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Ph.D. Dissertation

Contributions to Earth Observation Using GNSS-R Opportunity Signals

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A mi família,

Al Xavi, la llum de la meva vida.
PREFACE

During years a number of satellites have been developed to remotely sense Earth geophysical parameters for weather forecasting and climate studies. In recent years the use of reflected Global Navigation Satellite System Signals (GNSS-R) has shown its potential to retrieve geophysical parameters over the ocean, mainly altimetry and sea state, and over land, mainly soil moisture. It is known that sea roughness has an impact on L-band radiometric measurements, and therefore on the retrieved sea surface salinity (SSS). GNSS-R is an interesting tool to help improving the sea state effect correction to reduce the final SSS retrieval error. To demonstrate this idea the Passive Advanced Unit (PAU) project was proposed to the European Science Foundation (ESF) under the EURYI 2004 call. The main objective was the study of the direct relationship between the radiometric brightness temperatures and some GNSS-R observables to perform the state correction without using emission/scattering models. Once this goal was successfully addressed, the PAU objectives were broaden to include the development of new GNSS-R instruments and techniques, and the study of geophysical parameters retrieval from different surfaces. The present Ph.D. dissertation describes one of the research lines of the the PAU project, undertaken between February 2007 and December 2011, within the Passive Remote Sensing Group of the Remote Sensing Lab, at the Department of Signal Theory and Communications of the Universitat Politècnica de Catalunya.

The present Ph.D. dissertation focuses on GNSS-R techniques applied to the observation of different types of scattering surfaces (land surfaces: bare soils, vegetation-covered soils, snow-covered soils; inland-water surfaces and ocean surfaces), and the retrieval of different geophysical parameters. Two main GNSS-R techniques have been studied and applied to real data obtained during seven field experiments, the Delay-Doppler Map (DDM) processing technique and the Interference-Pattern Technique (IPT), selecting the one most appropriate to the observed surface. Furthermore, in the context of this Ph.D dissertation a new type of GNSS-R instrument has been developed, being the main tool for the application of the IPT and the retrieval of several geophysical parameters over land and inland-water surfaces.

After an introduction on GNSS-R and the PAU-project, the methodology, the instruments and the techniques used to retrieve soil moisture, vegetation height and topography in agricultural areas, snow thickness, water level in reservoirs, and wind speed in ocean surfaces, are described. These retrievals
show the potential that these opportunity signals have for monitoring a broad kind of effects. After that, some studies related to space-borne GNSS-R techniques are summarized. Finally a summary of the work performed in this Ph. D. dissertation, the main conclusions, and the future work lines are presented.

The presented results are a contribution to promote the use of the GNSS opportunity signals for monitoring geophysical parameters to increase the understanding of the Earth’s water cycle, and position these techniques as suitable tools that enhance water resources management.
ACRONYM LIST

ADC Analog-to-Digital Converter
ALBATROSS Advanced L-Band Emissivity and Reflectivity Observations of the Sea Surface
BNSC British National Space Centre
CALIPSO Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
C/A Coarse Acquisition
CCAR Colorado Center for Atmospheric Research
CDMA Code Division Multiple Access
CIALE Centro de Investigaciones Agrarias Luso Español
CU Colorado University
DEM Digital Elevation Model
DMC Disaster Monitoring Constellation
DDM Delay-Doppler Map
DoY Day of the Year
EADS-CASA European Aeronautic Defence and Space Company-Construcciones Aeronauticas Sociedad Anonima
EM Engineering Model
ERSL Earth System Research Laboratory
ESA European Space Agency
ESF European Science Foundation
EURYI EURopean Young Investigator
FM Flight Model
FPGA Field Programmable Gate Array
GLONASS GLObalnaya NAvigatsionnaya Sputnikovaya Sistema or GLObal NAivation Satellite System
GNSS Global Navigation Satellites System
GNSS-R GNSS– Reflectometry
GOIS GNSS-R Observations over Inland–water Surfaces
GPS Global Positioning System
GRAJO GPS and RAdiometric Joint Observations
GRIPAU GPS Reflectometer Instrument for PAU
HDF5 Hierarchical Data Format 5
IEEE Institute Electrical an Electronics Engineers
IF Intermediate Frequency
INTA National Institute for Aerospace Technology
IPT Interference Pattern Technique
I/Q In-phase/Quadrature
IR Infrared
IRNSS Indian Regional Navigational Satellite System
ISS International Space Station
JPL Jet Propulsion Laboratory
LAI Leaf Area Index
LAURA L-band AUtomatic Radiometer
LEO Low Earth Orbit
LHCP Left Hand Circular Polarization
LNA Low Noise Amplifier
LO Local Oscillator
LWC Leaf Water Content
MATLAB MATrix LABoratory
MERITXELL Multi-frequency Experimental Radiometer With Interference Tracking For Experiments Over Land And Littoral
MIRAS Microwave Imaging Radiometer by Aperture Synthesis
MOSFET Metal Oxide Semiconductor Field Effect Transistor
MOSSUS Monitoring Of Snow Surfaces Using SMIGOL-R
NASA National Aeronautics and Space Administration
NDVI Normalized Difference Vegetation Index
NOAA National Oceanic and Atmospheric Administration
PARIS Passive Reflectometry and Interferometry System
PARIS IoD PARIS In orbit Demonstrator
PAU Passive Advanced Unit
PAU-OR PAU-One Receiver
PAU-ORA PAU-One Receiver Airborne
PAU-RAD PAU-Radiometer
PAU-SA PAU-Synthetic Aperture
PDF Probability Density Function
PIC Peripheral Interface Controller
PLL Phase Loop Lock
PRN Pseudo-Random Noise
PSU Practical Salinity Unit
RADAR RAdio Detection And Ranging
REMEDHUS Red de Medición de la Humedad del Suelo
RF Radio Frequency
RFI Radio Frequency Interference
RHCP Right Hand Circular Polarization
RMS Root Mean Square
RMSE Root Mean Square Error
RSLAB Remote Sensing LABoratory
SAR Synthetic Aperture RADAR
SD Secure Digital
SEOSAT Scientific Earth Observation SATellite
SIR-C Spaceborne Imaging Radar-C band
SM Soil Moisture
SMA SubMiniature version A
SMIGOL-R Soil Moisture Interference-pattern GNSS Observations at L-Band Reflectometer
SMOS Soil Moisture Ocean Salinity
SNR Signal to Noise Ratio
SPM Small Perturbation Method
SSA Small Slope Approximation
SSS Sea Surface Salinity
SST Sea Surface Temperature
SSTL Surrey Satellite Technology Limited
TSIP Trimble Standard Interface Protocol
TTL Transistor-Transistor Logic
UK-DMC United Kingdom DMC
UPC Universtitat Politècnica de Catalunya
USA United States of America
USB Universal Serial Bus
UTC Coordinated Universal Time
VWC Vegetation Water Content
WGS-84 World Geodetic System 84
WS Wind Speed
μC micro-controller
μSat micro-satellite
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This chapter gives a general overview of the relevance of Earth remote sensing and the suitability of Global Navigation Satellite System Reflectometry (GNSS-R) for this purpose. The state of the art of the GNSS-R is presented, and the aim and innovation of this Ph.D. dissertation are explained.
1.1 Relevance of Remote Sensing to Climate Monitoring

The link between the oceans and the atmosphere, the biosphere and the solid Earth has a huge impact over all aspects of life on the Earth. The diversity of life forms has been possible thanks to the moderate temperatures, and the existence of water. One of the largest impacts on the ever-changing Earth environment is the human activity, which increases with population increase. This is linked to the increase of the capability to predict the Earth’s system. During the past decades a number of satellites have been developed to remotely sense the Earth’s geophysical parameters that are introduced into numerical models for weather forecast and to predict other climate phenomena.

The interest of the scientific community in remotely measuring Sea Surface Salinity (SSS) and Soil Moisture (SM) has increased in the last years and much effort has been spent in that direction by the European Space Agency (ESA), and the National Aeronautics and Space Administration (NASA) with the Microwave Imaging Radiometer by Aperture Synthesis/Soil Moisture and Ocean Salinity (MIRAS/SMOS, Figure 1.1a [1]), and the Aquarius (Figure 1.1b [2]), missions, respectively.

![Image](image1.png)

Figure 1.1 Artist’s views of missions (a) ESA SMOS [3], and (b) NASA Aquarius/SAC-D [4].

Both instruments carry an L-band radiometers, which are instruments that measure the spontaneous electromagnetic radiation emitted by all bodies at a physical temperature different from 0 Kelvin. Microwave radiometers where first used in radio-astronomy in the 1930’s [5]. Since the 1960’s a large number of microwave radiometers have been developed for remote sensing applications to measure a wide range of natural phenomena (for example [6]-[7]).
The Disaster Monitoring Constellation (DMC) was created as a multi-national network of satellites to provide optical multispectral imagery for disaster response and commercial imaging campaigns. One of this satellites is the United Kingdom DMC (UK-DMC) [8], developed by Surrey Satellite Technology Limited with support from the British National Space Centre (BNSC).

![UK-DMC satellite](image)

Figure 1.2 Artist view of UK-DMC satellite, [8].

This satellite provided the first GNSS-R measurements from space. A GPS receiver onboard the UK-DMC performed a GNSS reflectometry experiment to investigate the reception of reflected GPS signals off the ocean surface for oceanographic applications, such as the relationship between the reflected GPS signals and the sea state.

These three missions (SMOS, Aquarius and UK-DMC) are the most relevant ones for this Ph.D. dissertation, and represent the importance of the main retrievals that will be shown in next chapters. However, in addition to the geophysical parameters provided by these three missions (soil moisture, sea surface salinity, and sea state) many other space missions have been launched to measure other geophysical parameters such as water vapor in the atmosphere, clouds, precipitation, sea ice, surface elevation, ice sheets, land ice, and snow cover. Understanding these geophysical parameterers will provide the international science community with a more comprehensive data set essential for a better understanding of the Earth's climate processes. Accurate climate model predictions will provide decision makers with accurate information to make more informed political decisions.
1.1.1 Importance of the Sea Surface Salinity and the Soil Moisture Retrievals

Water plays a key role in all the geological and biological processes that take place in our planet. Cycling endlessly between oceans, atmosphere and land, it triggers and supports life, shapes the Earth and drives the weather and the climate (Figure 1.3). Recalling that oceans account for more than 96 % of the water on Earth, it is important to study the mechanisms that govern the ocean-to-atmosphere interface.

![Water cycle diagram](image)

Figure 1.3 The water cycle on Earth [9].

Figure 1.3 shows the importance of the water cycle, which regulates the climate and the heat exchange on Earth. Water evaporates from the ocean, resulting in an increase of the SSS. When it rains over the ocean, the SSS decreases creating a fresh-pool. On the other hand, if it rains over the land, it implies that soil moisture increases. At the same time, the water that precipitates over land, runs off, and returns to the ocean, and the cycle starts again. The land water also evaporates, returning to the atmosphere, or it is transpired by the vegetation canopies, taking heat from the ground and transferring it to the atmosphere.

1.1.1.1 The Sea Surface Salinity

The sea surface salinity (SSS) is an oceanographic parameter that depends on the balance between precipitation and fresh water river discharge, ice melting, atmospheric evaporation, mixing and circulation of the ocean’s surface water with the deep water below. It is usually expressed using the practical salinity unit (PSU) of the practical Salinity Scale of 1978 (PSS-78).
In the open ocean the SSS ranges between 32 psu and 38 psu, with an average value of 35 psu. It is maximum in sub-tropical latitudes, where evaporation is more important than precipitation. Conversely, the salinity drops below the average around the Equator, where there is more precipitation, and in Polar Regions, due to ice melting, and snowfall. Salinity and temperature are the two variables that control the density of the ocean water, which increases with increasing salinity and decreasing temperature. Density itself is a very important oceanographic parameter, since ocean currents are generated by horizontal differences in density, and also its vertical profile determines the effect that surface winds, heating, and cooling have on subsurface waters. Salinity, through density, also determines the depth of convection at high latitudes. During the formation of sea ice, composed mainly of fresh water, dense cold salty water masses remain in the surface. At some point the water column losses its balance, and denser water sinks. This vertical circulation is one of the engines of the global oceanic circulation known as the thermohaline circulation (Figure 1.4). This is the oceanic conveyor belt, and it is a key component of the Earth’s heat engine, and therefore it strongly influences the weather and the climate.

![Thermohaline circulation](image)

Figure 1.4 Thermohaline circulation acts as a global conveyor belt that redistributes heat throughout the whole planet.

Salinity also determines the behavior of the ocean-air interface where gas and heat exchange takes place. The increased precipitation at tropical latitudes can locally create fresh water pockets where the upper layer is more stable, thus reducing the gas transfer. SSS also influences the sea water vapor pressure, thus controlling the evaporation rates.

Nowadays Sea Surface Temperature (SST) along with other oceanographic parameters such as Wind Speed (WS) or sea surface topography are
monitored on a regular basis from spaceborne sensors. SSS retrievals from space are recently possible thanks to SMOS launched on November 2nd, 2009. Prior to that, while ocean circulation models already incorporate satellite SST, WS and altimetry, they lacked of accurate SSS data. To overcome this limitation usually temperature-salinity correlations were used, based on the density conservation principle over a certain water volume [10]. However, the validity of this principle was seriously questioned at the surface, where heat and gas exchange between sea and air takes place [11]. This results in modeling errors that hinder the modeling of surface currents. The severity of this lack of data is clearly understood considering that SSS was never measured before for 42% of the ocean surface, and that was measured less than four times over the past 125 years for 88% of the ocean surface [12]. But now SMOS and more recently Aquarius/SAC-D measurements are providing the SSS information needed to overcome this lack of information.

1.1.1.2 The Soil Moisture

On the other hand, soil moisture is another important variable of the water cycle over the land, controlling water fluxes between the atmosphere, the surface, and the subsurface.

Because a large amount of heat is exchanged when water changes its phase, the water cycle is fundamental to the dynamics of the Earth’s energy cycle. Also, since water is the ultimate solvent in the Earth’s system, biogeochemical cycles such as carbon, nitrogen and methane are embedded in the water cycle. Through these dynamics, soil moisture conditions the evolution of weather and climate over continental regions. Hence, global measurements of soil moisture are needed to improve the understanding of water cycle processes. Global soil moisture information will be transformational for the Earth’s system science; it will help characterizing the relationship between soil moisture, its freeze/thaw state, and the associated environmental constraints to ecosystem processes including land-atmosphere carbon, water and energy exchange, and vegetation productivity Figure 1.3. At the same time, global soil moisture information will enable societal benefit applications such as better water resource assessment, improved weather forecasts, natural hazards mitigation, predictions of agricultural productivity, and enhanced climate prediction, human health, and defense services. Soil moisture retrievals from space are recently possible thanks to SMOS, launched on November 2nd, 2009.
1.1.2 The Global Navigation Satellite System (GNSS) Signals for Remote Sensing of the Earth

Global Navigation Satellite Systems (GNSS) are satellite constellations that cover the entire Earth with navigation signals to provide time and position information to users located on or near the Earth’s surface. Such systems are used nowadays in a wide range of everyday situations, such as fleet management, search and rescue, wildlife tracking, vehicle guidance or leisure interactive maps, among many others. So far the American Global Positioning System (GPS) is the only fully operational GNSS. The Russian GLONASS system is partially deployed, whereas the European Galileo is scheduled to be operational in 2014, and the first two satellites of the constellation have been recently launched (October 20th, 2011). Other GNSS systems, such as the Chinese Compass navigation system by 2020 or the Indian Regional Navigational Satellite System IRNSS, are planned to be operational in the future. Altogether, more than 75 GNSS satellites will be available when all the currently planned systems are deployed. The retrieval of geophysical parameters using these GNSS signals as a source of opportunity (GNSS-R) can in principle be used to measure ocean surface roughness, altimetry, soil moisture, or ice properties. It is true that there are other systems that already perform those measurements, such as active scatterometers (roughness), radar altimeters, or microwave radiometers, but these new systems will help increasing spatial and temporal resolution. For the particular application of sea state determination, the GNSS-R approach boasts a low mass and power constraints, since there is no transmitter and a small antenna can be used. Also, the bistatic scattering geometry ensures a strong signal return in the specular direction, in opposition to the weak return for monostatic off-nadir configurations. It is also noteworthy that GNSS-R is directly sensitive to ocean roughness scales at L-band, and inherently less sensitive to power calibration.

This Ph.D. dissertation focuses on the use of GNSS-R signals to perform geophysical parameters retrievals observing different types of surfaces and using different techniques, selecting the most suitable technique for each type of surface. Specifically, this Ph.D. dissertation makes use of Global Positioning System (GPS) signals since they are the most widely available. Due to the interest of the GPS system in the frame of this Ph.D. Thesis, the structure of the GPS signals is explained in more detail in the next sections, and the state of the art of the GNSS-R scientific field is described.
1.2 Global Positioning System (GPS) Signals

The GPS was designed to provide 3-D positioning anytime, anywhere on Earth. To fulfill that goal at least four satellites have to be observed simultaneously at a given place and moment. In order to ensure the service even when one satellite fails it is necessary to consider a minimum of five visible satellites. These considerations result in a constellation of at least 24 satellites distributed in six orbital planes spaced 60° through the Equator with an inclination of 55°. Figure 1.5 shows the artist’s view of a GPS satellite and the constellation.

![GPS Satellite and Constellation](image)

Figure 1.5 Artist’s view of (a) GPS Block II-F satellite in Earth orbit and (b) GPS satellites constellation.

The ‘at least’ four satellites in the same orbital plane are not equally spaced, but distributed so that the effects of a single satellite failure are minimized. The orbital period is 12 sidereal hours, which implies that the ground track repeats daily with a time shift of four minutes. The near circular orbits (eccentricity smaller than 0.02) have a medium height of 20163 km above the Earth’s surface, resulting in a mean satellite speed of 3.87 km/s approximately. The actual satellite visibility depends on the latitude, but there are always a minimum of 5 satellites in view, and for more than 80 % of the time the minimum number is 7.

The GPS signal includes information about the distance to the satellite, range information, and the navigation message (ephemeris, to calculate the position of each satellite in orbit, and almanac, to provide information about the time and the constellation status).
As it can be seen in Figure 1.6 the GPS signal is formed from a carrier wave (L1 band = 1.57542 GHz), a code sequence, and the navigation data. There are two types of range information inside the GPS signal: one is the public Coarse/Acquisition code (C/A code sequence), and the other one is the Precision code (P-code sequence) reserved for military applications.

### 1.2.1 Coarse/Acquisition Code

The C/A code is a 1023 bit deterministic sequence called pseudo-random noise (also pseudo-random binary sequence) (PN or PRN code) which, when transmitted at 1023 megabits per second (Mbit/s), repeats every millisecond. These sequences only match up, or correlate strongly, when they are exactly aligned. Each satellite transmits a unique PRN code, which does not correlate well with any other satellite’s PRN code, one PRN code is highly orthogonal to the others. This is a form of Code Division Multiple Access (CDMA), which allows the receiver to recognize multiple satellites on the same frequency band.
1.2.2 Precision Code

The P-code is also a PRN sequence. However, each satellite's P-code is $6.1871 \times 10^{12}$ bits long, it is transmitted at 10.23 Mbit/s, and repeats once a week. The extreme length of the P-code increases its correlation gain and eliminates any range ambiguity within the Solar System. However, the code is so long and complex that it was believed that a receiver could not directly acquire and synchronize with this signal alone. The receiver would first lock onto the relatively simple C/A code and then, after obtaining the current time and approximate position, synchronize with the P-code.

Whereas the C/A PRNs are unique for each satellite, the P-code PRN is actually a small segment ($6.1871 \times 10^{12}$ bits) of a master P-code approximately $2.35 \times 10^{14}$ bits in length and each satellite repeatedly transmits its assigned segment of the master code.

To prevent unauthorized users from using or potentially interfering with the military signal through a process called spoofing, it was decided to encrypt the P-code. To that end the P-code was modulated with the W-code, a special encryption sequence, to generate the Y-code. The Y-code is what the satellites have been transmitting, since the anti-spoofing module was set to the "on" state. The encrypted signal is referred to as the P(Y)-code.

1.2.3 Gold Sequence

Since all of the satellite signals are modulated onto the same L1 carrier frequency, there is a need to separate the signals after demodulation. This is done by assigning each satellite a unique binary sequence known as a Gold code [14]. The PRN codes transmitted by the GPS satellites are deterministic sequences with noise like properties. A maximal-length sequence of length $N=2^n-1$ elements is generated. A Gold code is the sum of two maximum-length sequences. The GPS C/A code uses $n = 10$. The sequence repeats every ms so the chip length is $1\text{ms}/1023 = 977.5\ \text{ns} \approx 1\ \mu\text{s}$, which corresponds to a metric length of 300 m when propagating in the vacuum or in the air.

Each satellite's PRN identifier is unique and in the range from 1 through 32. The Gold codes are highly mutually orthogonal, so that it is unlikely that one satellite signal will be misinterpreted as another. As well, the Gold codes have good auto-correlation properties. There are 1025 different Gold
codes of length 1023 bits, but only 32 are used. These Gold codes are quite often referred to as pseudo-random noise, since they contain no data and are said to look like random sequences. However, this may be misleading, since they are actually deterministic sequences.

