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First Observations of GNSS Ionospheric Scintillations From DemoGRAPE Project

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Abstract The Istituto Nazionale di Geofisica e Vulcanologia leads an international project funded by the Italian National Program for Antarctic Research, called Demonstrator of Global Navigation Satellite System (GNSS) Research and Application for Polar Environment (DemoGRAPE), in partnership with Politecnico di Torino, Istituto Superiore Mario Boella, and with South African National Space Agency and the Brazilian National Institute of Space Physics, as key collaborators. DemoGRAPE is a new prototype of support for the satellite navigation in Antarctica. Besides the scientific interest, the accuracy of satellite navigation in Antarctica is of paramount importance since there is always the danger that people and vehicles can fall into a crevasse during a snowstorm, when visibility is limited and travel is restricted to following specified routes using satellite navigation systems. The variability of ionospheric delay and ionospheric scintillation are two of the primary factors which affect the accuracy of satellite navigation. The project will provide a demonstrator of cutting edge technology for the empirical assessment of the ionospheric delay and ionospheric scintillations in the polar regions. The scope of the project includes new equipment for the recording and dissemination of GNSS data and products installed at the South African and Brazilian bases in Antarctica. The new equipment will facilitate the exchange of software and derived products via the Cloud computing technology infrastructure. The project portal is accessible at www.demogrape.net. We report the first Global Navigation Satellite System (GNSS) signal scintillations observed in Antarctica.

New GNSS Setup and Monitoring in Antarctica

The South African National Space Agency (SANSA) and the Brazilian National Institute of Space Physics (INPE) have managed ionospheric scintillation receivers and Global Positioning System (GPS) receivers at SANAE (71°40′22″S, 2°50′26″W) and EACF (62°05′07″S, 58°23′29″W) in Antarctica since 2006. Between November and December 2015 SANSA and INPE assisted the Demonstrator of Global Navigation Satellite System (GNSS) Research and Application for Polar Environment (DemoGRAPE) [*Alfonsi*, 2016] team with the installation at SANAE and EACF of two pairs of Global Navigation Satellite System (GNSS) receivers (Figure 1).

Each of the two stations is equipped with a standard Septentrio PolaRxS receiver and a new-concept GNSS data acquisition system, exploiting software-defined radio (SDR) receivers technology. The receivers provide access to ionospheric delay and related measurements from not only the GPS (U.S.) system of navigation satellites but also from the Russian GLObal NAvigation Satellite Systems (GLONASS) and European Galileo satellites (Figure 2).

The Ionospheric Scintillation Monitoring Receivers (ISMRs) sample GNSS signal amplitude and phase at 50 Hz and derive both RINEX data and 1 min values of the amplitude scintillation index S_4 and the phase scintillation index $\sigma_{\phi,}$. S_4 is the standard deviation of the received power normalized by its mean value. σ_{ϕ} is the standard deviation of the detrended carrier phase, computed over different time intervals. The software-based data acquisition and monitoring system is composed of a radio front end (RFE) and of an SDR receiver [*Linty et al.*, 2015]. The RFE (developed in cooperation with the Joint Research Centre of the European Commission) performs GNSS signal conditioning and data grabbing: it first amplifies and filters the analog signal coming from the antenna, to remove out-of-band noise, then it downconverts the radio frequency signal to intermediate frequency (IF) or to baseband, to allow digital conversion. The baseband signal is digitized, using an analog to digital converter that samples the signal at 5 MHz. The stream of digital samples is finally stored in memory with 16 bit resolution as a binary file and denoted raw IF data. The SDR is a fully software-based receiver, running on a PC, able to postprocess the raw IF data. It generates log files and quick-look plots, containing the following parameters: carrier to noise power density ratio (C/N_0), S_4, σ_{ϕ}, elevation and azimuth, and a "scintillation event detection" decision based on a combination of them. In order to limit the amount of data stored, the raw IF data acquired by the RFE are stored only if this decision is positive.

