On the use of satellite navigation technologies in UAV applications

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SDR and GNSS for UAV

Motivation of the work

Join three modern technologies:

- Global Navigation Satellite System (GNSS)
- Software Defined radio (SDR)
- Unmanned Aerial System (UAS)

to design a flexible, low-cost UAS payload with different functionalities (all in one)

Outline

- Introduction: GNSS and SDR
- Experimental context: NavSAS research group and SMAT-F1 project
- Payload functionalities and experiments:
  - Test of GPS/Galileo software radio receiver on board of a small aircraft
  - GPS/Galileo software radio receiver for remote sensing applications
  - GPS/Galileo software radio receiver as a precise and low cost altimetry system
- Summary and future activities

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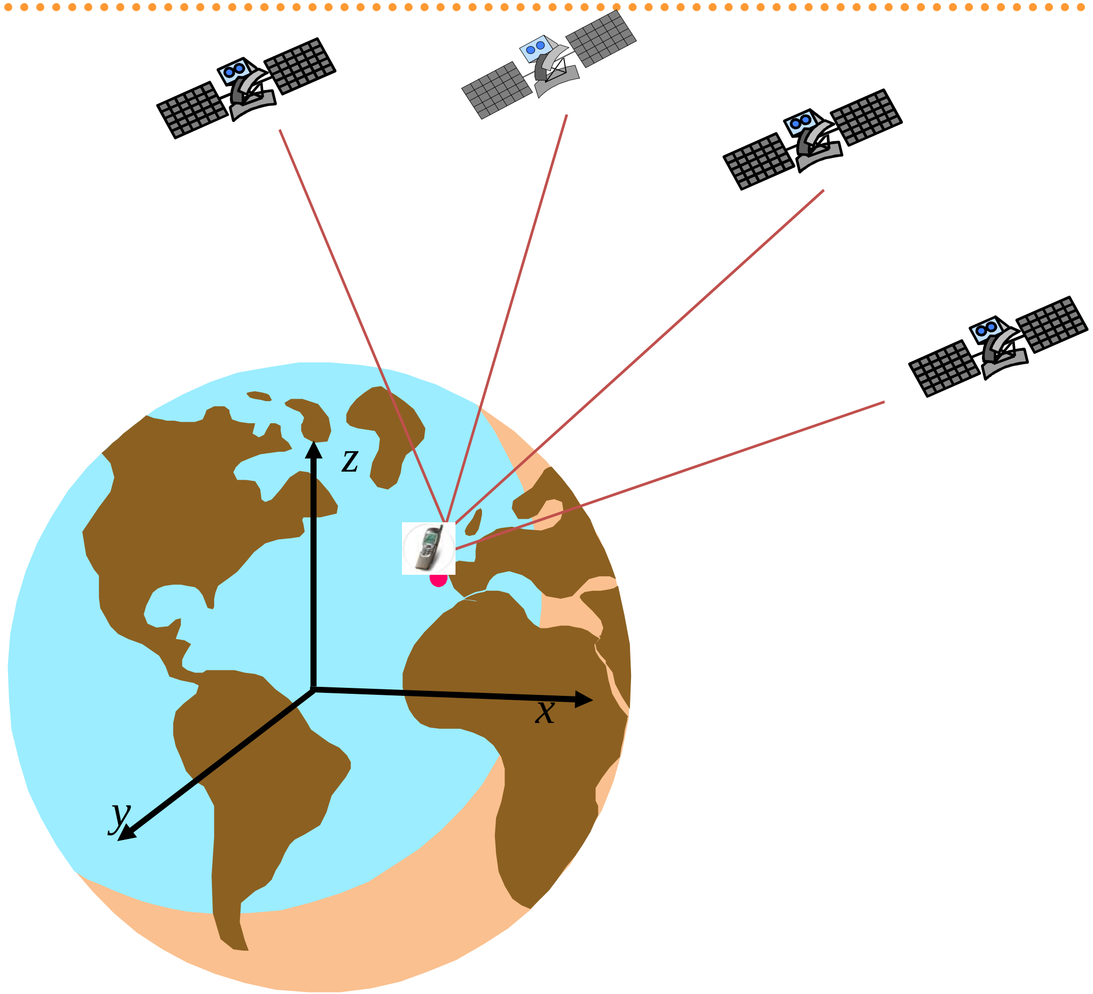
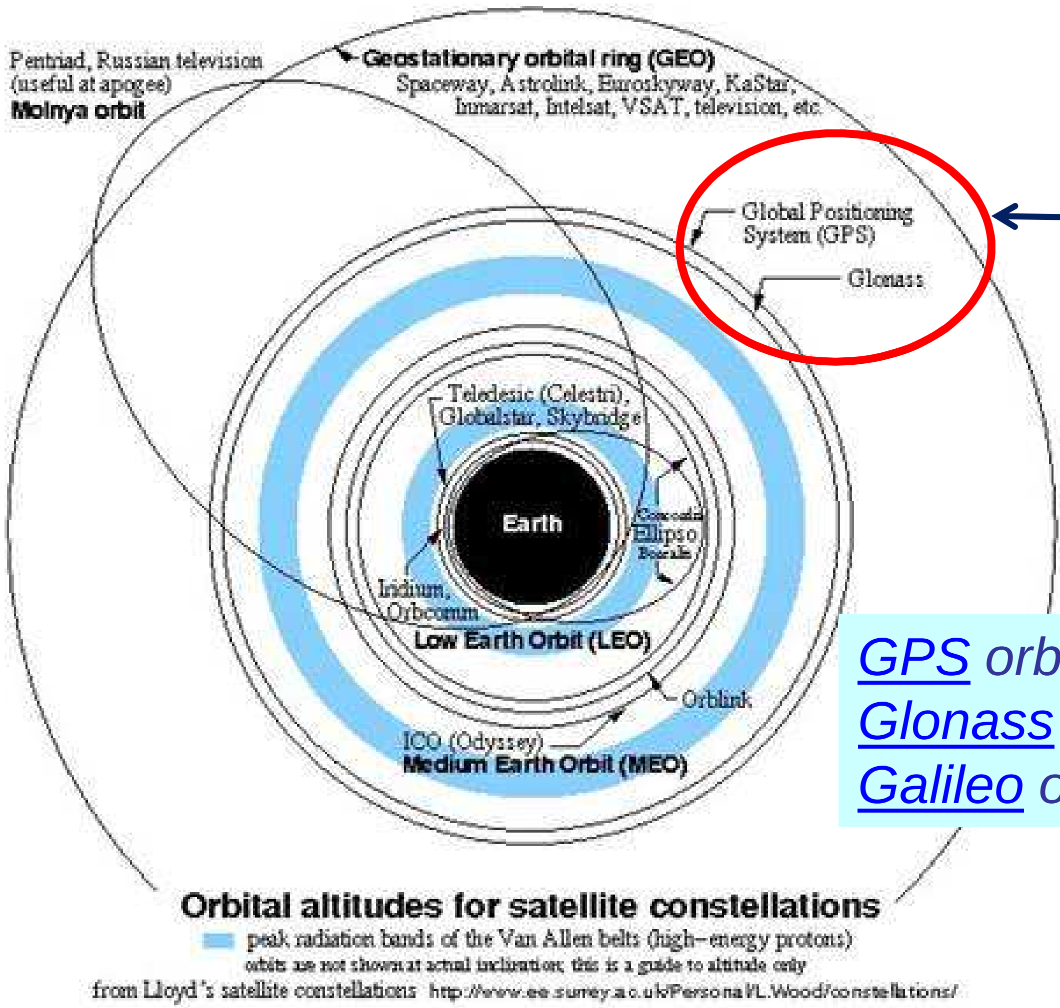
GNSS … in one slide



- A **Global Navigation Satellite System** (GNSS) consists of a constellation of satellites, whose payloads are especially designed to provide positioning of objects with global coverage.
- GNSSs implement the trilateration method.