1.3 State of the Art of GNSS-Reflectometry (GNSS-R).

Reflectometry using Global Navigation Satellite Systems signals (GNSS-R) was first devised in 1993 by Martin-Neira [15] for altimetry applications. During the past few years, the GNSS-R techniques have been the focus of several institutions around the world.

In the United States the following groups are related to GNSS-R field:

- The Earth System Research Laboratory (ERSL), at the National Oceanic and Atmospheric Administration (NOAA), have collaborated in a large list of studies, for example: land studies [16], [17] and [18], ocean studies [19] and [20], and ice surfaces [21] and [22]. Other laboratories from NOAA, as National Geodetic Survey and Atlantic Oceanographic and Meteorological Laboratory, have also been involved in some of the studies as [18] and [23], respectively.

- The Colorado University (CU) has collaborated in works and advances in this field. For example the Colorado Center for Atmospheric Research (CCAR), land [16] and [17], and ice [21]; the department of Aerospace Engineering Science, the department of Geological Sciences and the University Corporation for Atmospheric Research, land [18] and ice [22]. Some other universities from the U.S. have contributed to the GNSS-R studies, as the Electrical Engineering Research Laboratory at the University of Texas, with land studies as [24] and [25], and the Montana State University with a snow study [26].

- Also, the Langley Research Center at National Aeronautics and Space Administration (NASA) has performed studies over land ([16] and [27]), and ocean ([21], [23], and [28]).

In Europe the most important groups are related to GNSS-R field:

- The European Space Agency, from the Netherlands, has performed studies related to altimetry ([15], [29], and [30]), and ocean ([31]), or ice surfaces ([32]).
• The University of Surrey, the Surrey Space Center and the Ocean Circulation and Climate Division, from the National Oceanographic Centre of Southampton, all them from England, have performed studies over ocean surfaces ([35] – [37]), and also were involved in the ice study performed in [32].

• The department of Geodesy and Remote Sensing and EADS Deutschland, Immestad, from Germany, was also involved in the study performed in [32] over ice surfaces.

• Institut d’Estudis Espacials de Catalunya (IEEC), from Barcelona, has been involved in altimetry [30], ocean [33] and [34], and ice [32].

• Starlab, from Barcelona, have been involved in ocean [31] and [49], land [50], and inland-water [51] studies.

• The Remote Sensing Laboratory (RSLab) at the Universitat Politècnica de Catalunya, from Barcelona, land ([38] – [40]), ocean ([41] – [46]), snow [47], and inland-waters [48], where I have performed my Ph.D. Thesis.

There are other contributions to the field that come from the rest of the world, as:

• The Center for Space Science and Applied Research from Chinese Academy of Sciences, the Third Institute of Oceanography from State Oceanographic Administration, the Institute of Atmospheric Physic, and the China Research Centers of GPS, that has been involved in the first ocean GNSS-R experiment in China ([52] and [53]).

The GNSS-R potential has increased yearly, with improved receivers and signal processors, from generic GNSS receivers whose signals were recorded in magnetic tapes to instruments that measure full Delay Doppler Maps (the power distribution of the reflected GNSS signal over the 2-D space of delay offsets and Doppler shifts, DDM) in real time. The measurement of the DDMs provides information about the observed surfaces and is a suitable tool to get geophysical parameters. Other techniques based on interference patterns, as the one devised in this Ph.D dissertation, ([38] – [40], [47], [48]), and others similar ([24] – [26]), give interesting results and have been demonstrated to be powerful tools in the retrieval of parameters, as well from ground. At present, these techniques are already achieving good results in the retrieval of geophysical parameters such as soil moisture, vegetation height, topography, altimetry, sea state and ice and snow thickness, among others.
1.4 Conclusions

GNSS Reflectometry is nowadays a proven and convenient (cheap, small, low power) tool for Earth’s remote sensing, which is receiving more and more interest. A lot of effort and work has been performed since [29], and surely much more will be done in the coming years.

This Ph.D. dissertation will present some contributions to Earth observation using these GNSS opportunity signals. The novelty of the Ph.D. dissertation is the development of a new type of ground-based instrument (the Soil Moisture GNSS Observations at L-band (SMIGOL) reflectometer) to apply an original and simple technique (the Interference Pattern Technique or IPT) over a number of different scenarios that, after performing a several field experiments, and acquiring real data, has produced very good retrieval results.

Although this is the main core of the Ph.D. dissertation, parallel studies have been performed to retrieve other geophysical parameters, as:

- the vegetation water content, that required a specific instrument also designed and developed during the Ph.D, and a dedicated field experiment to validate the technique, named as GNSS-Transmission (GNSS-T) technique, and
- the wind speed over the ocean, that was part of my work during my visit to the Earth System Research Laboratory (ERSL) in the National Oceanographic and Atmospheric Administration (NOAA), at Boulder, Colorado, USA.

1.5 Ph.D. Thesis Structure

This Ph.D. Thesis is devoted to study some contributions to Earth observation using GNSS-R opportunity signals. It has been organized as follows:

- Chapter 2 provides the necessary context for this Ph.D. Thesis by giving an overview of the PAU-Project. Although, the SMIGOL-Reflectometer is the main instrument of this dissertation, a glimpse to the other Passive Remote Sensors built in the Remote Sensing Laboratory at the Universitat Politècnica of Catalunya (RSLab-UPC) in framework of the PAU project are provided. The main objectives
and goals of the PAU project are analyzed (PAU-RAD, PAU-Synthetic Aperture, griPAU, MERITXELL and SMIGOL).

- Chapter 3 details a new instrument, called Soil Moisture Interference-pattern GNSS Observations at L-band (SMIGOL) Reflectometer, that was originally developed during the second year of this Ph.D. Thesis, and has been upgraded and used in many different field campaigns to gather interferometric measurements, and test the theoretical developments.

- Chapter 4 focuses on soil moisture retrievals over bare soils using the SMIGOL-Reflectometer ground-based instrument. SMIGOL is a GNSS-R instrument that implements the Interference Pattern Technique (IPT), a technique consisting of the measurement of the power fluctuations of the interference signal resulting from the simultaneous reception of the direct and the reflected GNSS signals. A field experiment has been performed in order to validate the theoretical aspects of the IPT and the soil moisture retrieval algorithm. Results are presented and the main conclusions are summarized.

- Chapter 5 focuses on the study of vegetation-covered soils from the SMIGOL-Reflectometer ground-based instrument using the IPT. The vegetation effects are analyzed and the soil moisture retrieval algorithm is modified accordingly. Three field experiments are performed in order to test the IPT and the retrieval algorithms in presence of vegetation. Afterwards a new technique for a deeper vegetation analysis is presented and tested during a 11-month field experiment. The results are shown in this chapter and the main conclusions are summarized.

- Chapter 6 focuses on the study of snow-covered soils from the SMIGOL-Reflectometer ground-based instrument using the IPT. The snow effects are analyzed, and an algorithm for this type of surfaces has been developed. A long term field experiment, the Monitoring Of Snow using SMIGOL-R (MOSS) field experiment, was performed at the Val d’Aran to test the IPT and the retrieval algorithms in the presence of snow.

- Chapter 7 makes use of the same GNSS-R techniques as in Chapter 4 and 5. After analysing the effects of the geophysical parameters on the interference patterns over land, some similarities with other surfaces as the ones called inland-waters, are easily found. This chapter shows the theoretical aspects and the GNSS-R Observations
over Inland-water Surfaces (GOIS) field experiment performed to retrieve water level over reservoirs.

- Chapter 8 is the result of the Ph.D. Stay at the Earth System Research Laboratory (ERSL) in the National Oceanographic and Atmospheric Administration (NOAA), Boulder, Colorado, USA, during March – July, 2011. The Delay Doppler Maps (DDM) obtained as a result of processing the data collected by the GPS software receiver onboard the NOAA Gulfstream-IV jet aircraft are analyzed. Thereafter, the DDMs are used to retrieve surface wind speed using several different algorithms. In contrast to previous works where winds were retrieved by fitting the theoretically modeled curves into measured correlation waveforms, here no model is used. Instead, the DDMs characteristics are linked to the winds obtained by simultaneous GPS dropsonde measurements.

- Chapter 9 focuses on the main space-borne GNSS-R advances. The four space missions performing GNSS-R measurements are introduced here and some modest contributions of this Ph.D. Thesis are explained.

- Chapter 10 summarizes the main conclusions of the work developed during this Ph.D. Thesis. A general conclusion and the future research lines are also presented.
The aim of this chapter is to provide the necessary context for this Ph.D. Thesis by giving an overview of the PAU-Project. Although, the SMIGOL-Reflectometer is the main instrument of this dissertation, a glimpse to the other Passive Remote Sensors built in the laboratory in framework of the PAU project are provided. The main objectives and goals of the PAU project are analyzed (PAU-RAD, PAU-Synthetic Aperture, griPAU, MERITXELL and SMIGOL).
2.1 Introduction to the PAU Project

Within the frame of the European Young Investigator (EURYI) program, in 2003 the PAU (Passive Advanced Unit for ocean monitoring) project was proposed to the European Science Foundation (ESF) to test the feasibility of using Global Navigation Satellite Signals Reflectometry (GNSS-R) over the sea surface to make sea state measurements and perform\(^1\) the corrections of the L-band brightness temperature [41]. GNSS-R was originally devised for altimetric applications [29], and in PAU it is extended to attempt a direct correction for the sea state, without having to rely neither in numerical sea surface spectra models, nor in scattering and emission models. Most of the projects described in this chapter are ongoing activities with promising results. The main results of the current PAU project have been reported in [55].

Why GNSS signals to retrieve sea state? The concept is simple: when the electromagnetic wave is scattered over the sea surface, the scattered signal changes its polarization from right to left hand circular polarization mainly (RHCP and LHCP, respectively), and it arrives at the receiver mainly from the specular reflection point, determined by the shortest distance between the transmitting GPS satellite and the receiver. However, when the sea is roughed, the scattered signals come from a wider region (known as “glistening zone”) that enlarges with increasing sea state, in a similar manner as the Sun reflecting over the sea (Figure 2.1).

![Figure 2.1 Sun glint over the sea for: (a) calm, and (b) windy conditions [55].](image)

When observing the GNSS reflected signals, two points over the sea surface correspond to the same delay and Doppler coordinates, and the point with minimum delay corresponds to the specular reflection point. In the PAU project it was proposed to measure the complete DDMs to perform the

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\(^1\) Jointly with infra red (IR) observations to obtain the sea surface temperature (SST).
necessary sea state correction of the brightness temperature required for salinity retrievals.

When working in the direction of sea state monitoring using DDMs, other GNSS-R techniques were devised. Since then, new instruments and new techniques have been developed and tested in the Remote Sensing Laboratory to observe other kind of surfaces, as land, where soil moisture, vegetation height and topography can be retrieved, in-land quiet water bodies, where its level can be monitored, and snow-covered surfaces, where snow thickness can be retrieve.

2.2 Instruments Developed in the Frame of the PAU Project

A number of PAU instruments have been developed:

- the PAU-Real Aperture instrument with a 4x4 element array with digital beamforming and polarization synthesis that uses an innovative pseudo-correlation radiometer topology to avoid the classical input switch in a Dicke radiometer, and
- the PAU-Synthetic Aperture instrument, which is also used to test potential new technologically developments and algorithms for future SMOS-like missions.

In addition to these two, and in order to advance the scientific studies relating the GNSS-R and radiometric observables other PAU demonstrators have been developed:

- PAU-OR with just one element for ground tests and algorithms development, and griPAU, an improved PAU-OR instrument fully automated,
- PAU-ORA, a lighter version of PAU-OR for aircraft operations from a remote controlled plane,
- MERITXELL (Multi-frequency Experimental Radiometer With Interference Tracking For Experiments Over Land And Littoral) a classical Dicke radiometer, that includes L-, S-, C-, X-, K-, Ka-, and W-bands, plus a multi-spectral camera, a video camera, and a thermal infrared camera, in addition to the PAU/IR and PAU/GNSS-R units, and
• SMIGOL (Soil Moisture Interference-pattern GNSS Observations at L-band) instrument is a GNSS Reflectometer that works at GPS L1 band, which exploits the Interference Pattern Technique (IPT).

In these technology demonstrators the input signals (PAU-RAD and PAU-GNSS-R) are the same: the L1-GPS band. This should not be critical, since, due to the scattering on the sea surface, the scattered GPS signal is at least 23 dB below of the thermal noise signal (to be measured by PAU-RAD). Thanks to the 30.1 dB correlation gain, PAU-GNSS-R can detect the GPS signal when correlated with the correct Coarse/Acquisition (C/A) code, while the error introduced in PAU-RAD observables is negligible. Only when the specular reflection is coming from the antenna main beam a non-negligible error is introduced [56], but this can be avoided by steering the beam in a different direction. Signals’ bandwidth is limited to the GPS bandwidth (2.2 MHz) and the intermediate frequency (IF) is 4.309 MHz. Signals are then digitalized at 8 bits at a sampling frequency of 5.745 MHz, to allow the use of digital demodulation, using band-pass sampling techniques.

### 2.2.1 PAU-RAD

One of the technological goals of the project was to demonstrate the feasibility of combining in a single hardware two types of receivers: the radiometer itself (PAU-RAD) which, for stability reasons cannot be a total power radiometer, and the GNSS-Reflectometer (PAU-GNSS/R). In order to be able to use the same receivers for both the radiometer and the GPS-reflectometer, a new radiometer topology was devised (Figure 2.2).

![Figure 2.2 PAU-RAD concept block diagram.](image)

Another technological goal, as challenging as the first one, was to provide an L-band radiometer with a digital beamforming and polarization synthesis. This capability is a very useful novelty in microwave radiometry, since it allows obtaining simultaneously brightness temperature measurements at several incidence angles without mechanical scan. As compared to a real
aperture radiometer, instead of connecting the antenna output directly to the radiometer receiver, it is connected to the input of a Wilkinson power splitter that divides the signal ($S_a$) in two signals that are in phase. However, the 100 Ohm resistor of the Wilkinson power splitter that connects the two outputs also adds two noise signals that are 180° out-of-phase ($±S_w$).

Therefore, the signals at the input of the two channels of the radiometer are the sum and the difference of the antenna signal and the noise generated by the Wilkinson power splitter resistor, which is proportional to the physical temperature of the resistor. Once properly amplified, down-converted, and sampled they are finally cross-correlated leading to an output that is proportional to the difference between the antenna temperature and the physical temperature of the Wilkinson power splitter resistor. That is, the system output is the same as the one of the Dicke radiometer [57], but the input signal is not chopped, so that it can be used to track the GPS-reflected signal.

Details on this instrument can be found in [58] - [60]. Now, Figure 2.3 shows two photos of the instrument, the PAU-RAD instrument without the radome, and measuring an alfalfa field during the Palau d’Anglesola 2010 campaign.

![PAU-RAD instrument](image)

Figure 2.3 PAU-RAD instrument (a) without radome, and (b) Measuring an alfalfa field, in the 2010 Palau d’Anglesola field campaign [60].

**2.2.2 PAU-SA**

The receivers and frequency plan of PAU-Synthetic Aperture (Figure 2.4) is the same as for PAU-RAD real aperture, but since the number of receiving elements (Y-shaped array with 8 elements per arm plus a central one) is much larger than in the PAU-Real Aperture case (16 antenna elements),
limitations in the FPGAs processing capabilities, forced to retain only one receiver per element and polarization, and the Wilkinson input switch was removed.

Another of the objectives of PAU-Synthetic Aperture was to test new techniques, technologies and algorithms that could be eventually used in future SMOS missions. To better understand this, Table 2.1 summarizes the main parameters of the MIRAS instrument aboard SMOS mission [61] and the PAU-Synthetic Aperture ones. The right most column lists the rationale behind each technological decision.

The PAU-Synthetic Aperture is composed of a Y-shaped array of 8 antennas per arm plus the one in the center, plus an additional dummy antenna at the end of each arm, and an additional antenna is used for PAU/GNSS-R.

Figure 2.4 PAU-Synthetic Aperture (a) PAU- Synthetic Aperture’s topology, (b) View of the whole instrument with one arm opened, (c) the PAU – Synthetic Aperture mounted and deployed on its mobile unit, and (d) sketch of the functionalities of the PAU-Synthetic Aperture’s mobile unit [62].
Figure 2.4 shows the PAU-Synthetic Aperture topology, and two figures taken during the integration. Hardware and simulation details can be found in [62].

For more information about this instrument, the interested reader is referred to [62] - [64].

Table 2.1 MIRAS instrument and PAU-Synthetic Aperture main parameters [61],[63].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>MIRAS/SMOS</th>
<th>PAU-Synthetic Aperture</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency operation</td>
<td>protected band: 1400-1427 MHz</td>
<td>GPS L1 (1575.42 MHz)</td>
<td>availability of integrated circuits</td>
</tr>
</tbody>
</table>
| Bandwidth                     | 19 MHz                            | 2.2 MHz                | limitation of integrated circuits and FPGAs minimizes spatial decorrelation.
| Arm size                      | 4 m                               | 1.3 m                  | operation from a truck                                                    |
| Altitude                      | 755 km                            | ground-based experiments | -                                                                         |
| Antenna type                  | dual-polarization patch antenna (non simultaneous) | dual polarization patch antenna (simultaneous) | multiply by 2 the integration time eliminate polarization transitions |
| Number of antennas per arm   | 23                                | 8+1 (dummy)           | dummy antenna at edge for better pattern similarity                       |
| Total number of antennas      | 69                                | 31                     | reduced antenna spacing to increase alias-free field-of-view             |
| Antenna spacing               | 0.875 λ at 1400 MHz               | 0.816λ at 1575.42 MHz | double integration time allow full-polarimetric mode without pol-switching schemes |
| Receiver type                 | 1 per element                     | 2 per element (1 per polarization) | allow correlated noise from common LO leaking to outputs through mixers and generating correlation offset |
| Topology of the LO down-      | distributed LO (groups of 6 elements) | centralized reference clock + internal PLL in each receiver for LO generator. | use digital I/Q demodulation, low-pass filtering and power detection |
| converter                     |                                   |                        |                                                                           |
| Quantization                  | 1 bit IF sampling                 | 8 bit IF sub-sampling using a external ADC | match global frequency response using narrow digital low-pass filters |
| I/Q conversion                | analog                            | digital                | avoid phase quadrature errors and different receivers' noise temperature between I/Q branches |
| Frequency response shaped by...| analog RF filter                  | digital low-pass filter |                                                                           |
| Power measurement system (PMS)| analog, using detector diode      | Digital (FPGA)         | avoid detector diodes thermal drifts                                      |
| Digital Correlator Unit       | $f_{CLK} = f_{sample}$            | $f_{CLK} \gg f_{sample}$ | use of band-pass sampling techniques                                     |
| Imaging capabilities          | dual-pol or full-pol (sequential) | Full-pol (non-sequential) | flexibility                                                               |
| Integration time              | 1.2 s                             | 1 s, 0.5 s, 100 ms and 10 ms | flexibility                                                               |
2.2.3 griPAU: The GPS Reflectometer Instrument for PAU

In order to advance the development of the science behind the GNSS-R observables and their relationship with the brightness temperatures, two simplified instruments were developed, which consist of a 7 LHCP patch down-looking antenna array and a RHCP up-looking antenna. Two of these instruments have been built, one for ground based operations (PAU-One Receiver –rev 1– [43] and griPAU –rev 2– [65]), and another one for airborne operations (PAU-One Receiver Airborne) [66].

The griPAU instrument was deployed during the Advanced L-BAnd emissiviTy and Reflectivity Observations of the Sea Surface (ALBATROSS) 2009 field experiment in the Canary Islands (Figure 2.5).

![griPAU measuring at Mirador del Balcón, Gran Canaria, Canary Islands, Spain.](image)

In this particular implementation of the PAU concept, two 7-patch hexagonal arrays are used: one for a dual polarization radiometer (vertical and horizontal polarizations) at 1.400-1.427 GHz (instead of \( f_0 = 1.575 \) GHz, \( B = 2.2 \) MHz), and the second one for PAU-GNSS-R. The smaller up-looking patch antenna in the center is used to track the delay of the direct signal, and fed it to the reflectometer. Figure 2.6 shows the griPAU (PAU-GNSS-R) block diagram. This instrument includes an automatic tracking of the specular reflection point of the pre-selected GPS satellite to simplify the instrument’s operation, while at the same time ensures observations collocated in time and space, exactly in the 1.400-1.427 GHz band used for passive observations.
Figure 2.6 griPAU instrument (a) block diagram showing: commercial GPS receiver to provide Doppler estimates, up-looking receiving element to provide delay estimates (every 5 ms), and down-looking receiving element (with 7 LHCP hexagonal patch array) to collect the reflected signal. The whole system is embedded in a Xilinx Virtex-4 FPGA and has serial USB connectivity, and (b) a picture of the processing unit [65].

For more information about this instrument and the results achieved the interested reader is referred to [54], [55], [65], [66] and [67].