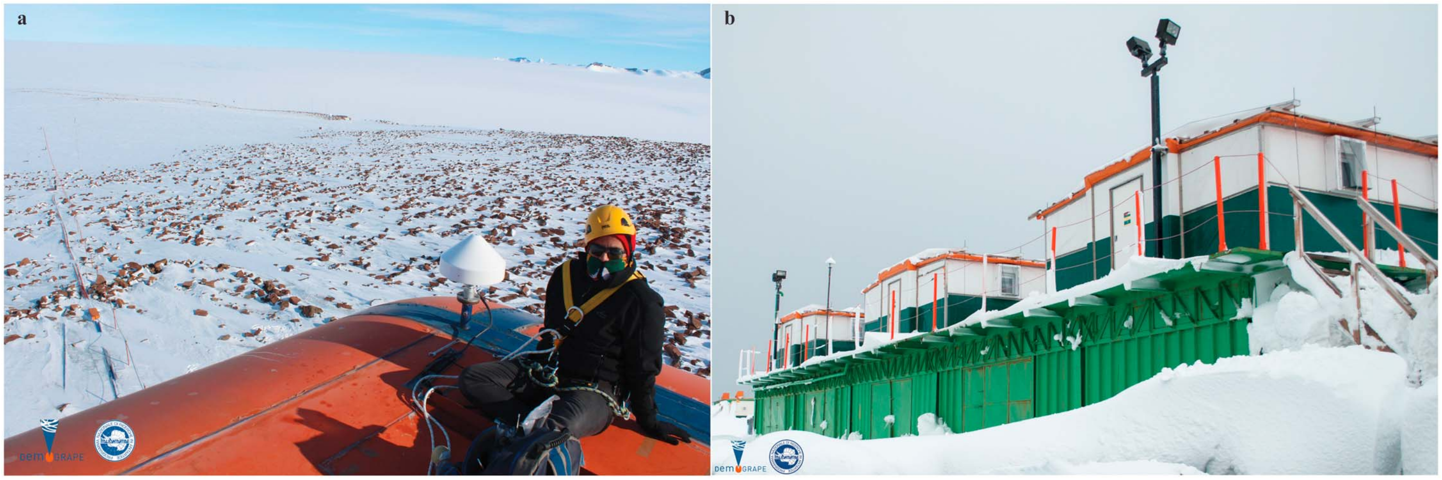

Figure 1. The antennas and environment of the GNSS receivers installed at (a) the South African base SANAE and (b) at the Brazilian base EACF during November–December 2015.

The SDR approach opens up new possibilities for the scientific community, adding flexibility to the implementation of the monitoring station. The SDR access to intermediate processing stages and to unconventional outputs with respect to ISMRs represents an advantage and introduces a higher level of configurability. The solution is also cost effective. In addition, the availability of raw IF data collected on site allows a deeper study of significant atmospheric events. Raw IF data can indeed be replayed and postprocessed, either by using different configurations and architectures of the receivers (e.g., acquisitions schemes, tracking structures, and tracking loops configurations) or by implementing advanced signal processing techniques and innovative algorithms tailored to ionosphere monitoring (e.g., higher rate scintillation monitoring, multipath and interference detection, and removal).

The Cloud Technology Infrastructure

Besides the novelty of a pair of scintillations monitors, DemoGRAPE relies, for the first time within the ionospheric science in Antarctica, on the Cloud technology (Figure 3) [*Rankin et al.*, 2011]. The data acquired in Antarctica, the related applications, and derived products are managed via an innovative method for data management based on Docker containers and Cloud computing technology infrastructure [*Mossucca et al.*, 2012]. The main innovation is on changing the way to access data and run analyses with an emerging service for user communities. The main issues for data analysis are on moving huge quantities of data. Data sets grow constantly, and the data owners offer several levels of data availability (public access, limited access, data licence, etc.). The innovative solution offered by DemoGRAPE is based on an advanced computing methodology that follows the state of the art in data management by moving applications, not data, using Docker containers services. Docker is an Open Source project that automates deployment of applications. The idea is based on three steps: (1) to create and compile an environment in a “container” that includes applications

