Raw GNSS data grabbing and software receivers: a solution to make an Ionospheric Scintillation Monitoring Receiver a multifold analysis platform

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POLITECNICO DI TORINO

BSS 2016 | Trieste (Italy) | June 29, 2016

Outline

- **Introduction**
- SDR approach and benefits
- An example of application
- Results and comparisons
- Final remarks

Why looking at different ways to monitor the ionosphere

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- GNSS-based monitoring of the ionosphere is a consolidated technique

Why looking at different ways to monitor the ionosphere

- GNSS-based monitoring of the ionosphere is a consolidated technique
- However, there are some open issues we should address

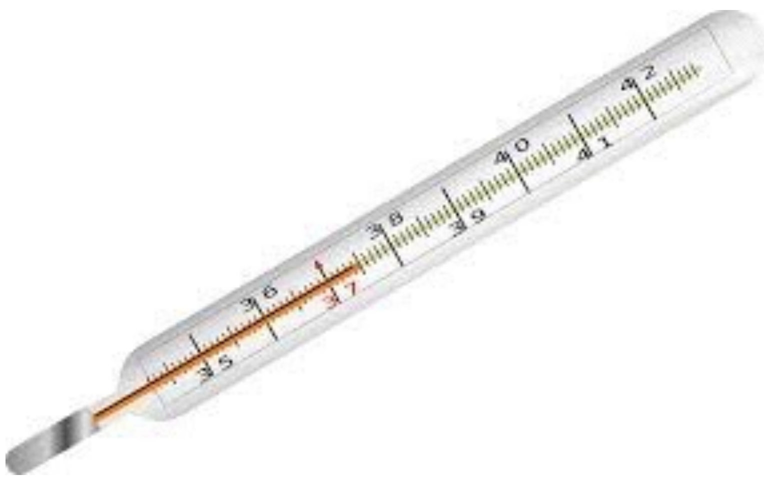
Issue #1

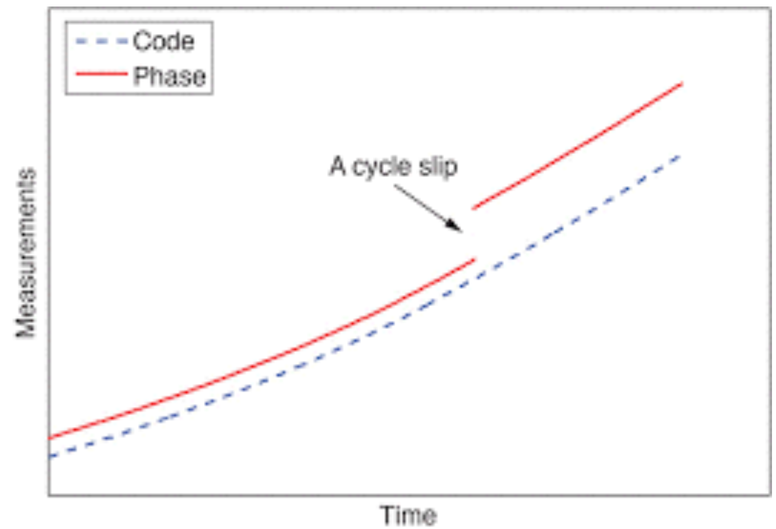
Issue #1

- *How is the ionosphere doing?*

Issue #1

- *How is the ionosphere doing?*
  - we see the ionosphere *through the eyes* of the GNSS receiver





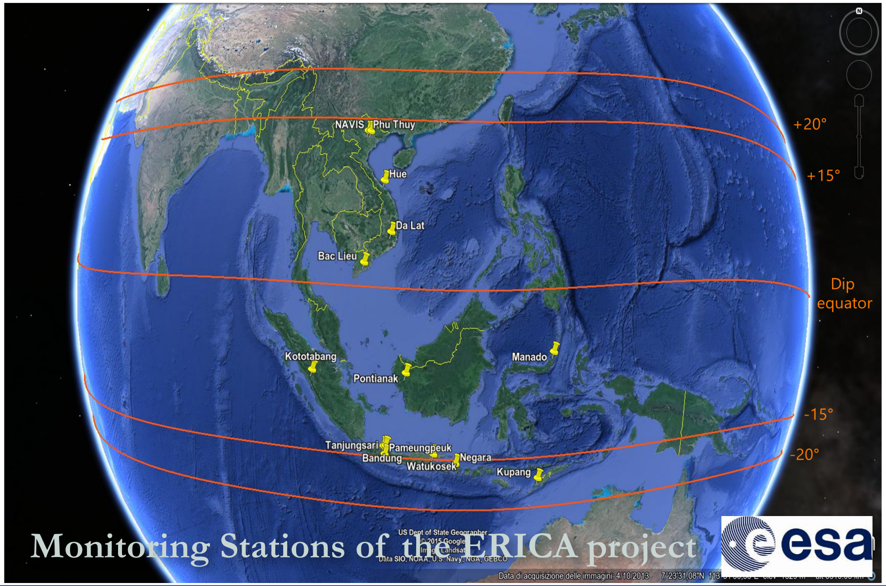
Issue #2

Issue #2

- Ionosphere behaviour is interesting in areas where it is hard to set monitoring stations

Start: 1 March 2015

Stop: 9 October2015



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Ionospheric scintillation monitoring

- **TEC** (total electron content), TEC gradients,…
- **S4** index for amplitude scintillation: normalized standard deviation of the received Signal Intensity (SI)
- **Phi60** (phase deviation) index for phase scintillation: standard deviation of the detrended carrier phase measurements

Ionospheric Scintillation Monitoring Receivers (ISMR) – hardware

Ionospheric scintillation monitoring

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- **Open the box:** knowledge of the implemented signal processing

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- **Have access to physical signal,** as much as possible

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- **New parameters to monitor** possibly giving different useful information on the physics of the atmosphere

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- **Have access to physical signal,** as much as possible
- **New parameters to monitor** possibly giving different useful information on the physics of the atmosphere
- **Possibly cheaper**

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Radio front-ends and Software Defined Radio (SDR) GNSS Receivers

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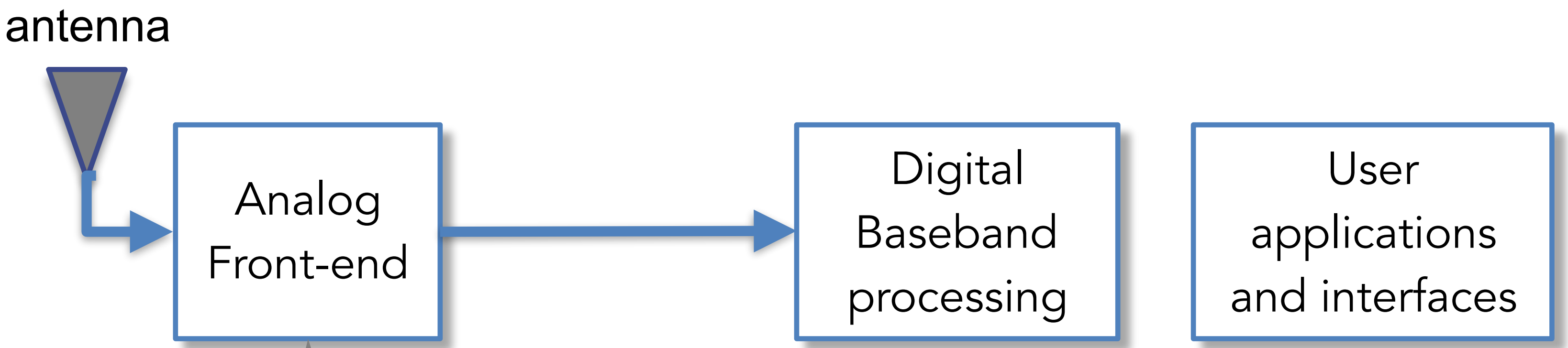
Ionospheric Scintillation Monitoring Receivers (ISMR) – hardware

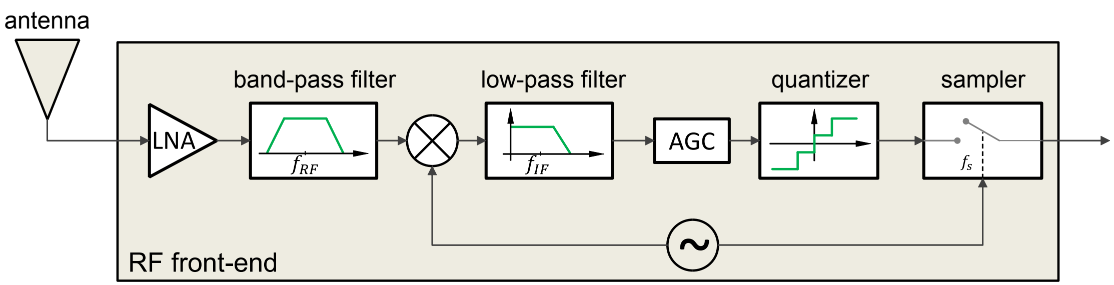
Radio front-ends and Software Defined Radio (SDR) GNSS Receivers

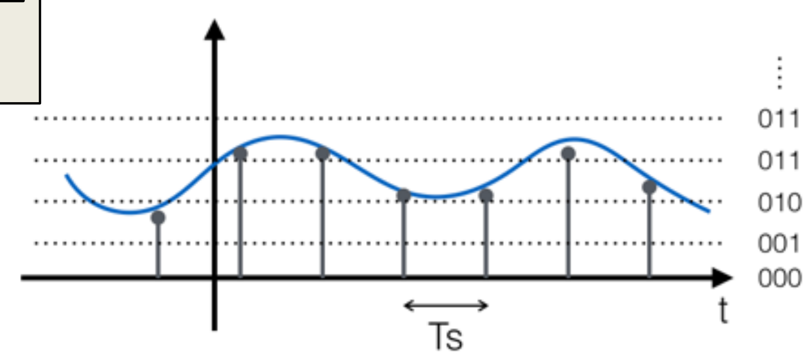
Ensemble of hardware and software technologies, enabling reconfigurable communication architectures