2.2.4 PAU-One Receiver Airborne

Figure 2.5a shows the PAU-One Receiver Airborne on the bay of a remote controlled aircraft. Details on the control, telemetry, data links and data storage can be found in [66] and [68]. Figure 2.5b shows the DDMs measured when the direct (RHCP) and reflected (LHCP) signals are collected simultaneously using two separated antennas connected to the inputs of a non-resistive 2-way power combiner [69].

The left-hand side peak corresponds to the direct signal, which has larger amplitude, while the right-hand side one corresponds to the reflected one, which is attenuated in the scattering and appears at a larger delay due to the longer signal path. The separation between peaks is 21 samples, which corresponds to ~ 770 m since in this implementation of the instrument, the sampling frequency is 8.18 MHz [69]. Therefore, since the antenna was pointing to the nadir direction and the GPS satellite was close to the zenith, the estimated height is ~ 385 m, which is very close to the flight height (379 m). This design offers several advantages over the previous ones (just measuring the reflected signal) since it intrinsically provides absolute calibration of the scattering coefficient (ratio of peaks between direct and
reflected DDM), it offers altimetry capabilities, and sea state determination using the full DDM.

Figure 2.7 PAU-ORA overview (a) PAU – One Receiver Airborne instrument block mounted on the bay of a Remote Control aircraft, (b) DDMs obtained collecting simultaneously the direct (RHCP) and reflected (LHCP) signals [69], (c) Brightness temperature maps measured over Vadillo de la Guareña (Zamora, Spain) and (d) Marquesa Beach (Ebre river mouth, Tarragona, Spain), [70].

2.2.5 MERITXELL

The Multi-frequency Experimental Radiometer With Interference Tracking For Experiments Over Land And Littoral (MERITXELL) radiometer is a step forward advancing our understanding of the potentials of combining data from several sensors: microwave radiometers, visible multi-spectral and TIR cameras, and a GNSS-Reflectometer. It will also be used in testing radio frequency interference (RFI) detection and mitigation algorithms for microwave radiometry [71].
The MERITXELL microwave radiometer is a multi-band dual-polarization Dicke radiometer covering 8 protected bands used for passive remote sensing: L, S, C, X, K, Ka, and W (see Table 2.2). To add flexibility and simplify the design, a spectrum analyzer is used as IF stage, for filtering and power detection for all bands. This allows an easy reconfiguration of the band and/or frequency response shape, since the antennas and amplifiers response exceed those indicated in Table 2.2. Antennas are 4 x 4 dual-polarization patch arrays at L, S, and C bands, and horn antennas with a lens in the aperture to provide a quasi-Gaussian beam for the other bands. In addition, MERITXELL includes visible camera, a thermographic camera (320 x 240 pixels) operating in the 8–14 μm range, a multi-spectral camera (640 x 480 pixels) with four spectral bands: red (λ₀ = 0.62 μm), green (λ₀ = 0.54 μm), blue (λ₀ = 0.45 μm) and Near Infra-Red (λ₀ = 0.80 μm), and a PAU-GNSS-R unit.

Table 2.2 MERITXELL microwave radiometer bands and antenna parameters [71].

<table>
<thead>
<tr>
<th>Band</th>
<th>Central frequency</th>
<th>Bandwidth</th>
<th>Antenna beamwidth</th>
<th>Main beam efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>1.4135 GHz</td>
<td>27 MHz</td>
<td>~25°</td>
<td>98 %</td>
</tr>
<tr>
<td>S</td>
<td>2.695 GHz</td>
<td>10 MHz</td>
<td>~25°</td>
<td>98 %</td>
</tr>
<tr>
<td>C</td>
<td>7.185 GHz</td>
<td>90 MHz</td>
<td>~25°</td>
<td>98 %</td>
</tr>
<tr>
<td>X</td>
<td>10.69 GHz</td>
<td>20 MHz</td>
<td>~5°</td>
<td>95 %</td>
</tr>
<tr>
<td>K</td>
<td>18.7 GHz</td>
<td>200 MHz</td>
<td>~5°</td>
<td>95 %</td>
</tr>
<tr>
<td>K</td>
<td>23.8 GHz</td>
<td>400 MHz</td>
<td>~5°</td>
<td>95 %</td>
</tr>
<tr>
<td>Ka</td>
<td>36.5 GHz</td>
<td>1 GHz</td>
<td>~5°</td>
<td>95 %</td>
</tr>
<tr>
<td>W</td>
<td>89 GHz</td>
<td>6 GHz</td>
<td>~5°</td>
<td>95 %</td>
</tr>
</tbody>
</table>

Figure 2.7a shows the schematic of the MERITXELL microwave radiometer, and Figure 2.7b shows the front view with the antennas mounted (cameras and PAU/GNSS-R will be placed in the hole in the centre of the top row).

At the time of writing this Ph.D. Thesis the construction of a truck with a telescopic robotic mast to hold and orient both the PAU-Synthetic Aperture and MERITXELL instruments is being repaired after a mechanical failure (Figure 2.4c). It has been designed to hold one of these two instruments up to a 8 m height above the ground level, while the other is in the parking position (e.g. MERITXELL in Figure 2.8), and withstand up to 100 km/h wind loads.
2.2.6 The SMIGOL-Reflectometer

The Soil Moisture Interference-pattern GNSS Observations at L-band (SMIGOL) instrument is a new type of GNSS-Reflectometer operating at the GPS L1 band. This instrument has been developed in this PhD. Thesis and has been the tool necessary to implement test and validate the Interference Pattern Technique (IPT) used in the large part of the retrievals implemented. Therefore, a short glimpse is given here, but afterwards both, the instrument and the IPT, will be widely explained.

Figure 2.8 a) MERIXELL microwave radiometer schematic, and b) front view [71].

Figure 2.9 SMIGOL-Reflectometer at Palau d'Anglesola, Lleida, Spain [40].
The SMIGOL-Reflectometer (Figure 2.9) is positioned at a certain height pointing to the horizon. A v-pol patch antenna, measures the power of the interference between the direct GPS signal and the one reflected over the surface. This technique is called IPT. The IPT has been tested by measuring with the SMIGOL-Reflectometer and performing several geophysical parameters retrievals depending on the observed surface:

- Soil moisture mapping over a bare soil [38] (Figure 2.10a).
- Crop growth monitoring over wheat and barley-covered soils [56], and maize-covered soils [39] and [40]. Figure 2.10b shows the vegetation growing retrieval over a wheat field.
- Topography mapping [39]. Figure 2.10c shows the topography retrieval over a barley field.

![Image](image_url)

Figure 2.10 Fields observed in the various field experiments: (a) Soil moisture retrieval achieved over bare soil and (b) wheat growing retrieval achieved over wheat-covered soil, both observed at Palau d’Anglesola, Lleida (Spain) during 2008 and (c) topography retrieval achieved over barley-covered soil observed at Vadillo de la Guareña, Zamora (Spain) during 2009 [38] - [40].
This technique is also suitable to observe quiet water surfaces, as lakes or reservoirs, retrieving the water level, and snow covered surfaces, retrieving snow thickness. Next chapters will explain the SMIGOL-Reflectometer hardware, and the IPT applied to the retrieval of different parameters over different surfaces.

2.3 Summary

This chapter has presented an overview of the PAU-project and the main instruments developed. The suite of PAU instruments that have been (and are currently being) developed at the Remote Sensing Lab of the Universitat Politècnica de Catalunya has been presented. These include: PAU-RAD, PAU-Synthetic Aperture, griPAU, PAU-One Receiver Airborne, MERITXELL and SMIGOL. These instruments have been developed for three purposes: 1) to analyze the nature of reflectometric observables and their relationship with the brightness temperature at L-band over the sea and the land, 2) develop and test parallel and useful GNSS-R techniques for the study of surfaces and 3) to be technological demostrators of improvements to be applied in future space-borne missions (SMOS follow-on missions), or secondary payloads that can help in the sea state correction.

It is important to remember that the present Ph.D. dissertation is focussed on the retrieval of geophysical parameters by using GNSS-R techniques, the most important and the core of the dissertation are the soil moisture and the vegetation height retrieval using the IPT, but other applications were devised and tested in the way. This Ph.D. dissertation accomplishes the second objective of the PAU-project.
Hardware Developed:
The SMIGOL-Reflectometer

A new instrument, called Soil Moisture Interference-pattern GNSS Observations at L-band (SMIGOL) Reflectometer, was originally developed during 2008, and has been upgraded and used in many different field campaigns to gather interferometric measurements, and test the theoretical developments.
3.1 Operational Version

3.1.1 Introduction

The SMIGOL-Reflectometer is a ground-based instrument that measures the instantaneous power of the interference of the direct GPS signal and the one reflected from the Earth’s surface. It operates at the GPS L1 frequency (1.57542 GHz). The geometrical configuration is shown in Figure 3.1.

![Geometrical configuration of SMIGOL Reflectometer and the GPS signals reflecting over a surface composed of several layers characterized by their dielectric constant ($\varepsilon_i$), thickness ($t_i$) and the roughness between layers.](image)

The reflectometer is located over the surface at a certain height ($h$) pointing to the horizon. Then, it measures the evolution of the power of the interference between the direct GPS signal and the reflected one over the land. These two signals (direct and reflected) arrive to the SMIGOL Reflectometer antenna within the same GPS chip interval (1ms/1023), and therefore they are coherently added. When a satellite is detected, the receiver starts the acquisition, and the power of the interference signal, called from now on interference power, is measured at 1 Hz during the satellite passage, while the satellite is visible. Each sample corresponds to a different elevation angle of the GPS satellite, so the received interference power is a direct function of the elevation angle.

Figure 3.2 shows a reduced version of the SMIGOL Reflectometer architecture, just to understand the general architecture.
Once the antenna collects the interference power at vertical polarization (v-pol), the GPS receiver processes it, and the raw data is transmitted to a computer. Then, the suitable SMIGOL retrieval algorithm, further explained in next chapters, is applied to these data to extract the geophysical parameters.

### 3.1.2 Main Features

#### 3.1.2.1 Maximum Height

The SMIGOL Reflectometer height \( (h) \) is limited by the coherence time of the direct and reflected signals. The coherence time is defined as the path difference of both signals \( (\Delta r) \) divided by the speed of light \( (c) \), and must be less than the GPS chip time: \( \tau_c = 1 \text{ ms} / 1023 = 0.97 \mu s \), being 1023 the number of chips of the coarse/acquisition pseudo-random noise code (C/A PRN code) \( [72] \). Since the GPS satellite height is much higher than the GPS receiver height \( (h) \) the paraxial approximation holds, and the differential transit time can be expressed as (3.1):

\[
\frac{\Delta r}{c} = \frac{r_{\text{reflected}} - r_{\text{direct}}}{c} \approx \frac{2h}{c \sin(90 - \theta_{\text{inc}})} \leq \tau_c = \frac{1 \text{ ms}}{1023} = 0.97 \mu s ,
\]

where \( r_{\text{direct}} \) is the distance covered by the GPS signal from the GPS satellite to the SMIGOL Reflectometer antenna, \( r_{\text{reflected}} \) is the distance covered by the GPS signal from the GPS satellite to the SMIGOL Reflectometer reflecting over the surface, \( \theta_{\text{inc}} \) is the incidence angle of the GPS signal, and \( h \) is the instrument’s height. The elevation angle is defined as \( \theta_{\text{elev}} = 90 - \theta_{\text{inc}} \).

Isolating \( h \) from Eqn. (3.1), it can be noted that the maximum’s instrument height is a function of the maximum incidence angle (Eqn. (3.2), Figure 3.3).
The requirement for the SMIGOL Reflectometer is having coherence between direct and reflected signals in the whole range of elevation angles. The measurements are limited to the range of elevation angles: 10° - 45°. The limitation $\theta_{\text{elev}} \approx 45^\circ$ is due to the patch antenna pattern, and the limitation $\theta_{\text{elev}} \approx 10^\circ$ is fixed to avoid distortion due to elements of the scene. As observed in Figure 3.3 to ensure the coherence of the signals in the whole range the maximum instrument height is $h \approx 25\,\text{m}$.

For all the experiments and algorithms performed in this Ph. D. Thesis it has been selected the range from 10° to 40°, which would allow a maximum height of 25 m, but the maximum height used has been 4.5 meters, just for operational reasons.

### 3.1.2.2 Antenna Footprint

As the SMIGOL Reflectometer is pointing to the horizon, the footprint over the surface cannot be defined as usually, using the antenna pattern. Actually, the SMIGOL footprint is defined as the glistening zone or area around the specular point from where the scattered signals are collected [73]. Figure 3.4 shows the glistening zone, defined as the area around the specular point where the normalized scattering coefficient is higher than 1/e (60% of the power of the antenna).
The scattering signals within this area contribute to the total received power, while the other scattering signals are much weaker, so that their contributions are not significant for the retrievals of the present work. The glistening zone has been computed for different soil surface’s roughness values, defined as the surface height standard deviation from a plane surface, and satellite elevation angles.

As it can be seen (Figure 3.4), the maximum variability of the glistening zone (spot over the surface) depends on the satellite elevation. For high elevation values ($\theta_{\text{elev}} = 45^\circ$) the difference is about is 0.10 m in radius from lower to greater roughness values (0 - 4 cm RMS value). However when the satellite elevation decreases this difference increases. Considering that the most common values for roughness are between 2 cm or 2.5 cm the maximum error in the spot size for higher elevation angles will be about 5

**Figure 3.4** Glistening zone for land scenario, defined by the boundary of the normalized scattering coefficient, $\sigma_0$, that is higher than 0.63. It has been computed for $h = 3$ m SMIGOL height and evaluated for 0, 1, 2, 3 and 4 cm of soil surface roughness value, from clear to dark gray, respectively, and for different satellite elevations: (a) $\theta_{\text{elev}} = 45^\circ$, (b) $\theta_{\text{elev}} = 30^\circ$, (c) $\theta_{\text{elev}} = 20^\circ$ and (d) $\theta_{\text{elev}} = 10^\circ$. The $(0,0)$ coordinate corresponds to the SMIGOL-Reflectometer location, and a maximum extension of 40 m for mapping retrievals is feasible.
cm and for lower elevation angles will be about 5 m, but due to the strong specular component of the GPS signal reflecting over the observed surfaces it has a low impact on the final retrievals.

3.1.2.3 Resolution

The resolution of the instrument is determined by two main parameters: the elevation angle at which the reflection occurs and the instrument height. The higher the instrument height is the lower is the resolution. The lower the elevation angle is the lower is the resolution. So, the lower resolutions occur for the higher instrument positions and the lower elevation angles. Figure 3.5 summarizes these three aspects.

![Resolution for different instrument heights](image)

Figure 3.5 Resolution of the SMIGOL-Reflectometer as a function of the elevation angle. The y-axis corresponds to the distance in meters over the surface of two consecutive reflection points due to the variation of the elevation angle. As an example, for h = 3 m, the distance between the reflections point at 10° and at 11° is 1.8 m, but it decreases as elevation angle increases and then, the distance between reflection points at 40° and 41° is 0.5 m.

As shown in Figure 3.5 for higher elevation angles, resolution keeps under 0.5 meters between consecutive specular points but when instrument height increases the resolution increases rapidly above 2 meters.
3.1.3 Hardware

3.1.3.1 General Architecture

The SMIGOL-Reflectometer is a system ready to be deployed into a field and rest there during long periods of time, working autonomously and managing the power supply system and the measuring and storing system with a degree of intelligence. The general block diagram can be seen in Figure 3.6.

![General scheme of the SMIGOL-Reflectometer.](image)

Figure 3.6 General scheme of the SMIGOL-Reflectometer.

As it is shown in Figure 3.6 the components of the SMIGOL-Reflectometer can be summarized as:

- GPS antenna. Designed to work at v-pol in the GPS L1 band. Focus is to have a very symmetric pattern.
- GPS amplifier. Needed to amplify the GPS received signals.
- GPS receiver. Receiving the GPS packets and sending them to the:
- Datalogger. Data is stored into a 2GB SD-card.
- PIC μC. This component gives the “intelligence” to the instrument and controls the status transitions.
- Power supply system. This part provides the SMIGOL-Reflectometer with an autonomous and safe operational system.
3.1.3.2 GPS Antenna Design

The SMIGOL-Reflectometer antenna is designed to work at v-polarization. The reason for that is explained in detail in next chapter. The working frequency corresponds to the GPS L1 band (f = 1.57542 GHz, then λ = 19 cm). Several designs were considered before implementing the final antenna, taking into account the main requirement to implement the technique: the antenna symmetry. The main reason for this requirement is also widely explained in the next chapter. For now, let us consider these two characteristics as the specifications for the design:

- v-polarization, and
- symmetric pattern.

First of all, a patch antenna based on air dielectric was built over a ground plane of 30 cm x 30 cm and FR4 substrate (Figure 3.7).

![Figure 3.7 GPS patch antenna. (a) Antenna sketch and (b) image of the antenna.](image)

This antenna, with a field of view of 90° in azimuth, was used to prove the concept, but in order to implement a final instrument the antenna size was decided to be reduced. In order to do that, two solutions were proposed:

- Dipole antenna.
- Patch antenna based on Rogers dielectric.

By considering the dipole antenna (Figure 3.8), which has by definition a symmetric antenna pattern, the observed area was increased from 90° in azimuth to 360°.
The other possible solution, the patch antenna based on Rogers dielectric (Figure 3.9), was also designed and analyzed.

Following with the idea of increasing the field of view a four face instrument was thought to be designed. Therefore as shown in Figure 3.9, 4 antennas were manufactured. The these antennas were measured using a network analyzer in order to analyze the matching for each of the antennas (S11, parameter in Figure 3.10)
Figure 3.10 Antenna matching measured with a network analyzer: (a) antenna face 1, (b) antenna face 2, (c) antenna face 3 and (d) antenna face 4.

The signal coming from the four antennas are combined with a non-resisitive power splitter (Figure 3.11).

Figure 3.11 Combiner designed at GPS L1 band to combine the four antenna signals for feeding the receiver.

The combiner takes as an input the four GPS signals coming from the antennas and gives one combined output to the receiver. The phase introduced by each one of the lines of the combiner must be the same, or
very close. In Figure 3.12 the phase measurements of the combiner are shown.

![Figure 3.12 Combiner phase measurements:](image)

(a) \(-147.99^\circ\), (b) \(-146.65^\circ\), (c) \(-147.02^\circ\) and (d) \(-147.24^\circ\).

As it can be seen in Figure 3.12 the phase introduced by the combiner is very well matched for the 4 lines: \(-147.99^\circ\), \(-146.65^\circ\), \(-147.02^\circ\) and \(-147.24^\circ\), respectively. In order to plug the combiner to the antennas 4 cables are needed and, as the combiner, these cables must introduce similar phases to the 4 chains, (Figure 3.13).
Figure 3.13 Phase introduced by the cables between the antennas and the combiner:
(a) $\cdot 12.43^\circ$, (b) $\cdot 15.85^\circ$, (c) $\cdot 13.14^\circ$, and (d) $\cdot 12.57^\circ$

The phase given by each one of the cables is $\cdot 12.43^\circ$, $\cdot 15.85^\circ$, $\cdot 13.14^\circ$, $\cdot 12.57^\circ$, respectively; with a phase difference always lower than $3.4^\circ$. These phase differences are low for the technique that is going to be applied, and choosing the suitable cable for each line of the combiner the global phase difference of each chain is reduced.

Both, the dipole antenna, which is the best and easiest way to reduce the size and increase the field of view, and the 4 patch antenna combined have an inherent and not avoidable problem. If the GPS signal is reflected in any element at the scene, the incoming signal arrives not only from the expected reflection point, but also from an unexpected reflection point. Then the interference produced at the antenna between direct and reflected GPS signals is distorted by the unexpected reflection. This undesired interference produced by the unexpected reflection cannot be isolated from the desired one, so that the shape interference pattern is destroyed and the geophysical parameters retrieval does not perform well.
This problem invalidates the use of a dipole antenna. The patch antenna can still be used if the four faces become independent. If the GPS receivers could be configured to avoid the GPS that are not in the field of view of each one of the antennas, filtering in azimuth coordinates, then the 4 patch antennas combined could be used. The selected receivers, from Trimble, only allow filtering the lower elevation angles. One can discard satellites under a certain elevation angle, but there is no mask in azimuth available. Therefore, this solution is not valid.

Based on the 4 patch antenna combined, another solution was proposed and finally implemented. The idea was to generate four independent chains, which implies the use of four GPS receivers, each receiver being connected to each of the antennas. Then, the combiner is eliminated and the signals coming from each one of the antennas became independent from the undesired reflections over the rest of the antennas.

Regarding to the symmetry requirement of the patch antennas, although the first antennas designed were good enough for the application, a new version was designed adding some elements and increasing the size of the ground-plane to improve the symmetry (Figure 3.14).

![Figure 3.14 Final antenna design. (a) patch antenna and (b) symmetry element, 180° hybrid.](image)

The patch is square (48.3 mm side), built with Rogers RO4003 of 1.5 mm thickness. As it can be seen in Figure 3.14 the final antenna designed has the feeders in the vertical and it incorporates a 180° hybrid to symmetrically supply the feeders and adapt the antenna impedance.

The matching of the new antenna has been measured using the network analyzer (Figure 3.15).
Figure 3.15 GPS antenna matching.