Satellite orbits

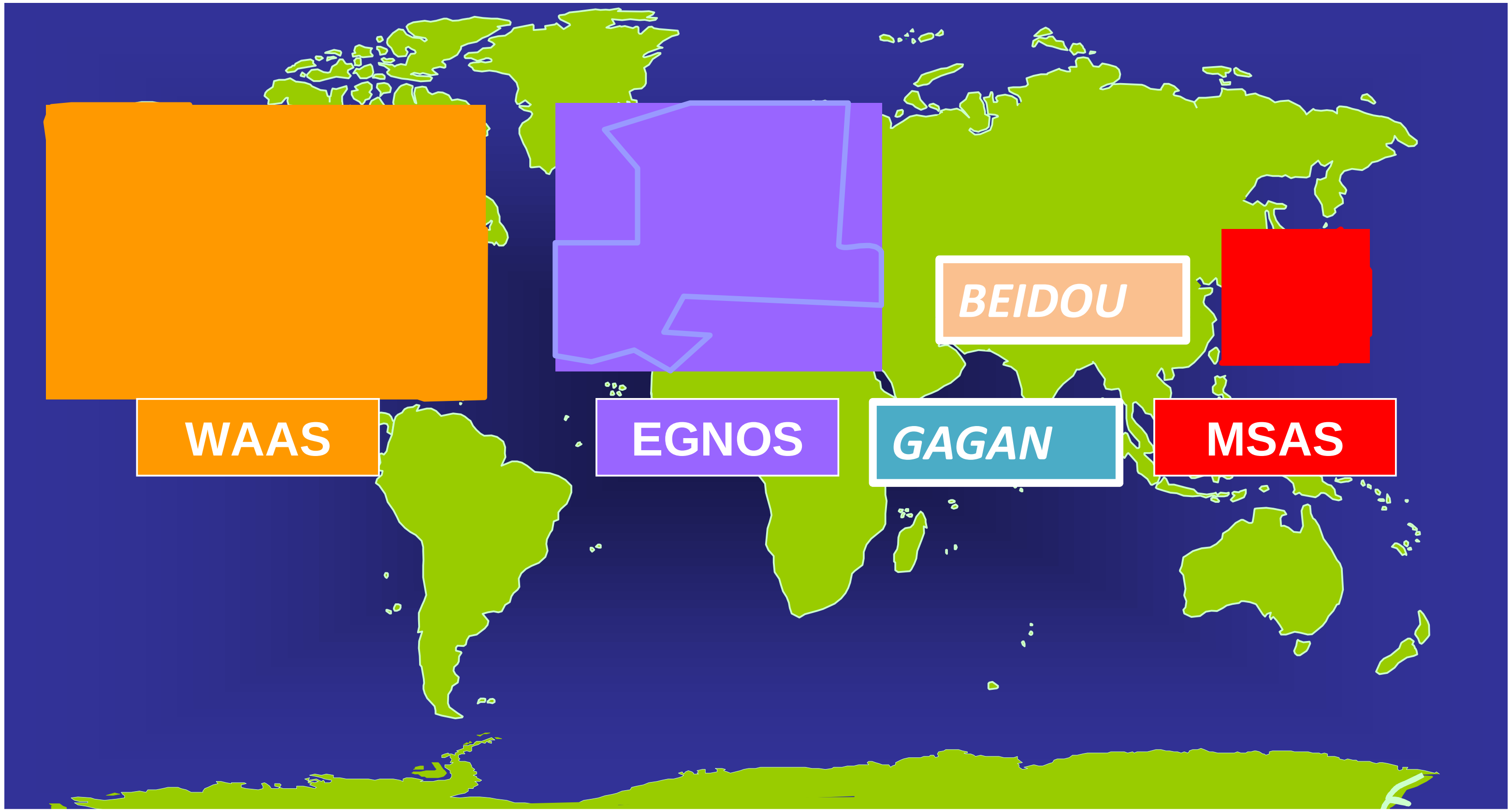


GNSS satellites:
GPS (USA)
Glonass (Russia)
Galileo (Europe)
Compass (China)

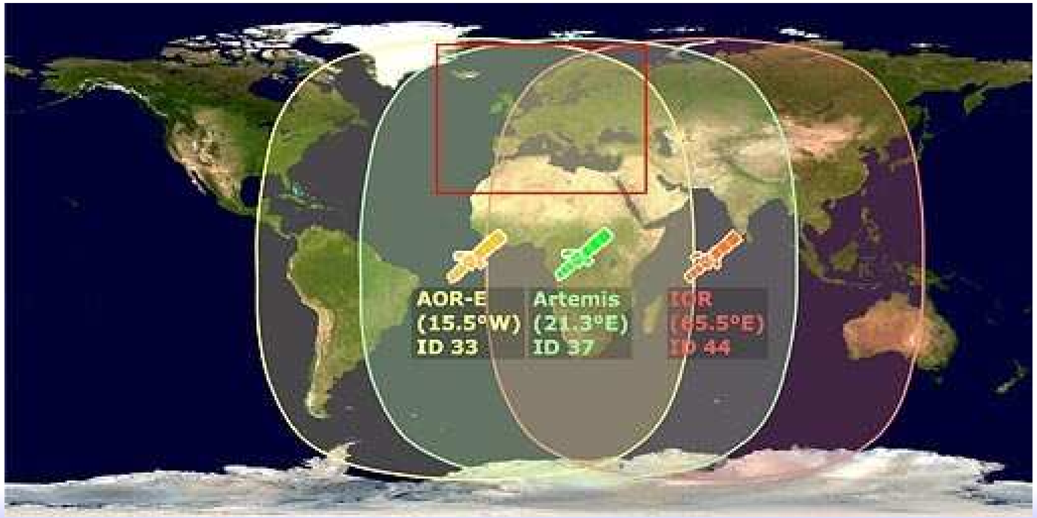
GPS orbit: 20,200 km
Glonass orbit: 19,100 km
Galileo orbit: 23,222 km

Current SBAS Systems

Satellite based augmentation systems



European Geostationary Navigation Overlay Service



- EGNOS is an European Satellite Based Augmentation System
- It is the first step towards an European GNSS system (Galileo)
- It augments the GPS satellite navigation system, allowing users in Europe and beyond to determine their position to within 1.5 meters.
- Currently EGNOS signals are broadcast by 3 GEO satellites
- 2 Mar 2011: the EGNOS Safety-of-Life signal was formally declared available to aviation
- More information available at: http://www.esa.int/esaNA/egnos.html

Galileo update

GALILEO is the European contribution to GNSS

21/10/2011: first two satellites of the constellation launched by Kourou (French Guiana)

"Today, with the launch of the first two Galileo satellites, Europe demonstrated that is able to manage big strategic projects"
Antonio Tajani, vicepresident of the European Commission

Follow future updates on:

http://www.navsas.eu
http://www.esa.int/SPECIALS/Galileo_IOV/

Software Defined Radio

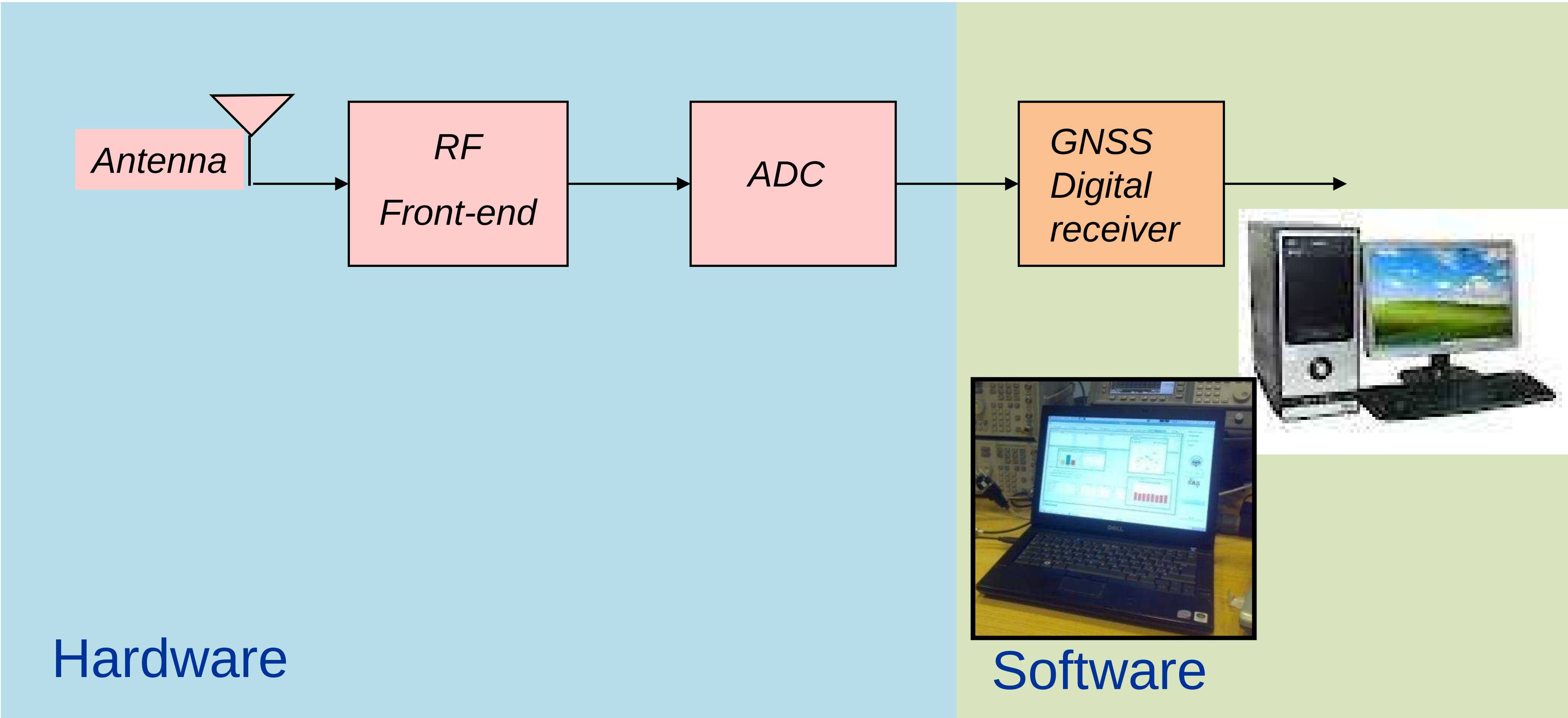
A software-defined radio system, or SDR, is a radio system where components that have been typically implemented in hardware (e.g. mixers, filters, amplifiers, modulators/demodulators, detectors, etc.) are instead implemented by means of software on a personal computer.

Main characteristics:

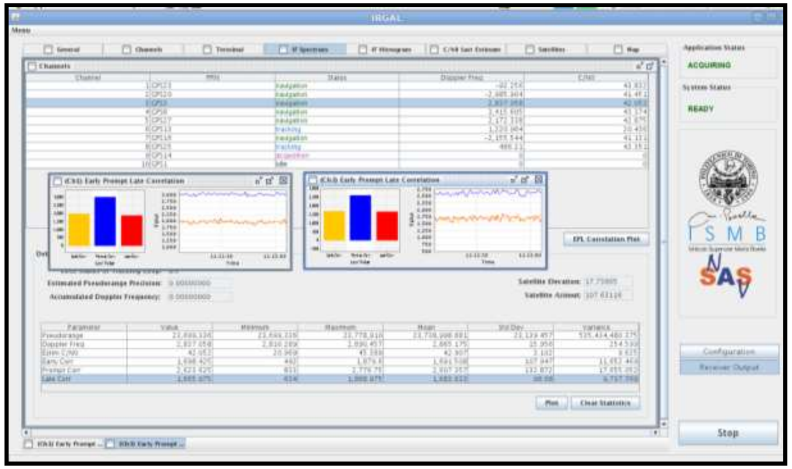
- flexibility
- reconfigurability

SDR main blocks

A basic SDR system may consist of a personal computer equipped with an analog-to-digital converter, preceded by some form of RF front end.