HW receiver architecture

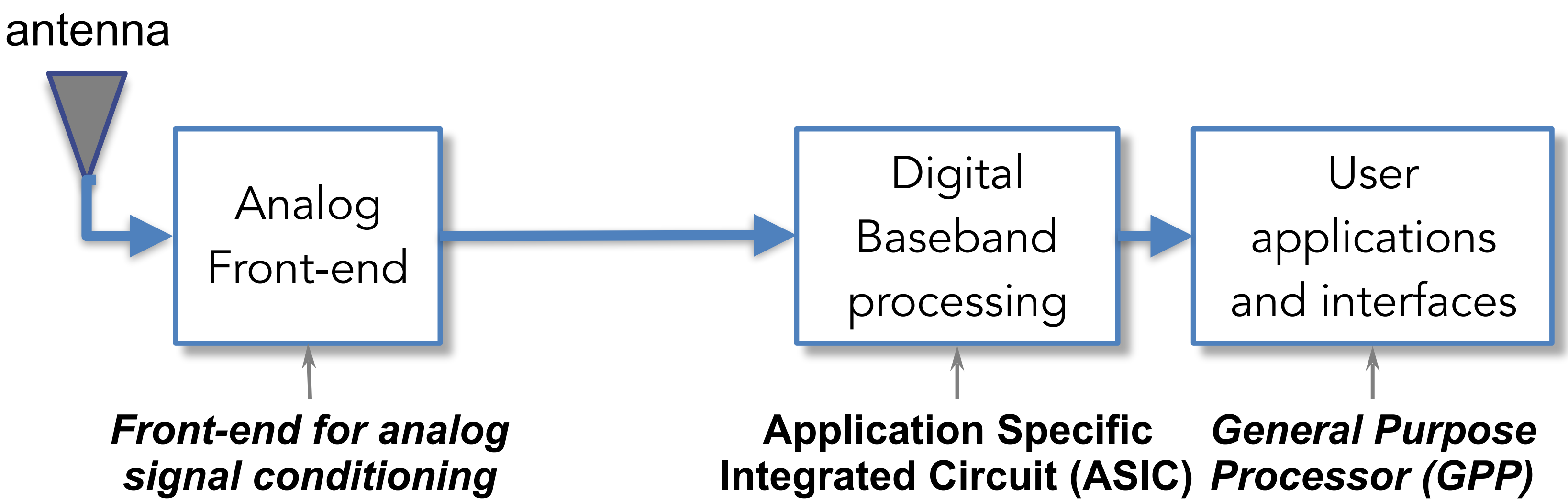


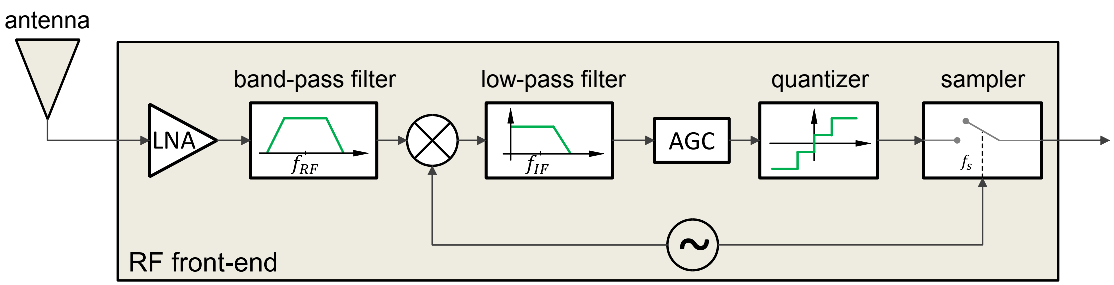
Front-end for analog signal conditioning

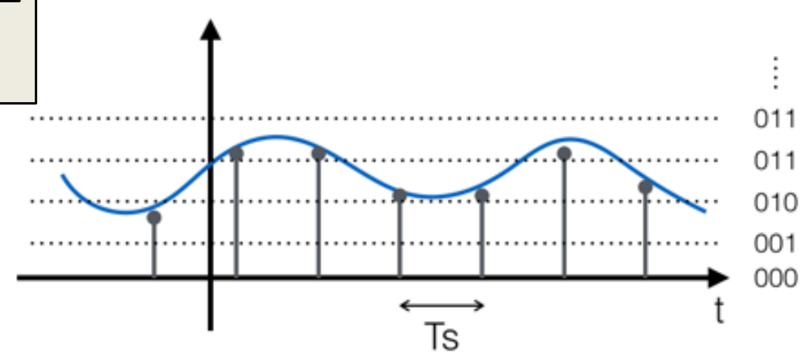




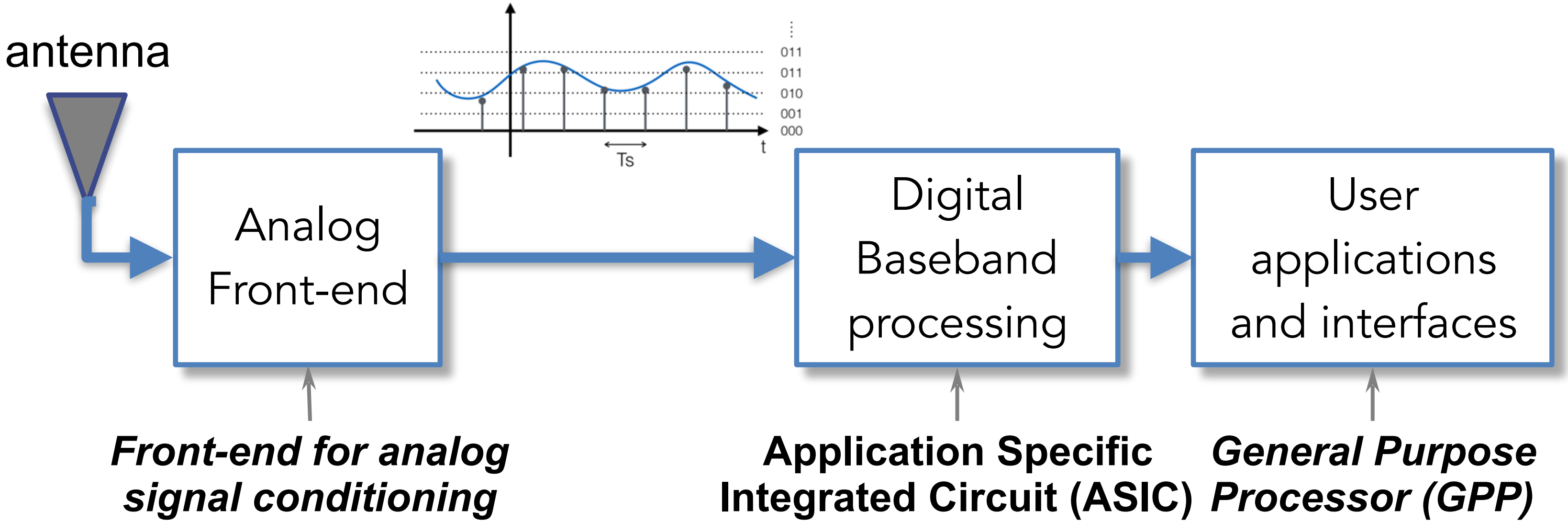
HW receiver architecture



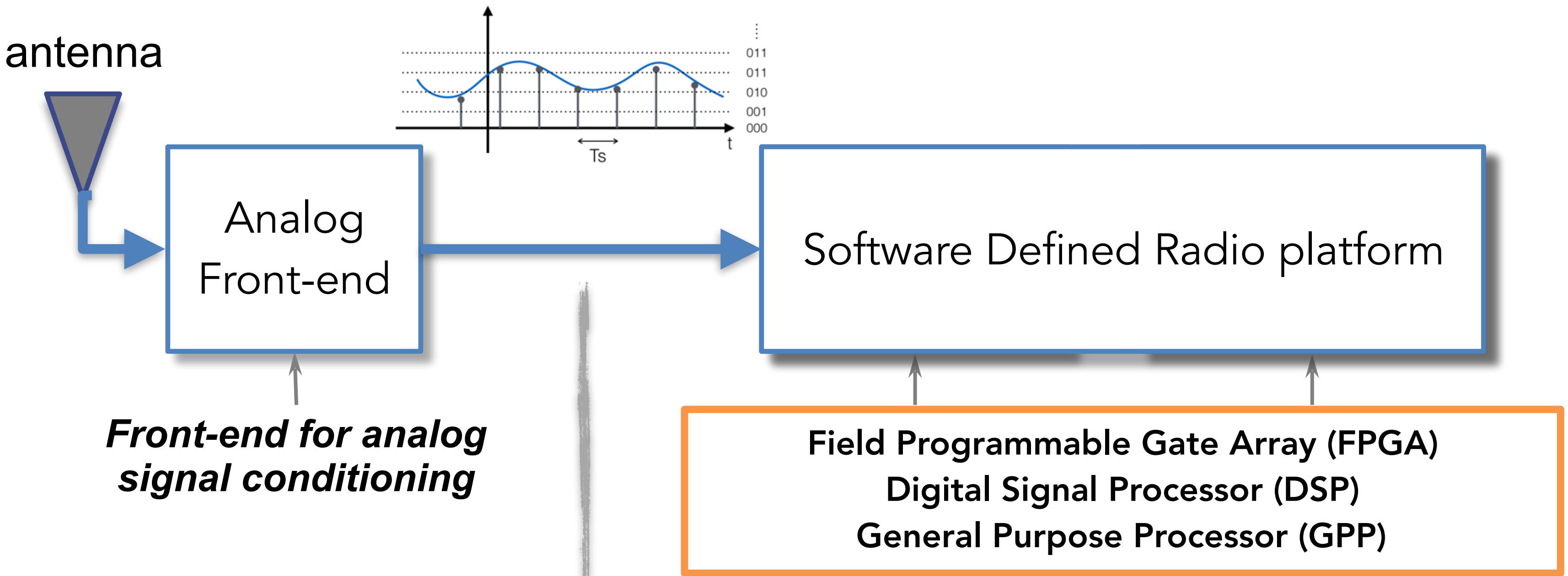




From HW to SW receiver



From HW to SW receiver



- Signal samples at f_s
- Quantised (1 bit -2 bytes)
- Stored as a binary file

- **Software defined:** FPGA + DSP + PC
- **Fully software:** GPP

- 1 minute = several Gb of data!!

