GNSS Remote Sensing: CubeSat case study

P-GRESSION system and its background at PoliTo CubeSat Team

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LIST OF ACRONYMS

GLONASS - Globalnaya navigatsionnaya sputnikovaya sistema (see GNSS)
GNSS - Global Navigation Satellite System
GPS - Global Positioning System
LEO - Low Earth Orbit
MEO - Medium Earth Orbit
SNR - Signal to Noise Ratio

LIST OF FIGURES

Introduction

This report has been realized with the intent of providing a summary of a few concepts and notions learned during the course of GNSS Techniques for Remote Sensing, describing their possible applications in a space-related scenario. In particular, this report will show how a CubeSat, a standardized type of small satellite, can be considered a perfect host for a GNSS Experiment Payload, and how the efforts of two separate teams at Politecnico di Torino are being joined together in the realization of such a CubeSat.
The exploitation of GNSS technology is very attractive for a space mission, as new types of techniques open up, thanks to the constant presence of the GNSS signal.

GNSS Constellation and Orbits

GNSS Systems available at this time are space-bound systems that are composed of numerous orbiting satellites, each one transmitting particular types of signals towards Earth. GNSS, which stands for Global Navigation Satellite System, is an acronym that represents similar satellite constellations made and managed by different countries. For example, under GNSS category, we can find the GPS (USA), GLONASS (Russia), Galileo (Europe), and more. In addition to space-bound transmitters, we can find the so called pseudolites, which are GNSS transmitters located on ground, that can help providing better accuracy in complex areas such as canyons. For the application described in this report, only the space-bound GNSS transmitters will be considered.

GNSS Satellites

This type of satellites are usually medium sized satellites, with mass ranging from a few hundreds to one or two thousand kilograms. Depending on the period in which they were built, they have a design life ranging from 7 (early satellites) to 12 or more years.

Orbits

The majority of the GNSS systems have satellites placed in Medium Earth Orbits (MEO), Earth orbits characterized by an altitude between the Van Allen belts and the geostationary orbits (GEO), that is between 2000 and 35786 km. Common satellites for this type of constellation orbit at a distance of around 20000 km, in orbits as close as possible to the circular one. The various satellites in the constellation are placed in similar orbits, and are spaced in the same orbit by an angular distance that can be even (in case of GLONASS) or they can be spaced with specific patterns (in case of GPS).

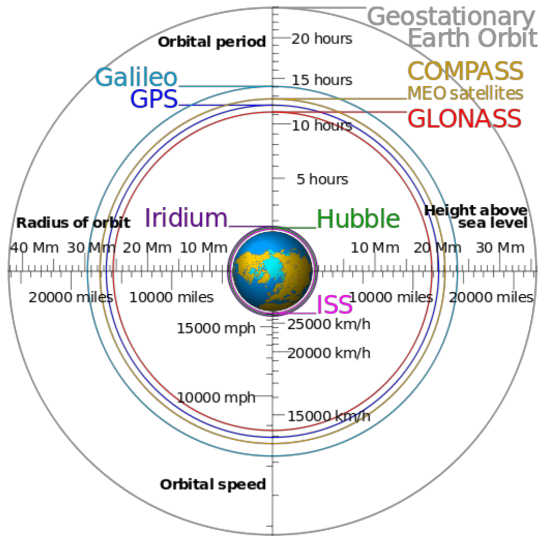

Figure 1 GNSS constellations and their orbits

For the GPS constellation there are six orbital planes, they have an approximate inclination of 55° and a separation of 60° in the right ascension of the ascending node, and for each orbit there are four satellites, spaced by 30, 105, 120 and 105 degrees. In case of GLONASS, inclination is 64.8°, there are three orbital planes and eight satellite per plane, which are evenly spaced.

Principles

The idea behind the functioning of this system is simple: a pulse is transmitted by the satellite, which contain information on the position of the satellite and the time when the pulse has been transmitted. On Earth, the reception of this signal is done with a certain delay, which is related to the distance between the transmitter and the receiver. By simply including the speed of light in the problem, we obtain that the following formula holds:

$$R = c \cdot \tau$$

where *tau* is the time delay between the reception and the transmission.
In the ideal case, the delay is only composed by the time it takes for the signal to reach the receiver, and therefore a total of 3 satellites are needed to fully locate the receiver in space (three coordinates, three satellites, trilateration problem). Unfortunately, the ideal case only holds when all the clocks are fully synchronized, to allow the precise measurement of the time delay.
Satellite clocks are very reliable, as they typically include technologies such as Rubidium, or Passive Hydrogen Maser. On the other hand, the receiver clocks are totally inaccurate, and they do not fulfill the requirements to precisely measure the time delay: only $1\,\mu s$ of delay equals to almost 300m error in distance.
In this sense, at least four satellites are needed to compute all the variables in the problem: three variables for the coordinates, and one for the time. Given that the receiver is in sight of four satellites, the position can be obtained, with a precision (for the civil use) of a few meters.