N-Gene software receiver



- N-Gene is a **real time software receiver** for GPS L1 and Galileo E1 signals
- N-Gene has been developed by the NavSAS group, thanks to the experience gained over the past years on GNSS technologies
- Powerful research tool, often used in projects and internal scientific programs
- Useful as data recorder, storing raw data samples to hard disk and for post-mission analysis
- Enables processing of simulated data compliant to both GPS and Galileo

SDR and GNSS

- In the last decade, there was a **rapid progress in the design of Software Defined Radio (SDR) GPS receivers**, which introduce a further level of flexibility in the design of GPS-based systems;
- GNSS software receivers have started finding their application outside the laboratory and new features have been added to improve performance;

- **We wanted to investigate the use of our real-time GNSS software receiver for future UAS applications:**
  - analysis performed on several data sets collected during real flights;
  - all the experiments carried out on board of an ultra-light aircraft, with comparable size and speed of an UAS.
- Currently, civilian UASs use hardware GPS receivers combined with IMU, but **there is a growing interest toward SDR technologies**:
  - **SDR receivers on board would allow for a reduced weight and size of the payload;**
  - **All the processing is demanded to software routines: flexible navigation units, easily reconfigurable with software updates, able to receive the new civilian GNSS signals.**
  - **Integration with other UAS sensors**

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The NavSAS research Group

Labs of the Navigation Technologies research area host the Navigation Signal Analysis and Simulation (NavSAS) research group, a joint team between ISMB and Politecnico di Torino University

Focus on advanced technologies for positioning systems and Global Navigation Satellite System (GNSS) receivers

At present, the NavSAS is composed of 20 researchers, most of them owning a Ph.D. in electronics engineering

The SMAT-F1 project

The work has been performed in the framework of the SMAT-F1 project

SMAT-F1 was the first phase of the wider SMAT research project, which is organized in 4 phases

SMAT-F1 was funded by the Piedmont Region, managed by Finpimonte and leaded by Alenia Aeronautica S.p.A. The project was also co-funded by European funds for regional development within the operative program 2007/2013

Starting Date: *1st of January 2009,* ***Ending Date:*** *30th of June 2011*

The main objective consisted in the definition, design and development of an advanced civilian system for environment monitoring, based on innovative Unmanned Aerial Systems

The final system will deploy a small fleet of UAVs, remotely controlled by a network of control stations. The system will be able to support:

- emergency managements in case of flood hazards, mudslides, fires;
- surveillance of remote areas;
- borders control

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Test on flight - procedures

1- Set up definition *(number of receivers and PC for data storage, antenna and RF section, power supply network)*

⇩

2- Preliminary test in lab *(simulate power drops and avoid system crashes, verify robustness to vibrations, verify free-space on disk for data collections)*

⇩

3- On board installation, hardware and software checks

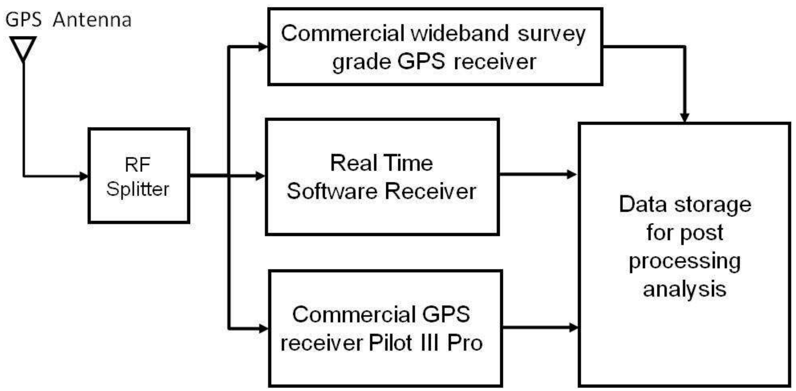
⇩

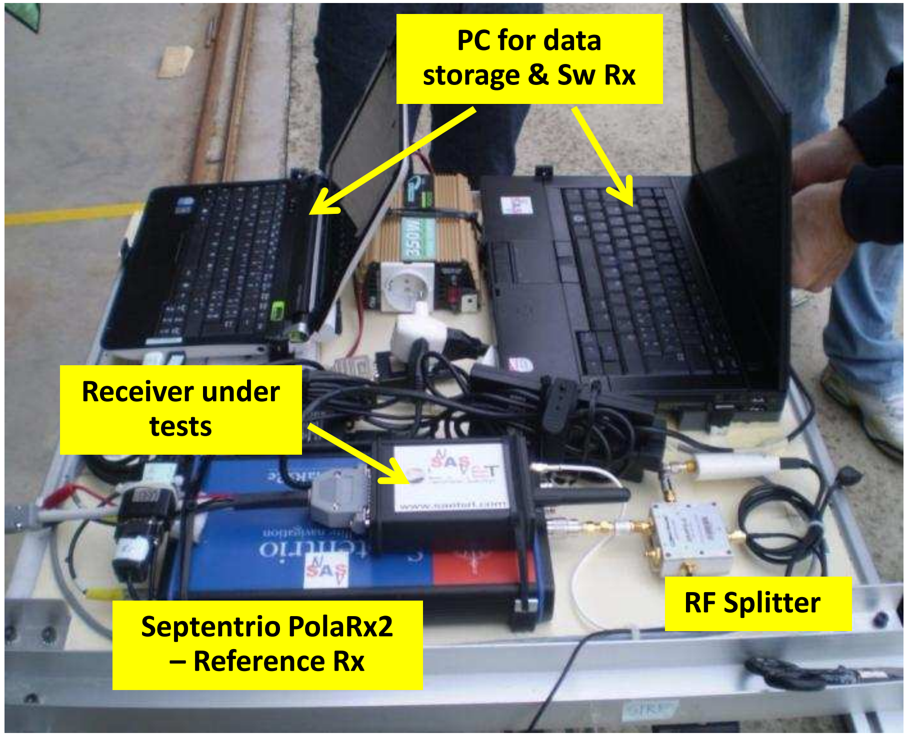
4- Flight test and data collections

⇩

5- Post processing analysis and assessment of the software receiver performance

System set up



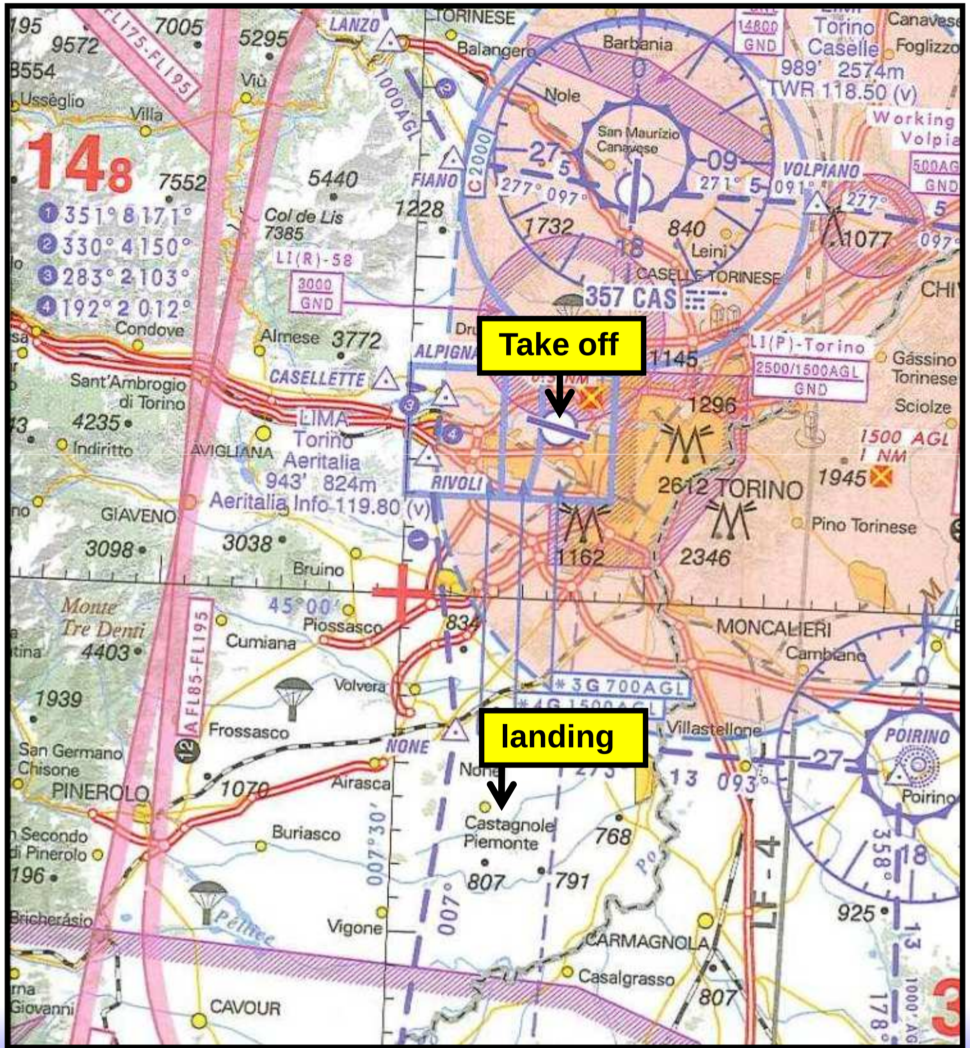


1. Test the ability of the N-Gene software receiver to track GPS signals on flight and provide accurate measurements. The software receiver is compared with:
   - Dual frequency GPS Receiver Septentrio PolaRx2e (taken as reference);
   - Single frequency GPS Receiver GARMIN Pilot III Pro (often used in ultra-light aircraft as navigation unit);

2. Investigates the benefits of the European GNSS Navigation Overlay System (EGNOS) signals, OS operative since the 1st of October 2009