As it can be seen in Figure 3.15, the matching obtained with this new antenna design is approximately -30 dB. This is a very tuned antenna, and the matching varies fast between -30 dB and -25 dB. In Figure 3.16, it can be observed that the matching is better than -25 dB for all the bandwidth of the GPS signal, which is 2 MHz.

The antenna has been measured at the Universitat Politècnica de Catalunya (UPC) anechoic chamber in order to obtain the antenna pattern diagram and analyze the symmetry achieved. Figure 3.16 shows some photos at the UPC anechoic chamber.

Figure 3.16 UPC anechoic chamber measurements: (a) installing the SMIGOL antenna and (b) installing the radiation source, the probe antenna.

The measurements obtained in the anechoic chamber were processed and the symmetry analyzed. Figure 3.17 shows the entire antenna diagram measured in the anechoic chamber.
Figure 3.17 Entire antenna diagram measured, copolar component. (a) 3-D plot in linear and (b) normalized polar plot in dB units.

The dynamic range of the antenna diagram is 40 dB (Figure 3.17). In order to better analyze the symmetry of the antenna, 3 cuts have been made over the Figure 3.17 antenna diagram, they are shown in Figure 3.18.

Figure 3.18 Antenna diagram cuts at (a) $\varphi = 0^\circ$, (b) $\varphi = 45^\circ$ and (c) $\varphi = 90^\circ$, with $\theta$ variable.
In Figure 3.18 three cuts over the antenna diagram are shown. For a beamwidth of 90° (± 45° from the boresight) the three cuts show the required symmetry, Δ(θ, φ) < 0.1 dB. At ± 45° all cuts are at -4 dB.

Another important parameter when designing and antenna is the cross-polar component, Figure 3.19.

Figure 3.19 Cross-polar component of the measured antenna diagram. Normalized polar plot in dB units.

Figure 3.19 shows that the cross-polar component, or radiation leakage at h-polarization, is better than 30 dB for the boresight direction.

Taking into account that a 1 face operational SMIGOL-Reflectometer was fast set to develop the theoretical aspects and test them into many field experiments. The four faces wireless SMIGOL-Reflectometer became an operational instrument at the end of this Ph.D. Thesis, and the simple face has been used throughout the whole Ph. D. Thesis.

3.1.3.3 GPS Amplifier

As the GPS signal arrives very attenuated to the antenna, it is needed to add an amplifier to the system. The selected amplifier is the SMA661AS, a low noise amplifier (LNA), [74], working at GPS L1 band. Its main characteristics are:

- Noise figure : 1.15 dB.
- Theoretical gain: 18 dB.
- Power supplied : 3.3 V.
- Low consumption: 8.5 mA.

In Figure 3.20 it is shown as the amplifiers are attached to the antennas.

![Figure 3.20 GPS amplifier attached to the antennas.](image)

These amplifiers were measured using the network analyzer, Figure 3.21.

![Figure 3.21 GPS amplifier, matching and amplification measurements.](image)

The matching is always better than 10 dB and the amplification is always around 13 dB.
As it can be observed in the four plots of Figure 3.21a, b, c and d, the matching and the amplification are measured. The matching of these amplifiers is always better than 10 dB and the amplification value is always around 13 dB. These two characteristics are good enough for the GPS applications that will be developed.

### 3.1.3.4 GPS Receiver

The GPS receiver selected is a commercial Trimble receiver. From all the available receivers, the receiver shown in Figure 3.22 has been selected, mainly because the low (34 mA) consumption.

![Figure 3.22 GPS receiver Trimble Lassen IQ. [75].](image)

The Trimble Lassen IQ [75] is 3 cm x 3 cm size and must be power supplied at 3.3 V. The receiver works using the TSIP protocol. Therefore receivers can be configured and managed using the TSIPCHAT.EXE, Figure 3.23.

![Figure 3.23 Main screen of the TSIPCHAT.exe software.](image)

The Trimble Lassen IQ can be configured via RS-232 to continuously provide the raw data packet, which includes the Signal to Noise Ratio (SNR) and the
GPS time. Note that having a constant noise the SNR can be understood as the power received. In TSIPCHAT.exe configuration program this can be done using the 0x35 or control+O command, then, when asked, the code to be introduced is [0 0 0 1]. That way the receiver is set to continuously provide raw data measurements. Also, the receiver is able to provide the position packet, which contains the elevation and azimuth position and the GPS time, but this packet is only provided if requested. In TSIPCHAT.exe it corresponds to 0x3C or >, then when asked, 0 must be introduced to get the information relative to elevation and azimuth for all satellites.

For the antenna connection the receiver has a H.FL coaxial connector, so a small cable is needed to do the transition from H.FL to SMA and connect the receiver to the amplifiers.

Figure 3.24 shows the GPS receiver Trimble Lassen IQ and the H.FL to SMA cable connected.

![GPS receiver board](image)

Figure 3.24 GPS receiver board.

### 3.1.3.5 Datalogger

The datalogger selected is the Logomaticv2, Figure 3.25.

![Datalogger](image)

Figure 3.25 One face SMIGOL-Reflectometer datalogger: Logomaticv2.
The logomaticv2 stores the data received at the reception (Rx) pin into a SD-card, which maximum compatible capacity is 2 Gb. This datalogger has a stop button to safely finishing storing the data into the SDcard before shutting down the device. The SMIGOL-Reflectometer can measure using this datalogger while only one face is working, but if four faces configuration is set, this datalogger has a too high consumption (80 mA). Since four dataloggers, one per GPS receiver, should be use, the consumption has to be reduced. Instead of the previous one, the final design of the SMIGOL-Reflectometer, the four faces one, incorporates the datalogger shown in figure Figure 3.26.

![Figure 3.26 Four faces SMIGOL-Reflectometer datalogger: Openlog.](image)

Openlog is a low consumption datalogger (8 mA). It allows that going from one face to four faces do not make the consumption feasible for the available power supply the consumption. In further section, in order to set up the power supply system requirements, an analysis of the global consumption is shown.

### 3.1.3.6 PIC μC

The PIC μC is the micro-controller that provides the SMIGOL-Reflectometer with intelligence. The main tasks of the PIC program are summarized below:

- Continuously battery voltage monitoring, via pin AN0, in order to protect the battery life. If battery voltage drops below 3.1 V, the system is automatically and safely stopped. It remains slept, while battery voltage is below 3.6 V, creating a hysteresis cycle. This hysteresis cycle is important because when stopping the system, the load is reduced and the battery voltage increases. If the voltage to start again the system was the same than the voltage to stop the system (not hysteresis cycle), it will enter in a infinite process on-off damaging the battery.
• Powering on the receivers, the amplifiers and the dataloggers, via Transistor-Transistor Logic (TTL) pins available using the scheme shown in Figure 3.27.

![Figure 3.27 Switch implemented with transistors N and P.](image)

When the PIN of the PIC µC is set to 0 the output of the circuit is 0, but when the PIN of the PIC µC is set to 1, the MOSFET·N puts a 1 in the MOSFET·P door and it drives the VCC to the output of this circuit powering on the whole system.

• Programming the GPS receiver to continuously receive raw data, via transmission pin (Tx).

• Every 30 seconds, sending the elevation and azimuth request to the receiver, via Tx.

• After 6 measurement hours, safely close the files opened in the datalogger, shutting down the dataloggers, the receivers, and the amplifiers.

• After 6 hours sleeping, start again the measurement process.

Figure 3.28 shows a summary of the PIC µC program.

![Figure 3.28 PIC µC program, states and transitions.](image)
Figure 3.29 shows an image of the PIC μC board, which is shared with the GPS receiver board.

Figure 3.29 PIC μC board.

3.1.3.7 Power Supply System

In order to design a suitable power supply system it is necessary to do a power consumption budget of the SMIGOL-Reflectometer.

1. For the one face SMIGOL-Reflectometer the consumptions is:
   - 1 amplifier = 8 mA,
   - 1 receiver = 34 mA,
   - 1 datalogger Logomaticv2 = 80 mA, and
   - 1 PIC μC = 10 mA
   The total consumption is 132 mA.

2. For the four faces SMIGOL-Reflectometer the consumption is:
   - 4 amplifiers = 32 mA,
   - 4 receivers = 136 mA,
   - 4 dataloggers Openlog = 32 mA, and
   - 1 PIC μC = 10 mA,
   The total consumption is 210 mA.
Assuming the worst case, the largest consumption, the power supply system must be well designed in order to allow measuring during long periods of time (at least 6 hours). Figure 3.30 shows the main sketch for the power supply system.

![Power supply system sketch](image)

**Figure 3.30 Power supply system sketch.**

As shown in Figure 3.30, the power supply system is composed of solar panels to give autonomy to the system, a switched power supply to maximize the current driven to the system, Li+ battery to operate when the Sun is not present, and a battery charger to charge the batteries and and be able to switch between current power generated in the solar panels or supply the power stored in the batteries. The requirement for this kind of systems is to have, during illumination, enough current to supply the system and to charge the battery at the same time. For that reason the switched power supply was added to the system.

The switched power supply, that keeps the input power equal to the output power, was tuned to give a continuous 6 V output and an increased current (800 mA), respect to the input current (300 mA). Assuming that the system load requires 210 mA to operate, the battery charger will distribute the output of the switched power supply between the system load (210 mA) and the charge of the battery (590 mA). If the battery has 4200 mAh, and the safety system (implemented in the PIC µC using the “voltage control” line shown in Figure 3.30) avoid the battery discharge under the 2100 mAh. In this configuration the system requires 3 hours 40 minutes to fully re-charge the batteries.

Figure 3.31 shows two photos corresponding to the power supply system.
The two solar panels (Figure 3.31c) are interconnected using a diode system (Figure 3.32, [76]) to avoid damaging the solar panels.

![Diode connection diagram]

Each individual solar panel gives $V_{OC} = 8$ V (OC stands for open circuit) and $I_{SC} = 300$ mA (SC stands for short circuit), but after the interconnection two solar panels of $V_{OC} = 16$ V and only $I_{SC} = 300$ mA is achieved. The current and voltage of the solar panels has been measured for an illumination condition (open circuit) of 16.65 V, using different resistors to simulate the system load, (Figure 3.33).
Figure 3.33 Solar panel current and voltage curves as a function of the resistance, for a specific light condition.

The output voltage and current of the solar panel go to the switched power supply (1 in Figure 3.31b), then the switched power supply output (2 in Figure 3.31b) is 6 V and 800 mA and goes to the battery charger (Figure 3.31a) input, there the current is distributed between the system load and the battery (Figure 3.31d), and the output goes to the input of the regulation stage (3 in Figure 3.31d). At this point the voltage is regulated to 3.3 V (4 in Figure 3.31b) and then to 1.8 V (5 in Figure 3.31b), also a voltage control line (6 in Figure 3.31b), the input of the regulation stage is carried to the PIC μC board to monitor the real voltage given to the system (as explained in previous section, pin AN0).

3.1.3.8 Structure

The structure is made of 4mm-width aluminum material, Figure 3.34.

Figure 3.34 Two images of the SMIGOL-Reflectometer structure.
This structure is a cube, robust and easily accessible from the top face. Although the structure was ready to work with four faces from the beginning, only one face components were installed to have the SMIGOL-Reflectometer ready and test the concept in many field experiments. This structure will be attached to the mast at the field experiment place using the bottom face.

3.1.3.9 Integration

Once everything was built, the different parts were integrated. All the circuitry was mounted and interconnected in vertical axis, all the boards has the same size. The antennas were attached at the structure ensuring the perfect contact between the ground plane of the antennas and the aluminum structure, avoiding anomalies in the antenna diagram and getting the results shown in previous section at the anechoic chamber. Figure 3.35 shows the integration process.

![Figure 3.35 Integration: (a) circuitry and (b) final view of the SMIGOL-Reflectometer, all integrated.]

Since SMIGOL has to operate in any kind of weather it needs a radome to prevent the electronic part from the sun, win, rain, or other meteorological phenomena. To achieve that, a radome has been built, Figure 3.36.

The radome is manually built using Depron, which is a dielectric material, resine and epoxy glue. This radome perfectly fits the SMIGOL-Reflectometer.
The attachment of the SMIGOL is a metal piece at the bottom face of the cube to make easier the installation at the field experiment. It is a small metal piece that is under the cube, to avoid interferences with the antenna, and can be attached using its holes to the wood mast of 3 or 4 meter high.

### 3.2 Extended Version

During the Ph.D Thesis, the priority was to have an operational instrument (one face), develop theoretical aspects and test them into several field experiments, in order to perform retrievals of the geophysical parameters of the observed surfaces. The final hardware design was thought to be done at the end of the Ph.D. Thesis, it is a more ready-to-operate version, and it has been part of the master thesis entitled “Design, development and test of a wireless sensor network to measure soil moisture” done by Alberto Alonso and advised by myself and Adriano Camps in the frame of this Ph.D. Thesis.

Two new functionalities were implemented:

- 4 faces SMIGOL-Reflectometer. After rebuilding the system to add the 4 faces capability, this implies adding four chains and reconfigure the PIC to control all the components, the instrument was tested Palau d'Anglesola, Lleida, Spain. The measurements were processed using all the theory developed, which is explained in next chapters. Just to prove the 4 faces capability, Figure 3.37 shows a retrieved soil moisture map over the agricultural field.
Figure 3.37 (a) Soil moisture map retrieved applying the algorithms, developed in this Ph.D Thesis and explained in next chapters, for a 4 faces SMIGOL-Reflectometer. (b) Sky projection of the GPS satellites.

- Wireless 4 faces SMIGOL-Reflectometer. In the previous version of SMIGOL-Reflectometer to download the stored data it was necessary to reach the instrument and access the SD-card located in the dataloggers. Adding a wireless communication link, all the manually data download is avoided and the data can be send to a base station. Then installing more than one wireless 4 faces SMIGOL-Reflectometer a kind of network is created able to cover a large extension.

An interesting application was created to control the instruments and getting the data from a base station. This application, named as GDAIS, was developed by Pau Haro in his final project “Generic Data Acquisition and Instrument control System (GDAIS)” directed by Xavier Bosch and Adriano Camps, 2011. A particular application to control the 4 faces SMIGOL-Reflectometer, wireless or not, was developed and tested. The data is stored into a computer in HDF5 [77] format, which is compatible with MATLAB. So data stored can be directly load in MATLAB program and processed.

3.3 Summary

This chapter has described the SMIGOL-Reflectometer hardware and technical aspects. The main characteristics for the well performance of the measurements taken from this instrument that works at GPS L1 band are: the symmetry of the antenna pattern and the polarization of the antenna (v-
pol). Although the results of this Ph.D. Thesis have been performed using a simple face SMIGOL-Reflectometer, in parallel, a new version of the instrument is being developed and will be ready to be deployed during 2012. This new version will incorporate 4 faces and wireless capability. The simple face SMIGOL-Reflectometer has been demonstrated to be a suitable tool to implement the IPT and test the algorithms obtaining good results. These results and algorithms are going to be presented in next 4 chapters.
4

Use of GNSS-R for Soil Moisture Monitoring

This chapter focuses on soil moisture retrievals over bare soils using the SMIGOL-Reflectometer ground-based instrument. SMIGOL is a GNSS-R instrument that implements the Interference Pattern Technique (IPT), a technique consisting of the measurement of the power fluctuations of the interference signal resulting from the simultaneous reception of the direct and the reflected GNSS signals. A field experiment has been performed in order to validate the theoretical aspects of the IPT and the soil moisture retrieval algorithm. Results are presented and the main conclusions are summarized.
4.1 Introduction

Knowledge of the surface’s soil moisture content provides useful information for hydrological studies due to its influence in the global water cycle. It is known that soil moisture can be retrieved using L-band microwave radiometry [78]-[80], RADAR or Synthetic Aperture RADAR (SAR) [81]-[83]. While the spatial resolution of L-band microwave radiometers on board a satellite is poor (about tens of kilometres), radar systems are more affected by surface roughness effects. As shown in chapter 1, in the state of the art of GNSS-Reflectometry, GNSS reflectometers have been used to retrieve soil moisture, vegetation height, sea state, and snow and ice properties testing and validating their capability to retrieve surface geophysical parameters. As compared to SAR or RADAR systems, a GNSS reflectometer has the advantage of being a passive instrument, in which the signals emitted by the GNSS satellites are taken as sources of opportunity. In addition, as compared to microwave radiometers thermal stability is not a stringent requirement and the nature of the GNSS signals produces a self-calibrated observable. Furthermore the frequencies of operation of GNSS-R systems are in the L-band which is a suitable band to retrieve soil moisture [78]-[83].

In this chapter the Interference Pattern Technique (IPT), a particular type of GNSS-R technique well suited for ground-based observations, is introduced for soil moisture monitoring. It is based on the simultaneous reception of the direct and the reflected waves, which are coherently added at the antenna, where the interference occurs. The received signal power changes as a function of time due to the movement of the GNSS satellites. The IPT studies the temporal evolution of the power of the interference signal as a function of the angular position. The first studies performed using a similar technique [24], [25], showed results on dielectric properties of soils using a Left Hand Circularly Polarized (LHCP) antenna. Also, in [26] the properties of a snow-covered metallic plane were studied using a LHCP antenna. It was found that when a LHCP antenna is used, the horizontal polarization masks the angular information since it does not exhibit the null reflectivity at the Brewster’s angle that the vertical polarization does. Therefore, a similar technique has been implemented by changing the polarization basis and using only a vertical polarized antenna. The IPT has been successfully applied over land surfaces to implement the soil moisture retrieval.

From now on, among all the possible GNSS signals only the Global Positioning System (GPS) ones will be used in this Ph.D. thesis since they
were the only one widely available. However, all the concepts and algorithms are extensive to other GNSS signals as soon as they become widely available (e.g. GLONASS, Galileo, Compass,...).

4.2 Theoretical Aspects: The GNSS-R Interference-Pattern Technique (IPT)

4.2.1 Theory

The theoretical aspects of the IPT are explained in this section. The geometrical configuration of the IPT is shown in Figure 4.1.

![Figure 4.1 IPT geometrical configuration. SMIGOL-Reflectometer measuring the interference between the direct GPS signal and the reflected one over the surface.](image)

As shown in Figure 4.1, the SMIGOL-Reflectometer instrument is located at a certain height (h), over the surface with the antenna beam pointing to the horizon. Both the direct and the reflected signals are automatically added at the antenna creating constructive/destuctive interference. As explained in Chapter 3, the antenna pattern must be symmetric because otherwise it will affect the interference pattern. The rationale is explained in Eqns. (4.1) – (4.6).
The power received at the antenna \((P)\), can be expressed as (4.1).

\[
P \propto |E_i + E_r|^2 ,
\]

(4.1)

where the \(E_i\) and the \(E_r\) are the incident and reflected electric fields. Then:

\[
P \propto |E_i + E_r|^2 = \left| E_{0i} \cdot F_i(\theta)^{1/2} \cdot e^{j\phi_i} + E_{0r} \cdot R(\theta, \varepsilon_r) \cdot F_r(\theta)^{1/2} \cdot e^{j\phi_r} \right|^2 ,
\]

(4.2)

where \(R\) is the reflection coefficient (or the Fresnel reflection coefficient “\(r\)” for a flat surface), which is function of the elevation angle \(\theta\) and the dielectric constant \(\varepsilon_r\), \(F_i(\theta)\) and \(F_r(\theta)\) are the antenna patterns for the direct and the reflected GPS incoming signals, \(E_{0i}\) is the magnitude of the incident electric field, \(\phi_i\) and \(\phi_r\) are the phases of the incident and reflected waves, respectively.

Assuming:

\[
F_i(\theta) = F_r(\theta) ,
\]

(4.3)

eqn. (4.2) can be written as:

\[
P \propto |E_i + E_r|^2 = F_i(\theta) \cdot |E_{0i}|^2 \cdot |1 + R(\theta, \varepsilon_r) \cdot e^{j\Delta\phi}|^2 ,
\]

(4.4)

where \(\Delta\phi\) is the phase difference between reflected and direct waves:

\[
\Delta\phi = \frac{4\pi}{\lambda} \cdot h \cdot \sin(\theta) ,
\]

(4.5)

where \(\lambda\) is the wavelength defined as the speed of the light over the working frequency \((f = 1.57542 \text{ GHz})\) and \(h\) is the instrument height.

When eqn. (4.4) is expressed in decibels logarithmic unit:

\[
P_{\text{dB}} \propto 10 \cdot \log(|E_i + E_r|^2) = \ldots
\]

\[
\ldots = 10 \cdot \log \left( F_i(\theta) \cdot |E_{0i}|^2 \right) + 10 \cdot \log \left( |1 + R(\theta, \varepsilon_r) \cdot e^{j\Delta\phi}|^2 \right) = \ldots
\]

\[
\ldots = A(\theta) + 10 \cdot \log \left( |1 + R(\theta, \varepsilon_r) \cdot e^{j\Delta\phi}|^2 \right) .
\]

(4.6)

\(A(\theta)\) becomes an amplitude modulation term (different for each value of \(\theta\)) of the interference pattern. \(A(\theta)\) does not affect the shape (nulls and peaks) of the interference pattern as shown in Figure 4.2.
As it can be seen in Figure 4.2a, the only difference between the interference pattern obtained considering a cardioid antenna diagram with gain equal to 3.5 dB (blue line), and another one considering an omnidirectional antenna with gain equal to 1 (red line), is exactly the cardioid antenna diagram plus 3.5 dB of gain (Figure 4.2b). The position of the minimum amplitude oscillation of the red and blue plots in Figure 4.2a (around 24°) and the amplitude and the speed of the oscillations are not affected by the antenna diagram. The antenna pattern only modulates the shape of the interference pattern. If the assumption shown in eqn. (4.6) does not hold ($f_t(\theta) \neq f_r(\theta)$) the effect of the antenna diagram cannot be split from the effect of the interference between direct and reflected signals.