Remote Sensing

“Remote Sensing” is a method to collect and analyse data without a direct contact between the instrument and the object to be analyzed. A possible use of this technique is the observation of the Earth’s surface and atmosphere, using it as an instrument for remote measurement of some geophysical properties. For this type of observation, satellites are used as platforms to host measurement instruments and sensors. Orbiting around the Earth, such satellites represent an interesting technology that potentially allows (depending on the orbit) the scan of the complete Earth surface.

Anyway, the type of measurements provided by the various remote sensing techniques, can be exploited not only on satellites, and not only around our planet, thus enabling interesting development of new mission scenarios.

Passive Remote Sensing

In this type of measurement, radiations coming from Earth’s surface (e.g. solar ray reflection) are being detected by sensors and analyzed. It has to be noted that the source of the radiation can be both the surface itself (in case of emitted radiation, such as thermal radiation) or can be reflected by the surface (such as light). In addition, naturally occurring radiation (in case of reflected ones) can be subject to intense time variations, with different periods.

Active Remote Sensing

In this second type of measurement, the signal to be analyzed is generated by the satellite platform, pointed towards the Earth and then received by the sensors on the same platform, exploiting the fact that the signal is reflected by the surface. One of the main advantage is the ability to obtain measurements potentially anytime, being the source for illumination the satellite itself. Another positive effect is that these type of systems can be used to perform observations in wavelengths that are not usually provided by natural sources, such as the sun. An example of these wavelengths can be the microwave domain. The major drawback of this technology is the requirement of the generation of a large amount of energy to adequately illuminate targets.

Its use is more important when the remote sensing is integrated in world meteorological monitoring system, or exploited by public emergency departments like the italian “Croce Rossa”.

Considerations

Passive sensor that operate at very high frequencies, such as radiometers and imaging cameras, measure natural surface emission in the visible, IR and thermal regions of electromagnetic spectrum. Instruments in this category, including those on imaging satellites such as Landsat and SPOT, often encounter difficulties related to the atmosphere (clouds for example), which can severely distort or block the high frequency radiation. At lower frequencies, between approximately 1 and 30 GHz, active instruments are used to overcome such problems when attempting to remotely sense the Earth’s surface. Microwave and radar instruments such as scatterometers, synthetic aperture radars (SAR) and altimeters are all able to effectively penetrate the atmosphere and make measurements in diverse weather conditions.

The signals of GPS navigation satellites reside in this range, specifically at frequencies commonly called L-Band, which are capable of penetrating cloud cover.

Even though GNSS signals are an active source, when used for remote sensing the ubiquitous GNSS transmissions are often considered as part of the environment. GNSS can be exploited for both Earth's surface and atmospheric remote sensing.

Reflectometry / Scatterometry

Reflectometry is a technique to measure the properties of a medium in which signal waves are propagated. The main principle is based on the reflection of waves at the interface of interest: when the waves encounter a discontinuity, part of the energy is reflected back, and part is transmitted to the following medium. The analysis of the reflected signal can provide information about the medium under consideration, or about the interface itself.

In the case of a satellite-borne application, the interface of interest is Earth surface, which is the junction between the atmosphere and the planet itself.

This type of measurement can also include in the computation the noise measurement (obtained without using the active illumination source), which is then subtracted to the active measurement, in order to remove the signal component that is not due to the object which is analyzed.

Applications of both reflectometry and scatterometry experiments will be discussed in the 3STAR chapter.

GNSS Reflectometry

GNSS-based remote sensing is under many aspects an evolution with respect to the traditional remote sensing techniques.

One of the most striking characteristic of this type of measurement is the configuration of the system: although the GNSS signal is an artificial generated one, it is not emitted by the same system that acts as receiver and performs the measurements. In this sense, the GNSS signal can be considered a signal belonging to the environment.

In addition, two antennas are needed: one must be pointed towards the GNSS constellation (in order to receive the original signal) and one must face Earth surface (in order to catch the reflected signal).

A second difference with respect to the traditional approach is the relative low frequency of GNSS signals, avoiding the use of expensive transmitters (which can also generate high-power noise signals).