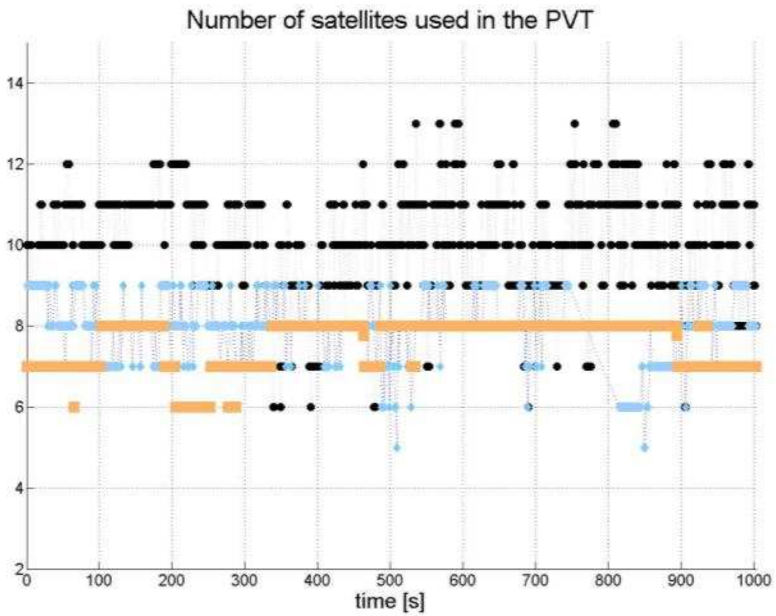
Test plan

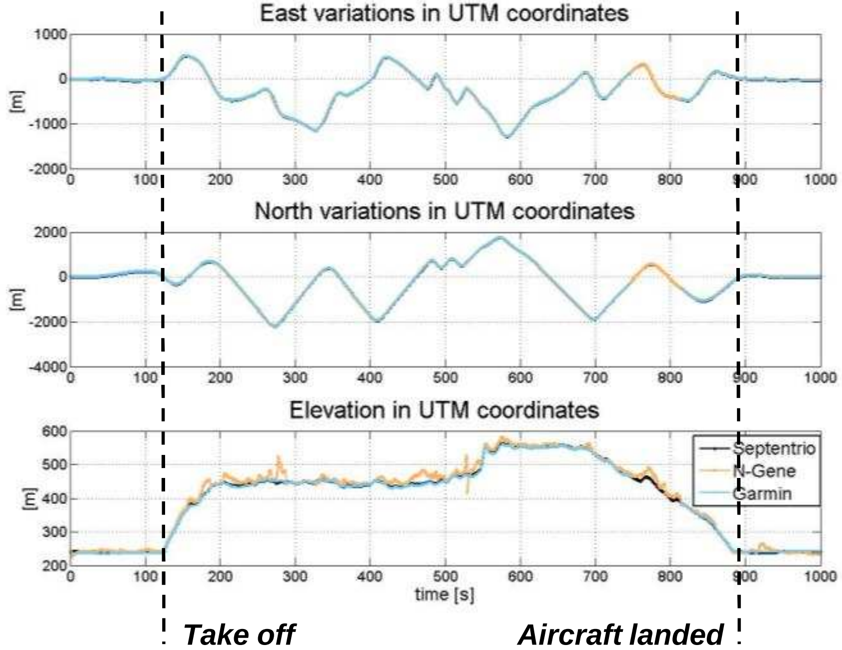
- Test flights and data collections accurately planned on map. One of the most significant experiment took place on the 17th of November 2009 and lasted approx. 16.5 minutes;
- The aircraft took off from a small airport south of Torino (Latitude: 44°52'59.6748", Longitude: 7°33'38.199") and performed several flight trials over the Torino area;
- All the receivers logged their measurements in proprietary binary files;
- N-Gene stored on disk the raw samples at the output of the RF front end for the whole flight.



GPS signal availability

Septentrio PolaRx2e (**black**), Garmin Pilot III Pro (blue), N-Gene software Rx (orange)





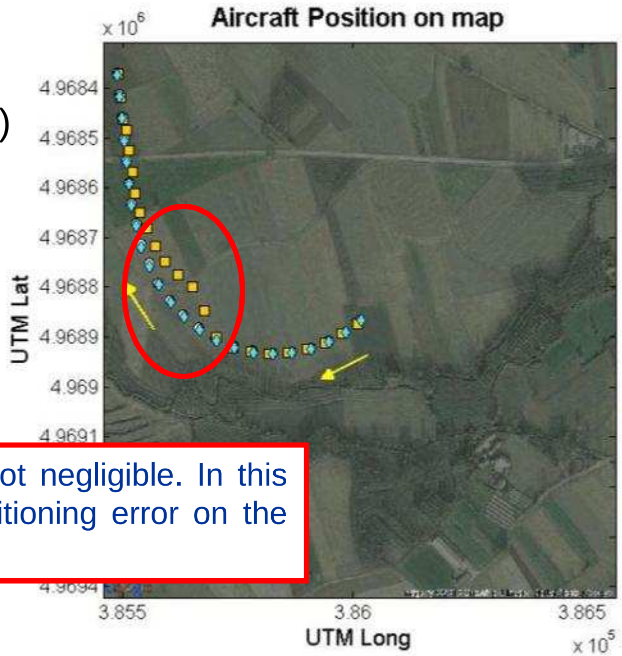
Unexpectedly the Pilot III Pro was unable to provide positions (no satellites tracked in the log file) for 68 seconds;

Both N-Gene and the Septentrio PolaRX2e were able to use at least 6 satellites for the whole flight. The Septentrio PolaRx2e tracked, on average, 10 satellites

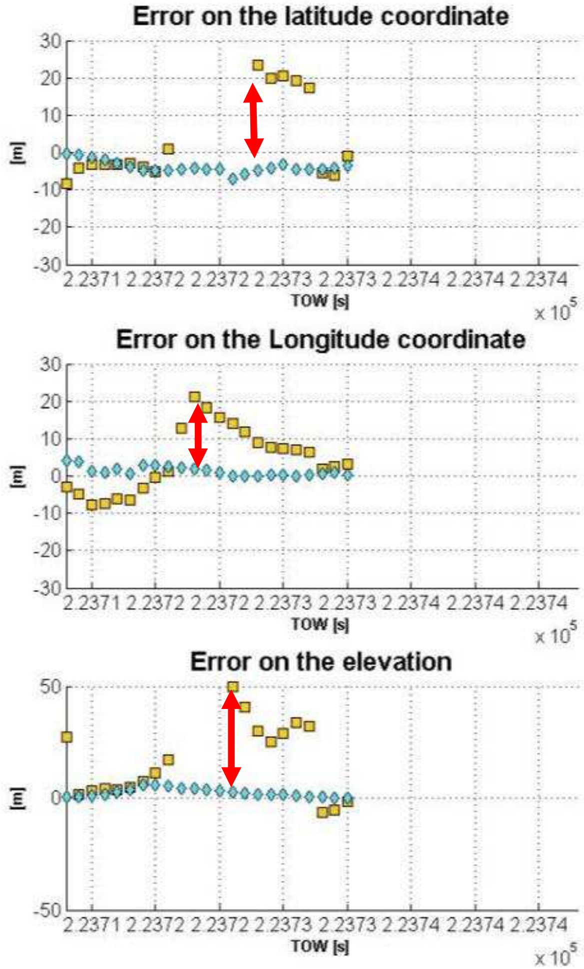
Positioning accuracy

Garmin Pilot III Pro (blue)

N-Gene software Rx (orange)



Difference between receivers not negligible. In this case, N-Gene suffers of a positioning error on the order of several meters

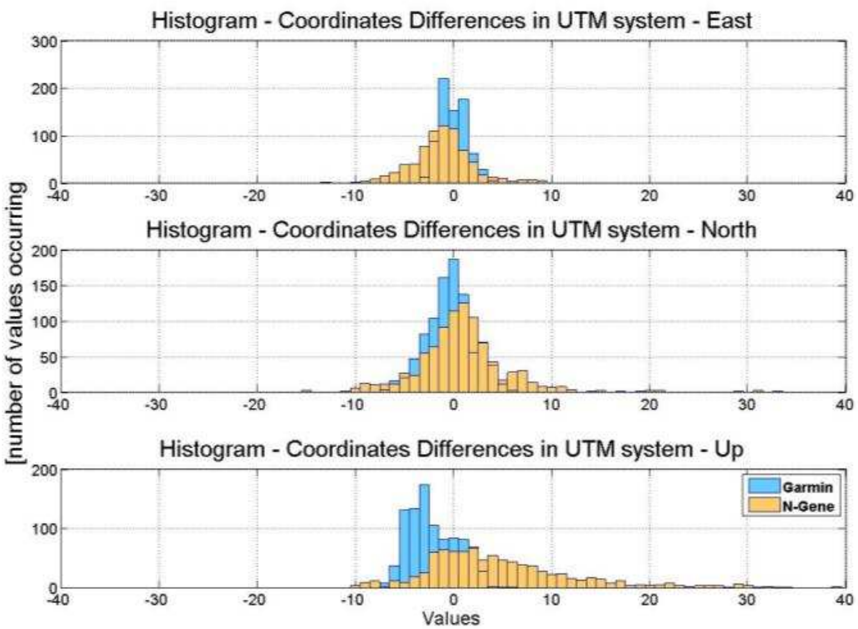


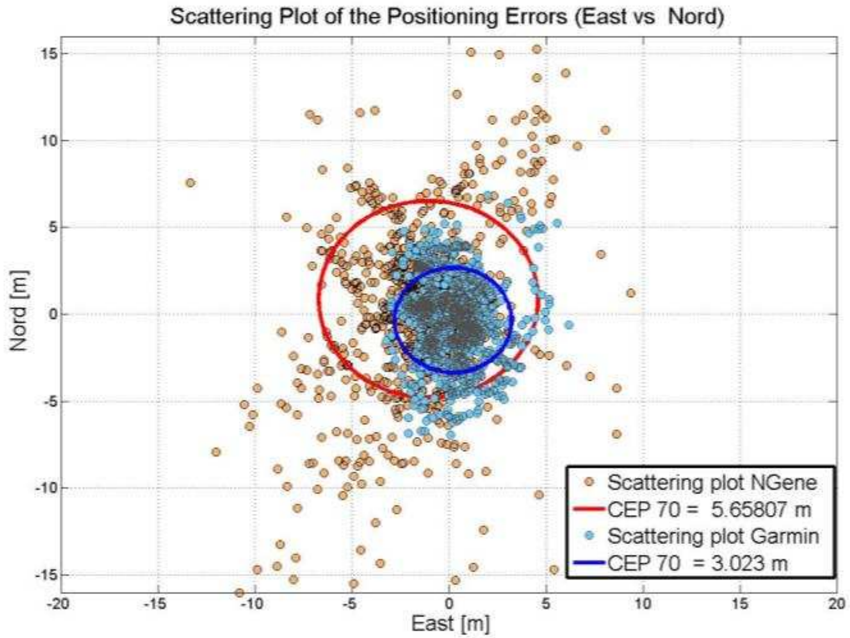
Positioning accuracy*:* evaluates the difference in magnitude between the true (unknown) position and the position fix reported by the receiver <u>at a specific time instant</u>.