Although several models for the incoherent scattering of electromagnetic waves over soil surfaces exist (for example [84] among many others), a coherent specular reflection model [85] has been implemented to compute $R$ (in the flat surface case $R$ becomes the Fresnel reflection coefficient “r”). The link between the main geophysical parameters (surface soil moisture and soil surface roughness) and the GPS observables (signal level, angular patterns) is performed through eqns. (4.6) – (4.13) and the dielectric constant model [86]. The model assumes the GPS L1 frequency (1.57542 GHz), a rough soil surface, and a multi-layered soil, which has different dielectric constant values, as described below.

For a single interface between two layers, the Fresnel reflection coefficients at horizontal and vertical polarizations are:

$$r_h = \frac{n_i \cos(\theta_{inc}) - n_{i+1} \cos(\theta_r)}{n_i \cos(\theta_{inc}) + n_{i+1} \cos(\theta_r)} ,$$

$$r_v = \frac{n_{i+1} \cos(\theta_{inc}) - n_i \cos(\theta_r)}{n_{i+1} \cos(\theta_{inc}) + n_i \cos(\theta_r)} ,$$

Figure 4.2 Effect of a symmetric antenna pattern in the interference pattern.
where $\theta_{\text{inc}}$ is the incidence angle, $\theta_t$ is the transmitted angle, $n_i$ is the refraction index of the incident signal medium, and $n_{i+1}$ is the refractive index of the transmitted signal medium.

In the proposed technique, linear polarization antennas (h: horizontal and v: vertical) are required instead of circularly polarized (LHCP: left or RHCP: right hand) for two main reasons:

- $\eta_h$ and $\eta_v$ have a larger variation with the incidence angle than $\eta_{\text{LHCP}}$ and $\eta_{\text{RHCP}}$, and therefore provide more information than a circularly polarized antenna, and

- a single linear polarization antenna can receive the direct and reflected signals simultaneously, while if a RHCP antenna were used, it will collect the direct signal, but not the reflected one, which will mostly be LHCP (except for the cross-polarization of the antenna pattern and the polarization mixing of the reflected signal on the rough surface).

Eqn. (4.9), can be used to express $\theta_t$ as a function of the $\theta_{\text{inc}}$ and the dielectric constant ($n_i = \sqrt{\varepsilon_{r_i} \cdot \mu_r}$, where $\mu_r$ is the permeability constant assumed to be equal to 1 (magnetic medium).

$$n_i \cdot \sin(\theta_{\text{inc}}) = n_{i+1} \cdot \sin(\theta_t). \quad (4.9)$$

Then, eqns. (4.7) and (4.8) result in eqns. (4.10) and (4.11), respectively:

$$\eta_{h,i+1} = \frac{\varepsilon_{r_{i+1}} - \varepsilon_{r_i} \sin^2(\theta_{\text{inc}})}{\sqrt{\varepsilon_{r_i} - \varepsilon_{r_i} \sin^2(\theta_{\text{inc}})} + \varepsilon_{r_{i+1}} - \varepsilon_{r_i} \sin^2(\theta_{\text{inc}})} \cdot \varepsilon_{r_{i+1}} \frac{\varepsilon_{r_i} - \varepsilon_{r_{i+1}} \sin^2(\theta_{\text{inc}})}{\sqrt{\varepsilon_{r_i} - \varepsilon_{r_i} \sin^2(\theta_{\text{inc}})} + \varepsilon_{r_{i+1}} - \varepsilon_{r_i} \sin^2(\theta_{\text{inc}})}. \quad (4.10)$$

$$\eta_{v,i+1} = \frac{\varepsilon_{r_{i+1}} \frac{\varepsilon_{r_i} - \varepsilon_{r_{i+1}} \sin^2(\theta_{\text{inc}})}{\sqrt{\varepsilon_{r_i} - \varepsilon_{r_i} \sin^2(\theta_{\text{inc}})} + \varepsilon_{r_{i+1}} - \varepsilon_{r_i} \sin^2(\theta_{\text{inc}})}}{\varepsilon_{r_i} - \varepsilon_{r_i} \sin^2(\theta_{\text{inc}})} \cdot \varepsilon_{r_{i+1}} \frac{\varepsilon_{r_i} - \varepsilon_{r_{i+1}} \sin^2(\theta_{\text{inc}})}{\sqrt{\varepsilon_{r_i} - \varepsilon_{r_i} \sin^2(\theta_{\text{inc}})} + \varepsilon_{r_{i+1}} - \varepsilon_{r_i} \sin^2(\theta_{\text{inc}})}. \quad (4.11)$$

Equations (4.10) and (4.11) are then computed at the interfaces between soil layers and are combined to obtain the surface’s reflectivity coefficient ($R$). For the sake of simplicity, a three-layer reflectivity model (air + two soil layers) has been used to derive eqn. (4.12). However, it can be readily extended to an $m$-layer model in an iterative way:
\[ R_i = e^{-\left(\frac{4\pi\sigma}{\lambda}\right)^2} \cdot \frac{r_{i,i+1}^2 + r_{i+1,i}^2 e^{S \cdot e^{j2\psi}}}{1 + r_{i,i+1}^2 + r_{i+1,i}^2 e^{S \cdot e^{j2\psi}}}, \]  

where \( \sigma \) is the soil surface roughness and the phase term \( \psi \) is given by:

\[ \psi = \frac{2\pi n_{i+1}}{\lambda} \cdot t_{i+1} \cdot \cos(\theta) = \frac{2\pi}{\lambda} \cdot t_{i+1} \cdot \sqrt{\varepsilon_{r_{i+1}} - \varepsilon_{r_i} \cdot \sin^2(\theta_{\text{inc}})}, \]

being \( t_{i+1} \) the thickness of the \( i + 1 \) layer and \( S \) the surface's roughness correction factor [85] defined as:

\[ S = -8 \cdot \left(\frac{\pi \sigma_i}{\lambda} \cdot \sqrt{\varepsilon_{r_{i+1}} - \varepsilon_{r_i} \cdot \sin^2(\theta_{\text{inc}})}\right)^2, \]

and \( \sigma_i \) the standard deviation of the roughness of the interface between layers, assumed to be small (< 2 cm) and equal for all layers.

The multiple interferences coming from the transmitted and reflected waves that occur between layers are already taken into account applying the boundary conditions of the electric and magnetic fields. The paraxial approximation has been assumed, so that the direct and reflected signals are considered to arrive to the antenna with the same angle.

The total received power will vary as a function of the incidence angle due to a fading-type behaviour, which is different at h- and v- polarizations, and depends on the geophysical parameters that characterize the soil. Figure 4.3 shows the simulated received power at the antenna considering horizontal (H) and vertical (V) polarizations.

![Interference power received at the antenna, H-polarization](image)

![Interference power received at the antenna, V-polarization](image)

Figure 4.3 Interference power received at the antenna for (a) H-pol and (b) V-pol.

As observed in Figure 4.3b the received power at v-pol presents a minimum amplitude oscillation in the interference pattern, called from now on “notch”. In order to understand the presence of the notches in the
interference patterns it is necessary to analyze the reflectivity at v-pol. Simulating the interference power and the reflectivity of a bare soil scenario (Figure 4.4) it is found that the notch position matches the Brewster's angle (Table 4.1).

![Figure 4.4](image)

Figure 4.4 Simulated interference power received versus reflectivity, for different soil moisture (SM) values. Note that the Brewster's angle value matches with notch position, 29.0° for (a) SM = 0% and 17.2° for (b) SM = 20% (see Table 4.1).

The Brewster's angle is the angle at which total transmission occurs for the vertical polarized wave (reflectivity near to 0). As it is well known, the Brewster's angle [87] is computed following eqn. (4.15).

\[
\theta_B = \arctan \left( \frac{n_2}{n_1} \right) = \arctan \left( \frac{\varepsilon_{r_2} \mu_{r_2}}{\varepsilon_{r_1} \mu_{r_1}} \right) = \arctan \left( \sqrt{\frac{\varepsilon_{r_2}}{\varepsilon_{r_1}}} \right), \quad (4.15)
\]

where \(\varepsilon_{r_2}\) corresponds to the dielectric constant of the soil layer, and \(\varepsilon_{r_1}\) corresponds to the dielectric constant of the air layer considered equal to 1. The permeability values of each medium, \(\mu_{r_1}\) and \(\mu_{r_2}\), are assumed to be equal to 1. The Brewster angle is then a function of the soil dielectric constant, whose value highly depends on the soil moisture. Table 4.1 shows the computed Brewster's angle for different soil moisture values [86].

Table 4.1 Dielectric constant of soils and equivalent Brewster's angle as a function of the Soil Moisture (SM).

<table>
<thead>
<tr>
<th>(\varepsilon_{r_1}) (SM)</th>
<th>SM = 0 %</th>
<th>SM = 10 %</th>
<th>SM = 20 %</th>
<th>SM = 30 %</th>
<th>SM = 40 %</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\theta_s)</td>
<td>61.0°</td>
<td>66.2°</td>
<td>72.8°</td>
<td>76.4°</td>
<td>78.4°</td>
</tr>
<tr>
<td>(90° - \theta_s)</td>
<td>29.0°</td>
<td>23.7°</td>
<td>17.2°</td>
<td>13.6°</td>
<td>11.6°</td>
</tr>
</tbody>
</table>
4.2.2 Retrieval Algorithm for Bare Soil Scenarios

4.2.2.1 Main Features of the Algorithm

As observed in the previous section, there is a direct link between the location of the Brewster's angle and the soil moisture content. The Brewster's angle is clearly seen and identifiable in the interference power received at v-pol. Therefore, finding the minimum amplitude oscillation in the interference pattern (or “notch”) the Brewster's angle is obtained and then the soil moisture at that particular elevation angle. Recall that each elevation angle corresponds geometrically to a particular point over the surface. Furthermore the amplitude of the oscillations is also soil moisture dependent (see Figure 4.5).

![Interference power considering different soil moisture values](image)

Figure 4.5 Interference power computed using different soil moisture values.

As it can be observed in Figure 4.5, when soil moisture increases the amplitude of the oscillations increases too. Therefore, not only the notch position is influenced by soil moisture but also the amplitude. In order to better understand the technique and the effect of the different geophysical parameters, a simulator was implemented in which all parameters can be freely modified.

The surface is modeled using three-layer model (air + 2 soil layers) in order to consider the effect of the roughness value between different layers. The first soil layer has been defined by its surface soil moisture value and a finite thickness and the second layer has been defined as an increase of the soil moisture value, which is the stationary behaviour for the most of the time, and an infinite thickness.
Figure 4.6 summarizes the main simulation results.

Figure 4.6 (a) and (b) influence of the surface roughness ($\sigma$) and the roughness of the interface between layers ($\sigma_I$) over the notch amplitude, and (c and d) over the notch position as a function of the soil moisture.

The relationship between the notch amplitude and the surface soil moisture as a function of the surface roughness ($\sigma$) is shown in Figure 4.6a. As it can be seen, an error in the soil surface roughness estimation hampers the soil moisture retrieval. In Figure 4.6b, assuming the value of the soil surface roughness known, it can be seen that an error in the roughness value of the interface between layers ($\sigma_I$) estimation introduces an error in the soil moisture retrieval up to 10%. Figure 4.6c shows the relationship between the notch position and the soil moisture as a function of $\sigma$. As it can be seen a variation of $\sigma$ is not affecting the notch position. Figure 4.6d shows the influence of $\sigma_I$ in the notch position. As it can be seen an uncertainty in the knowledge of the interface roughness introduces an error up to $3 \cdot 4\%$ in the soil moisture retrieval, which is acceptable for many applications\(^2\).

\(^2\) The SMOS soil moisture accuracy requirement is 4% volumetric soil moisture or better [88].
Therefore, building an algorithm based on notch position is more robust and it is preferred to retrieve the surface’s soil moisture.

Another important point that can be easily observed from Figure 4.5 is that the speed of the oscillations does not vary when varying the soil moisture or the soil surface roughness. The speed of the oscillations only depends on the path difference between direct and reflected signals, which is considered in the phase term given by eqn. (4.5). As eqn. (4.5) shows, the phase only depends on the frequency, which is constant in that case, the elevation angle, and the instrument height (Figure 4.7).

![Figure 4.7 Interference power received at the antenna for different instrument heights (different colors in the figure).](image)

As it can be seen in Figure 4.7, varying the instrument height (h) changes the speed of the oscillations. When h increases (grey plot) oscillations are faster, and when h decreases (black plot), the oscillations are slower. The inherent sensitivity of the IPT to phase differences directly translates into sensitivity to topography variations of the surface. If a flat surface is considered, the instrument height respect each reflection point is constant. However in real scenarios surfaces are not flat, they have topographic profiles and each reflection point has an equivalent instrument height (Figure 4.8).

![Figure 4.8 IPT considering topography in the observation area.](image)
As it can be seen in Figure 4.8, each reflection point over the surface, that is each satellite elevation angle ($\theta_i$ with $i = 1,2,..n$) corresponds to a different instrument height value ($h_i$ with $i = 1,2,..n$), understood as the equivalent instrument height. The effect over the interference pattern is illustrated in Figure 4.9 using a synthetic topography profile.

![Surface topography features](image)

**Figure 4.9** Variations of the received interference power caused by surface topography as a function of the elevation angle.

Figure 4.9 shows two synthetic surfaces, one with topography variations and the other flat. The instrument is located at $h = 9$ m. Therefore, the oscillations observed correspond to the difference between $h$ and surface topography. The results presented in Figure 4.9b show how changes on the surface height create phase differences, that translate into different speeds of oscillation that the one shown in Figure 4.9a.

### 4.2.2.2 Soil Moisture Retrieval Algorithm

Based on the explained main features and in order to simplify the algorithm for the soil moisture retrieval it is needed to know the topography. Once topography is known, the minima and maxima of the measured interference pattern oscillations match in elevation angle position with the simulated.
Then, the soil moisture retrieval based on amplitude matching becomes simpler. The algorithm is summarized in Figure 4.10 and explained in next subsections.

![Algorithm for bare soils geophysical parameters retrieval](image)

**Figure 4.10 Algorithm for bare soils geophysical parameters retrieval**

4.2.2.2.1 **Surface Topography Retrieval**

The speed of the oscillations of the interference power can be used to infer the topography, as demonstrated in Figure 4.9. The algorithm first searches all maxima and minima amplitudes positions of the measured interference power (Figure 4.11).

![Interference power vs elevation angle](image)

**Figure 4.11 Algorithm search for all maxima and minima and splits interference power in windows, containing one maxima and one minima.**
As shown in Figure 4.11, it splits the interference power into elevation angle windows containing at least one period (one minimum and one maximum, \( \Delta \theta_{\text{os}} \)).

Once these elevation angle windows are set, the algorithm modifies the value of the instrument “height” in an iterative way in order to adjust the theoretical power fluctuations to the measured ones by minimizing the error between them in each window (Figure 4.12).

![Image]

Figure 4.12 Topography retrieval algorithm adjustment.

The retrieved values correspond then to the equivalent instrument heights, \( h(\text{sat}, \theta, \varphi) \), at each elevation and azimuth angles, from which the topographical profile can be easily inferred by subtracting the actual instrument height at the origin (h), to the retrieved equivalent instrument heights:

\[
h_{\text{surf}}(\text{sat}, \theta, \varphi) = h(\text{sat}, \theta, \varphi) - h.
\]

### 4.2.2.2 Soil Moisture Retrieval

The notch amplitudes of the interference powers are sensitive to soil moisture (Figure 4.5). This feature allows the retrieval of the soil moisture, once the topography is known. For the soil moisture study, a series of numerical simulations have been run for different soil moisture values providing a full set of reflectivity values. When these reflectivity values are introduced in the theoretical IPT algorithms the impact of these changes on the theoretical interference powers can be analyzed. The evolution of the notch position has been studied (Figure 4.13).
Figure 4.13 Soil moisture content related to the notch position.

Figure 4.13 shows the relationship between soil moisture content and the notch position. The soil moisture retrieval algorithm takes as an input the notch position, then, using Figure 4.13, the soil moisture value is obtained from the notch position: \( SM(\text{sat}, \theta_{\text{notch}}, \varphi_{\text{notch}}) \). This value is used as the initial value for the soil moisture algorithm. Then the amplitude of the simulated oscillation is adjusted to the measured one in an iterative process, for each window \( \Delta \theta_{\text{os}} \), containing one maximum and one minima as in Figure 4.11, finally obtaining \( SM(\text{sat}, \theta, \varphi) \).

### 4.2.2.2.3 Data Merging

Once all satellites have been processed, the algorithm starts the data merging. Elevation (\( \theta \)) and azimuth (\( \varphi \)) are transformed into \( x \) and \( y \) coordinates over the surface. Then, the topography and soil moisture values are merged by using [89]. It must be considered that:

- To perform the topography retrieval large series of data (at least 3 months) must be merged obtaining \( h_{\text{surf}}(\theta, \varphi) \).

- To perform the soil moisture retrieval the available data is organized in groups of 6 hours of measurements (6 – 8 satellite data) to prevent mixing the Sunrise with the noon measurements. Then \( SM(\theta, \varphi) \) product is obtained, but to measure enough satellite signals to obtain a map.

Finally the topography and soil moisture maps of the observed surface are generated by the algorithm.
4.3 Field Experiment and Results

4.3.1 Field Experiment Description: Palau Field Experiment 1

The field experiment was carried out at Palau d’Anglesola, Lleida, Spain (41°39’34.53”N, 0°51’7.71”E), over a wheat field from January to September 2008 covering the different growth stages of the wheat, Figure 4.14. In this chapter only the soil moisture retrievals over bare soils are considered, therefore the selected measurements correspond to August and September 2008, after the harvest.

![Google map of the field experiment location at Palau d’Anglesola, Lleida, Catalonia, Spain.](image)

Figure 4.14 Google map of the field experiment location at Palau d’Anglesola, Lleida, Catalonia, Spain.

Figure 4.15 shows the measurement site main descriptors. The SMIGOL Reflectometer location, the measurement station, the irrigation channel and the observation area, a wheat field, are clearly shown in the different images. Note that there is a negative slope from the location of the SMIGOL Reflectometer to the irrigation channel.
In August the soil is mainly dry, but in September the first seasonal rains occurred and soil became wet. Two Decagon ECH2O soil moisture probes [90] were located in the wheat field at 5 and 20 cm (Figure 4.16), in order to measure the volumetric water content at these depths.

The soil moisture at 5 cm is systematically higher than at 20 cm. The soil surface roughness has been obtained as a result of 30 points in-situ measurements in the field and, the averaged value (~ 2 cm) has been assumed to be constant in mean for the whole field.
4.3.2 Bare Soil Measurements for Soil Moisture Retrieval

The algorithm for bare soil retrieval has been applied to the measurements and the equivalent theoretical interference powers have been obtained. Figure 4.17 shows representative measurements.

Figure 4.17 Measurements obtained at Palau d’Anglesola, Lleida, Spain compared with the theoretical approximation after applying the algorithm to retrieve soil moisture. On 22nd August, measurements corresponds to (a) GPS satellite 10 with RMS error = 0.24 dB, (b) GPS satellite 15 with RMS error = 0.27 dB and (c) GPS satellite 26 with RMS error = 0.22 dB; and on 25th September measurements corresponds to (d) GPS satellite 10 with RMS error = 0.19 dB, (e) GPS satellite 15 with RMS error = 0.20 dB, and (f) GPS satellite 26 with RMS error = 0.22 dB.
The measured signal and the computed theoretical signals have been analysed in terms of the RMS value of the error between them using eqn. (4.17):

\[
\text{RMS}_{\text{error}} = \sqrt{E \left( (P - \hat{P})^2 \right)},
\]

where \(P\) is the measured power and \(\hat{P}\) is the computed theoretical power.

The algorithm can retrieve a soil moisture value inside the 14° to 30° range of elevation angles, where the notches occur. Rigorously, the retrieved value is only valid at exactly the notch angle, as mentioned before, but thanks to the amplitude of the fluctuation the algorithm can retrieve the soil moisture for the whole range of elevation angles.

Processing several GPS satellites’ passages and applying the data merging a soil moisture map can be obtained (Figure 4.18).