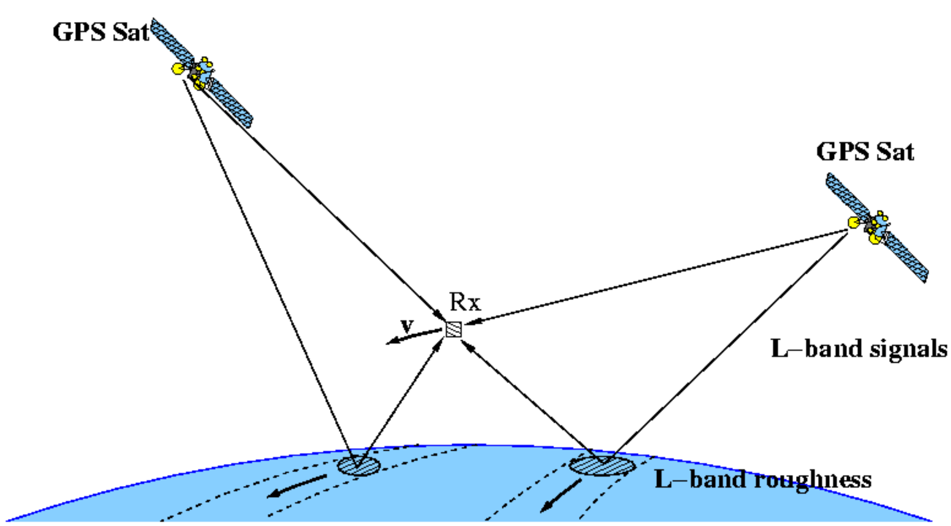

Figure 2 GNSS reflectometry experiment example

Radio-occultation

Radio occultation using GNSS signal is a technique for retrieving information on the atmospheric properties, exploiting the refraction of the GNSS signal by the atmosphere. In this case, the effect of the signal properties distortion is the atmosphere. The magnitude of the refraction depends on the temperature and water vapor concentration. A typical space-borne application is done by using a LEO satellite, mounted with GNSS receivers.

One of the main advantages of this method is that it provides a quasi-real time measurement of the atmospheric properties. In addition, given the fact that the relative position between the GNSS satellite emitting the signal and the LEO one changes, vertical profiles of the measured properties are obtainable.

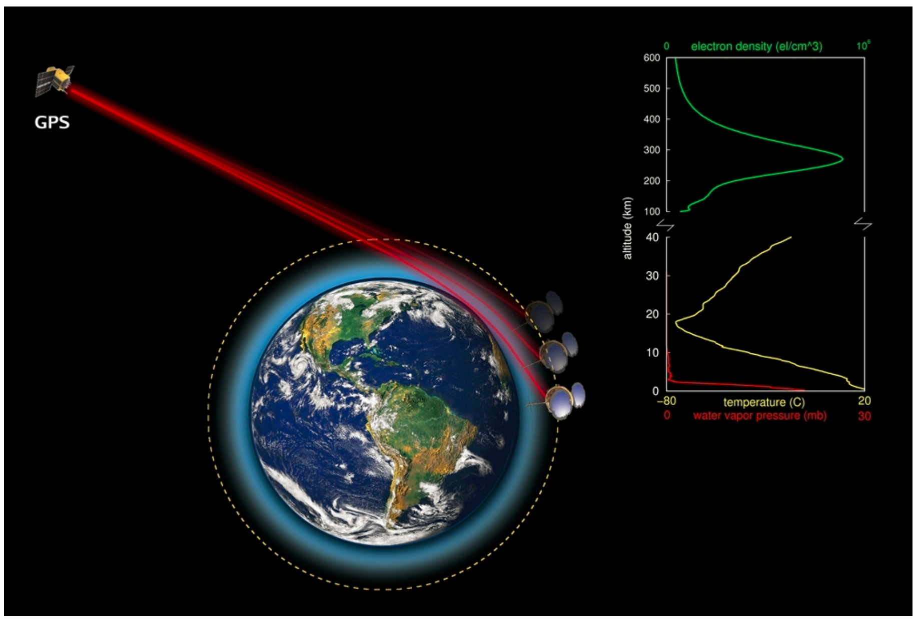

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FIgure 3 GNSS radio occultation experiment example

3-STAR Mission

The mission objectives for the 3STAR project have been derived by means of the typical system engineering process, which starts with the definition of the mission statement. The mission statement for the 3STAR project can be summarized as follows:

> *"The project aims at educating and inspiring space engineering students on complex systems development and operations, international cooperation and teamwork. The mission wants to contribute to the humanitarian exploitation of Space, by supporting communications capability in developing countries and/or allowing areas without infrastructure to access space-based services, and to enhance the knowledge on remote sensing applications for future small space missions."*

The following objectives can be obtained from the mission statement:

- The program shall have educational relevance: hands-on practice education and training of students on a real spacecraft project
- The mission shall carry one or more payload related to the peaceful and humanitarian exploitation of space
- The mission shall demonstrate one or more remote sensing applications based on non space qualified systems

The 3STAR program is a project developed at university level, so the main objectives are both the scientific and the educational relevance of the activity. The main constraint is represented by the limited available budget for the program development. Taking into account these assumptions, the mission and system requirements can be established, and the technical specifications can be derived for both the space and the ground segments. The primary objective for 3STAR has been to support and contribute to the HUMSAT mission. In particular, several primary program sub-objectives could be defined:

- To provide telecommunications services in support to humanitarian and emergency applications
- To monitor parameters related to climate change
- To settle international collaboration among universities and research centres from all over the world
- To validate the GENSO network on a large scale basis
- To promote high-level education on space systems

An additional objective is to perform on orbit remote sensing measurements, employing different remote sensing techniques for Earth observation, atmosphere profiling for climate studies, and eventually warning services.
At the current state, given that the HUMSAT program has not been approved and therefore hasn't started, 3STAR mission is no more defined, and we are switching to a flexible mission program, where the payload is not defined, but multiple ones could be supported.