Front ends

- The popularity of software radio in communications brought to the availability on the market of several low cost solutions for the ADC stages
- Clock and front-end synchronisation are of paramount importance to preserve the information
  - A good external clock source is needed
  - Careful settings for multi band data grabbing
  - The front-end quality fixes the constraints for the following processing (e.g. Bandwidth, quantisation levels)

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Advantages for GNSS processing

- Availability of **raw IF data**
  - They can be **post-processed** or **re-played**
  - "Different receivers" can work on the same scenario
- High **flexibility** and **configurability** of station
  - Full access to the receiver architectural configuration
  - The platform is not one receiver but almost any receiver that you want
    - Multiconstellation, loop orders, acquisition strategies,…
  - Advanced algorithms for processing: e.g. multipath reduction
- Shorted development time and **lower cost** (tailored to specific application) and possibility to have a network of SDR receivers

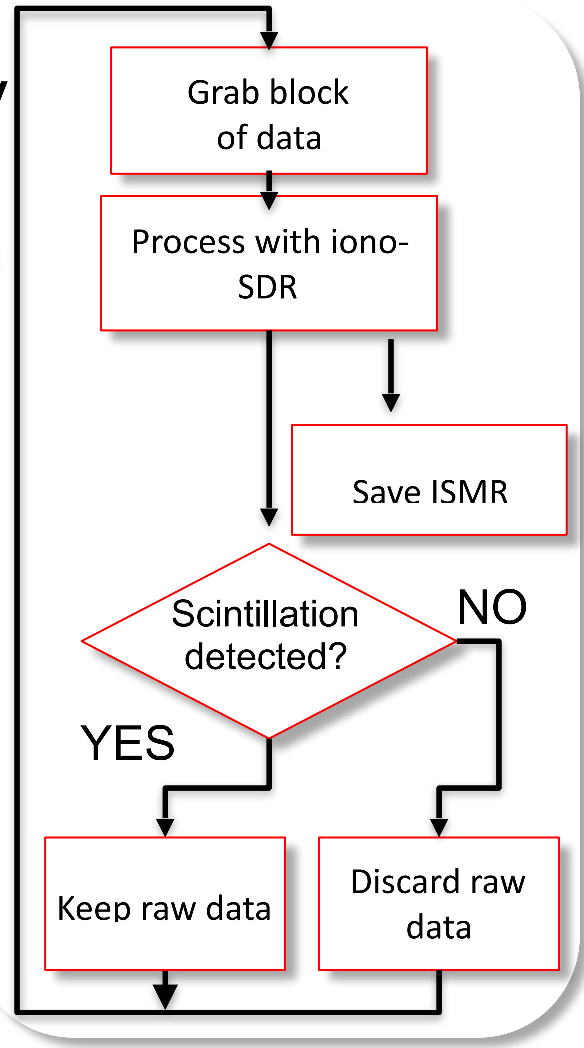
Advantages for GNSS processing

- As for the **ionosphere monitoring**
  - finer study of the impact of the ionosphere on the signal degradation
  - Implementation and test of innovative algorithms tailored to ionosphere monitoring
  - **Remote processing** (see later…)
  - **Re-play** of interesting scenarios

The bottleneck of data storage

- The amount of stored raw data is a **tradeoff between loss of information and storage capability**
  - USRP, 5 MHz, IQ, 16 bits, L1+L2 →**144 GB/hour**
  - postcorrelation data (ISMR, RINEX, …) →**30 MB/h**

- A **policy for raw data storage** is needed
  - **what and when** (event related)
    - automatic triggering based on rough estimation of scintillation parameters
    - regularity in time of the events
  - **where**
    - local storage units
    - data transfer?



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- Network and bandwidth resources are limited, expensive, especially in critical areas
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  - Raw data can be transferred moving the storage memories where they are recorded
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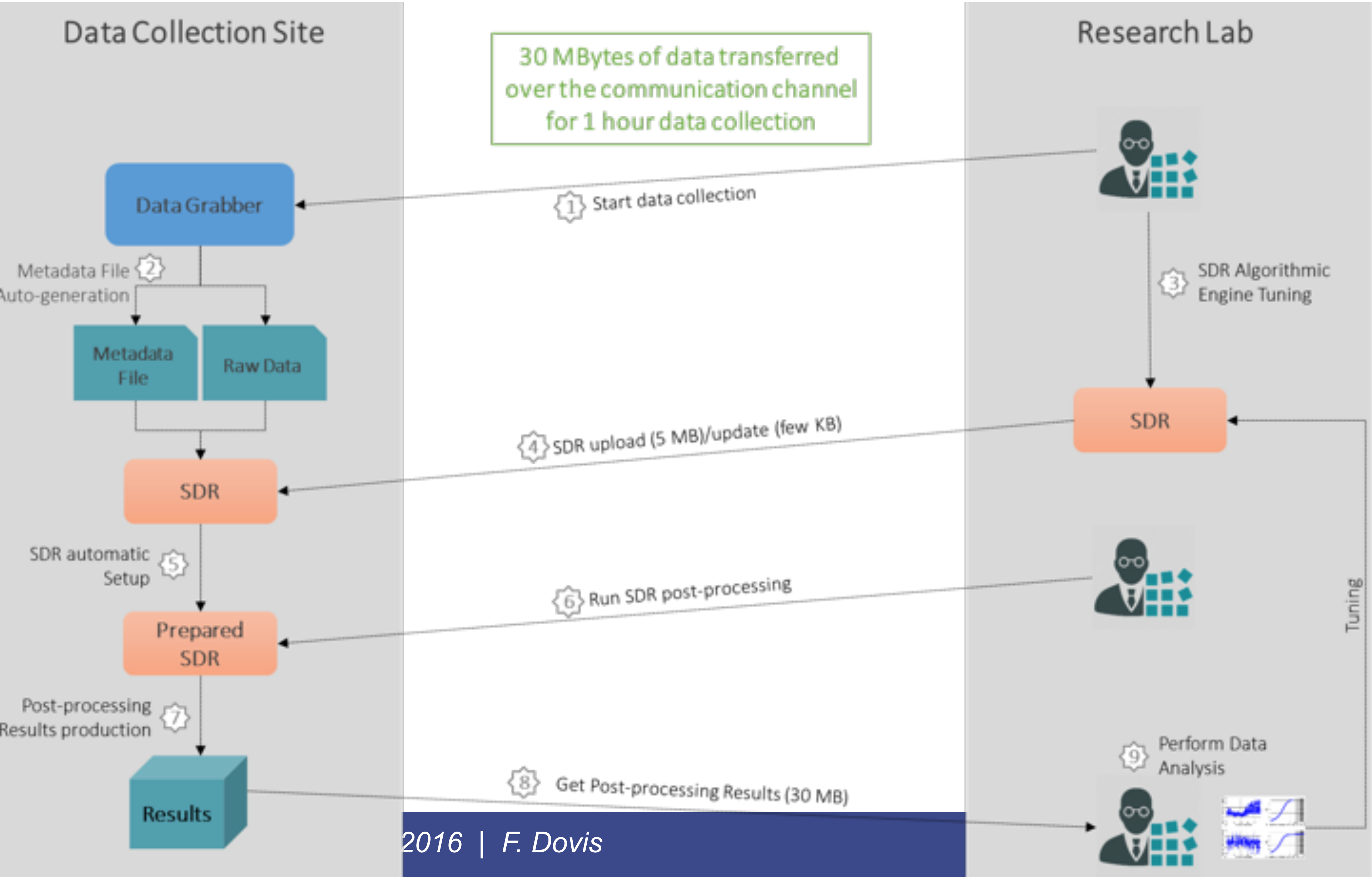
- Remote processing:
  - paradigm shift from "moving data" to "moving software"
  - exploiting meta-data and SDR

ION GNSS
SDR standard
working group

Example of remote post-processing



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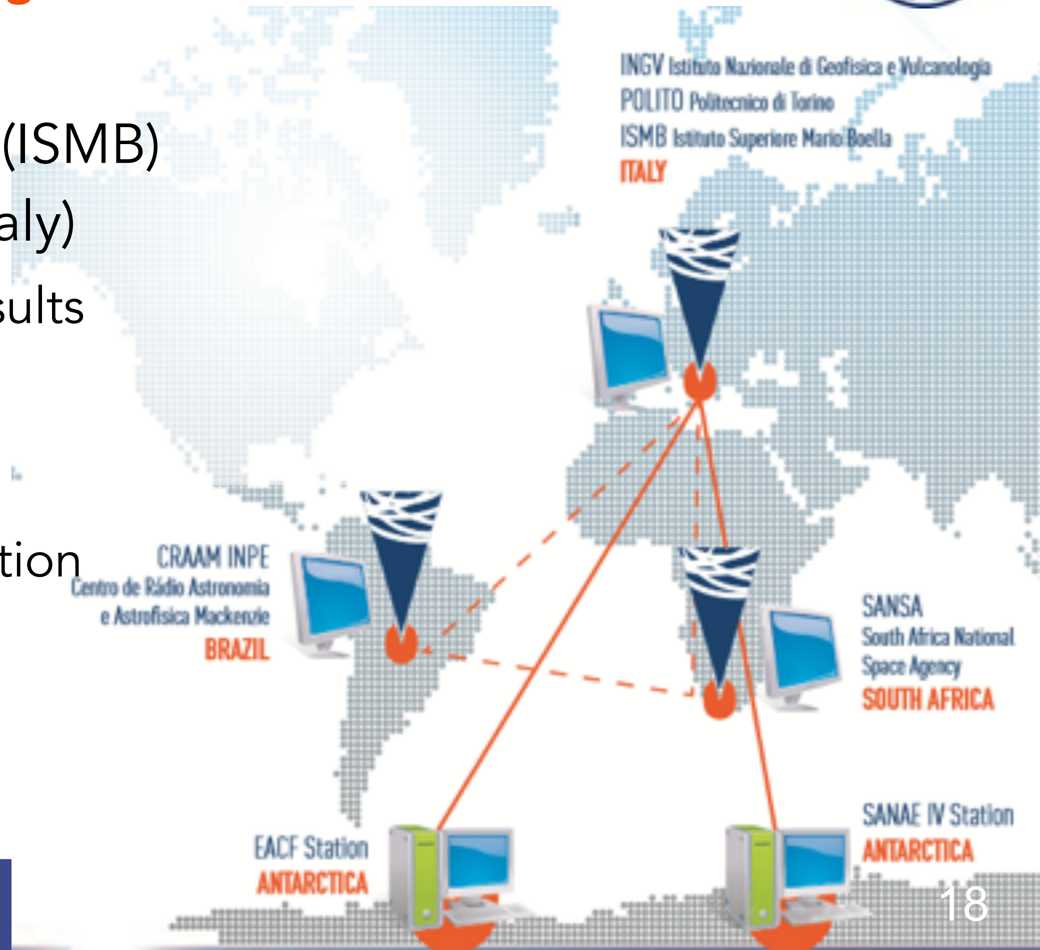
DemoGRAPE