![Figure 4.18 Soil moisture map retrieved for the bare soil scenario, fit in Google Earth map at Palau d’Anglesola site, Lleida, Spain (41°39’34.53”N, 0°51’7.71”E), in (a) August and in (b) September, after seasonal rains.](image)

Note that the wheat field has a slight negative slope from the top to the bottom of the pictures. The map size depends on the instrument height, but as height increases the resolution decreases (the size of the glistening zone enlarges). In our case, the instrument was located at 2.6 m height and the obtained measurements come from elevation angles in the range 7° - 45°. Taking into account that the antenna has a beamwidth of 90° (roughly a quarter of a circle) and the minimum elevation angle is 7° (equivalent to a 21 m radius area) the map size is approximately:
Finally, Figure 4.19 shows a scatter plot between the soil moisture measured close to the instrument using the ECH2O soil moisture probes and the SMIGOL Reflectometer retrieved one.

![Scatter plots of soil moisture retrieved using SMIGOL Reflectometer and soil moisture retrieved by the ECH2O soil moisture probes at (a) 5 and (b) 20 cm during August-September.](image)

As it can be seen at Figure 4.19, retrieved measurements and ground data measurements are similar to 5 cm ECH2O data for September measurements after seasonal rain, but they are more similar to 20 cm ECH2O data for all August measurements, and for the first measurements of September before the seasonal rain. This occurs because dry soils have a penetration depth larger than wet soils. Note that ECH2O soil moisture probes are located near the SMIGOL Reflectometer. The RMS error between the 5 cm probe soil moisture measurement and the SMIGOL Reflectometer retrieved one is just 2.7 % for August/September observations. The RMS error between the 20 cm probe soil moisture measurement and the SMIGOL Reflectometer retrieved one is 3.1 % for August/September observations.

### 4.4 Conclusions

This chapter has presented a new technique to measure surface soil moisture based on the power variations of the interference signal between the direct and reflected GPS signals:

\[
A = \frac{A_{\text{circle}}}{4} = \frac{\pi r^2}{4} = \frac{\pi (21 \text{ m})^2}{4} = 346 \text{ m}^2 .
\]
• a simple soil moisture retrieval algorithm has been devised based on the position of the notch of the interference pattern at v-polarization and the amplitude of the oscillations of the pattern, and

• experimental data over a bare soil field has been presented to validate the technique.

Next chapter focuses on the study of the vegetation effects, and the data processing of different field campaigns, including the vegetation growth stages and different crops.
This chapter focuses on the study of vegetation-covered soils from the SMIGOL-Reflectometer ground-based instrument using the IPT. The vegetation effects are analyzed and the soil moisture retrieval algorithm is modified accordingly. Three field experiments are performed in order to test the IPT and the retrieval algorithms in presence of vegetation. Afterwards a new technique for a deeper vegetation analysis is presented and tested during a 11-month field experiment. The results are shown in this chapter and the main conclusions are summarized.
5.1 Introduction

The IPT has been proven to work over bare soils scenarios, where few geophysical parameters play a role in the equations: soil moisture, soil surface roughness, and topography. However when vegetation covers the soil, the surface must be modeled to include an extra layer, going from air+soil to air+vegetation+soil model. This chapter is split in two main sections.

- The first one focuses on vegetation height monitoring. It is performed using the IPT and a new algorithm built to retrieve three geophysical parameters: topography, vegetation height, and soil moisture. For the IPT, the vegetation water content (VWC) is assumed to be the typical value of each crop, therefore there is an error in the vegetation height and the soil moisture retrievals that is intrinsic to this assumption.

- The second one focuses on VWC retrieval. In order to provide information about the VWC independently from any other geophysical parameter, a new technique is proposed and analysed, testing it with real measurements, the GNSS-Transmission (GNSS-T) technique.

5.2 Vegetation Height Monitoring

5.2.1 Theoretical Aspects: Effects of the Vegetation in the IPT

As mentioned above, the IPT consists of the measurement of the direct GPS signal and the reflected one over the surface, which are coherently\(^3\) added by the antenna. When introducing a vegetation layer in the modeled surface, the interference patterns of the received power look like Figure 5.1.

\(^3\) Provided the instrument’s height is less than \(-25\) m (see chapter 3).
In the previous chapter it has been shown how the measurements of the SMIGOL Reflectometer over a bare soil field were used to retrieve the soil moisture of the field, using the notch positions to achieve maps with a $\sim 3 - 4\%$ soil moisture error. In the case of vegetation-covered soils, where a vegetation layer with a finite thickness is considered between the air and the soil layers, more than one notch appears and the number of them depends on the thickness of this layer (Figure 5.2).

Figure 5.2 Simple 1 layer vegetation-covered soil model. Simulated interference power received versus reflectivity: (a) bare soil produces one notch, (b) 60 cm vegetation layer + soil layer produces 3 notches and (c) 90 cm vegetation layer + soil layer produces 4 notches. Note that first notch is due to the Brewster’s angle, but new notches appear due to oscillations in the reflectivity value associated to multiple reflections within the vegetation layer.
One of the notches observed is due to the Brewster’s angle and the rest of notches are due to the oscillations in the reflectivity caused by multiple reflections in the vegetation layer. As it can be observed in Figure 5.2, as the vegetation height increases the number of notches increases too, and their positions move to the left, lower elevation angles. The algorithm to retrieve vegetation height is based in this feature, which is independent of topography, soil moisture or surface roughness. If the vegetation layer thickness is increased up to 3 m, soil layer effects are theoretically negligible, and the equivalent model air + vegetation + soil model is transformed into air + vegetation model. Figure 5.3 shows the evolution of the reflectivity for different vegetation thickness.

![Reflectivity value vs elevation angle](image)

Figure 5.3 Equivalent reflectivity of the air + vegetation + soil model, as a function of the elevation angle, for different thickness of the vegetation layer. For the Brewster’s angle computations, it has been considered a soil moisture value of 0 % and a dielectric constant for the vegetation layer of 1.47 + 0.36j (typical for wheat plants).

As it is shown, as vegetation thickness increases the Brewster’s angle tends to that of the ensemble air + vegetation layer, with no influence of the soil layer. When a vegetation layer is considered (assuming typical values for plant parameters [91]), the variations of soil moisture and soil surface roughness only affect the amplitude of the entire interference power, as in the case of bare soils. In this case, the notches positions only change with the vegetation height, except for the notch related to the Brewster’s angle, which for lower vegetation heights still has a little movement due to the variations on soil moisture. Assuming a vegetation water content value of 5 kg/m², when vegetation height increases over 20 cm, soil moisture does not affect the Brewster’s angle notch position. When vegetation reaches 3 meters height, it can be considered as an infinite layer, where soil parameters do not affect the interference power at all. This assumption is very exigent, crops have lower values for vegetation water content and they
are not as dense as the theoretical case considered, so that, the vegetation height could be monitored above 3 meters height.

The vegetation modeling can be done as follows:

- Using a full electromagnetic model that describes the different interactions that the GPS signal suffers when impinging in the soil + vegetation layer [92], [93]. This software package was originally developed for vegetation-covered soils emissivity computations, and with the appropriate changes it is also a suitable tool to model the GPS scattering of the ensemble soil + vegetation in terms of the four main different interactions: vegetation-only, soil-vegetation, vegetation-soil, and soil-vegetation-soil. The structure of the plants is modelled using Lindenmayer systems (L-systems) [94], [95]. Moreover, each part of the plant (trunks, branches, leaves and fruits) has its own particular scattering model [93]. Several types of vegetation can be specifically modelled, from more complex structures such as trees or vineyards to simpler ones as maize, fescue or alfalfa. For the two first field campaigns under study in this Ph.D. Thesis, where wheat and barley fields are observed, the composition of the plants basically needs to be characterized in two parts: a thin trunk, with a certain height and a specific dielectric constant, and at the end a little branch, simulating the wheat fruit, with its dielectric constant. The dispersion of the wheat over the observation area can be configured as a random distribution or it can be defined by the trunk separation. Figure 5.4 shows an example of the final wheat or barley fields’ simulations.

![Figure 5.4 Emisveg software products for wheat or barley features. (a) Wheat or barley plant, and (b) wheat or barley field within the antenna footprint.](image)

The simpler modeling of these two plants structure makes the full electromagnetic model work properly.

However, in the case of maize plants, more complex structures, many plant characteristics must be taken into account into the full
electromagnetic model. Therefore every stage of the maize growth must be specifically modeled, in terms of leaves and trunk, and what was a more accurate tool converts the vegetation modeling into a very complicated process (Figure 5.5).

![Maize plant simulation](image)

Figure 5.5 Maize plant simulation using L-systems in the full electromagnetic software, [94], [95].

Therefore, the vegetation layer in case of maize plants was decided to be modeled, as well a constant layer defined by a thickness value and a specific dielectric constant (Figure 5.6). The validity of this approximation will be checked with the experimental results obtained.

![Vegetation layer simulation](image)

Figure 5.6 Surface modeled by constant layers described by its thickness (t) and its dielectric constant (εr).
5.2.2 Description of the Retrieval Algorithms

The algorithm described for bare soils cannot be used when vegetation covers the soil layer. Therefore, a new and more complex algorithm needs to be developed and it is now detailed.

First of all, the algorithm focuses on the use of the IPT for correcting the surface’s topography which, as in the case of bare soils, calls for a coarse resolution digital elevation model estimation, and second on the retrieval of the vegetation height and the soil moisture of vegetation-covered soils.

For each satellite (sat) raw data, the vegetation-covered soils algorithm (Figure 5.7) proceeds as follows:

![Image of algorithm diagram]

Figure 5.7 The vegetation-covered soils algorithm.

Retrieval of the surface’s topography, which is a function of the elevation ($\theta$) and the azimuth ($\varphi$) angles of the satellite passage, $h_{\text{surf}}(\text{sat}, \theta, \varphi)$. Recall that topography is independent of the other scenario parameters.

Once the topography is known, the vegetation height retrieval is performed. This retrieval obtains as many vegetation height estimates as number of notches are detected ($h_{\text{veg}}(\text{sat}, \text{notch})$). Recall that vegetation height can be obtained independently from the soil moisture or soil roughness, because it is directly related to the number and position of the notches of the received interference power.
Finally, focusing on the interference power amplitude and using as inputs the topography, the vegetation height, and the measured in-situ roughness value, the soil moisture can be retrieved. The retrieved soil moisture values are a function of the elevation ($\theta$) and the azimuth ($\varphi$) angles of the satellite passage ($\text{SM(sat, } \theta, \varphi)$).

Once all available satellites have been processed, the topography and soil moisture values are merged using [89], as in the case of bare soil scenarios, and the vegetation height values are averaged all together. The requirements to perform the three different retrievals are:

- To perform the topography retrieval, large series of data (at least 3 months) must be combined obtaining $h_{\text{surf}}(\theta, \varphi)$.

- To perform the soil moisture retrieval the available data is organized in groups of 4 hours of measurements (6 – 8 satellite data) to prevent mixing sunrise and noon measurements. Then $\text{SM(} \theta, \varphi)$ product is obtained.

- To perform the vegetation height retrieval ($h_{\text{veg}}$), the only restriction is to avoid mixing long time series. 4 hours of measurements are averaged.

Then a change of coordinates is applied from ($\theta, \varphi$) to ($x, y$) to finally generate the topography and soil moisture maps of the observed surface. In the following sub-sections these three retrievals are explained.

### 5.2.2.1 Surface Topography Retrieval

The algorithm for surface topography retrieval is not affected by the presence of the vegetation. Just in case of very dense and tall vegetation where it can be considered as an infinite layer, the retrieved topography corresponds to the top of the vegetation layer. Therefore, as in the case of bare soils, the speed of the oscillations of the interference power is used to infer the topography. The algorithm first searches all maxima and minima amplitude positions of the measured interference power. Then the algorithm splits this power into elevation angle windows containing at least one period, previously named as $\Delta \theta_{\text{os}}$. Once these elevation angle windows are set, the algorithm modifies the value of the instrument virtual “height” in an iterative way in order to adjust the theoretical power fluctuations to the measured ones by minimizing the error between them, exactly the same way as in the bare soils algorithm.
Again, the retrieved values correspond to the instrument “height”, \( h(\text{sat}, \theta, \varphi) \), at each elevation and azimuth angles, from which the topographical profile can be easily inferred by subtracting the actual instrument height at the origin, \( h \), to the retrieved instrument “heights”:

\[
h_{\text{surf}}(\text{sat}, \theta, \varphi) = h(\text{sat}, \theta, \varphi) - h.
\]  

(5.1)

5.2.2.2 Vegetation Height Retrieval

As mentioned before, when vegetation covers the observation surface the analysis of the received power is more complex than in the case of a bare soil surfaces. The vegetation layer changes the number of notches and their position, as seen in Figure 5.2. The Brewster's notch is sensitive to soil moisture for low vegetation heights, but as the vegetation height increases it moves to the position corresponding to the Brewster’s angle of the ensemble air + vegetation (Figure 5.3). Then, notches become insensitive to soil moisture, but sensitive to vegetation height. However, the amplitude of the notch is still sensitive to soil moisture, at least up to 3 meters height, when the layer start being considered infinite (just for theoretically very dense and moisture vegetation). Recall that the amplitude of the whole received power is sensitive to soil moisture, not only the notches' amplitude. These three main features are shown in Figure 5.8.

![Figure 5.8](image)

Figure 5.8 Theoretical simulations computed with 20 % and 40 % soil surface moisture for (a) 70 cm plant height, and (b) 150 cm plant height with.

An extensive series of numerical simulations changing the vegetation height has provided a full set of reflectivity values that have been introduced in the IPT retrieval algorithms to estimate the received power. The evolution of
the notches position has been studied. Recall that the instrument height has no influence on the notches, neither on the number, nor on the position, only on the speed of the oscillations. Furthermore, soil moisture only affects the oscillations amplitude. Therefore, by analyzing the notches behaviour, vegetation height can be retrieved (Figure 5.9).

Figure 5.9 Variation of the notch position as a function of the vegetation height.

As observed in Figure 5.9, as vegetation grows, the notches of the interference power pattern move towards lower elevation angles, and new ones appear at larger elevation angles. Therefore, larger vegetation heights exhibit a higher number of notches. As it can be seen for a plant height of 50 cm, 3 notches appear in the interference power pattern at: 11°, 21.5°, and 29° elevation angles, while for a plant height of 150 cm up to 9 notches appear at: 6°, 11°, 16°, 19°, 23°, 27.5°, 32°, 38°, and 41°.

The vegetation height retrieval algorithm first computes the number of notches and their position in the measured interference power. This information, in combination with Figure 5.9, and applying a maximum likelihood algorithm based on homogeneity of the plants (with a certain tolerance due to natural dispersion in the plant growing) results into the retrieval of height values (one per notch), \( h_{veg}(sat, notch) \). The number of vegetation height values obtained with the algorithm is actually equal to the number of notches found. If the observed field is homogeneous, all values must be the same, but actually it is not, and different vegetation values are obtained, since a notch position is associated to a particular physical point in the observation area. As GPS signals are reflecting in different parts of the field, there are different vegetation height values.
5.2.2.3 Soil Moisture Retrieval over Vegetation-Covered Soils

The notch amplitudes of the interference powers are sensitive to soil moisture (Figure 5.8). This feature allows the retrieval of the soil moisture, once the vegetation height is known.

For the soil moisture study, a series of numerical simulations for different soil moisture values and vegetation heights provides a full set of reflectivity values of the ensemble: air + soil + vegetation. When these reflectivity values are introduced in the theoretical IPT algorithms the impact of these changes on the theoretical interference powers can be analyzed. The evolution of the notch amplitudes has been studied (Figure 5.10).

![Soil moisture as a function of the notch amplitude for different vegetation heights](image)

Figure 5.10 Soil moisture content related to the notch amplitude for different vegetation heights. These amplitudes refer always to the notches located at higher elevation angles. Note that vegetation typical parameters for plant water content have been considered.

Figure 5.10 shows the relationship between the soil moisture content and the notch amplitude, for different vegetation heights. In fact, this is the behaviour of the notches corresponding to the higher elevation angles. The other notches of the received power pattern also have soil moisture information, but the most suitable notches for the soil moisture retrieval are the ones that contain the less attenuated soil information. Higher elevation angles mean larger incidence gradients, and lower elevation angles mean lower incidence gradients. From this fact, it can be understood that, at least for this type of vegetation structures, which are mostly vertical, the notches at higher elevation angles contain more information about the soil properties than the lower ones because of the weaker interaction of the GPS signal with the vegetation layer, i.e. the GPS signal crosses less vegetation.
larger thickness for higher elevation angles and then the soil influence in the reflected signals is larger. The soil moisture retrieval algorithm takes as an input the retrieved vegetation heights from the notches’ position (Figure 5.9). Then, depending on the notch amplitude and the vegetation height the soil moisture value is inferred, $SM(sat, \theta_{notch}, \varphi_{notch})$ (Figure 5.10). To exemplify that, a 50 cm vegetation height is retrieved, if the notch 3 has 1.5 dB of amplitude, a soil moisture value of 16% is retrieved (see red arrow in Figure 5.10). An error of ± 10 cm in the estimation of vegetation height will give an error of 1.2 % of soil moisture (Figure 5.10).

Once the soil moisture value corresponding to a particular elevation angle is retrieved the algorithm proceeds as in the case of bare soils: extending to the whole range of elevation angles in an iterative process that adjusts the amplitudes of the measured interference power and the theoretical one, $SM(sat, \theta, \varphi)$.

5.2.3 Field Experiments and Results

The three different proposed retrievals have been applied to the data obtained from SMIGOL Reflectometer and the available ground-truth. The following sub-sections explain the results achieved in each of the retrievals.

5.2.3.1 Palau Field Experiment 1

5.2.3.1.1 Field Experiment Description

The Palau field experiment 1 took place at Palau d’Anglesola in Lleida, Spain (41°39’34.53”N, 0°51’7.71”E). The SMIGOL Reflectometer was located at 2.6 m above the observation surface pointing to the horizon. From February 2008 to October 2008 it was measuring a wheat field, which has a smooth negative slope, and covered the different growth stages of the wheat, from no vegetation up to 60 cm vegetation height, including the dry up process of the wheat. Figure 5.11 shows some pictures of the field during the experiment.
Figure 5.11 Palau field experiment, the different growth stages of the wheat: (a) January, bare soil conditions, (b) 23rd February, 2008, $h_{\text{veg}} = 10$ cm (c) 19th April, 2008, $h_{\text{veg}} = 45$ cm (d) 25th June, 2008, $h_{\text{veg}} = 53$ cm.

The experiment ground-truth was acquired with Decagon ECH2O soil moisture probes [90], and temperature sensors were located inside the field at 5, 10 and 20 cm.

5.2.3.1.2 Wheat-Covered Soil Measurements for Soil Moisture and Vegetation Height Retrieval.

The vegetation height of the observed wheat plants has been retrieved for different stages during the vegetation growth, and has been compared to the ground-truth data. Figure 5.12 shows the main results.

In Figure 5.12a the wheat vegetation height retrieved during the Palau field experiment 1 has been plotted against the ground-truth. Part of the dispersion in the retrieved heights is due to the random height of the plants, and the fact that each retrieved value corresponds to a different part of the field.
The mean retrievals agree well with the ground-truth data. The correlation coefficient ($\rho$) between measurements and retrievals is $\rho = 89\%$, the determination coefficient is $R^2 = 79\%$, and the root mean squared error (RMSE) is $\text{RMSE} = 5.4$ cm. The main descriptors used are described in Appendix 1, from eqn. (A.1) to eqn. (A.5). Figure 5.12b shows the SMIGOL-Reflectometer measurements superimposed to the ground-truth data of the plants growing during the field campaigns, as it can be seen in mean the algorithm follows the actual wheat growth.

Figure 5.13 Main results for soil moisture retrieval over vegetation covered soils: (a) retrieved maps, big black dot indicates the SMIGOL Reflectometer position and the small black dot indicates the soil moisture probes location and the retrieved value (b) ground-truth provided by soil moisture probes, showing the mean soil moisture value ($\bar{SM}$) computed. Map scale is 13 m and the data corresponds to March 11th, 2008, DoY = 71, the ground-truth is the measurement of two ECH2O soil moisture probes (at 5 cm and 20 cm depth).
Finally, the soil moisture retrieval algorithm over vegetation-covered soils has been applied to the SMIGOL data, and soil moisture maps of the observed areas have been obtained. Since soil moisture changes are much faster than topography, only data from one day at the maximum is processed to perform soil moisture retrievals. Figure 5.13 shows the results obtained.

5.2.3.2 GRAJO Field Experiment

5.2.3.2.1 Field Experiment Description

The GPS and RAdiometric Joint Observations (GRAJO) field experiment took place at Vadillo de la Guareña in Zamora, Spain (41°18’N, 5°22’E). This experiment is the result of the cooperation between the Centro de Investigaciones Agrarias Luso Español (CIALE), University of Salamanca, and the Universitat Politècnica de Catalunya (UPC). It was carried out at the Red de Medición de la Humedad del Suelo (REMEDHUS) area in the frame of the Soil Moisture and Ocean Salinity (SMOS) mission preparatory activities. The field experiment consisted of three plots: bare soil, perennial grass and barley, measured with the L-band AUtomatic RAdiometer (LAURA) radiometer [96]. The SMIGOL Reflectometer is observing the barley field, repeating the Palau field experiment for this type of plant. Also the GPS Reflectometer Instrument for Passive Advanced Unit (griPAU) (GNSS-R reflectometer) instrument [44] was used in this field campaign to support an intensive measurement period during July 2009, and measured Delay-Doppler Maps [20] over land surfaces.

