Multi-constellation GNSS observation of ionospheric scintillation at SANAE-IV in Antarctica

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AGENDA

DemoGRAPE project
Why study scintillation in Antarctica?
SANAE-IV, SANSA, INPE, INGV
First multiconstellation S4 observations
September 2017 storm
SANSA (South Africa), INPE (Brazil), ISMB (Istituto Superiore Mario Boella, Italy) and POLITICO (Politecnico di Turino, Italy) are key collaborators on an international project DemoGRAPE coordinated by INGV (Italy) which is designed to improve satellite navigation in Antarctica.

DemoGRAPE is a demonstrator using cutting edge technology for the empirical assessment of the ionospheric delay and ionospheric scintillations in the polar regions from multiple GNSS constellations.

DemoGRAPE equipment has been installed at the South African base (SANAE-IV) in 2015 and has been maintained and operated by SANSA with support from INGV since 2015.
Background (2)

• The DemoGRAPE project at SANA comprises
  – Septentrio PolaRxS receiver and
  – A GNSS software defined radio (SDR) receiver,

• These instruments provide access to ionospheric delay and related measurements from the following navigation satellite systems
  – GPS (US),
  – GLONASS (Russian)
  – Galileo (European Space Agency) satellites.

• Software and data exchange continues to take place via the Cloud computing infrastructure.

• Quicklook plots of the signal to noise ratio (C/No) and of scintillation indices and summary files from the SDR receiver are sent to the data-node at SANSA, to INGV and to POLITO every 24 hours.
Why study scintillation in Antarctica?

- At high latitude GNSS navigation degradation is *more severe* than elsewhere because the polar ionosphere is often hit by solar energetic particles driven by the cusps of the geomagnetic field into the high latitude atmosphere.
- Precise positioning based on GNSS can be heavily corrupted, resulting in *positioning errors of tens of meters* or, even worst, in the positioning blackout due to the loss of satellite lock.
- Satellite navigation is often used for overland travel in Antarctica. Navigation errors may be hazardous to life and limb.
Crevasces near SANAЕ from the air
White-out in Antarctica
Crevasse from closer by

Photo: Helena Kruger
SOUTH ATLANTIC MAGNETIC ANOMALY

Main Field Total Intensity F at ground level from IGRF10

Total geomagnetic field in μT as calculated from IGRF10-model
Flux of energetic electrons observed by a polar orbiting satellite 800 km above the Earth’s surface during a large magnetic storm.
### Antarctic Observatory Locations

<table>
<thead>
<tr>
<th>Coordinates</th>
<th>Comandante Ferraz (EACF)</th>
<th>SANAE IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geographic</td>
<td>62°34’S, 58°23.5’W</td>
<td>71°40’S, 2°50’W</td>
</tr>
<tr>
<td>Geomagnetic dipole coordinate IGRF</td>
<td>52°95’S, 10°90’ E</td>
<td>66°45’, 48°00’E</td>
</tr>
</tbody>
</table>
IPY4 (Participants in ICESTAR project 63)
SANSA is part of the South African National Antarctic Programme (SANAP)
DemoGRAPE First expedition: EACF

Estação Antártica Comandante Ferraz, King George Island, South Shetland Islands

October 23 – November 24, 2015
DemoGRAPE Second expedition: SANAIE IV

Queen Maud Land Region of Eastern Antarctica

December 2, 2015 – March, 2017
Proposed relation of DemoGRAPE Antenna at SANAE-IV
Brazilian Station in 2017 relocated to CRAAM-INPE

Brazilian Centro de Radioastronomia e Astrofísica Mackenzie (CRAAM)
DemoGRAPE activities in Italy, Brazil, South Africa
Cloud Computing concept

See http://www.demogrape.net/
The Cloud computing advantages for Antarctic sciences

• Keep the intellectual property of the owners’ data and software
• Reduce time machines consuming
• Optimize data transmission and storage requirements
• Allow to run the software where data are stored without moving the data
The GNSS multiband antenna is shared by the Septentrio PolaRxS PRO high sampling rate GNSS receiver and the SDR GNSS receiver.
**HW receiver architecture**

- Antenna
- Analog front-end
- Digital Baseband processing
- User applications and interfaces

*Front-end for analog signal conditioning*  
*Application Specific Integrated Circuit (ASIC)*  
*General Purpose Processor (GPP)*

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**SDR receiver architecture**