Garmin Pilot III and the N-Gene compared with the Septentrio PolarRx2e **(taken as reference, capable of centimeters level accuracy)**

Positioning accuracy II

Garmin Pilot III Pro (blue), N-Gene software Rx (orange)





Gaussian trend of the error on Lat and Long. **3σ error on horizontal positioning within 10 meters**. Higher errors on the up coordinate, can be reduced with a PVT based on Kalman filer (Results refers to classical least square method)

CEP defines the radius of a circle centered at the reference position, which would contain the position estimates with the associated probability. CEP on horizontal positioning comparable with the Garmin Pilot III Pro.

Lesson learnt

- The SMAT project gave the opportunity to test new GNSS technologies in a challenging aerospace application.

- **The experiments performed on-flight revealed that N-Gene had performance comparable with a commercial single frequency GPS receiver ($CEP_{70\%}$ = 5 meters on horizontal positioning).**
  - in all the experiments, we verified a robust tracking of GPS and EGNOS signals;
  - There was still the need of some improvements (e.g.: better accuracy on the up coordinate through a Kalman-based PVT computation, carrier phase measurements, integration with INS).

- We proved that the SDR technology offers a high level of flexibility, without extra hardware:
  - The receiver can be used standalone and configured with custom settings;

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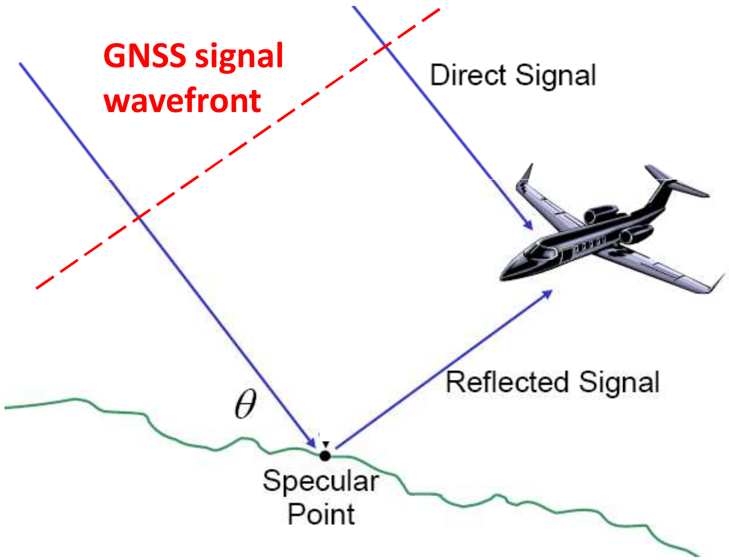
GPS backscattering

GNSS signals are a source of opportunity for monitoring the Earth's surface and the atmosphere in L band



- GPS reflectometry for exploiting land and ocean characteristics;
- Sea-water and sea-ice monitoring (altimetry[(1)], ocean surface[(2)], winds detection, ice topography);
- Soil moisture[(3)] and snow cover characterization.

(1) D.Masters, P.Axelrad, V.Zavorotny, S.J.Katzberg and F.Lalezari, "A Passive GPS Bistatic Radar Altimeter for Aircraft Navigation", In the Proceedings of the ION 2001 Conference.

(2) T.M.Elfouhaily, D.R.Thompson, L.A.Linstrom, "Delay-Doppler Analysis of Bistatically Reflected signals from the Ocean Surface", IEEE Transaction on Geoscience and Remote Sensing, vol.40, pp.560-573, 2002.

(3) D.Masters,"Surface Remote Sensing and Applications of GNSS Bistatic Radar: Soil Moisture and Aircraft Altimetry", Ph.D Thesis, University of Colorado at Boulder, 2004.

Work in cooperation

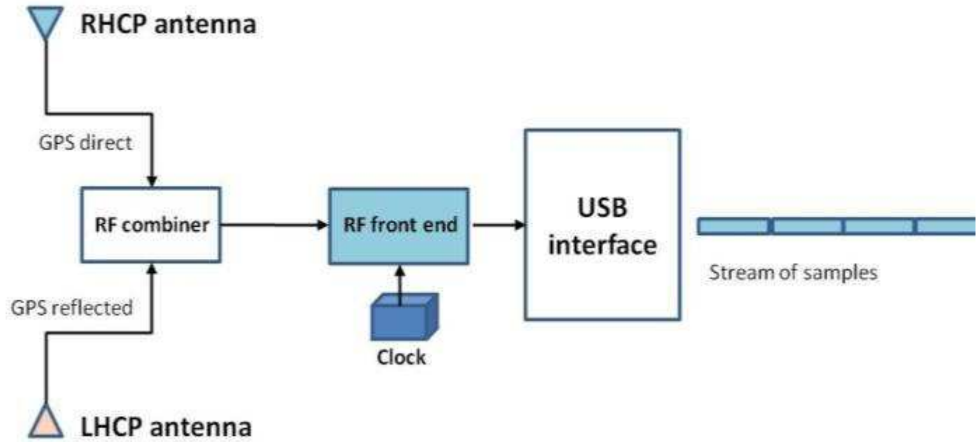
This work has been performed in cooperation with:

- Remote sensing group of Politecnico di Torino
- Envisens technologies

Objectives and real measurements

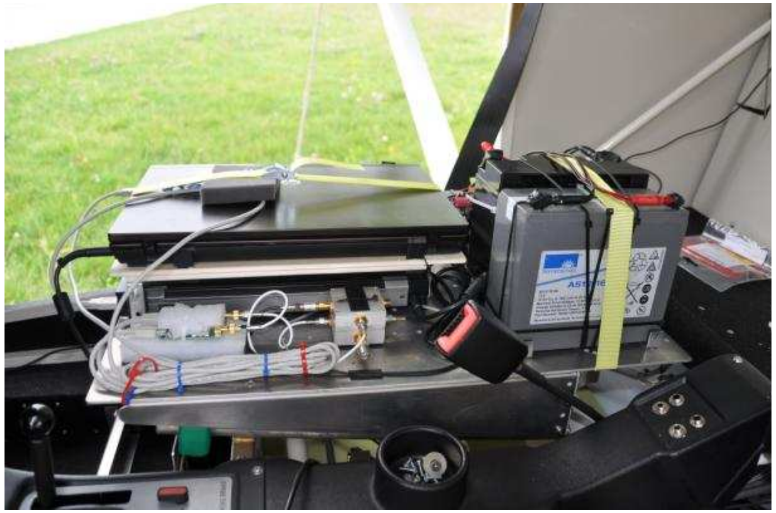
Objectives: data collections on board of a small aircraft with GPS reflected signals from the river surface and rice fields.

Measurements performed during a flight test on the 5th of May



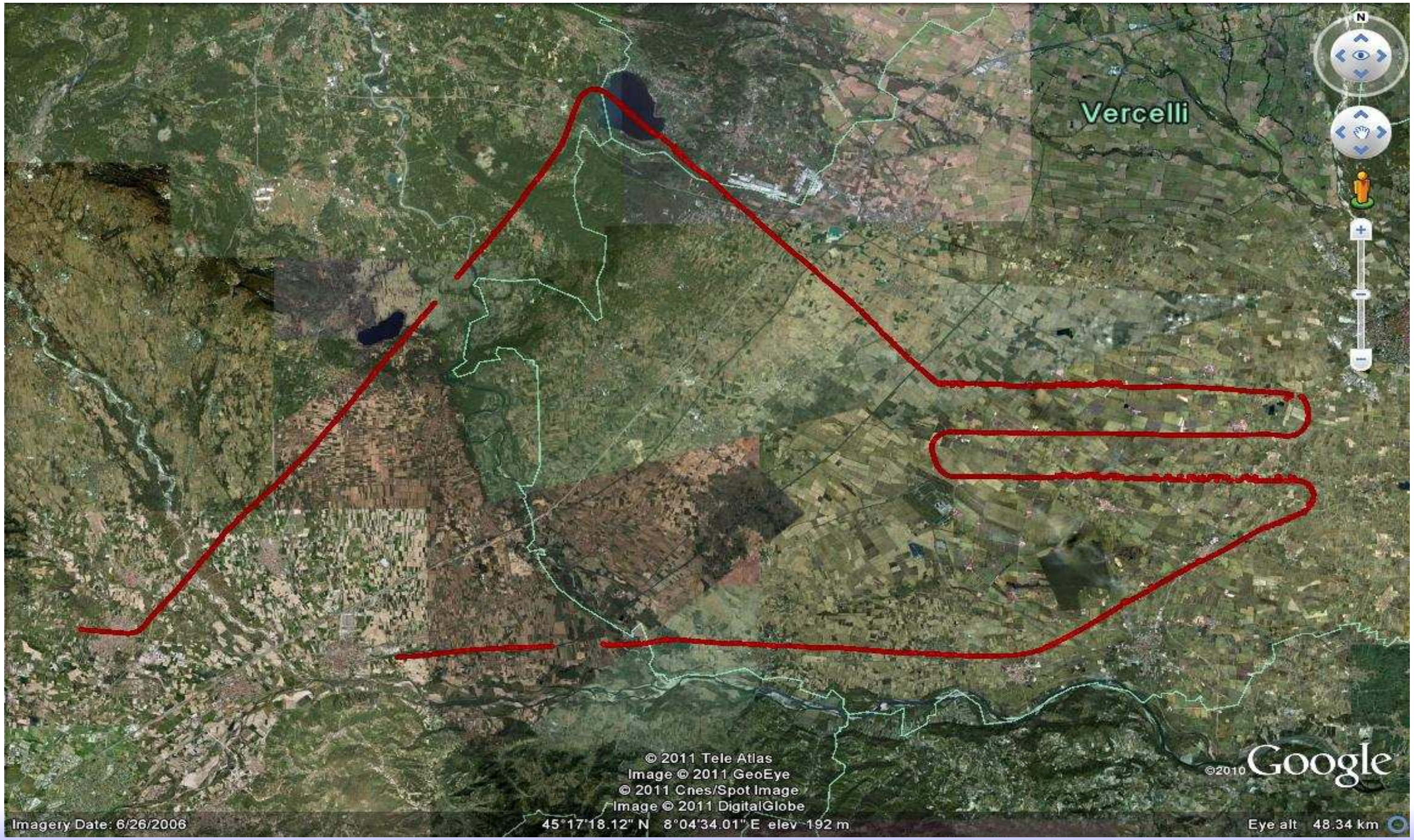
- We used a simple approach, combining direct and reflected signals at RF, using low cost GPS front end;
- This does not require custom design of the RF part;