3-STAR CubeSat

The 3-st@r program is an educational CubeSat project which is under development at the Department of Mechanics and Aerospace Engineering of Politecnico di Torino by the ASSET team (DIMEAS), NavSAS team and Remote Sensing Group (DET), under the supervision of Dr. Eng. Sabrina Corpino who is the project manager of this program.
The program has been thought in response to the GEOID (GENSO Experimental Orbital Initial Demonstration) call for proposals issued by the Education Office of the ESA (European Space Agency). GEOID is expected to be the communication backbone of the initial version of the HumSAT system. The main goal of HumSAT is to use the constellation of satellites and GENSO (Global Educational Network for Satellite Operations) ground stations, in order to provide humanitarian initiatives with appropriate support, especially in developing areas or areas without infrastructures. The 3-st@r satellite will be one of the CubeSats in the GEOID constellation. It will be a 3U CubeSat derived from the e-st@r program experience. In addition, the 3-st@r satellite will host two payloads: the HumSAT payload, and the P-GRESSION (Payload for Gnss REmote Sensing and Signal detection) payload. Many students are now involved in the program for their final Master thesis, and the 3-st@r project is also being very successful among undergraduate students and lot of them are working on it with enthusiasm during the class works in regular courses.

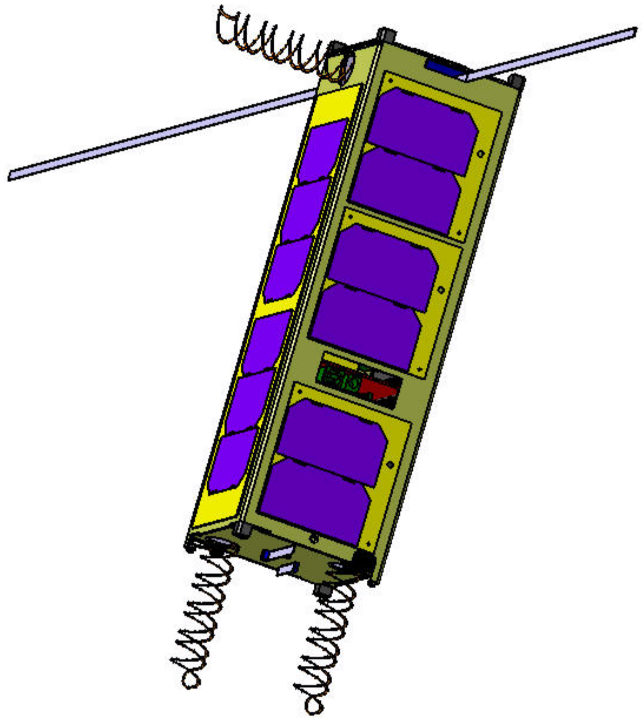

Figure 4 3STAR preliminary CAD drawing

Applications

Detected Land Reflections

Bistatic scattering from land is used for the detection of some parameters of soil, and to detect the altimetry profile of the Earth's surface.

For the former use, information about parameters of soil are obtained by studying the reflected signal power. In this sense, received power depends on relative humidity of the soil: dry soils scatter great power from the incident signal (great contribution due to the glistening zone), while wet soils and water surfaces spread minor power, reflecting GNSS signals better. Plotting a graph of received powers, some power peaks are observable, corresponding to major wet points.