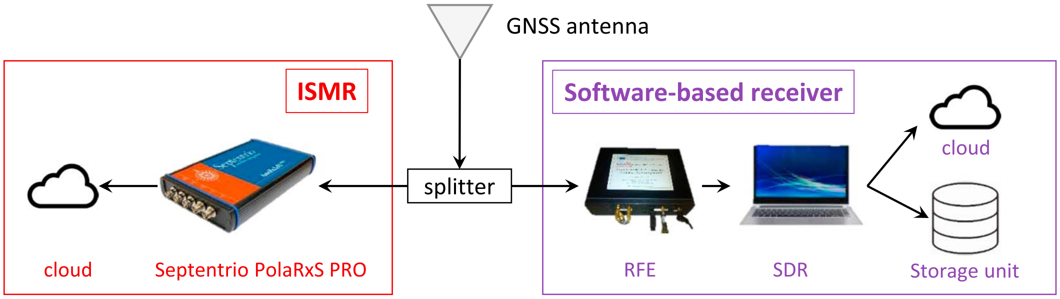

Figure 2. Block diagram of the Antarctica installation setup. The GNSS multiband antenna is shared by the Septentrio PolaRxS PRO high sampling rate GNSS receiver and the SDR GNSS receiver.

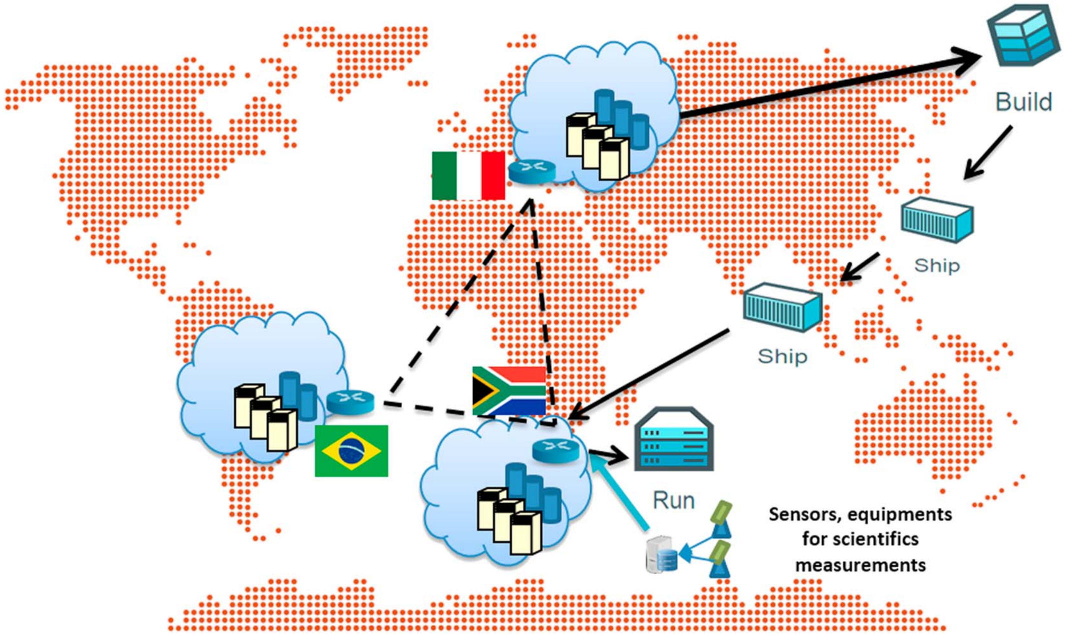

Figure 3. The concept of DemoGRAPE data exchange via the Cloud.

and all their dependencies for creating a binary code, (2) to move this container to a target host where available data are stored, and finally, (3) to proceed to the execution of the binary file.

In terms of data and applications security and privacy, the available data are not moved but rather operated on by applications that consist of interpreted code, source code, and binary code. Processed data are made available at public prototype level, while the raw data are stored in the DemoGRAPE infrastructure and made available according to the policy of the single institution owner. This approach allows partners from different countries to share also those data sets that are too big to be moved via Internet connectivity.