- Antenna
- RFE
- Raw IF data
- SDR

*Front-end for analog signal conditioning*

*Field Programmable Gate Array (FPGA)*  
*Digital Signal Processor (DSP)*  
*General Purpose Processor (GPP) (fully software)*
Other related instruments at SANAE

**SuperDARN HF radar:** Ionospheric dynamics,

**VLF receivers** (part of World-Wide Lightning Location Network): Particle precipitation studies and recording of whistlers in the magnetosphere,

**Magnetometers:** characterization of long-term magnetic field variation and geomagnetic storms,

**GNSS receivers:** for Total Electron content and ionospheric scintillation monitoring,

**Riometers:** for studying high energy particle precipitation,

**Ozone radiometers:** for detecting the impact of particle precipitation on mesospheric ozone
Other Physical Science Instrumentation at SANAE-IV

- Aurora cameras
- Neutron Monitors
- Seismometer
- Meteorology

GPS Scintillation receivers:
- Novatel
- PolaRxS
- SDR

- GPS Ionospheric scintillation monitor (2006)
- FGE 3-axis magnetometer (2007)
- Overhauser Total Field magnetometer (2006)
- DI flux magnetometer on non-magnetic theodolite (2006)
COSMIC Ray sensor in Astrid Satellite Radome
## Co-located instruments at SANAE-IV

https://sandims.sansa.org.za/

<table>
<thead>
<tr>
<th>Type</th>
<th>Model</th>
<th>Version</th>
<th>Commissioning Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geomagnetic Instruments</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Legacy Magnetometer</td>
<td>DI-Fluxgate Magnetometer</td>
<td>None</td>
<td>1961-01-01</td>
</tr>
<tr>
<td>DTU 3-axis Fluxgate Magnetometer Model FGE</td>
<td>DTU Fluxgate</td>
<td>K2</td>
<td>2015-01-01</td>
</tr>
<tr>
<td>Fluxgate Magnetometer FGE</td>
<td>DMI-FGE Fluxgate Magnetometer</td>
<td>None</td>
<td>2008-01-15</td>
</tr>
<tr>
<td>Overhauser Scalar Magnetometer</td>
<td>Overhauser GSM-19</td>
<td>7.0</td>
<td>2007-05-25</td>
</tr>
<tr>
<td>Rock Magnetometer</td>
<td>Rock Magnetometer</td>
<td>None</td>
<td>2011-01-01</td>
</tr>
<tr>
<td>SANAE Pulsation Magnetometer</td>
<td>Pulsation Magnetometer</td>
<td>None</td>
<td>2012-04-30</td>
</tr>
</tbody>
</table>
### Co-located instruments at SANAE-IV

https://sandims.sansa.org.za/

<table>
<thead>
<tr>
<th>Ionospheric Instruments</th>
<th>Models</th>
<th>Details</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dual Frequency GPS Reference Station Receiver</td>
<td>Ashtech uZ12</td>
<td>None</td>
<td>2011-08-16</td>
</tr>
<tr>
<td>GPS Ionospheric TEC and Scintillation Monitor</td>
<td>GSV4004B</td>
<td>1.77</td>
<td>2006-12-25</td>
</tr>
<tr>
<td>Beam Forming Riometer</td>
<td>SSR</td>
<td>None</td>
<td>1997-04-01</td>
</tr>
<tr>
<td>Wide Angle Riometer</td>
<td>SSR</td>
<td>None</td>
<td>1998-02-21</td>
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<tr>
<td>SuperDARN</td>
<td>T3</td>
<td>1.0</td>
<td>2013-10-02</td>
</tr>
<tr>
<td>SuperDARN</td>
<td>T3</td>
<td>None</td>
<td>2012-01-01</td>
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<table>
<thead>
<tr>
<th>Magnetospheric Instruments</th>
<th>Models</th>
<th>Details</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automatic Whistler Detector</td>
<td>Automatic Whistler Detector</td>
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<td>2012-01-30</td>
</tr>
<tr>
<td>AWESOME Narrowband Receiver</td>
<td>AWESOME Narrowband</td>
<td>None</td>
<td>2009-02-17</td>
</tr>
<tr>
<td>AWESOME Synoptic Receiver</td>
<td>AWESOME Synoptic</td>
<td>None</td>
<td>2013-10-13</td>
</tr>
<tr>
<td>MSK Narrowband VLF Receiver</td>
<td>UltraMSK</td>
<td>1.0 beta 14</td>
<td>2011-01-01</td>
</tr>
<tr>
<td>VLF Receiver</td>
<td>DVRAS</td>
<td>None</td>
<td>2012-02-10</td>
</tr>
</tbody>
</table>
# SANSA’s high latitude Geophysical Instruments