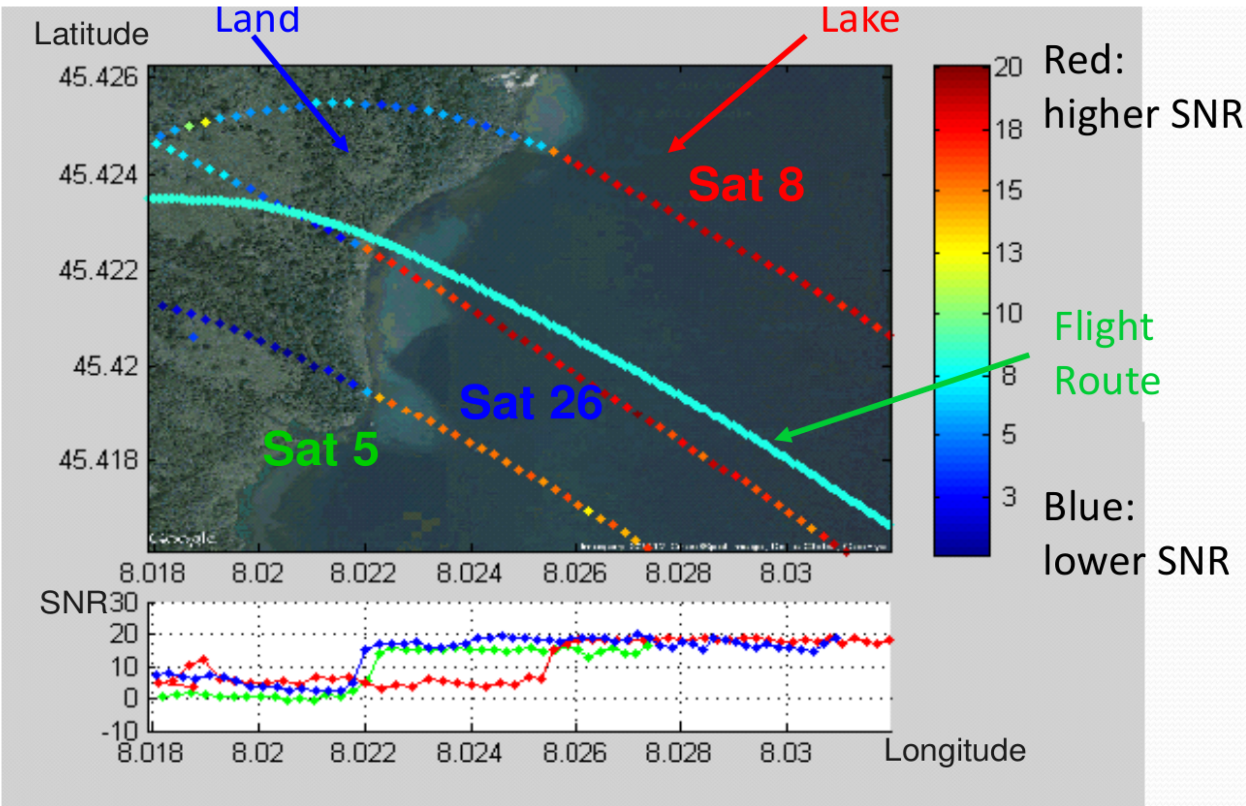

Figure 5 Example of signal characteristics over different types of surface

An example of this type of procedure is shown in Figure 6 and Figure 7, referred to a bistatic GPS experiment on the UK-DMC satellite passing over North America.

