, Dovis F, Romero R, Abadi P, Alfonsi L, Spogli L, Di Mauro D, Floury M (2015) Ionosphere monitoring in South East Asia: activities in GINESTRA and ERICA projects. In: Proceedings of IEEE IAIN world congress, pp 1–7

Romano V, Macelloni G, Spogli L, Brogioni M, Marinaro G, Mitchell CN (2013) Measuring GNSS ionospheric total electron content at Concordia, and application to L-band radiometers. Ann Geophys 56(2):1–10

Romero R, Linty N, Dovis F, Field RV (2016) A novel approach to ionospheric scintillation detection based on an open loop architecture. In: Proceedings of IEEE NAVITEC 2016, ESA, Noordwijk. The Netherlands, September 14–16, pp 1–9

Romero R, Linty N, Cristodaro C, Dovis F, Alfonsi L (2017) On the use and performance of new galileo signals for ionospheric scintillation monitoring over Antarctica. In: Proceedings of ION ITM 2017, Institute of Navigation, Monterey, California, USA, January 30–31, pp 989–997

Shanmugam S, Jones J, MacAulay A, Van Dierendonck AJ (2012) Evolution to modernized GNSS ionospheric scintillation and TEC monitoring. In: Proceedings of IEEE/ION PLANS 2012, Institute of Navigation, Myrtle Beach, South Carolina, USA, April 23–26, pp 265–273

Skone S, Lachapelle G, Yao D, Yu W, Watson R (2005) Investigating the impact of ionospheric scintillation using a GPS software receiver. In: Proceedings of ION GNSS 2005, Institute of Navigation, Long Beach, California, USA, September 13–16, pp 1126–1137

Van Dierendonck AJ, Klobuchar J, Hua Q (1993) Ionospheric scintillation monitoring using commercial single frequency C/A code receivers. In: Proceedings of ION GPS 1993, Institute of Navigation, Salt Lake City, Utah, USA, September 22–24, pp 1333–1342

Vilà-Valls J, Closas P. Curran JT (2017) Multi-frequency GNSS robust carrier tracking for ionospheric scintillation mitigation. J Sp Weather Sp Clim 7(A26):1–14

Nicola Linty is an assistant professor at the Department of Electronics and Telecommunications (DET) of Politecnico di Torino (Italy) and member of the NavSAS research group. His research interests cover the field of signal processing and simulation, applied to satellite navigation. In particular, his work deals with the design and development of innovative algorithms for GPS and Galileo receivers.

Fabio Dovis is an associate professor at the Department of Electronics and Telecommunications of Politecnico di Torino as a member of the NavSAS group. His research interests cover the design of GPS and Galileo receivers and advanced signal processing for interference and multipath detection and mitigation. He has relevant experience in European projects in satellite navigation as well as cooperation with industries and research centers.

Lucilla Alfonsi is a researcher at Istituto Nazionale di Geofisica e Vulcanologia at the Upper Atmosphere Physics unit. Starting from 2003, Dr. Alfonsi is mainly involved in scientific studies and applications devoted to the assessment of the ionospheric disturbances on the GNSS signals, with special emphasis on the corruption effects causing severe positioning errors.