<table>
<thead>
<tr>
<th>Location</th>
<th>Instruments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SANAE-IV, Antarctica</strong></td>
<td>SuperDARN HF Radar, Magnetometers(Overhauser, Pulsation, Rock, Fluxgate, DTU), Riometers(wide-angle(30, 51.4 MHz), beamforming(38.2 MHz), GNSS Receivers(Geodetic(Trimble), Scintillation and TEC monitors(Novatel GSV4004B, Septentrio PolaRsX PRO, 4tuNe SDR), VLF(AWESOME, UltraMSK, DVRAS, Whistler Detector), Ozone monitor, Neutron Monitor</td>
</tr>
<tr>
<td>2.84°W</td>
<td></td>
</tr>
<tr>
<td>71.67°S</td>
<td></td>
</tr>
<tr>
<td>Mag 61.85°S</td>
<td></td>
</tr>
<tr>
<td><strong>Gough Island</strong></td>
<td>Scintillation and Total Electron Content (TEC) monitors (Novatel), Dual Frequency GPS Receiver (Trimble)</td>
</tr>
<tr>
<td>9.88°W</td>
<td></td>
</tr>
<tr>
<td>40.34°S</td>
<td></td>
</tr>
<tr>
<td>Mag 43.01°S</td>
<td></td>
</tr>
<tr>
<td><strong>Marion Island</strong></td>
<td>Magnetometers (LEMI), Scintillation and TEC monitor (Novatel), VLF(DVRAS, UltraMSK, Whistler Detector), Tidal Gauge, WWLLN, Dual Frequency GPS Receiver, Seismometer</td>
</tr>
<tr>
<td>37.86°E</td>
<td></td>
</tr>
<tr>
<td>46.87°S</td>
<td></td>
</tr>
<tr>
<td>Mag 52.04°S</td>
<td></td>
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</table>
SANDIMS Data Portal

https://sandims.sansa.org.za/

SANDIMS is the repository of all Geomagnetic, Ionospheric and Magnetospheric data gathered from SANSA Space Science's instrumentation network.

Instrumentation Network

Instruments in the network are grouped into the above three classes, and further sub-classed by Instrument Type, each of which is represented by one or more Instrument Models. Specific instruments so classified are the Field Instruments of the network, which extends throughout South Africa and Namibia, as well as Gough and Marion islands in the southern oceans and the SANAE IV research base in Antarctica. The SANDIMS Metadata Model includes GPS location, manufacturer and Principal Investigator information, as well as technical parameters of the instruments (most importantly sampling interval) and their antennae. Metadata associated with a data bundle may be exported and shared using NASA's DIF v10.0 interchange format.
ESWUA Data Portal

http://eswuax.rm.ingv.it/index.php/polar-sao-paulo

electronic SPACE WEATHER upper atmosphere

HOME ITALY EUROPE ARCTIC ANTARCTICA MEDITERRANEAN SOUTH AMERICA IONORING DOWNLOAD ISMR

ESWUA

Region SOUTHAMERICA Station ISACCO_SA00 Lat -23.55 Lon -46.63 elevation mask 20

UTC

2019-08-18
13:07:45

21 min

S4 vertical
Geographical coverage of SANAE ISM 15 August 2007 00:00 to 23:59 UT
First recording of scintillations using data from the Galileo GNSS system.

First observations of an ionospheric storm using the suite of scintillation receivers deployed by the DemoGRAPE project at SANAE-IV. There is a clear enhancement of phase scintillation ($\sigma_\phi$) on both the L1 and L2E5 frequencies visible on all three GNSS constellations received at SANAE on 1 January 2016, a day with a moderate geomagnetic storm (Dst = -100 nT).
There is a clear enhancement of phase scintillation ($\sigma_\phi$) on both the L1 and L2E5 frequencies visible on all three GNSS constellations received at SANAЕ on 20 January 2016, a day with a moderate geomagnetic storm (Dst = -100 nT).
Storm indicators on 6-10 September 2017