- Objective: improve quality of GNSS position solution in polar regions
- Italian project founded by PNRA with **international** partners
- Permanent **ionosphere monitoring stations** installed in two Antarctica stations
- A federated **cloud infrastructure** (ISMB) (nodes in Brazil, South-Africa, Italy)
  - to efficiently share data and results
- A **demonstrator**
  - running processors
  - assessing ionospheric propagation impact on GNSS signals



http://www.demogrape.net

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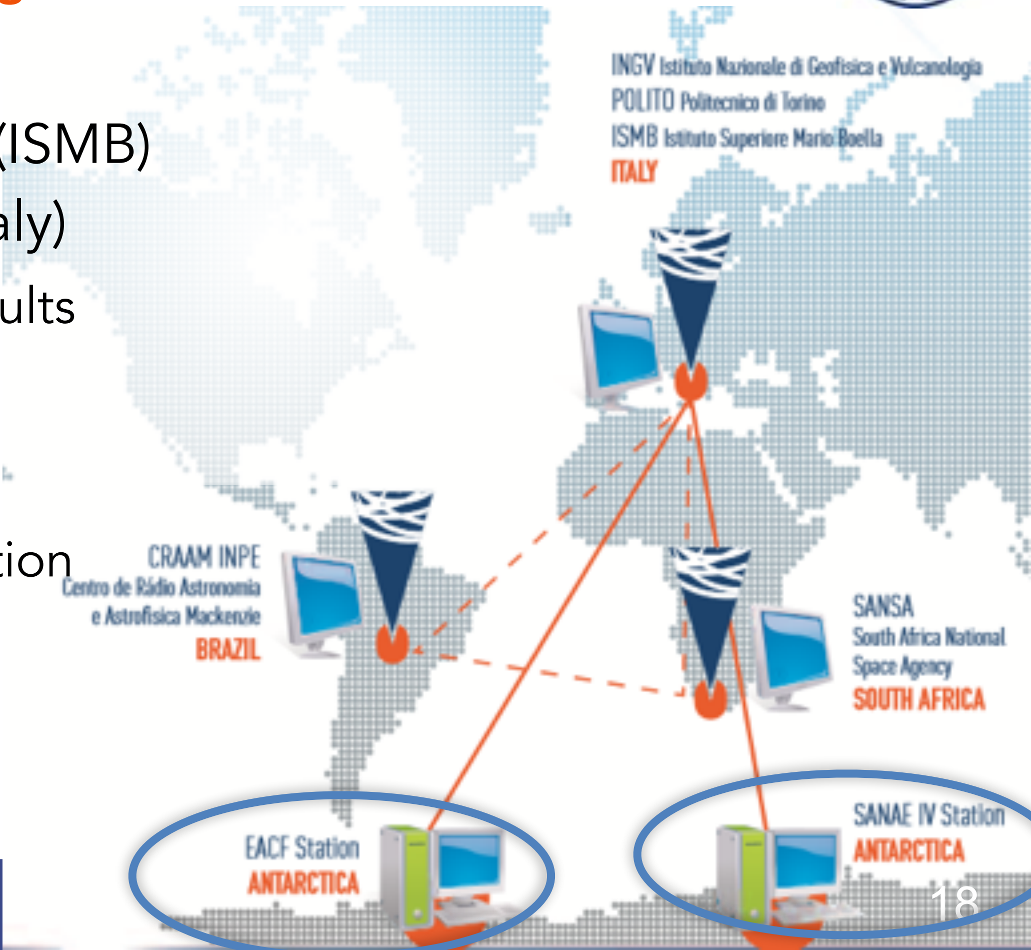

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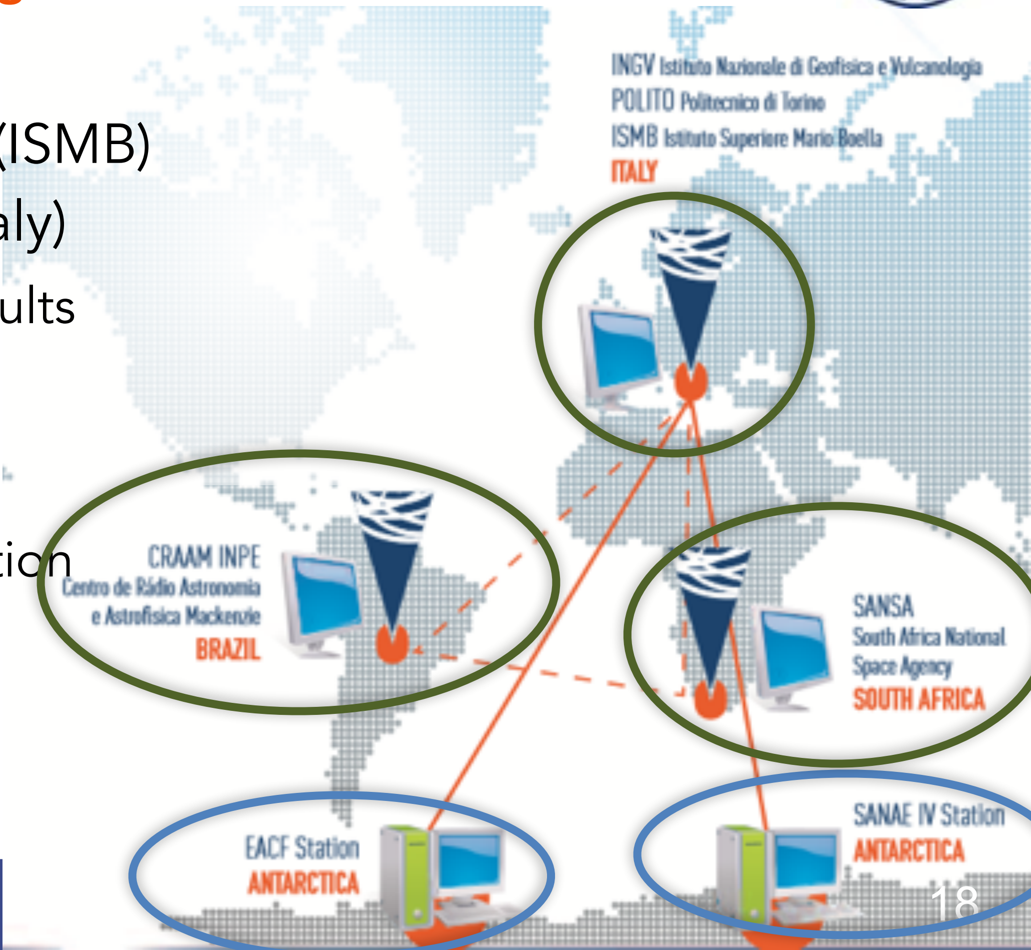


http://www.demogrape.net

First expedition: EACF

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

October 23 – November 24, 2015

62° 05’ 07’’ S
58° 23’ 29’’ W

EACF installation

- XXXI Italian Expedition of the Italian National Antarctica Research Program (PNRA)
- Cooperation with the Brazilian National Institute for Space Research (INPE)

Ionosphere monitoring station

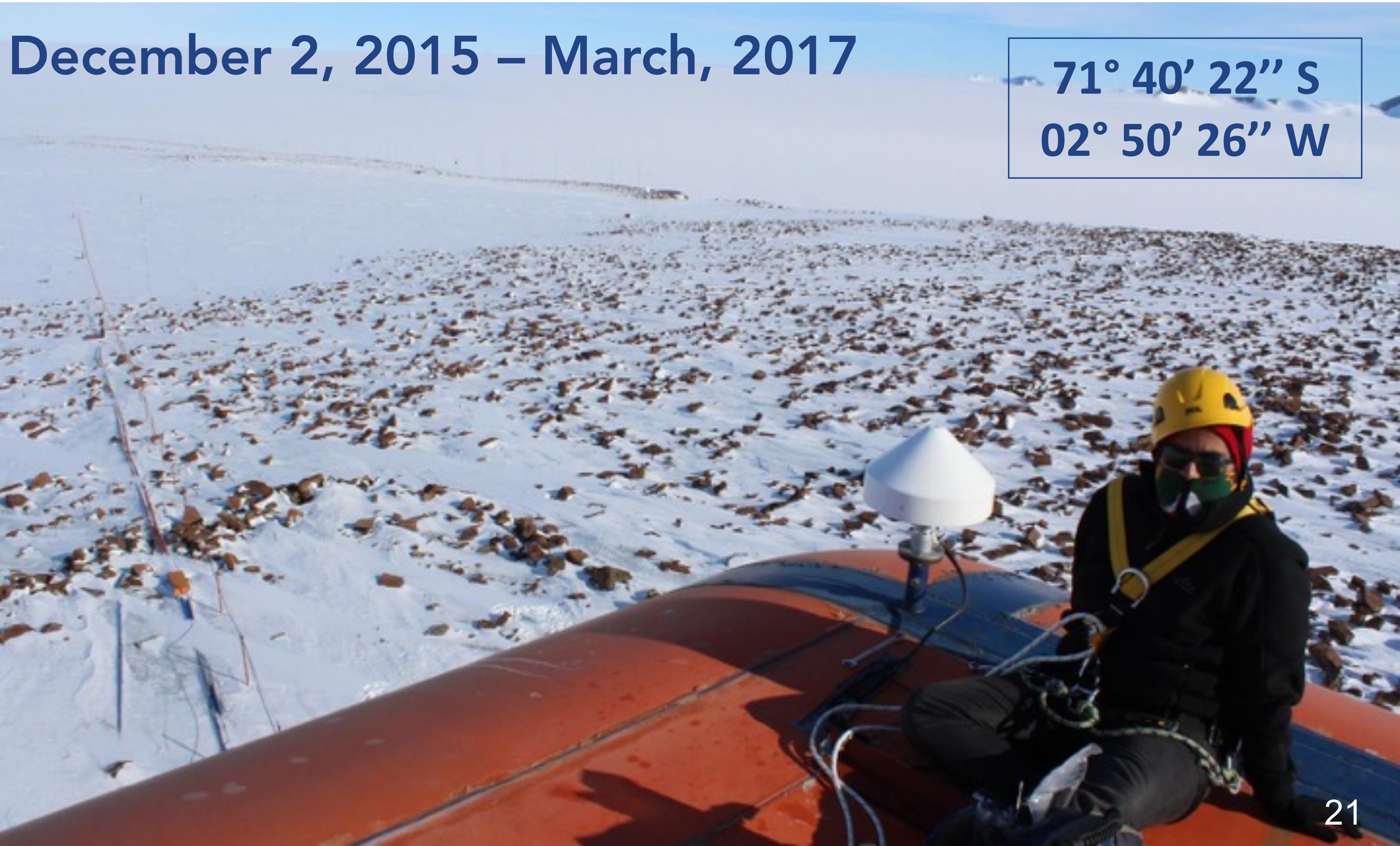
GNSS antenna

Second expedition: SANAE IV

Queen Maud Land Region, Eastern Antarctica

December 2, 2015 – March, 2017

71° 40’ 22’’ S
02° 50’ 26’’ W



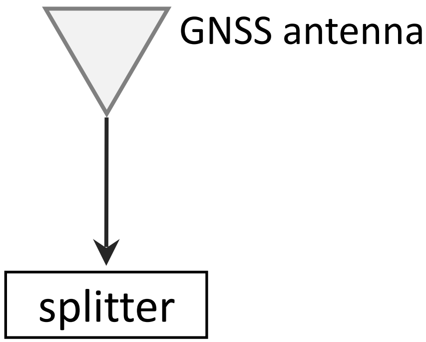
SANAE IV installation

- Cooperation with the South African National space Agency (SANSA) and South African national Antarctic Program (SANAP)