Experimental set up

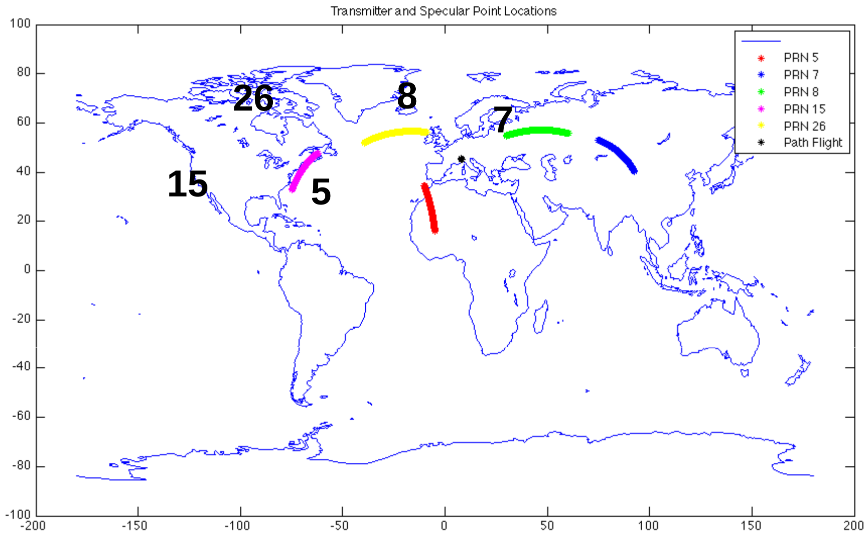


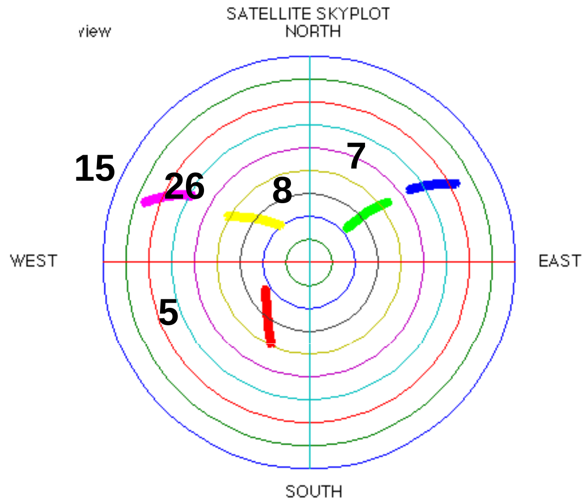
Flight route

Relatively easy to utilize GPS reflections over water.
Selected an environment for flight test crossing small lakes, rivers and rice fields.