8 Sep 2017
Dst(min) = -124 nT
Frequency of occurrence of ionospheric scintillation observed at SANAE by means of the Septentrio receiver of the DemoGRAPE project at SANAE-IV. There is strong enhancement of amplitude scintillation without any concurrent enhancement in the phase scintillation ($\sigma_\phi$) on L1 on a day with a moderate geomagnetic storm (Dst = -124 nT, AE > 2000 nT).
Scintillations recorded at SANAE on 8 September 2017

Frequency of occurrence of ionospheric scintillation observed at SANAE by means of the Septentrio receiver of the DemoGRAPE project at SANAE-IV. There is strong enhancement of amplitude scintillation without any concurrent enhancement in the phase scintillation ($\sigma_\phi$) on L1 on a day with a moderate geomagnetic storm (Dst = -124 nT, AE > 2000 nT).
Scintillations recorded at CRAAM-INPE 6-8 September 2017
CRAAM-INPE S4 Scintillation occurrence 6-8 September 2017

6-10 Sep 2017
S4>0.15 occurrence = 15%
CRAAM-INPE $\sigma_\phi$ Scintillation occurrence 6-8 September 2017

6-10 Sep 2017
$\sigma_\phi > 0.15$ occurrence = 15%
1. Correlate Scintillation with geomagnetic activity
2. Compare L1 and L2 scintillation levels
3. Compare Galileo, GLONASS, and GPS scintillation
4. Map scintillation IPPs to TEC gradient locations (derived from dTEC & spatial derivatives)
5. Estimate size of structures from spatial distribution of IPPs with $\sigma_\phi >$threshold
6. Estimate scintillation proxies (ROTI, sDPR) from TEC & TEC-rate and correlate with S4 and $\sigma_\phi$
7. Compare error estimates (GDOP, horizontal position error, loss of lock, lock-time) with S4 and $\sigma_\phi$
8. Compare different integration times of $\sigma_\phi$ (1, 3, 10, 30, 60 sec)
9. Compare Signal-to-Noise ratio (C/No) with S4 and $\sigma_\phi$
10. Compare SI index with S4 and $\sigma_\phi$
11. Compare spectral indices ($p$, $T$) with scintillation intensity and size of scintillation structures
12. Estimate drift velocity and ionospheric height from comparison of S4 and ROTI.
13. Estimate the influence of base vibration (due to wind gusts) on S4 and $\sigma_\phi$
14. Develop azimuth-dependent elevation threshold map to reduce multipath.
Student Projects using data from DemoGRAPE

- **Politecnico di Torino (Feb 2019):**
  - 1 Internship, 1 MS thesis, 1 BS thesis, 1 student project, 2 PhD
  - MS theses:
    - *Ariel Belga Fedeli,* “An open-loop receiver architecture for monitoring of ionospheric scintillations by means of GNSS signals”
    - *Chunhui Li,* “GNSS Data processing and characterization of ionospheric scintillations”
  - PhD theses: “Innovative machine learning techniques for scintillation detection and mitigation.”
    - *Rayan Imam*
    - *Caner Savas*
Student Projects related to DemoGRAPE

• **INGV:**

• 2 PhD (TREASURE) students:

  • *Juliana Damaceno:* “Forecasting model of TEC and scintillation parameters”

  • *Hossien Gobadi:* “Disentangling refractive from diffractive contribution in GNSS scintillation.”
Conclusions

• The DemoGRAPE multi-instrument GNSS data recorded since 2015 provides a valuable resource that has been used in several research projects and publications.

• New developments have improved the real-time access to the data.

• The new instruments continue to provide new research opportunities at international level in Antarctica, and will further global partnerships in Space Research.
Publications(1)


8. Linty, N. and Hunstad, I., 2016. Installation and configuration of an ionospheric scintillation monitoring station based on GNSS receivers in Antarctica. Rapporti Tecnici-INGV


Acknowledgement

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  – the Italian Ministry of Education, Universities and Research
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  – the Italian National Research Programme for Antarctica
    (Programma Nazionale di Ricerche in Antartide, PNRA), in the
    framework of the DemoGRAPE project, under contract
    2013/C3.01.

• This work is also based on research supported by the South
  African National Research Foundation through Grant 93084
  to the South African National Space Agency.

• The DemoGRAPE equipment at SANAE IV was installed, and
  is maintained by the Engineering and Data Acquisition Unit
  of SANSA Space Science under the leadership of Dr Gert
  Lamprecht and Mr Jonathan Ward.
Thank you for your attention

SANSA – in service of humanity