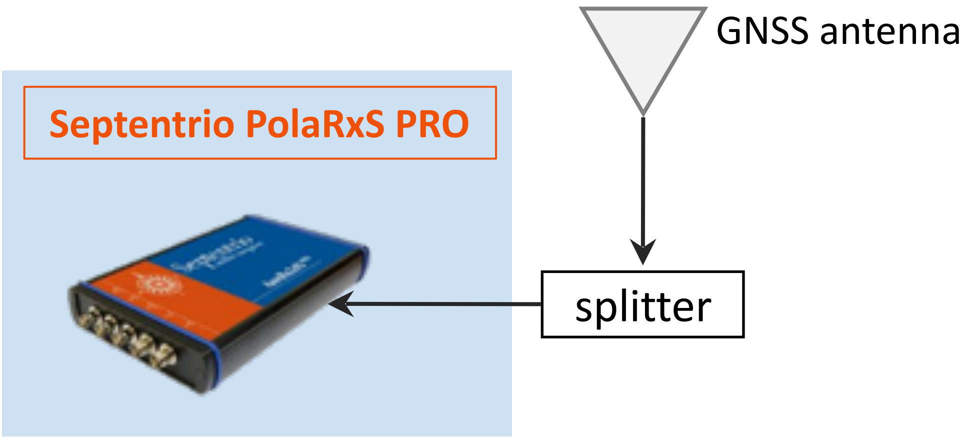
Ionosphere monitoring station

GNSS antenna

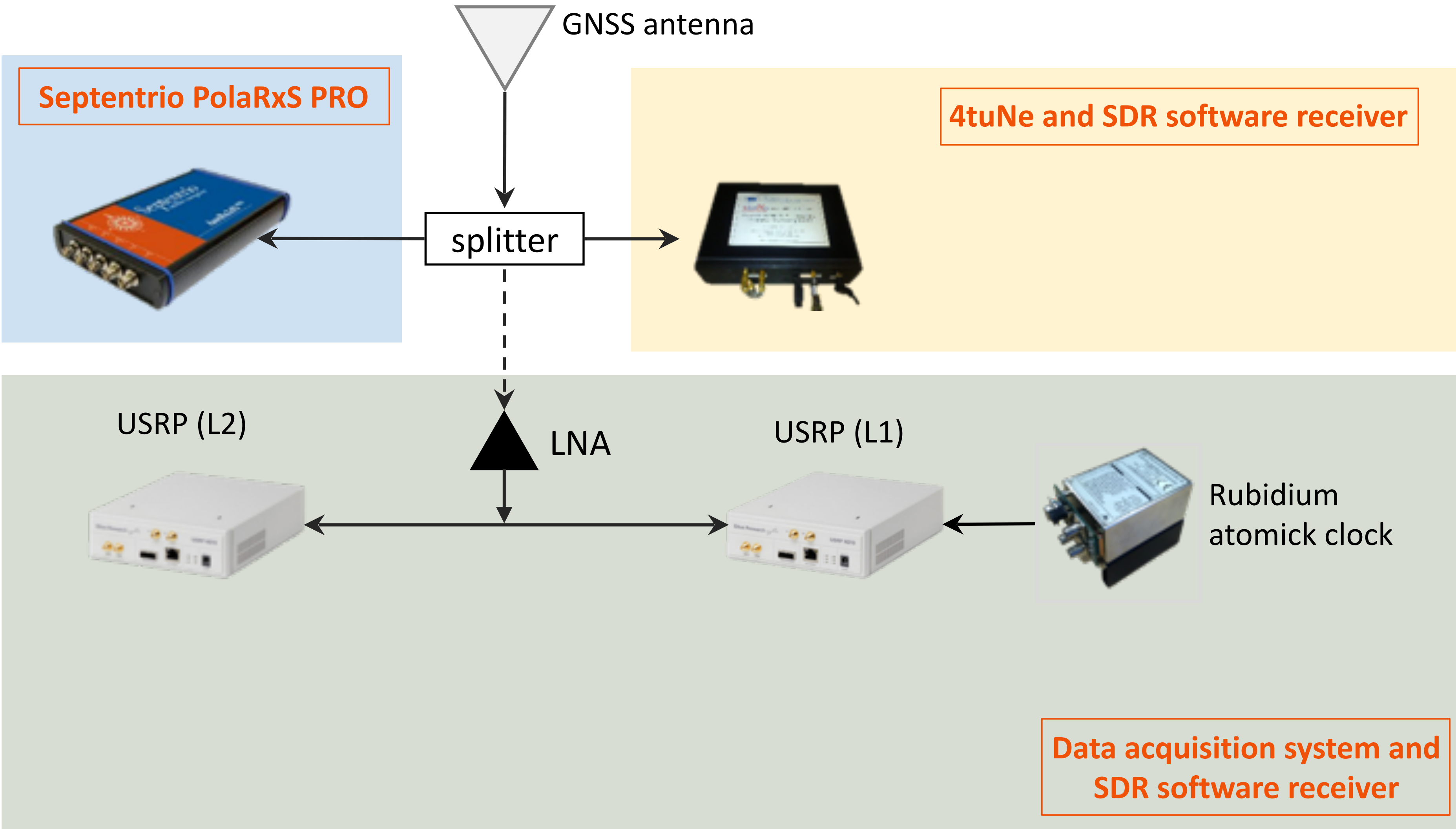
Antarctica stations set-up



Antarctica stations set-up



Antarctica stations set-up



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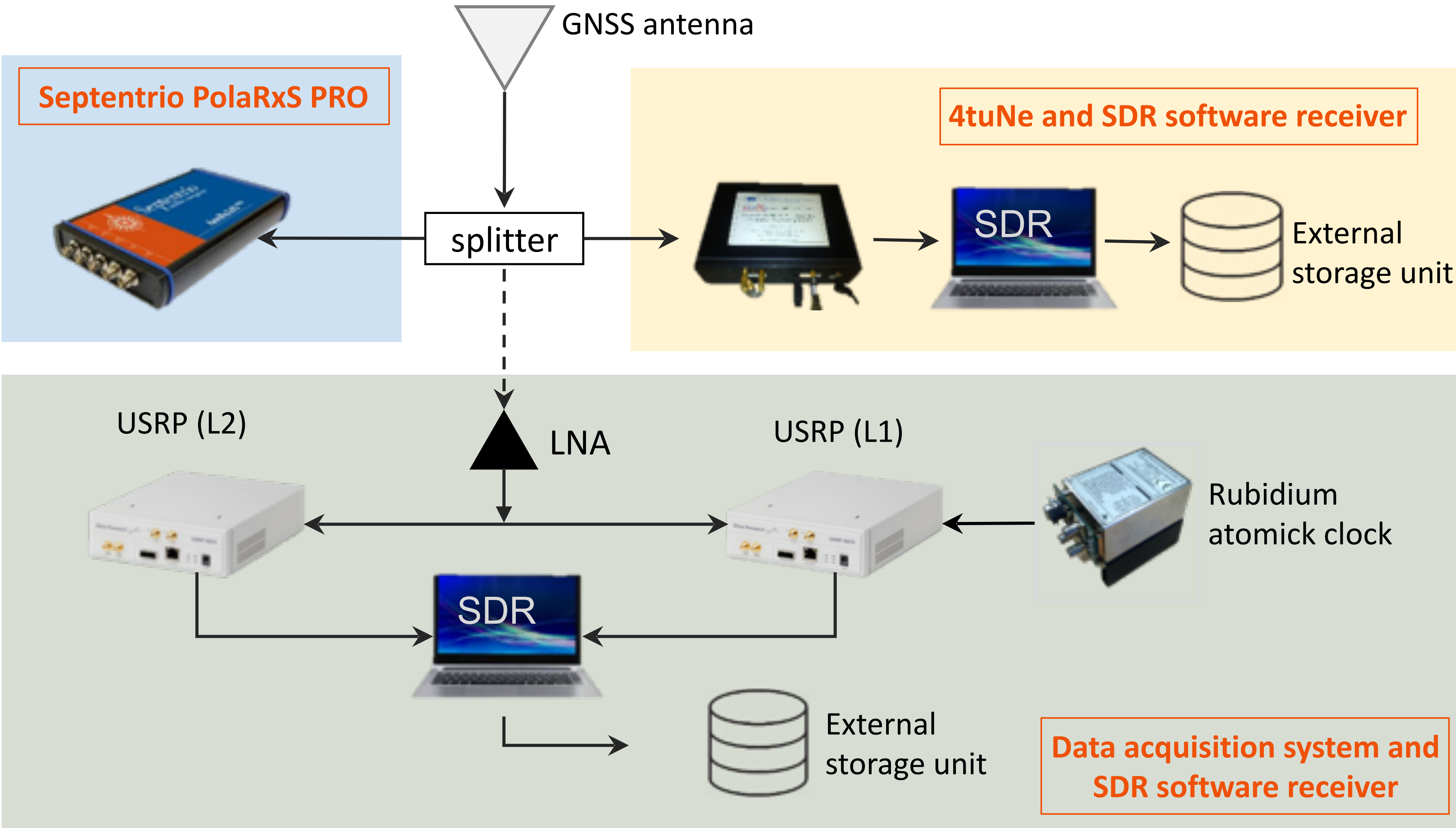