The CIALE team was in charge of the in-situ ground-truth [97]. Related to the barley plot: two hydra probes were installed at 5 cm depth registering the soil moisture, and the temperature every 30 minutes. Also, thermistors were installed at at 5, 25, 50, and 100 cm, to measure the temperature profile. Vegetation was also controlled during the whole cycle (from November 2008 to July 2009) in terms of thermal IR measurements (soil and vegetation), Normalized Difference Vegetation Index (NDVI) measurements, Leaf Area Index (LAI), height, dry and wet weight, Vegetation Water Content (VWC), dew and rain events, phenologic stage, green cover percentage, and litter. About the topography map, the CIALE team provided a Digital Elevation Model (DEM) measured using a GS200 3-D Laser scanner [98], with a 3 mm resolution.
The UPC team was in charge of the radiometric and GNSS reflectometric measurements. The SMIGOL Reflectometer was located at 3 m above the barley field pointing to the horizon. The field experiment started on November 2008 and lasted until May 2010, at the end of the SMOS commissioning phase. The experiment covered the different growth stages of the barley. Figure 5.14 shows some pictures of the field.

Figure 5.14 GRAJO field experiment. (a) SMIGOL Reflectometer and LAURA Radiometer at REMEDHUS site, (b) zoom, (c) barley on 3rd March, 2009, \( h_{\text{veg}} = 8.5 \text{ cm} \), (d) barley on 13th April, 2008, \( h_{\text{veg}} = 20 \text{ cm} \), and (e) barley on 28th May, 2008, \( h_{\text{veg}} = 55 \text{ cm} \).

5.2.3.2.2 Barley-Covered Soil Measurements for Topography, Soil Moisture and Vegetation Height Retrieval.

Figure 5.15 shows the results achieved after almost 3 months of satellites measurements while observing the barley field.
Figure 5.15 Estimated topography from SMIGOL superposed to the DEM of the observed field (map scale 27 m). DEM data has been provided by the CIALE team, University of Salamanca, using a GS200 3-D laser scanner. For every sample the size of the grid was setup to acquire a nominal angle of 1 μrad, or what is the same, a grid of 2 cm width at 20 meters [98].

Radial segments correspond to the points on the Earth where reflected signal from a GPS satellite happens. The measurement errors of the DEM are about 3 mm at 100 m [98], [99]. Figure 5.15 shows the retrieved topographical profile map superimposed to the DEM. Measurements correspond to December 2008, and February and March 2009. Although vegetation was present in March, it does not affect the topography retrieval, since the presence of vegetation only affects the number of notches and their position, but not the frequency of the oscillations of the interference pattern, which is only affected by topography.

Figure 5.16 shows the error between ground-truth and measurements.

Figure 5.16 Difference between the DEM and the retrieved topographical profile map.
Although the largest part of the retrieved map has a 10% error (RMSE = 27 cm, σ = 16 cm, bias = 22 cm) two areas with a larger error can be noticed: the area around the (0, 0) meters coordinate, where errors are related to the secondary lobes antenna pattern distortion which are measuring the multiple-scattering in the scaffolding where the instruments were instsallated, and the area around the (-12, 20) meters coordinate, where the increased error is associated to the proximity of an electricity mast.

The vegetation height of the observed barley plants has been retrieved for different stages during the vegetation growth, and has been compared to the ground-truth data. Figure 5.17 shows the main results.

![Figure 5.17 Results for the vegetation height SMIGOL retrieval algorithm: (a) the scatter plot of the retrieved values and the ground-truth values ans (b) the retrieved vegetation height superimposed to the wheat growing during the GRAJO field campaign from 5 cm barley height to its harvest on July 2008.](image)

In Figure 5.17a the barley height retrieved during the GRAJO field experiment has been plotted against the ground-truth. The mean retrievals agree well with the ground-truth data. The correlation coefficient (ρ) between measurements and retrievals is ρ = 97 %, with the coefficient of determination $R^2 = 94\%$, and the root mean squared error (RMSE) is RMSE = 3.1 cm. Recall that the main descriptors used are described in Appendix 1, from eqn. (A.1) to eqn. (A.5). Figure 5.17b shows the SMIGOL-Reflectometer measurements superimposed to the ground-truth data of the plants growing during the field campaigns, as it can be seen in mean the algorithm follows the actual wheat growth.

Finally, the soil moisture retrieval algorithm over vegetation-covered soils has been applied to the SMIGOL data, and soil moisture maps of the observed areas have been obtained. Figure 5.18 show the soil moisture maps obtained for two significative days.
Figure 5.18 Map scale is 27 m. (a, b) data corresponds to April 18\textsuperscript{th}, 2009, DoY = 108. (c, d) May 1\textsuperscript{st}, 2009, DoY = 121. In these two results the ground-truth is measured by two Hydra probes located at 5 cm depth, CHD and CHI.

As it can be seen, the retrieved soil moisture values agree with the ground-truth data measured with the different soil moisture probes. Table 5.1 summarizes these results.

Table 5.1 Summary of soil moisture retrieval, comparing the ground-truth data obtained from different probes and the SMIGOL retrieved values.

<table>
<thead>
<tr>
<th>Date</th>
<th>Retrieved value</th>
<th>Probe 1</th>
<th>Probe 2</th>
<th>Error 1</th>
<th>Error 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>April 18\textsuperscript{th}, 2009 (DoY=108)</td>
<td>16.4 %</td>
<td>CHD @ 5cm 19.6 %</td>
<td>CHI @ 5cm 18.5 %</td>
<td>3.2 %</td>
<td>2.1 %</td>
</tr>
<tr>
<td>May 1\textsuperscript{st}, 2009 (DoY=121)</td>
<td>11.5 %</td>
<td>CHD @ 5cm 8.9 %</td>
<td>CHI @ 5cm 13.5 %</td>
<td>2.6 %</td>
<td>2.0 %</td>
</tr>
</tbody>
</table>

The error is 2.1 – 3.2 % on April 18\textsuperscript{th} and 2.0 – 2.6 % on May 1\textsuperscript{st}. Comparing the two results from the GRAJO field experiment it is clearly observed that the change in the soil moisture value recorded by the probe (5%) is also detected by the SMIGOL Reflectometer measurements, and the retrieval algorithm.
5.2.3.3 PALAU Field Experiment 2

5.2.3.3.1 Field Experiment Description

From March 2010 to November 2010 the SMIGOL-Reflectometer was deployed at Palau d'Anglesola, Lleida, Spain (41° 40' N, 0° 52' E), measuring a maize field during the whole growing cycle. The SMIGOL-Reflectometer was placed at 4.15 m height, with the antenna boresight pointing to the horizon (SE), and it was working with a solar panel · battery charger system that gave the instrument autonomy to measure in the middle of a farm field with very low maintenance requirements during the long field experiment.

![Image](a)
![Image](b)
![Image](c)
![Image](d)

Figure 5.19 SMIGOL-Reflectometer measuring the different growth stages of maize at Palau d'Anglesola, Lleida, Spain: (a) 10th May, 2010, \( h_{veg} = 12 \) cm, (b) 3rd July, 2010, \( h_{veg} = 210 \) cm, (c) 18th September, 2010, \( h_{veg} = 280 \) cm, and, (d) 30th October, 2010, harvested.

Figure 5.19 shows some pictures taken along the Palau field experiment 2. The ground-truth data for vegetation height was weekly measured from 10 random measures, and the soil moisture was measured using two ECH2O soil moisture probes [90], at the same time as the SMIGOL-Reflectometer measurements.

Figure 5.20 shows the location in the maize field of the SMIGOL-Reflectometer (white square mark), and the two ECH2O soil moisture
probes (probe 1 corresponds to the orange dot mark and probe 2 corresponds to the yellow one).

Figure 5.20 SMIGOL-Reflectometer position in the maize field, with the soil moisture probes location.

5.2.3.3.2 Maize-Covered Soil Measurements for Soil Moisture and Vegetation Height Retrieval.

The retrieval algorithm has been applied to the measurements, first the topography retrieval and secondly the vegetation height retrieval.

Figure 5.21 Ground-truth measured for maize height versus retrieved maize height during the field experiment.

Figure 5.21 shows the maize height computed by applying the retrieval algorithm to the SMIGOL-Reflectometer measurements in contrast to the in-situ measured ground-truth for the same days. The agreement is even better with a Pearson correlation coefficient $\rho = 99.7 \%$ and a coefficient of determination $R^2 = 99.5 \%$. Recall that the main descriptors used are
described in Appendix 1, from eqn. (A.1) to eqn. (A.5). Note that these values are even higher than for the wheat and barley fields, which suggests that the model is performing even better for the maize field (more densely packed vegetation). The retrieved values using the SMIGOL Reflectometer measurements are highly correlated to the maize growth and, despite the dispersion in the measurements due to the non-homogeneity of the maize plants height, the mean value agrees very well with the ground truth.

Figure 5.22 extends the result on Figure 5.21, summarizing all the information related to the maize growth.

![Figure 5.22 Maize height retrieved superimposed to the ground-truth.](image)

Figure 5.23 shows six soil moisture maps completed after applying the retrieval algorithms to the SMIGOL-Reflectometer measurements during different days. Two different soil moisture evolutions are shown:

- One is described in Figure 5.23a, b and c. These figures show that the irrigation occurred on Day of the Year (DoY) = 161 and the retrieved soil moisture was mostly around 32 %. Then, it can be easily seen that 4 days after the irrigation (DoY = 165) it became dryer (retrieved soil moisture value is 25 %), and 6 days after the irrigation (DoY = 167) the retrieved soil moisture is mostly around 22 %.

- The other one is described in Figure 5.23d, e and f. These figures show that the retrieved soil moisture was mostly around 17 % on DoY = 179 after 9 days from the previous irrigation, then on DoY = 181 the field was irrigated, and the soil moisture value increased to a value
around 30 %, but after 3 days the soil moisture had decreased again down to 25 %.

![Soil moisture retrieved maps for DoY: (a) 161 (field is firstly irrigated, SM probes = 34.56 %), (b) 165 (4 days after first irrigation, SM probes = 30.37 %), (c) 167 (6 days after first irrigation, SM probes = 23.43 %), (d) 179 (9 days after second irrigation, SM probes = 18.63 %), (e) 181 (third irrigation, SM probes = 35.57 %), and (f) 184 (3 days after third irrigation, SM probes = 29.5 %).](image)

Figure 5.23 Soil moisture retrieved maps for DoY: (a) 161 (field is firstly irrigated, SM probes = 34.56 %), (b) 165 (4 days after first irrigation, SM probes = 30.37 %), (c) 167 (6 days after first irrigation, SM probes = 23.43 %), (d) 179 (9 days after second irrigation, SM probes = 18.63 %), (e) 181 (third irrigation, SM probes = 35.57 %), and (f) 184 (3 days after third irrigation, SM probes = 29.5 %).

A more quantitative comparison between ground-truth and SMIGOL-Reflectometer measurements for Palau field experiment 2 has been performed processing 25 days of data including three irrigation events. Figure 5.24 and Table 5.2 summarize this more extended analysis. Figure 5.24a shows the comparison between the SMIGOL-Reflectometer soil moisture retrieved values and the soil moisture values measured at 5 cm and 20 cm depth using the ECH2O soil moisture probes. Figure 5.24b and c show the error of the SMIGOL-Reflectometer measurements with respect to the 5 cm depth probe and the 20 cm depth probe, respectively. By observing these two plots it can be seen that soil moisture sensing depth follows the soil moisture sensed by the probes located at 5 cm when fields are irrigated, but in some cases when soil dries the soil moisture sensed is also close to probes located to 20 cm depth. This is due to the fact that this type of soil is very homogeneous. Note that when the estimated soil moisture value has a
low error respect to 20 cm depth probe, it also has a low error respect to 5 cm depth probe, which demonstrates the homogeneous profile of the dry soils, when no rain or irrigation occurs, and a soil moisture sensing depth about 5 cm.

Figure 5.24 Soil moisture retrieval analysis: (a) Comparison between soil moisture retrieved and measured at 5 cm and 20 cm depth, (b) error respect to 5 cm depth probe, and (c) error respect 20 cm depth probe. Note at (b) and (c), dots represent the ground-truth values and bars indicate the errors.

Table 5.2 summarizes the values for soil moisture for these 14 days of data analysis. First column corresponds to the DoY, and second and third columns to the ECH2O soil moisture probes values obtained at 5 cm and 20 cm depth, respectively. The fourth column provides the SMIGOL-Reflectometer measurements, three soil moisture values that correspond to the three closest points inside the observed area to the ECH2O soil moisture probes. Finally the fifth and the sixth columns correspond to the computed
differences between the soil moisture values measured with the probes and the ones obtained from SMIGOL-Reflectometer, for the 5 cm depth probe and the 20 cm depth probe, respectively. The underlined DoYs correspond to the irrigation days. The one marked in bold letters denotes the smallest difference.

Table 5.2 Soil moisture ground-truth and retrieved values and differences between them. The three soil moisture values of the SMIGOL-Reflectometer measurements (4th column) correspond to the three closest values inside the observed area to the ECH2O soil moisture probes. DoY = 161, 170, and 181 correspond to days of irrigation and have the highest soil moisture values.

<table>
<thead>
<tr>
<th>DoY</th>
<th>Probe 1 (5 cm)</th>
<th>Probe 2 (20 cm)</th>
<th>SMIGOL-Reflect. Measurements</th>
<th>Error vs Probe 1</th>
<th>Error vs Probe 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>159</td>
<td>20%</td>
<td>24%</td>
<td>21.3%, 22.4%, 24.2%</td>
<td>[1.3 - 4.2]%</td>
<td>[0.2 - 2.7]%</td>
</tr>
<tr>
<td>161</td>
<td>35%</td>
<td>28%</td>
<td>33.7%, 34.1%, 35.9%</td>
<td>[0.9 - 1.3]%</td>
<td>[5.7 - 7.9]%</td>
</tr>
<tr>
<td>165</td>
<td>29%</td>
<td>27%</td>
<td>29.3%, 30.2%, 31.6%</td>
<td>[0.3 - 2.6]%</td>
<td>[2.3 - 4.6]%</td>
</tr>
<tr>
<td>167</td>
<td>26%</td>
<td>27%</td>
<td>22.7%, 23.0%, 24.6%</td>
<td>[1.4 - 3.3]%</td>
<td>[2.4 - 4.3]%</td>
</tr>
<tr>
<td>169</td>
<td>24%</td>
<td>27%</td>
<td>24.8%, 25.8%, 26.7%</td>
<td>[0.8 - 2.7]%</td>
<td>[0.2 - 1.7]%</td>
</tr>
<tr>
<td>170</td>
<td>37%</td>
<td>32%</td>
<td>35.6%, 36.5%, 36.9%</td>
<td>[0.1 - 1.4]%</td>
<td>[3.6 - 4.9]%</td>
</tr>
<tr>
<td>172</td>
<td>30%</td>
<td>29%</td>
<td>30.5%, 31.7%, 32.1%</td>
<td>[0.5 - 2.1]%</td>
<td>[1.5 - 3.0]%</td>
</tr>
<tr>
<td>174</td>
<td>26%</td>
<td>27%</td>
<td>24.3%, 24.9%, 25.0%</td>
<td>[1.0 - 1.7]%</td>
<td>[2.0 - 2.7]%</td>
</tr>
<tr>
<td>176</td>
<td>23%</td>
<td>24%</td>
<td>20.5%, 21.1%, 21.9%</td>
<td>[1.1 - 2.5]%</td>
<td>[2.1 - 3.5]%</td>
</tr>
<tr>
<td>177</td>
<td>24%</td>
<td>22%</td>
<td>21.2%, 21.4%, 21.8%</td>
<td>[2.2 - 2.8]%</td>
<td>[0.2 - 0.8]%</td>
</tr>
<tr>
<td>179</td>
<td>25%</td>
<td>21%</td>
<td>17.9%, 18.3%, 19.7%</td>
<td>[5.3 - 7.1]%</td>
<td>[1.3 - 3.1]%</td>
</tr>
<tr>
<td>181</td>
<td>37%</td>
<td>31%</td>
<td>34.8%, 35.7%, 36.2%</td>
<td>[0.8 - 2.2]%</td>
<td>[3.8 - 5.1]%</td>
</tr>
<tr>
<td>183</td>
<td>33%</td>
<td>29%</td>
<td>31.0%, 31.8%, 32.6%</td>
<td>[0.4 - 2.0]%</td>
<td>[2.0 - 3.6]%</td>
</tr>
<tr>
<td>184</td>
<td>29%</td>
<td>28%</td>
<td>28.9%, 29.4%, 30.2%</td>
<td>[0.1 - 1.2]%</td>
<td>[0.9 - 2.2]%</td>
</tr>
</tbody>
</table>

The differences between the SMIGOL-Reflectometer measurements and the probes are between 0.1 % and 8.0 %. Note that values in Table 1, agree with probe located at 5 cm with very low errors for all the 14 days. There is only one value with a high error on DoY 179, but it can be due to an error in the soil moisture probe lecture which in fact was supposed to have lower value because no rain or irrigation occurred between DoY 176 and 179. Also note, that when errors are low for probe located at 20 cm depth they are also lower than the probe located at 5 cm depth, which demonstrates the homogeneity of the soil in dry conditions.
5.3 Vegetation Water Content (VWC) Monitoring

5.3.1 Introduction

From the retrievals’ error obtained in previous section, it is demonstrated that assuming the typical vegetation water content (VWC) for the crop under study is a good approximation. Regarding to the nothes’ position (used to compute the vegetation height), recall that Figure 5.9 has been used for the wheat, barley and maize, being maize one of the most moisture plants. The results obtained imply that the VWC value used does not affect this retrieval. However, regarding to soil moisture retrieval, it has an error associated to VWC, which as seen from results in previous sections is low. For maize the error can be up to 8 % while for wheat or barley it didn’t go higher than 4 %. As the VWC of maize reaches higher values than the wheat or barley one, i.e. the VWC variation during the maize growth is larger, the approximation of the VWC to typical value is worst. Using the IPT and the SMIGOL-Reflectometer is not possible to split the effect of the VWC from the effect of the soil moisture. Here it is proposed a complementary technique to the IPT, also based on GNSS opportunity signals that taking simultaneous measurements can help to reduce the error in soil moisture retrievals.

The applicability of GNSS techniques to measure the attenuation and the impact of the presence of vegetation canopy on the GPS measurements has been addressed in previously published works [101], [102]. This study employs a simple GNSS technique that consists of measuring the GPS signals in open sky conditions and under vegetation. Then, comparing these measurements and computing the equivalent attenuation, information about the water content is inferred from the attenuation. In order to test and validate this technique, a field campaign was conducted during an entire seasonal cycle of deciduous trees from February to December 2010 of a walnut-tree area in Palau d'Anglesola, Lleida, Spain. Trees were selected instead of crop just for practical reasons: the ground-truth was need to be gathered weekly and farmers did not allow to cut maize, wheat or barley plants, but cutting a limited number of the tree’s leaves had no impact on the tree fruit production.
Two replicas of the instrument, denoted as A and B, composed by a RHCP antenna, a GPS receiver, a microcontroller, and a data-storage device have been deployed under the vegetation cover, and in open sky conditions, simultaneously performing power measurements, as shown in Figure 5.25.

Figure 5.25 shows instruments A and B measuring the power of the received GPS signals. The two instruments are identical and have identical antennas with identical orientations.

The received powers by the two instruments are used to compute the attenuation due to the vegetation, as follows:

\[
\frac{P_A}{P_B} = \frac{|L \cdot E_A|^2}{|E_B|^2} = \frac{|L|^2 |E_{0_A} e^{j\phi_A}|^2}{|E_{0_B} e^{j\phi_B}|^2} = |L|^2 = L^2, \tag{5.2}
\]

where \( P_A \) and \( P_B \) are the powers received by instruments A and B, respectively, \( L \) is the attenuation due to the vegetation, \( E_{0_A} \) is the amplitude of the incident electric field (same for both instruments, since the
attenuation has already been taken into account by using the factor $L$, and $\phi_A$ and $\phi_B$ are the phases of the incident electric field for each instrument.

Then the attenuation is obtained in a straightforward way from:

$$ L = \sqrt{\frac{P_A}{P_B}}. $$

(5.3)

Then, using the relationship [103]:

$$ L = e^{\tau \cos(\theta_{inc})}, $$

(5.4)

the vegetation opacity ($\tau$) can be obtained from the computed $L$:

$$ \tau = \ln(L) \cdot \cos(\theta_{inc}). $$

(5.5)

Furthermore the relationship between $\tau$ and the Vegetation Water Content (VWC), [104], is:

$$ \tau = b \cdot VWC, $$

(5.6)

where $b$ is a factor that depends on the vegetation type.

In order to estimate the $b$-factor for walnut trees, a field experiment has been performed to test the concept and gather ground-truth data on the vegetation water content to relate the measured power difference, or attenuation, to the vegetation water content.