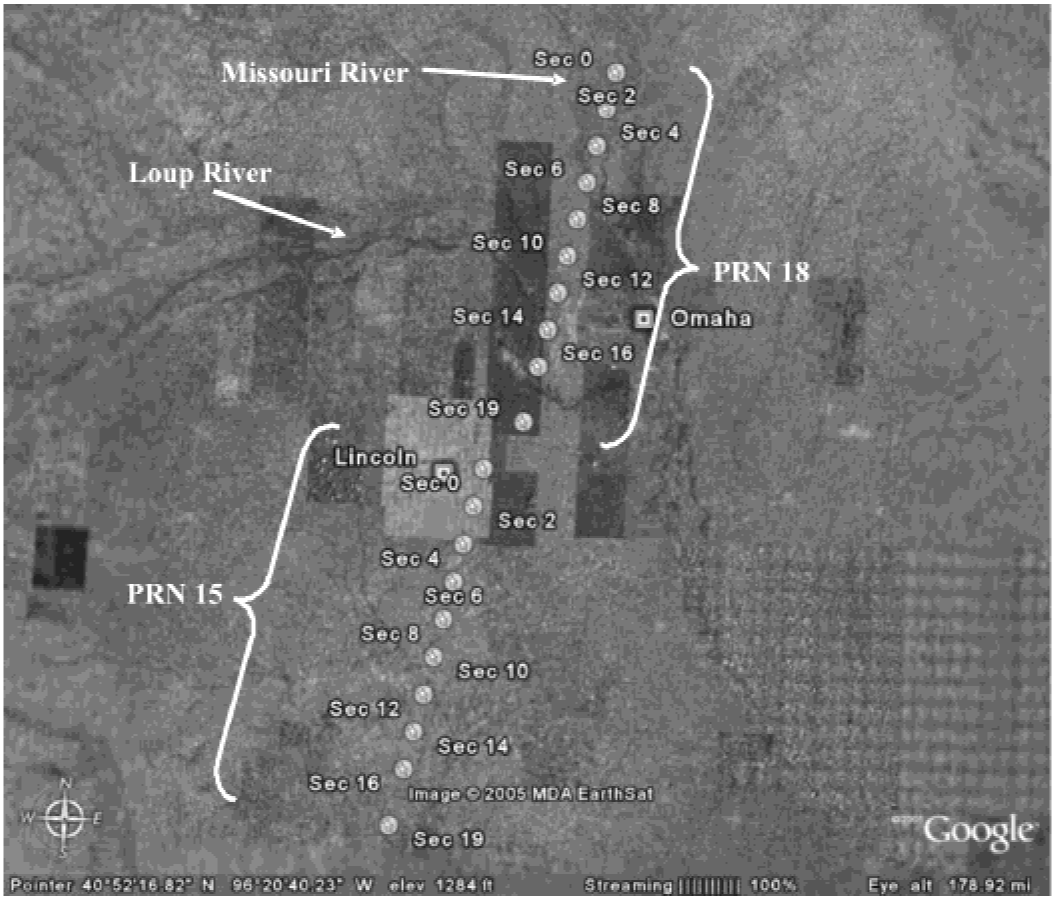

Figure 6 Surface sampled in the experiment

In Figure 6 is reported the scanned zone on which was effectuated a 100 ms measurement with 1 ms resolution. Collected data are shown in Figure 7.

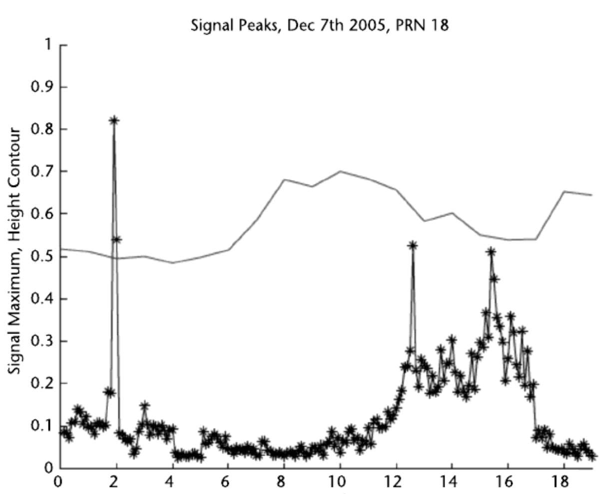

FIgure 7 Collected data in the experiment

From examining the fluctuation in the reflected signal with respect to the terrain several interesting links can be observed. The first is the obvious spike in the signal magnitude as the reflection point crossed a river (see second 2 in Figure 7). As the signal passes over water it would be expected to increase in magnitude, hence the suspicion that the increase in received signal power at second 12 in Figure 7 may be due to the presence of some other rivers.

These measurements could then be studied with respect to reliable in situ ground truth information and compared to models to determine if the reflections are responding to a useful surface observable such soil moisture or surface vegetation content.

For the latter use, altimetric profile tracking is obtained by studying the transmitted and reflected signals' flight times and delay. In Figure 8 is shown an example of a direct and reflected signal retrieved from an aircraft; the distance between the direct signal peak to the reflected one represents the delay time.

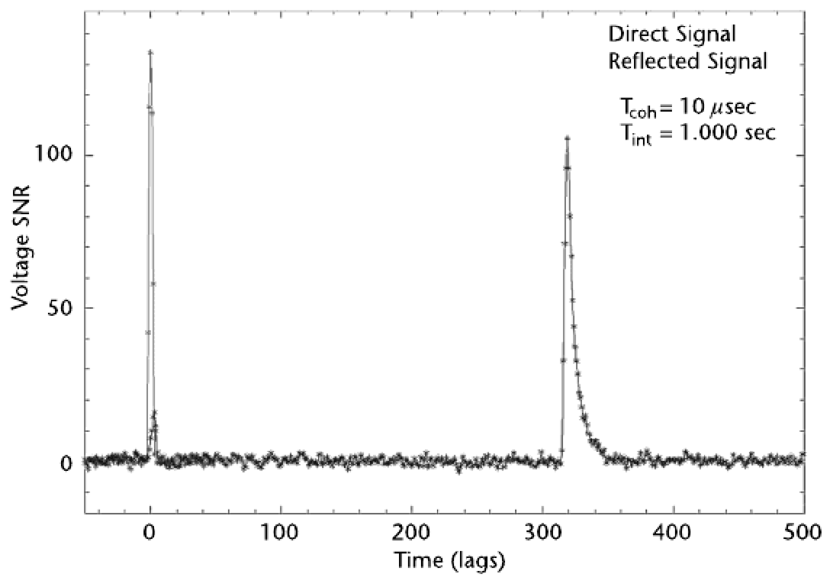

Figure 8 Example of direct and reflected signal from an aircraft

An example of the altimetric profile of the scanned zone by the satellite is shown in Figure 7.

Detected Sea Ice Reflections

An important practical application is the possibility to detect the extension and depth of sea ice surface. This technique is nowadays under development, and will be very useful for glacier and ice cap monitoring.