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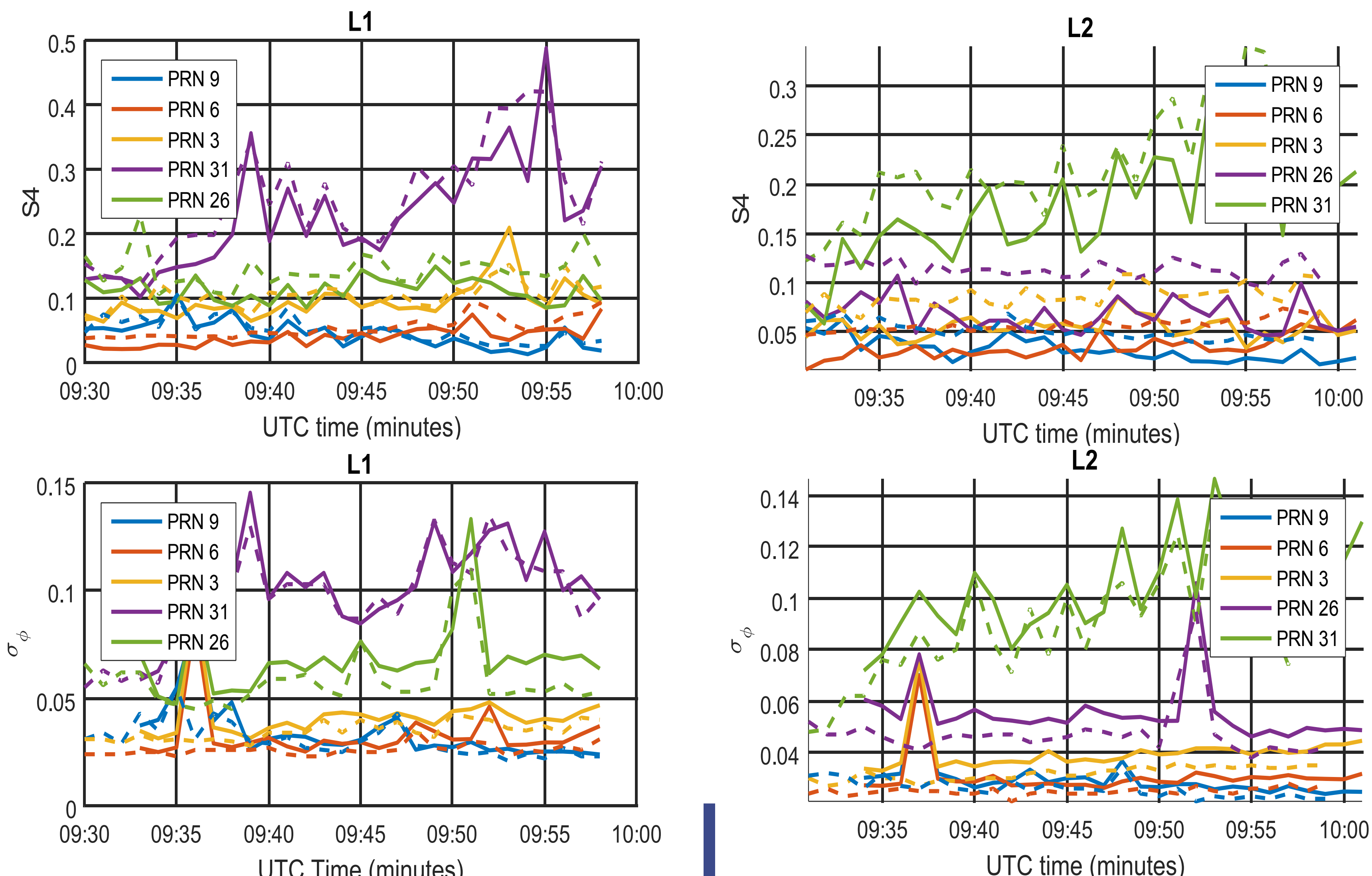
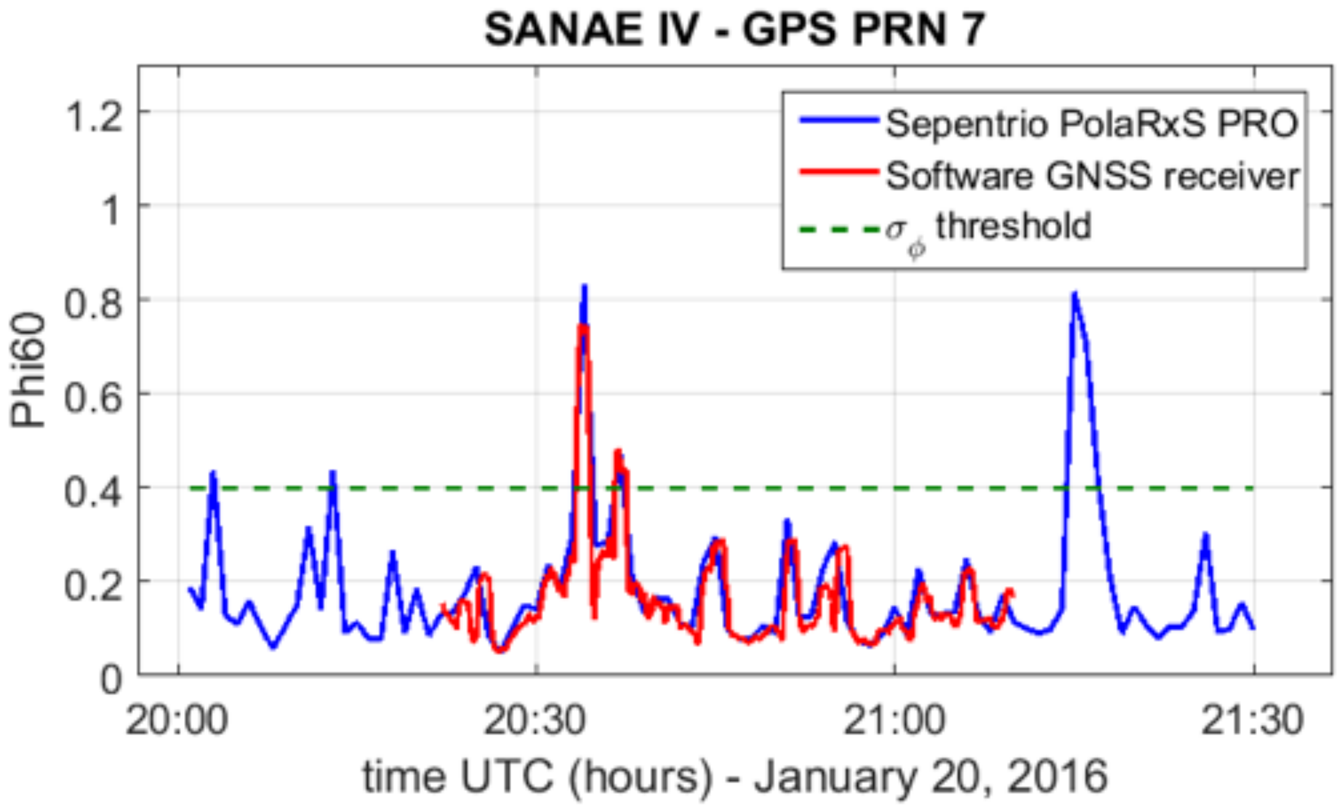
System validation (EACF)

Coherency between receivers (USRP+SDR vs Septentrio)



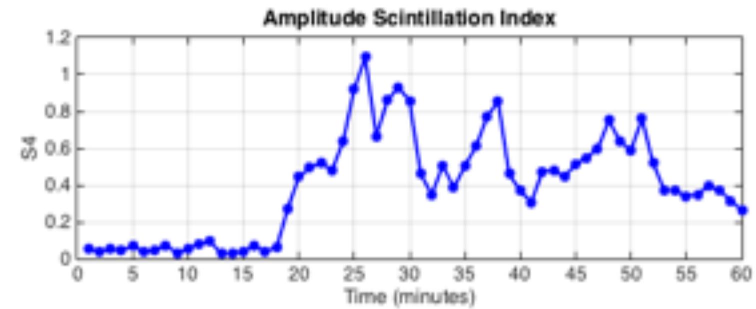
Event monitoring

- Phase scintillation detected
- Higher σ_{ϕ} *output rate* for the SDR-based receiver (1 s vs 60 s)