The new methodology of moving applications to data over Cloud computing and Docker services is a key enabling technology for assisting various scientific communities. The infrastructure of the DemoGRAPE demonstrator is geographically distributed and consists in three servers located in three different countries: Italy, Brazil, and South Africa (Figure 3). These nodes have different functions inside the platform: (i) own data collected in Antarctica region, (ii) provide computing resources for running application, and (iii) be part of the Docker platform.

The users' access to the system will be soon enabled through a web portal specifically developed for the project and reachable from the project portal (www.demogrape.net). This user interface will allow registered users to access applications, see the availability of data of the different partners, and eventually move the application to the node containing the useful data. This procedure will be done in an easy and user-friendly way by means of a simple graphical interface which will assist the user through all the steps. Users will be authorized to visualize and use their own applications and those that are marked as public by developers of other countries. Instead, data uploaded in the platform will be shared between all users. The data and related derive products will not be provided in real time at this prototype level of the demonstrator.

The use of a Cloud infrastructure is ideal for the Antarctic sciences because it preserves the intellectual property of data and software owners; it reduces the load of data transmission, having the possibility, rather, to move the applications to the data; and it reduces the computing time and the telematics resources.

The DemoGRAPE Contribution

The first GNSS scintillations from DemoGRAPE have been captured on January 2016 from SANAE station [*Pilosu et al.*, 2016a, 2016b, *Cilliers et al.*, 2016]. One of the events occurred during a moderate geomagnetic storm that started on 19 January and peaked on 20 January 2016 (as shown by the *Dst* index in Figure 4).

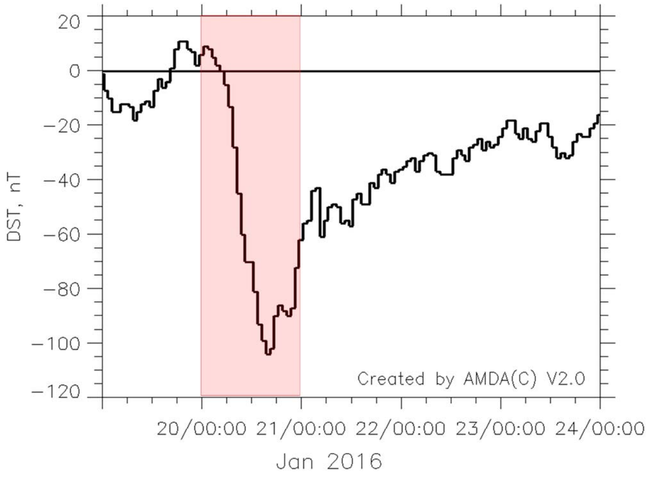

Figure 4. *Dst* index variation from 19 to 23 January 2016. The red box identifies the day recording phase scintillations at SANAE (20 January 2016).

The storm was caused by a transit of a coronal mass ejection erupting filament recorded on 14 January (IPS Daily Report—14 January 16).

Galileo, GPS, and GLONASS phase scintillations occurred in the UT afternoon and evening of 20 January, with moderate to severe scintillations that maximize between 20 and 22 UT (Figure 5), at the beginning of the storm recovery phase as shown in Figure 4.

Figure 6 shows the detection of phase scintillation on the ray path from Galileo satellite 11, as detected by the Septentrio ISMR and the SDR-bases system at SANAE on 20 January 2016. Similar results, for different constellations (GPS) and for other ionospheric events, were also analyzed [*Linty et al*., 2016]. 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 the scintillations.