Ocean altimetry sensing

The primary scientific motivation for developing GNSS ocean altimetry is improving mesoscale eddy measurements. Mesoscale eddies represents one of the largest global climate modelling errors and they play an important role in the transports of momentum, heat, salt nutrients and other chemical properties of the ocean. GNSS ocean altimetry has the potential to map the Earth in about one to two days and with 25-km spatial resolution. The challenge for GNSS altimetry is to overcome the lower bandwidths and signal power compared to radar altimeters, which will likely involve using large receiver antennas.

Also for these experiments, the primary observable was the time delay between the direct and reflected signal arrival (Figure 8), from which it's possible to deduce sea waves altimetry.

Ocean winds sensing

It is obvious that for practical reasons the one-dimensional approach with multiple satellites is limited to relatively low-flying platforms when the size of annulus-generated footprints and distances between them are of the order of several hundred kilometres, over which most parallel reflections would be too far apart for use in deriving wave direction. For wind vector retrievals using orbital-based receiver, a more preferable approach would be utilizing a full two-dimensional waveform obtained from a single GNSS satellite. For wind sensing to be reliable using GNSS signals, the ocean waves and wind must be at equilibrium or under conditions of well-developed seas.

In 2008, an approach was proposed by Cardellach and Rius proposing a new algorithm for extracting the PDF of the sea surface slopes from GNSS reflected signals. An advantage of this new approach is that the resulting inversion system is linear, with no need for a priori or iterating sequences. From two-dimensional waveforms, or delay-Doppler maps one can generate the so-called two-sided PDFs retrieved separately from two sides of the glistening zone. Finally, the algorithm has been tested on real data. It was found that the retrieved PDFs reflect the effect of the wind direction, consistent with the ENVISAT SAR near-simultaneous observations.

Additionally, the retrieval of sea surface directional mean square slope from GNSS reflection delay-Doppler-map (DDM) data was achieved during an experimental flight at 1-km altitude. This work involved processing the entire DDM to more precisely infer ocean roughness directional parameters.

Occultation Measurements

A receiver on-board a LEO satellite tracks one or more GPS signals as they pass through the Earth's atmosphere.

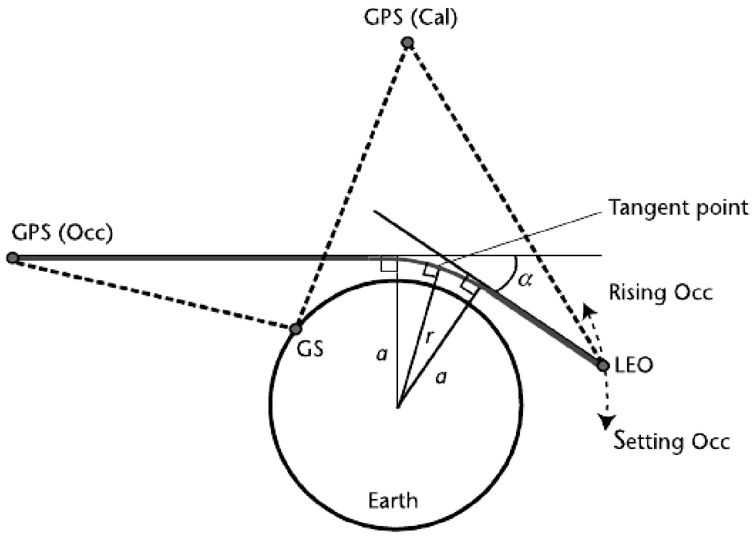

Figure 9 Geometry of GPS Radio Occultation. The signal transmitted by the GPS is bent, by an angle of α, as it travels through the Earth's Ionosphere and atmosphere to the LEO. Under spherical symmetry, each ray can be identified uniquely by an impact parameter a.

Due to the motion of the occulting GPS transmitters and LEO satellites, the GPS signals essentially slice through different vertical layers of the atmosphere over the course of an occultation event. After this event, precise measurements of the signal carrier phase and amplitude as a function of time can be inverted to yield a vertical profile of the refractive index of the atmosphere.