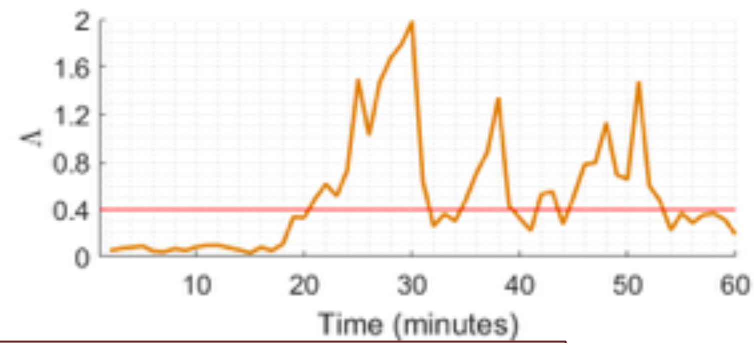


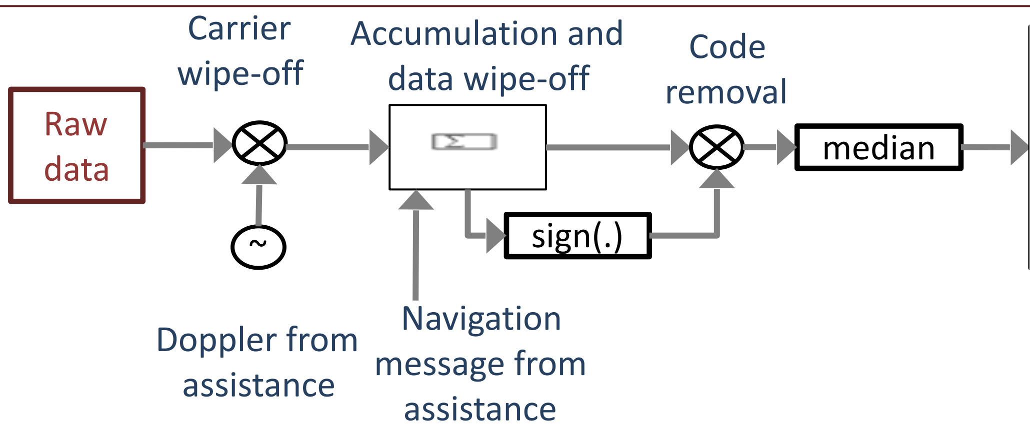
New RX monitoring architectures

S4 Reference



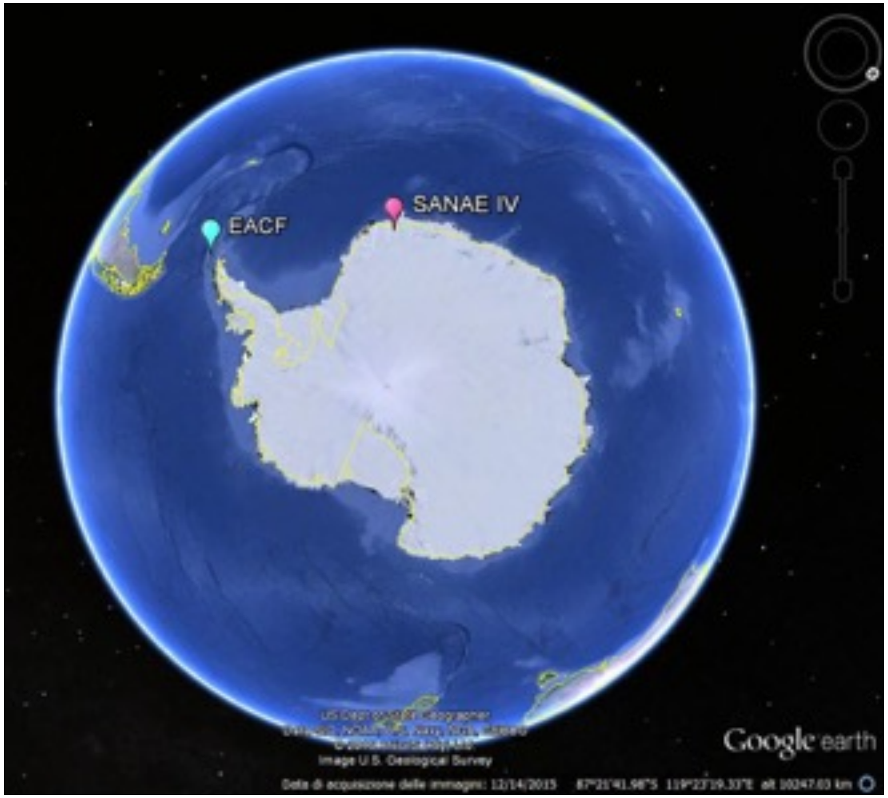
New metric based on the **Skewness** of the samples distribution (measure of the asymmetry of the probability density function)

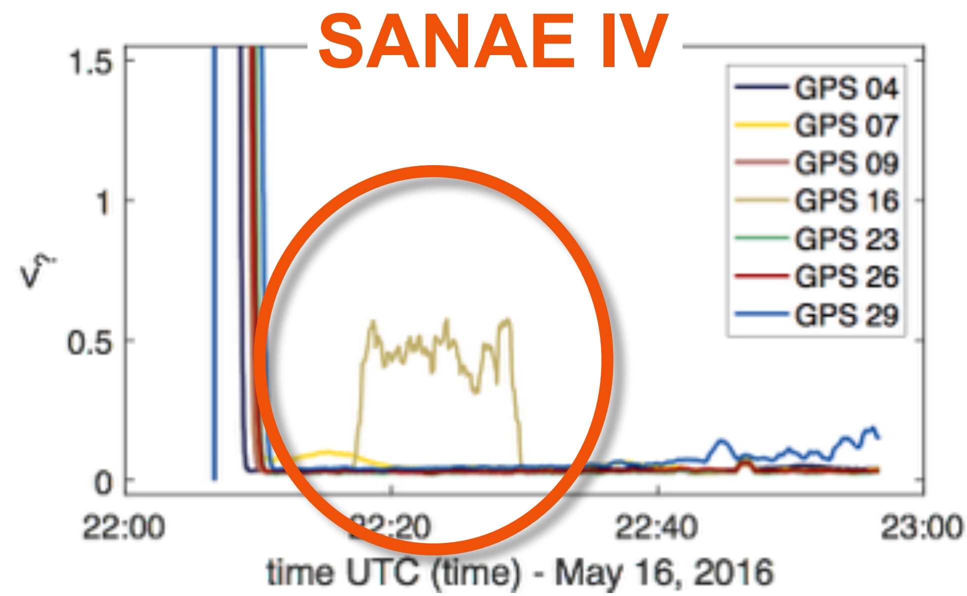


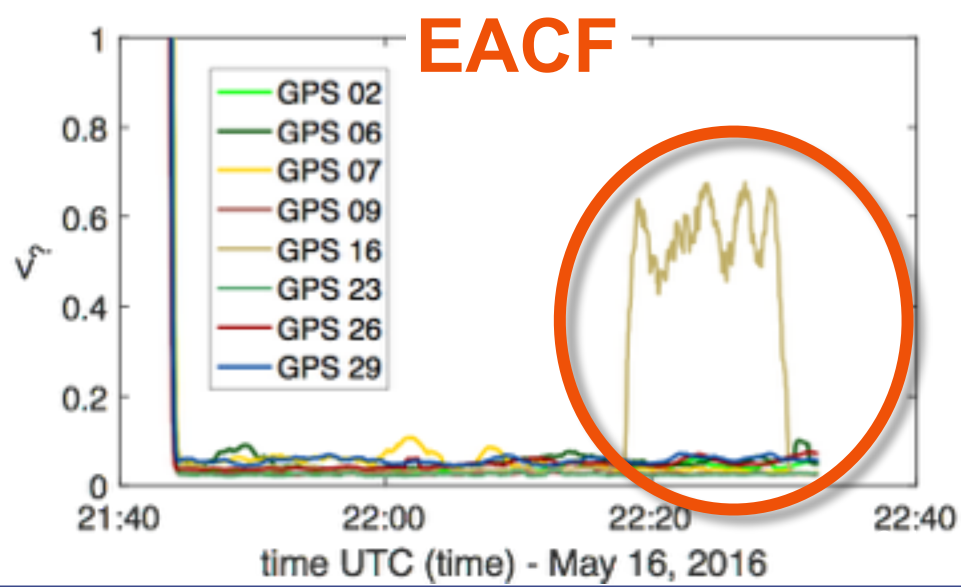


Open loop architecture robust to strong amplitude scintillation

Multi-sites observations: clock anomaly







- 2560 km apart
- different geomagnetic latitude

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Final remarks

- The data grabber + SDR approach can provide **consistent and reliable results**, in agreement with professional receiver
- SDR is emerging more than ever as a valuable **lower-cost** alternative to traditional hardware monitoring receivers
- The capability to record **raw IF samples** is a **great added value** in regions such as polar or equatorial areas
- The SDR approach opens up **new possibilities** for the scientific community
  - reprocessing valuable information
  - deeper insights into physics of the ionosphere
  - increase the density of the monitoring network

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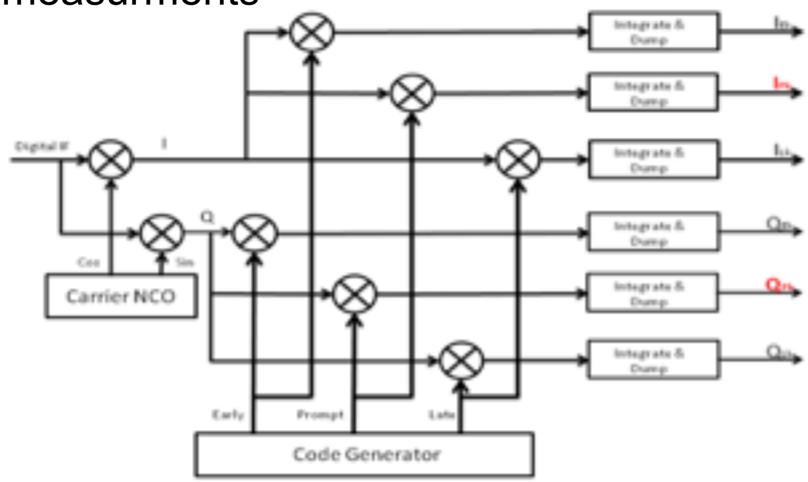
Backup slides

Measuring Amplitude Scintillations

Receiver channel for amplitude measurments



Raw signal intensity samples can be calculated on the basis of the *Narrow Band Power* (*NBP*) and *Wide Band Power* (*WBP*)

$$NBP = \left(\sum_{k=1}^{M} I_k\right)^2 + \left(\sum_{k=1}^{M} Q_k\right)^2$$

Difference between *NBP* and *WBP* is proportional to received signal power.

$$SI_{\mathrm{raw}} = NBP - WBP$$

Total S4 is standard deviation of normalized SI

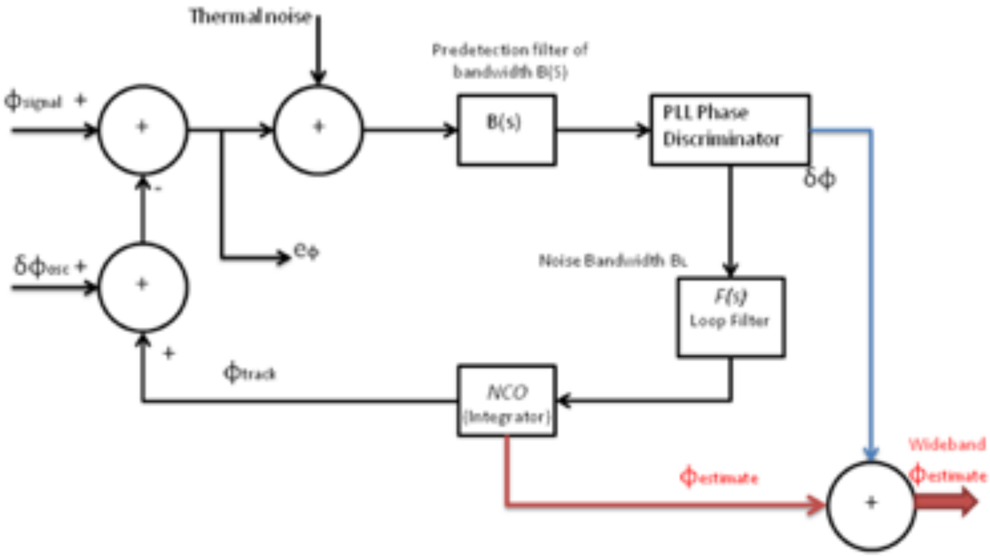
$$S4 = \sqrt{\frac{\langle SI^2\rangle - \langle SI\rangle^2}{\langle SI\rangle^2}}$$

Corrected S4 takes into account the receiver noise contribution and removes it

$$S4_c = \sqrt{\frac{\langle SI^2\rangle - \langle SI\rangle^2}{\langle SI\rangle^2} - \frac{100}{S/N_0}\left[1 + \frac{500}{S/N_0}\right]}$$

Measuring Phase Scintillations

Receiver diagram for phase measurements



- The Phase Lock Loop (PLL) is the weakest link in the receiver chain.
- A narrow bandwidth makes it more robust but filters out higher frequency phase scintillation effects.
- By adding the current phase error back on to the phase estimate, the loop can be configured to have narrow loop bandwidth for robustness but still provide wide bandwidth phase data.