PRNs in view

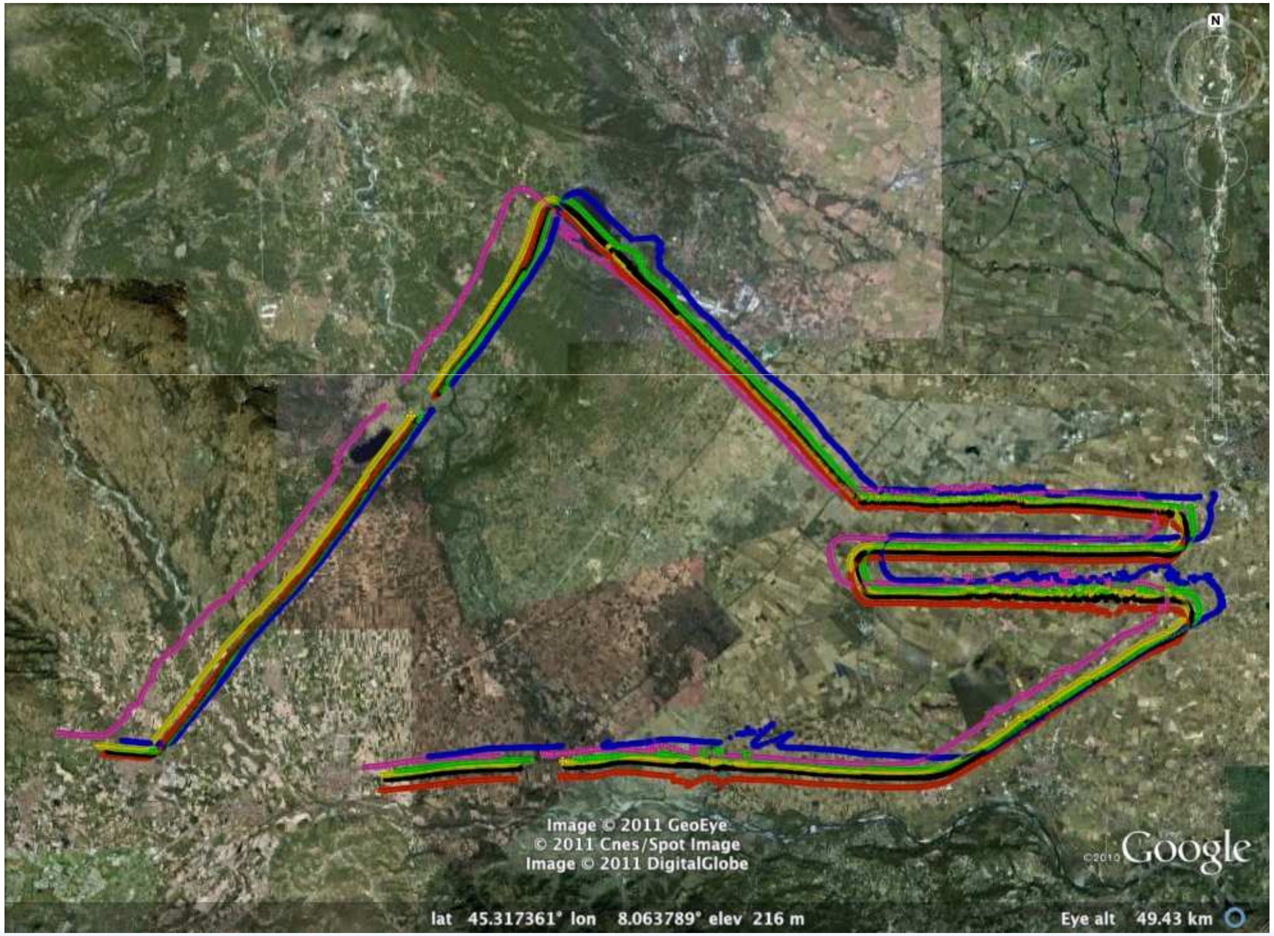




Focus on 5 satellites with sufficient elevation: PRN 5,7,8,15 and 26

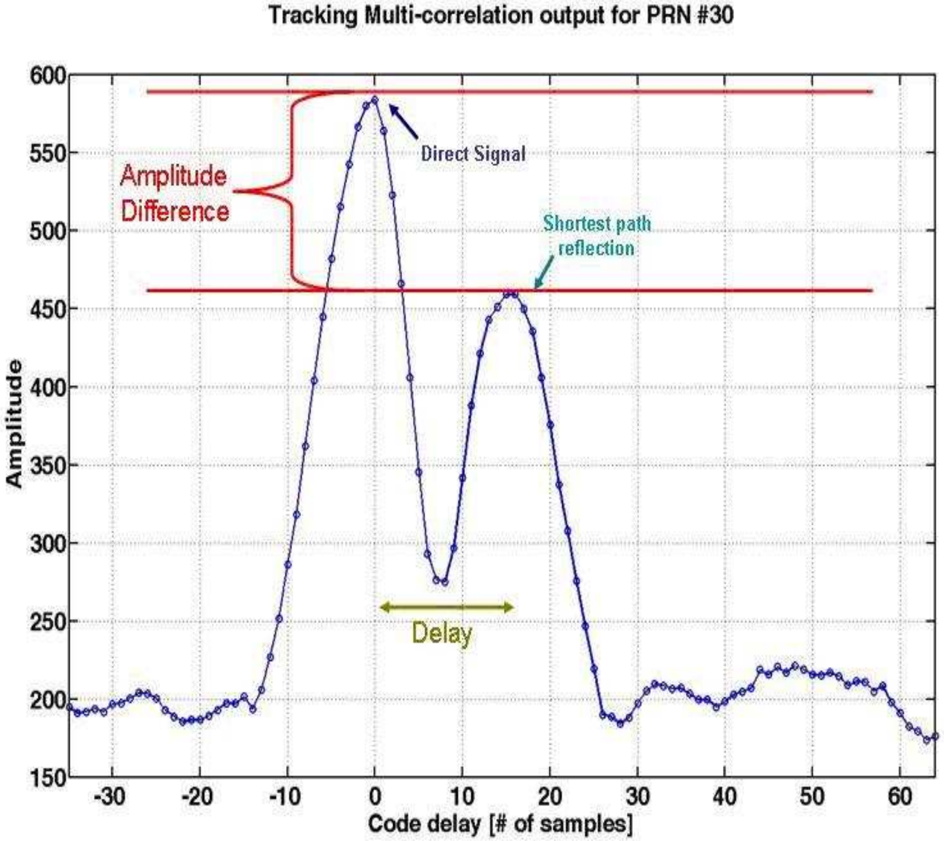
Specular reflection points

Reflection points computed in post processing for all PRNs



Post processing analysis

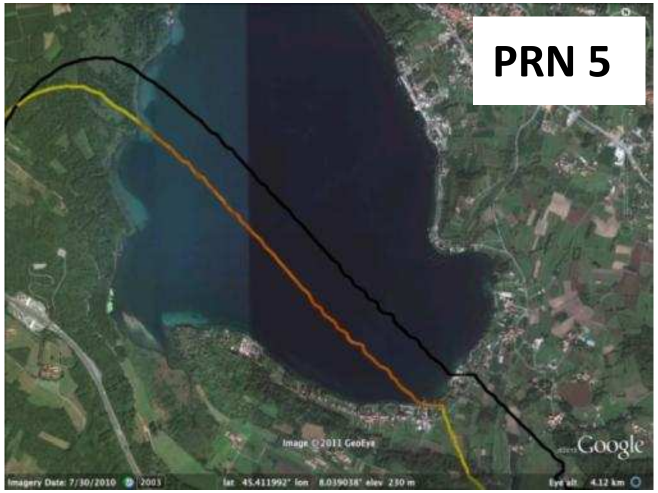
Combined Signals

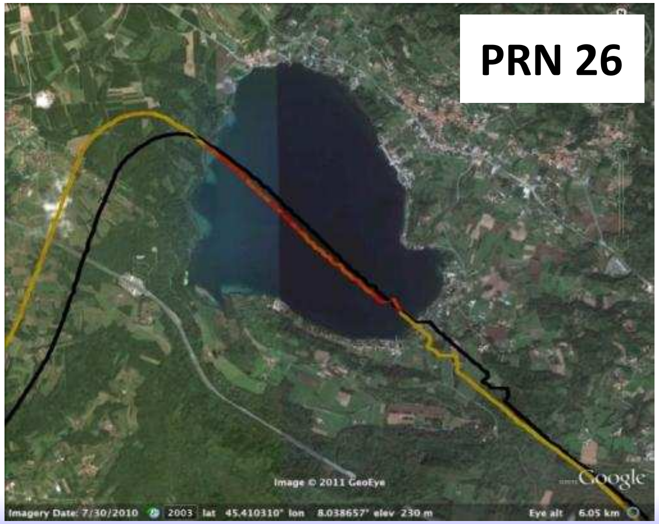


***TRACKING*:**

- ***we used additional correlators, 1 sample spaced from -6 to 6 chips delay, to have a better image of the correlation peak due to reflections***
- ***the amplitude of the reflected signal is almost half of the direct one that arrives 20 samples ahead with respect to the reflected one.***
- ***the measure of the reflected signal power is fundamental for the characterization of the reflecting medium***

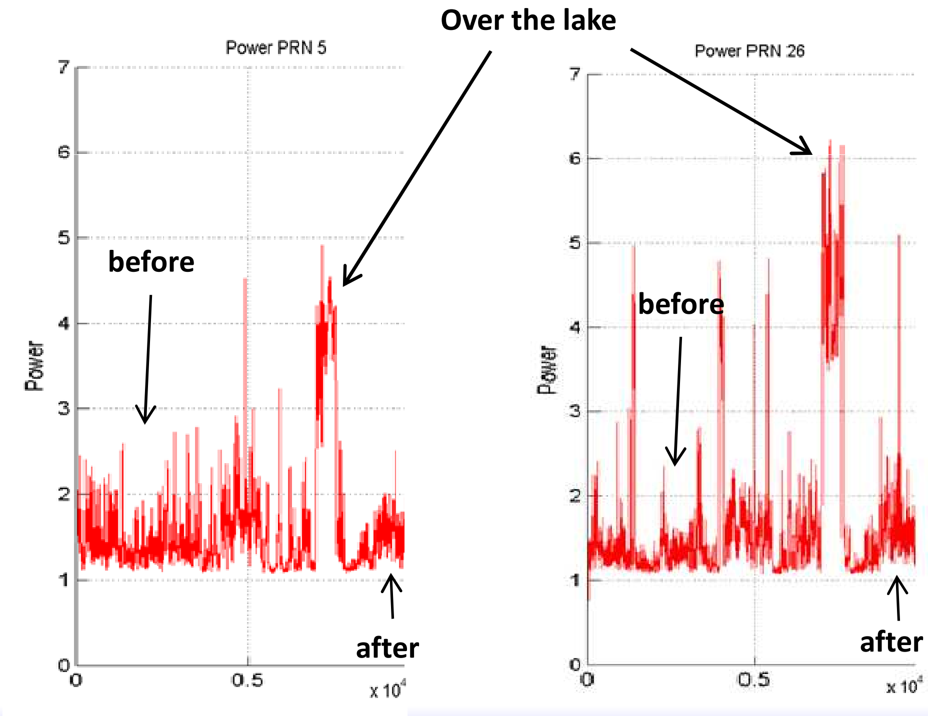
Flying over the Viverone lake



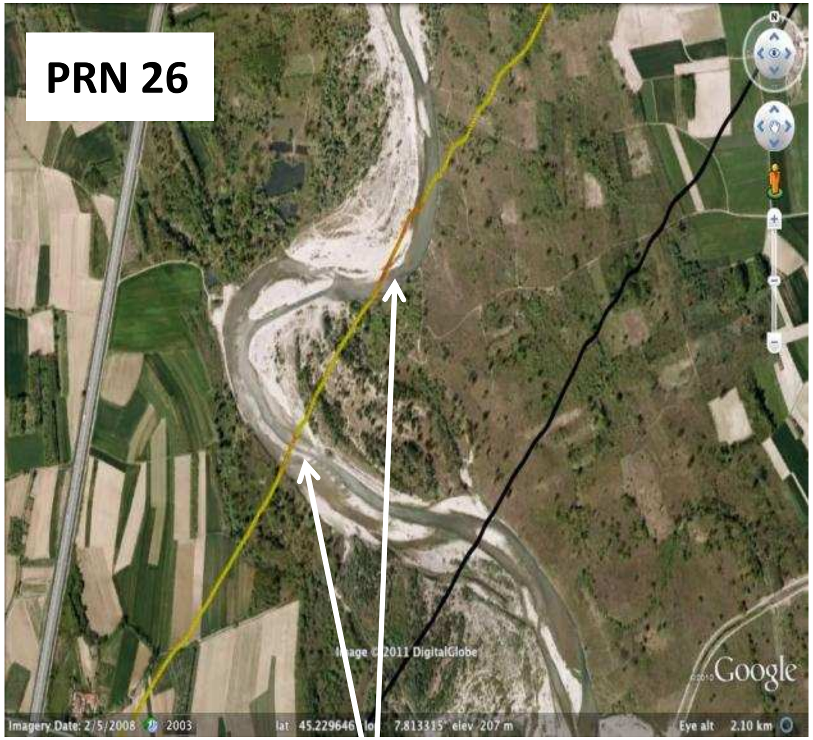


Satellite imagery indicates reflection power increase corresponds to specular points over the lake

orange/red line on map indicates significant reflected power, while yellow indicates poor reflections.



Flying over rivers



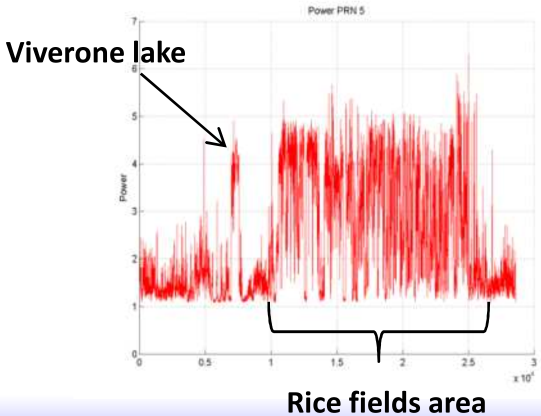
Satellite imagery indicates reflection power increase corresponds to specular point along, and crossing, rivers

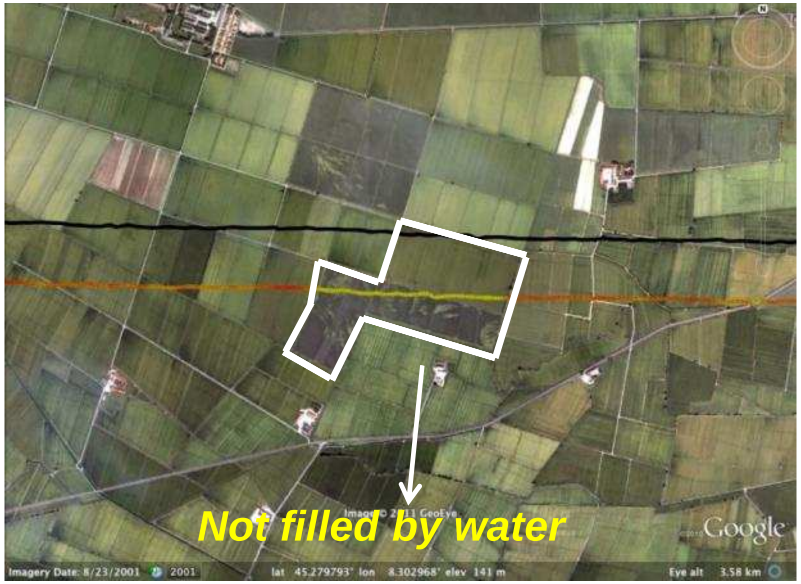
Flying over crops

During the flight over crops the reflected power fluctuates more than over lakes.