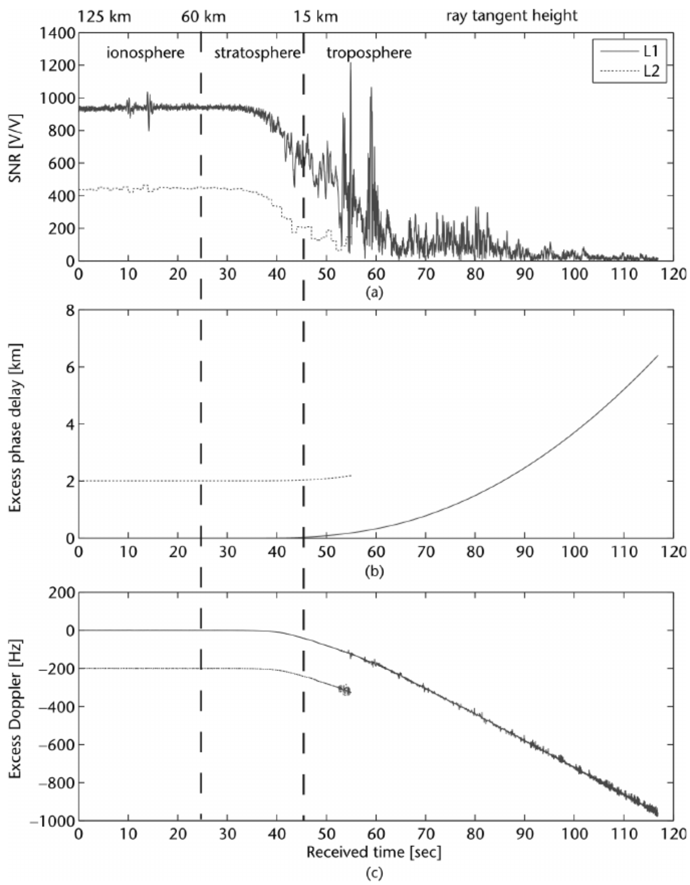

Figure 10 An example of GPS occultation measurements: (a) 1-sec SNR; (b) excess phase delay in kilometres; and (c) excess Doppler in Hertz. The L2 excess phase and Doppler have been shifted by 2 km and -200 Hz, respectively. Note that the L2 SNR is much lower than L1 due to the need for codeless tracking. Typically no useful L2 data are available in the lower and middle troposphere.

The refractive index is directly related to electron density in the ionosphere (Appleton – Hartree Equation), while it is a function of pressure, temperature, and water vapour in the neutral atmosphere (Bean and Dutton Equation). Another important aspect of R.O measurements is “Delay”: the fundamental quantity measured in a GPS occultation is the time delay of the GPS signal, which varies like a function of the index of refraction of the intervening medium. This disadvantage can be calculated thanks an equation, and the first step of data processing is own this i.e. the removing of delay due only to the ionosphere and atmosphere.
Very important is to “remove” GPS and LEO clock effects from the signal to be inverted. Figure 9 gives an example of GPS occultation measurements, as observed by one of the COSMIC satellites on December 2007. This example is a typical setting occultation, with the ray tangent points located over the tropical south Pacific Ocean. The entire occultation lasted about two minutes, with a starting tangent height of about 125 km above the Earth’s surface. The Figure 10 shows the 50 Hz SNR (essentially the “amplitude” of the signal) and the excess phase delay (the main GPS observable to be inverted is the excess phase or phase delay, i.e. the measured signal phase minus the phase experienced in case of vacuum propagation) in function of received time. In addition the Figure 10 shows also the excess Doppler, which is the time derivative of the excess phase.

Atmospheric Retrievals

Occultation measurements can be used to derive atmospheric profiles. The retrieval process involves two steps.

First step: the time derivative of the excess phase delay (the excess Doppler) and SNR measurements are used to calculate the bending angle profile ($\alpha(a)$), where "a" is the so called ray impact parameter (the distance of the trajectories' asymptotes).

Second step: the bending angle profile is inverted to give the refractivity profile and subsequently the temperature, pressure, and humidity profiles.

Weather and Climate Applications

Given the possibility to obtain a high number of atmospheric profile globally distributed around the world (in particular above oceans, where radio soundings are not available), GPS occultation measurements have proven to be very useful for both weather and climate applications.

A great deal of research has been carried out on the methodology and effectiveness of assimilating GPS R.O data into global as well as regional numerical weather prediction (NWP) models. The simplest, least computationally expensive approaches are to assimilate the bending angle or refractivity profiles. Several studies have demonstrated convincingly that assimilation of GPS data yielded positive impacts on the forecasts.

Another scientific area where GPS occultation has proven useful is in delineating the characteristics of the tropopause, which separates the convectively mixed troposphere and the convectively stable stratosphere. The tropopause plays a crucial role in tropical dynamics and the vertical transport of trace gases; moreover, the tropopause height can be a sensitive indicator of climate change. The high vertical resolution that GPS occultation temperature profiles make them especially suitable for studying the tropopause.

Attitude and Orbit Determination for a CubeSat

An additional application that could be enabled by the on-board GNSS receiver is on-board orbit determination. As long as the satellite is in a lower orbit than the GNSS satellites, the orbit can be precisely determined.

One of the major issue to account for is the presence of the Doppler effect, as the speeds of the satellite wrt the GNSS ones can be high, and this must be corrected via software on-board, increasing computational power requirements.

Increasing efforts are being spent in developing cubesat-compatible GNSS receiver (see Hollenstein work) that can reach very low consumption (60mW for each receiver). This could enable a second application of the GNSS signal, which is attitude determination.

In this sense, different receivers positioned apart from each other could determine different positions in time, therefore allowing for attitude determination. In this case, one of the main drawbacks of cubesat is their small dimensions, therefore resulting in high uncertainties of the position delta between the receivers.

In this case, receivers mounted on deployable booms could be envisioned.