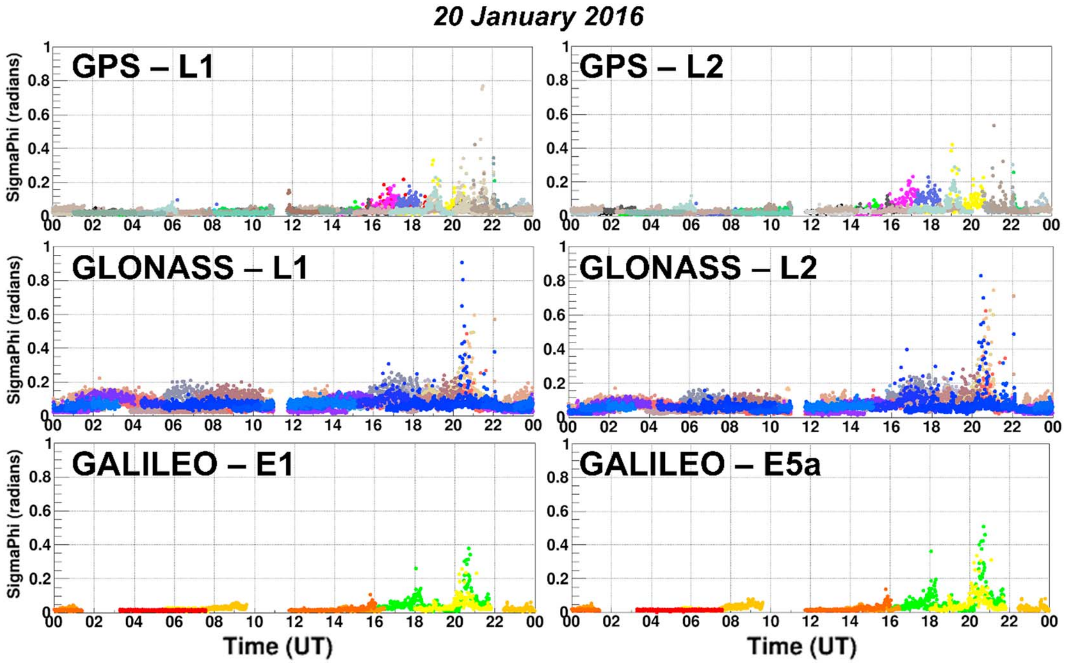

Figure 5. GPS, GLONASS, and Galileo phase scintillations recorded at SANAE on 20 January 2016. Different colors identify the satellites in view.

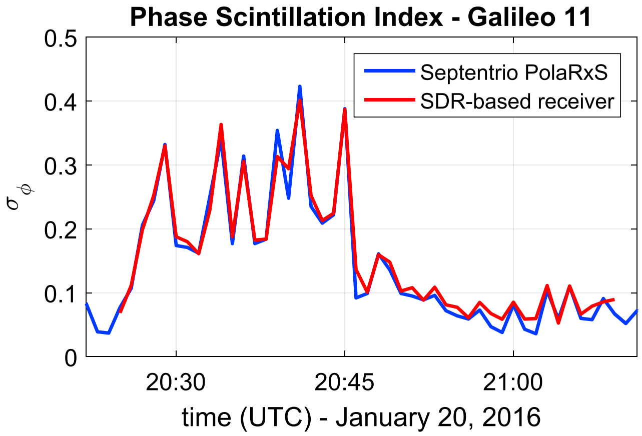

Figure 6. Detection of phase scintillation exceeding the σ_ϕ threshold on the ray path from Galileo satellite 11 on 20 January 2016 at SANAE.

Since the installation, the system in both stations has been continuously collecting data (with the exception of shutdowns due to maintenance procedures). 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).

DemoGRAPE will make a new contribution to the understanding of the scintillation threats on high-precision GNSS applications in Antarctica and suggests new possible methods to optimize scientific achievements. The project is designed to act as a pilot for future initiatives in a very multidisciplinary field, supporting scientists dealing with geodesy, space weather, and upper atmosphere studies; security operators managing terrestrial and air transports; and satellite operators dealing with satellite L band observations. All these stakeholders can take advantage from the DemoGRAPE results because it is designed to demonstrate the possibility to access the information needed to compute the positioning from an empirical assessment of the ionospheric delay and to monitor corruption of the radio signals due to scintillation.

In this context DemoGRAPE is offering a tool for new research opportunities at international level in Antarctica.

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