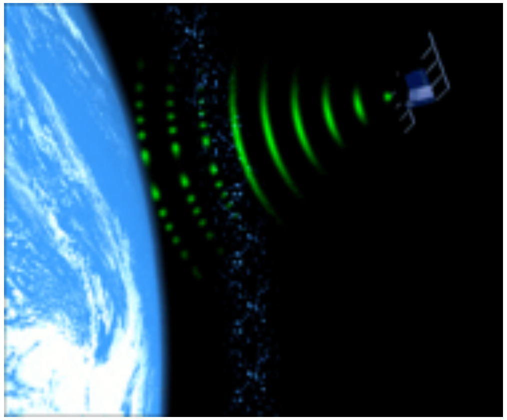
- Though $\delta\varphi(t)$ cannot be measured directly by the receiver, it can be estimated by detrending the carrier phase measurements with a 6^{th} order butterworth high pass filter.

What is a raw data

- sequence of digital samples
- at a certain sampling frequency f_s
- Quantized on a certain number of bits (form 1 bit up to 2 bytes)
  - Down-converted at IF
  - Stored in memory as binary file
  - Ideal for post-processing
  - **Big files:** 10 minutes of L1 raw data, f_s = 16 MHz, char format → 10 GB

Ionospheric Scintillations

- Rapid fluctuations in the received signal amplitude and phase, originating from a scattering effect in the ionosphere due irregular electron concentration
- Intensity depends on solar and geomagnetic activity, seasons, time, signal frequency and latitude



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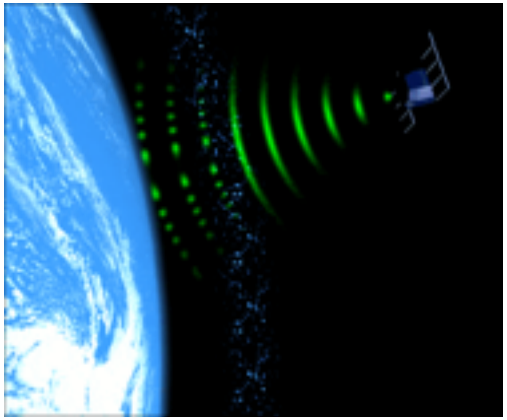

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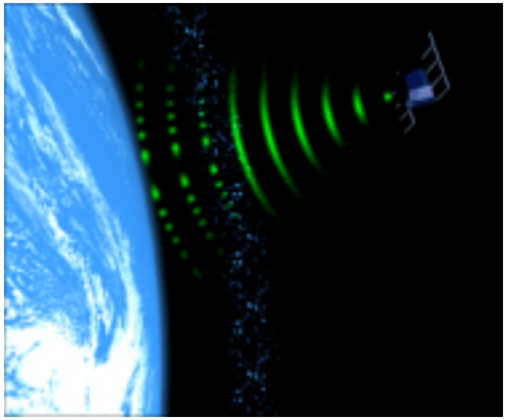
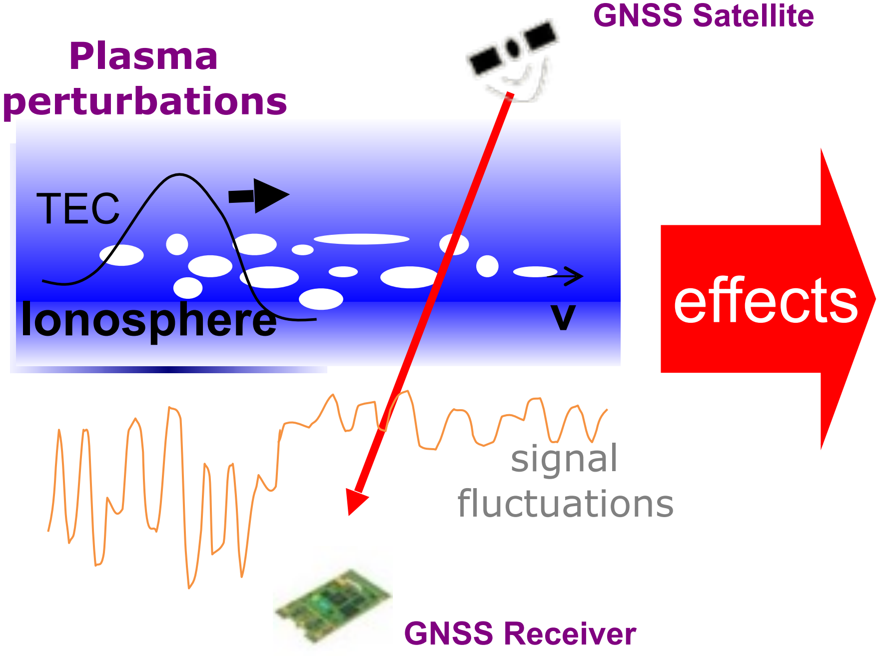
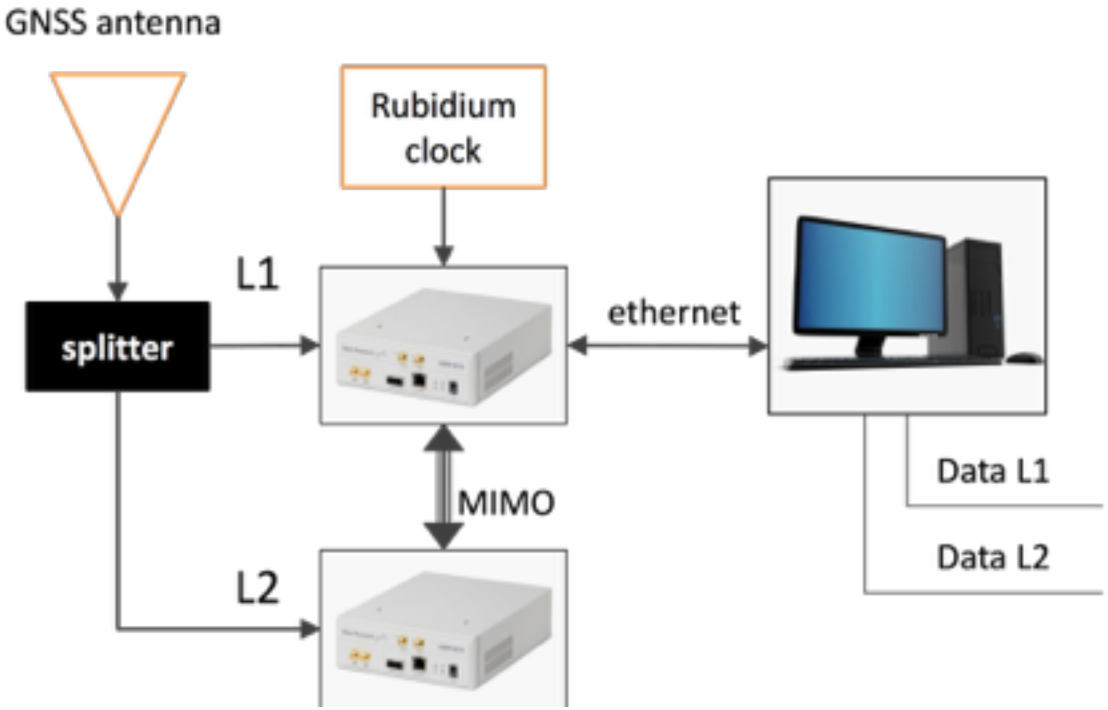


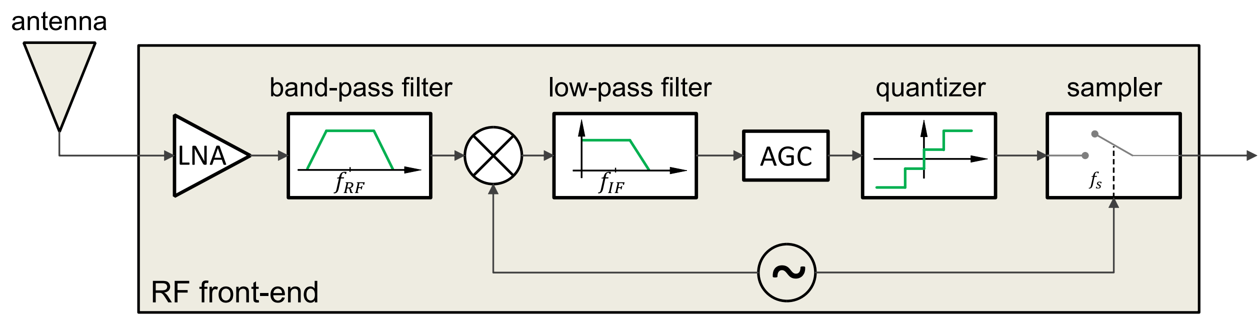


- C/N_0 degradation
- Pseudorange and carrier phase measurement noise increases
- Cycle slips
- Loss of lock
- Degradation of positioning accuracy
- Loss of positioning availability

Front-end development



- Universal Software Radio Peripheral (USRP)
- Store **raw data** for post processing



Front-end development