Satellite imagery indicates:

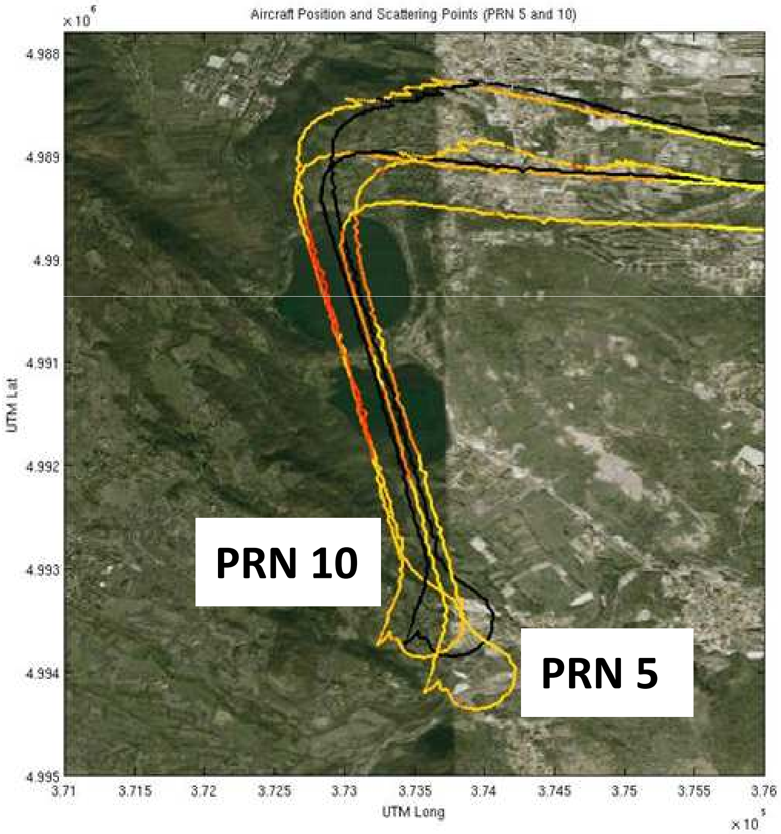
- reflection power increase over rice crops,
- reflection power decrease over fields not filled by water.

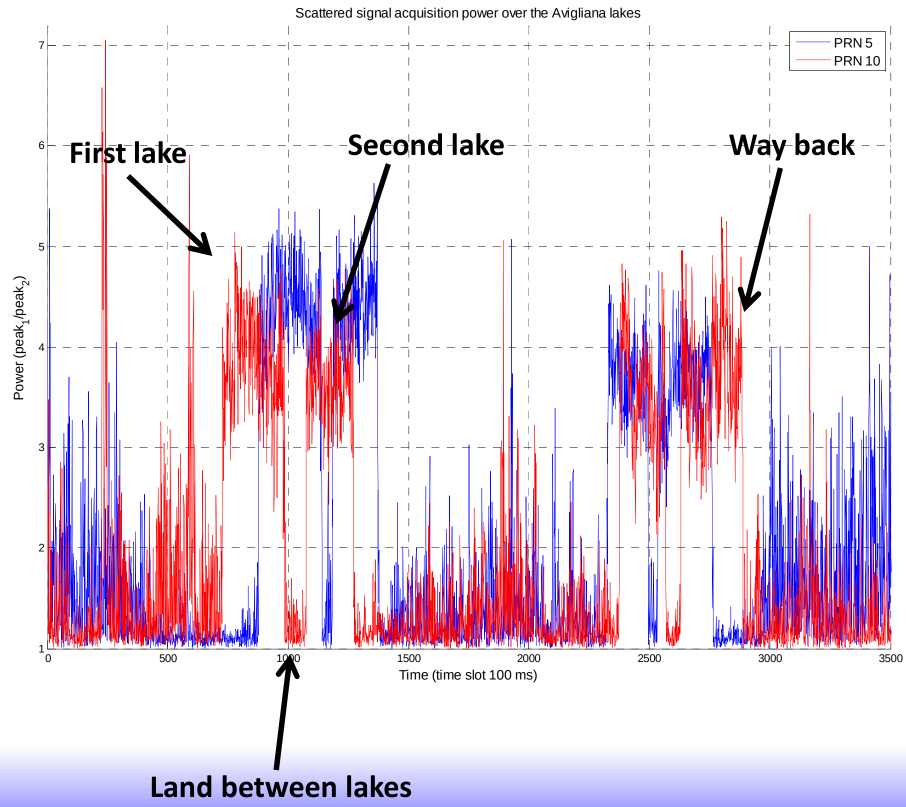




Other results: Avigliana lakes

First results obtained processing the data set collected during a shorter test flight over Avigliana. The first test helped to refine the algorithms for the analysis of the data collected during the second flight.





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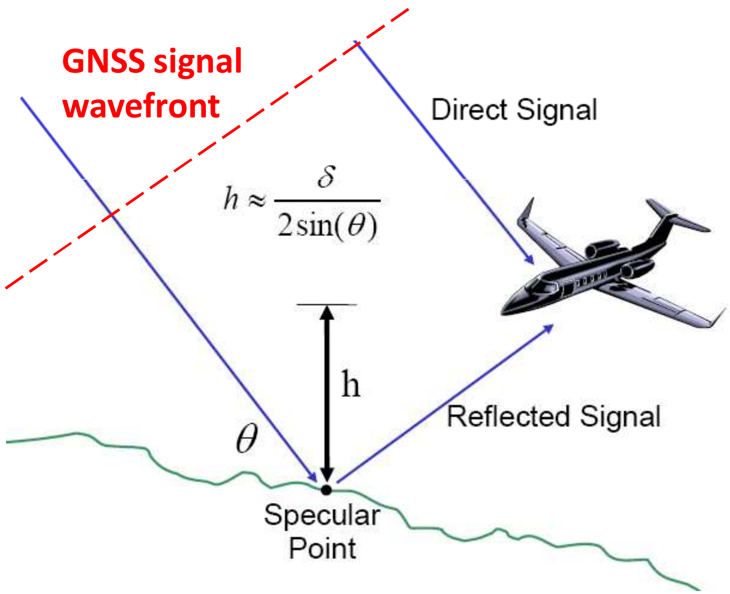
Altimetry using direct and reflected signals

Objectives: estimate the aircraft height through carrier phase measurements on the reflected signal (0.1 m level accuracy achievable)



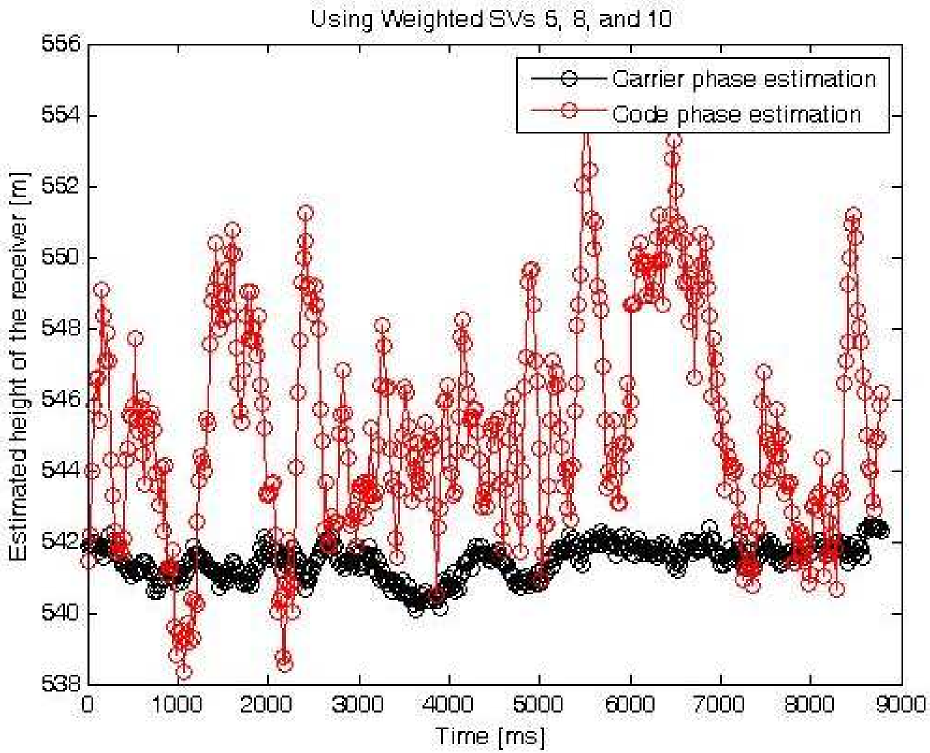
- Relative positioning concept applied to direct and reflected signals.
- Using both code and carrier phase measurements, apply the least squares algorithm to solve for phase ambiguity relative to each satellite and height between receiver and reflection point.

$$L_C(t) = c\Delta\tau(t) = 2h(t).\sin(\varepsilon(t)) + b$$

$$L_P(t) = 2h(t).\sin(\varepsilon(t)) + b + N_P\lambda$$

- Integer ambiguity resolution applying lambda method.
- Height re-estimation using only code or carrier phase measurements separately.

Height estimates (code vs carrier)



Variance of heights using carrier phase measurements is around 21 cm vs 3 meters using code phase measurements.

Outline

- The NavSAS research group and overview of Global Navigation Satellite Systems (GNSS);

- Work performed in the framework of SMAT-F1 project:
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Summary

We have verified that a single SDR platform, programmed to receive GNSS signals, can be a low-cost and flexible device for different applications:

- Navigation
- Remote sensing
- Altimetry

The SDR is very flexible, and work is in progress to program the SW modules to enable new applications.