### 5.3.3 Walnut-Tree Field Experiment

The Walnut-tree field experiment has been performed at Palau d'Anglesola, Lleida, Spain. Two instrument replicas were located in two different fields, a walnut-tree field (41º39'N, 0º51'E) to measure under vegetation and a bare field (41º40'N, 0º53'E) to measure in open sky.

Measurements were made weekly from February to December 2010 (Figure 5.26).
Figure 5.26 Walnut-tree field experiment. Evolution of walnut trees during the entire field experiment during 2010.

Figure 5.26 shows some photographs to illustrate the evolution of the walnut trees during the field experiment. The most important change in the walnut water content is due to the evolution of the leaves, which has been carefully observed, as shown in Figure 5.27.
Figure 5.27 Walnut-tree field experiment. The evolution of walnut-tree leaves during the entire field experiment.

Figure 5.27 shows the evolution of the leaves as a function of time. The whole birth-growth-death process has been monitored, not only in terms of measurements, but also in terms of ground-truth data, which was gathered weekly.
The leaves' water content is then the main parameter to be studied. The following equations based on previous work [105] provide the main relationships:

\[
WC_{\text{leaf}} = LAI \cdot EW_{T\text{leaf}} \cdot d_w, \tag{5.7}
\]

where the \(WC_{\text{leaf}}\) is the Water Content of the leaves, \(LAI\) is the Leaf Area Index, \(d_w\) is the mass density of water (\(d_w=1000\) kg/m^3).

\[
LAI = A_{\text{leaf}} \cdot \eta, \tag{5.8}
\]

where \(A_{\text{leaf}}\) is the total area of the leaves (for circular leaves \(A_{\text{leaf}} = N_{\text{leaves}} \cdot \pi \cdot (r_{\text{leaf}})^2\), where \(r_{\text{leaf}}\) is the mean radius of the leaves and \(N_{\text{leaves}}\) is the total number of leaves in the tree), and \(\eta\) is the plant density per unit area. \(LAI\) is a unitless quantity. The Equivalent Water Thickness of the leaves (\(EWT\)) is computed as:

\[
EWT_{\text{leaf}} = \frac{(FWT_{\text{leaf}} - DWT_{\text{leaf}})}{d_w A_{\text{leaf}}}, \tag{5.9}
\]

where \(FWT_{\text{leaf}}\) is the fresh weight of the leaves and \(DWT_{\text{leaf}}\) is the dry weight of the leaves.

In order to provide accurate ground-truth measurements, three stems with 19 leaves (\(N_{\text{samples}}\)) have been weighed every week when collected (\(FWT_{\text{leaf}}\)), and again after drying (\(DWT_{\text{leaf}}\)). The difference between these two weights is denoted as \(\Delta W_{\text{GT}}\). Then, the difference between \(FWT_{\text{leaf}}\) and \(DWT_{\text{leaf}}\) can be found as:

\[
FWT_{\text{leaf}} - DWT_{\text{leaf}} = \frac{N_{\text{leaves}} \cdot \Delta W_{\text{GT}}}{N_{\text{samples}}}. \tag{5.10}
\]

This equation extrapolates the ground-truth measurements to the whole crown and to do that it is necessary to consider previous works [106], [107], which describe the basic structure of 20 year-old walnut trees based on 3-D digitizing techniques. A fruit walnut tree, similar to the ones in the field experiment, has about \(N_{\text{leaves}} = 16300\) leaves and the leaves density is \(= 0.0189/m^2\).

Applying eqns. (5.7) – (5.10), the ground-truth water content for the leaves has been computed and is summarized in Figure 5.28.
Figure 5.28 Leaves’ water content (LWC) ground-truth measured for the whole cycle of the field experiment.

Figure 5.28 shows the water content in kg/m² of the leaves for the whole cycle of the walnut-tree as a function of time, from birth to death.

Since winds were below 2-3 m/s during the entire field experiment, for the GPS frequency it can be assumed that decorrelation times associated to the movement of the leaves are long enough so that they do not affect the performance of the GNSS receiver. Then, the acquired measurements can be processed using the procedure described in subsection 5.3.2. However, if the winds had been stronger they would have to have been taken into account [108], [109]. From the powers measured by the two instruments, the equivalent vegetation opacity is computed. Figure 5.29 summarizes some of the results.

As satellites move across the sky, their positions in terms of elevation ($\theta_{elev}$) and azimuth ($\phi$) vary as a function of time as well, and a map is retrieved by simple observation. Then, Figure 5.29 shows the vegetation opacity maps in $\xi$-$\eta$ coordinates ($\xi \triangleq \sin(\theta_{elev}) \cdot \cos(\phi), \eta \triangleq \sin(\theta_{elev}) \cdot \sin(\phi)$). Each map shows 12 hours of measurements.
### 5.3.4 Results

From the measured maps based on tree composition, the most suitable area has been selected. It is an homogeneous area in terms of leaf density and well-covered by satellites. This area under study has been analyzed by annuli (the area between two concentric circles) of 5° steps in elevation angle.

First, the measurements have been stored as vectors for each one of these coronas. This means that for each corona (a narrow elevation angle range) one τ-vector is obtained, where each sample of the vector corresponds to measurements on a different day. Then, the relationship between the measurements and ground truth can be studied in order to analyze the correlation and the goodness of the fit between them. The main descriptors used: Pearson correlation coefficient (r), probability of error in the computation of the Pearson correlation coefficient (Pe), coefficient of determination (R²) and root mean square (RMS), are described in Appendix 1, from Eqn. (A.1) to Eqn. (A.5).

These parameters are summarized in Figure 5.30.

![Figure 5.30](image)

**Figure 5.30** Fitting descriptors. Goodness of the fit between τ retrieved and the LWC measured as a function of the elevation angle.

As can be seen in Figure 5.30 the highest correlation coincides with the lowest probability of error, with high R² values, more likely to be a line. The lowest RMS error was in the annulus between 55° and 70° elevation angle (for 60° elevation angle r = 93 %, with a Pe almost 0, an R² = 79%, and RMS error of 3%). This result is consistent with the fact that at these elevation angles the GPS signals pass through the crown, where the composition of the leaves is more uniform than that of the trunk and branches. At lower and higher elevation angles the measurements are decorrelated from the
ground-truth data due to the effect of branches and trunks and the effect of clear sky, respectively.

Then, from Figure 5.30, the results discussed below focus only on the range 55°-70° of elevation angles. Figure 5.31 shows the opacity of the leaves versus the water content of the leaves (WC_{leaf}), and the associated regression lines. Note that the computed parameter $r$ is shown in each plot title.

![Figure 5.31](image)

Figure 5.31 $\tau$ retrieved versus the LWC measured for a) $\theta_{\text{elev}} = 70^\circ$, b) $\theta_{\text{elev}} = 65^\circ$, c) $\theta_{\text{elev}} = 60^\circ$, d) $\theta_{\text{elev}} = 55^\circ$.

The $b$-factor that relates the opacity of the leaves to their water content can be computed from the results in Figure 5.31 and eqn. (5.6). Figure 5.31 shows the resulting $b$-factor.
Figure 5.32 Computed b-factor of the leaves as a function of the elevation angle.

As can be seen in Figure 5.32, the b-factor depends on the incidence angle since the leaves in this range of elevation angles (55°-70°) are not homogeneous. The value for the leaves in the most homogeneous area is around 0.82 – 0.88. Since the highest correlation is computed for 60°, the b-factor selected to compute the retrieval in Figure 5.33 is 0.81, corresponding to 60° elevation angle.

Figure 5.33 LWC retrieved applying the b-factor obtained for the highest correlation ($\theta_{elev} = 60^\circ$) compared to the ground-truth data measured (green line and dots) for a) $\theta_{elev} = 70^\circ$, b) $\theta_{elev} = 65^\circ$, c) $\theta_{elev} = 60^\circ$, d) $\theta_{elev} = 55^\circ$. 

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As can be seen in Figure 5.33 the inhomogeneity of an area of leaves affects the retrieval, but when the area observed has plenty of leaves, the retrieval is more accurate.

### 5.4 Conclusions

This chapter, based on the SMIGOL-Reflectometer ground-based instrument measurements, extends the study performed in Chapter 4 over bare soils to more complex land surfaces, including the effects of vegetation cover. New retrieval algorithms have been developed and topography, vegetation height, and soil moisture retrievals over vegetation-covered soils have been validated using these experimental data.

In order to obtain good topography retrievals (RMSE = 27 cm) it is necessary to average measurements acquired during several days, and several satellite passages, assuming that all points inside the glistening zone have the same height. Furthermore, in order to improve results, other antennas with better antenna diagrams can be used avoiding the effects caused for the current diagram at 45º incidence angle, where attenuation that received powers suffers provide poor quality measurements.

Three types of crops have been studied to retrieve both the vegetation height and soil moisture: wheat, barley and maize:

- Regarding to vegetation height retrieval, the results for barley and wheat are quite satisfactory: RMSE = 3 – 5 cm, and the $\rho = 89\% – 97\%$. In the case of maize, a taller and denser type of vegetation the results are also good: RMSE = 6.3 cm and $\rho = 99.74\%$.

- Regarding to soil moisture retrieval over vegetation-covered soils, the results agree with the soil moisture measured by the different probes. In the case of wheat and barley fields, changes in soil moisture detected by probes are also detected by the SMIGOL system, with 2 – 5 % error. In the case of maize, despite the high vegetation thickness, the changes in soil moisture that are detected by probes are also detected by the SMIGOL instrument. Three irrigation-drying cycles of the observed field have been monitored and analyzed to prove the SMIGOL capability of detecting soil moisture variations with and error lower than 8 %.

Then, the IPT has been demonstrated to be a very useful tool to retrieve land geophysical parameters. The SMIGOL-Reflectometer, the instrument
implementing the IPT, has allowed the measurement over different areas providing the necessary information for testing the IPT and the developed algorithms, giving as a result, these good retrievals of topography, soil moisture and vegetation height monitoring.

It is difficult to isolate the vegetation water content (VWC) effect when performing the vegetation height and soil moisture retrievals. Taking into account the good results obtained for vegetation height and soil moisture retrievals, it is deduced that the VWC has a very weak influence on these retrieval. A GNSS technique has been proposed and used to retrieve the VWC. The experiment has been performed on a walnut-tree field and the VWC, in this case leaf water content (LWC) has been studied. This was accomplished by computing the differential attenuation of the signals received by two receivers (open sky and under vegetation). Then, the \( b \)-factor has been computed to relate the vegetation opacity, \( \tau \), and the LWC, as shown in Eqn. (5.11), obtaining 0.81 for 60º elevation angle. If leaves are the dominant part in the plant structure, one can approximate \( LWC \approx VWC \), but this is not the case of a tree structure. It has been demonstrated that \( \tau \) depends not only on the type of vegetation (different for trunks and branches), but also on the homogeneity of the observed area. In order to consider the whole range of measurements it would be necessary to get a more accurate ground-truth, not only for leaves, but also for the trunk and branches, and then compute the whole walnut-tree equivalent water content as a function of elevation angle, as in the following.

\[
\tau(\theta_{\text{elev}}) = \left\{ \begin{array}{l}
(b_{\text{leaves}} \cdot \text{WC}_{\text{leaves}}) \cdot \alpha_{\text{leaves}}(\theta_{\text{elev}}) + \\
... + (b_{\text{trunk}} \cdot \text{WC}_{\text{trunk}}) \cdot \alpha_{\text{trunk}}(\theta_{\text{elev}}) + \\
... + (b_{\text{branches}} \cdot \text{WC}_{\text{branches}}) \cdot \alpha_{\text{branches}}(\theta_{\text{elev}}) \end{array} \right\} = \cdots
\]

\[
... = \sum_{i=1}^{3} b_i \cdot \text{WC}_i \cdot \alpha_i(\theta_{\text{elev}}),
\]

(5.11)

where \( b \) is the \( b \)-factor for each part, \( \text{WC} \) is the water content for each part, and \( \alpha \) is the fraction of each part for the elevation angle observed.

The main purpose of the study was to show the potential of GNSS techniques to retrieve the water content of the walnut-tree leaves. This has provided a first approximation to infer the \( b \)-factor of the leaves and shows good agreement between the GNSS measurements and the ground-truth data of the leaves (\( r = 93 \% \), with a \( P_e \) almost 0, an \( R^2 = 79\% \), and rms error of 3%).

Is it possible to implement the SMIGOL-Reflectometer over a space platform? It could be possible but it would be necessary to change the configuration. The space-borne configuration should consist of:
• an up-looking vertical polarized antenna with a variable delay line to measure the direct GPS signal, and

• a down-looking vertical polarized antenna to measure the reflected over the Earth surface GPS signal.

Thanks to the variable delay line, both signals are coherently added after the antennas, not in the antenna itself as in the ground-base version. Then, combining direct and reflected measurements the interference powers are obtained and most of the present theory can be applied.
Use of GNSS-R for Snow Monitoring

This chapter focuses on the study of snow-covered soils from the SMIGOL-Reflectometer ground-based instrument using the IPT. The snow effects are analyzed, and an algorithm for this type of surfaces has been developed. A long term field experiment, the Monitoring Of Snow using SMIGOL-R (MOSS) field experiment, was performed at the Val d'Aran to test the IPT and the retrieval algorithms in the presence of snow.
6.1 Introduction

The Interference Pattern Technique (IPT) has been developed and tested during almost 3 years to retrieve land geophysical parameters. During this time the main theoretical aspects have been implemented into retrieval algorithms as shown in chapters 4 and 5: soil moisture, topography and vegetation height. Based on the experience gained on vegetation height retrievals, and realizing that the vegetation layer could be modeled by a simple model consisting of a single layer with a specific dielectric constant, the concept was extended to the observation of snow-covered surfaces. This chapter presents the measurements of the instrument located at a meteorological station in the Pyrenees during the winter season and the snow thickness retrievals.

6.2 Theoretical Aspects

As mentioned in previous chapters, the IPT consists mainly of the measurement of the interference pattern between the GPS direct and reflected signals (the interference power), after they impinge over the ensemble soil surface and snow layer. The received power can be expressed as a function of the elevation angle due to the fact that satellites are moving and changing their position (elevation and azimuth coordinates). The interference power has an oscillating pattern in which notches (minimum amplitude oscillations) are relevant points of information about the layer thickness (Figure 6.1).

![Figure 6.1 Theoretical interference powers considering a snow layer between the air and the soil of (a) 5 cm and (b) 40 cm thickness.](image)
As previously observed in Chapter 5, where the vegetation height was directly linked to the number of notches and their positions in the interference power pattern, over a snow layer, the snow thickness can also be inferred from the number and position of the notches. Theoretical simulations like the ones in Figure 6.1 have been performed varying the snow thickness and monitoring the notch positions. Figure 6.2 summarizes the simulation results.

![Figure 6.2 Theoretical notch position evolution](image)

Figure 6.2 Theoretical evolution of notches. The notches position and the number of them (each black line defines the evolution of one notch) describe the snow thickness. The snow layer has been simulated considering a snow wetness volume of 2% and a snow density of 0.08 g/m³, [110].

From Figure 6.2 it can be seen that each black line (numbered from 1 to 9) corresponds to a different notch that moves to the left as snow thickness increases. Note that notches move to the left very fast with small changes in the snow thickness with a sensitivity between 0.75°/cm and 1.35°/cm depending on the snow thickness. For example, if the snow thickness is constant to 20 cm, the interference power will show a notch at 16.5° of elevation angle, due to the evolution of notch 2, and a notch at 37° of elevation angle, due to the evolution of notch 3, red arrows in Figure 6.2. But if snow thickness decreases just 10 cm, in some part of the observed field, an extra notch will appear at 34° elevation angle, corresponding to the evolution of notch 2 (green arrow in Figure 6.2). So in that non-homogeneous assumption the interference powers will present 3 notches, two of them due to notch number 2 and one due to notch number 3. Furthermore, snow thickness is a parameter that has a high variability depending on the surface's topography, and often it cannot be assumed to be the same in the whole field. In some parts of the same scenario the snow can
accumulate and have a thickness of 50 cm while in other parts the thickness could just be 10 cm, depending on the local topography, even in a very small piece of surface. It is then clear that notches are the most sensitive part of the interference powers to the snow thickness, but the high sensibility to topography and snow thickness variability make very difficult to apply a retrieval based only on the position and the number of notches to infer a single value of snow thickness.

The best way to proceed is to calibrate the measurements and develop a semi-empirical procedure. The general scheme for the retrieval algorithm is shown in Figure 6.3.

![Diagram](image)

**Figure 6.3 General scheme for the algorithm when observing a snow-covered surface.**

The topography retrieval is applied as explained in previous Chapters 4 and 5. The final data merging is performed as in [89]. The snow thickness retrieval is explained using Figure 6.4, where the main steps for the algorithm are summarized.
The algorithm starts from a known and low snow thickness given by an ultrasonic sensor. Then, for the same day of measurements, the algorithm selects the notches in the received powers and computes the snow thickness based on Figure 6.2. Probably more than one solution can be valid for that number and position of the notches. Therefore, in order to solve the uncertainty, the algorithm computes the minimum error respect to the ground-truth (5 cm) and selects a unique solution. This solution and the notches information are stored for each one of the satellites to be used as calibration measurements.

Then the evolution of notches with respect to the calibration measurements is tracked. The algorithm tracks the notch movement, considering an increase or a decrease, and gets all the different solutions. The criterion to solve the uncertainty when processing the tracked measurements has been stated to be that snow falling affects all the surface, so that the increase or decrease of snow thickness is supposed to have the same trend. This eliminates some solutions, but still gives more than one solution.

Finally the ground-truth variation respect to the previous day helps to select the right increment and the most probable solution is selected (previously obtained from Figure 6.2). If the algorithm works, at the beginning the snow
cover is more or less constant but when increasing the snow thickness layer, some dispersion must be observed in the field. Although all the surface must show the increase or decrease as ground-truth detects, some parts of the field will accumulate more or less snow.

6.3 MOSS Field Experiment

In order to test the theoretical considerations, the Monitoring Of Snow using SMIGOL-R (MOSS) field experiment was performed at Comalada mountains. The SMIGOL-Reflectometer was located in a meteorological station at the Pla de Beret, Vall d’Aran, Lleida, Spain. The Figure 6.5 shows a Google maps’ image with the experiment exact location.

Figure 6.5 The measurements site at Pla de Beret, Vall d’Aran, Lleida, Spain (42°42’44”N, 0°56’22”E).

The SMIGOL-Reflectometer was installed on November 5th, 2010 into the meteorological station pole and it was there until the end of the snow season in May 2011 to measure the variations of the snow thickness. Figure 6.6 shows some pictures of the site and the SMIGOL-Reflectometer at Comalada.
Figure 6.6 Field experiment at Comalada mountains, Pla de Beret, Vall d'Aran (Lleida, Spain): (a) and (b) field of view of the instrument, and (c) and (d) SMIGOL-Reflectometer mounted in the pole of the meteorological station.

This MOSS field experiment was conducted in cooperation with the Institut Geològic de Catalunya and the Consell General d'Aran, located at Vielha, Val d’Aran, who provided the permits to install the SMIGOL-Reflectometer at the meteorological station, and the ground-truth data for the snow thickness during the whole experiment. Figure 3 shows the ground-truth available data from DoY = 307 (November, 5th, 2010) to DoY = 417 (February, 17th, 2011).

Figure 6.7 Snow thickness ground-truth data, provided by the the Institut Geològic de Catalunya and the Consell General d’Aran, located at Vielha, Val d’Aran. Ground-truth measured daily with an ultrasonic sensor installed in the same meteorological station.
The ambient temperature was expected to go under -15°C, so that the SMIGOL-Reflectometer was rebuilt in order to be operational at these low temperatures. The main difference with respect the standard version of the SMIGOL-Reflectometer is the external box, which was selected to be resistant to low temperatures, and the batteries used. The batteries were selected to be Lead-Acid batteries instead of Li+ batteries because Lead-Acid batteries work down to -40 °C. All the other components, receiver, dataloggers, PIC, amplifiers kept working down to -40°C by manufacturer's specifications.

6.4 Results

The SMIGOL-Reflectometer measurements have been processed and the algorithm (Figure 6.4) that computes the equivalent snow thickness at notch positions has been applied. Figure 6.8 shows the measured interference powers of three satellites and the corresponding retrieved interference powers after applying the retrieval algorithm over snow-covered surfaces (topography and snow height).

Figure 6.8 Measured interference powers compared to simulated interference powers, after applying the algorithm for retrieval when measuring snow-covered surfaces, for different satellites: a) SV 13, b) SV 16 and c) SV 23.
As it can be seen in Figure 6.8 the oscillations of the retrieved powers match well the oscillations of the measured interference powers, in terms of location of the maxima and minima. Furthermore the notch positions of the theoretical interference powers obtained from algorithm also match the notch positions of the measured interference powers. The mean power level is not adjusted, but it is simply the antenna gain term, not included in the simulation.

The algorithm has been applied from November 10th 2011 (DoY = 312) to the end and several maps have been retrieved. Figure 6.9 and Figure 6.10 show some of those maps.

The maps in Figure 6.9 and Figure 6.10 have been performed using the information from the different notches in the measured interference powers. So that, the maps are composed by spots, each spot corresponding to a snow thickness value retrieved from a particular notch. As it can be seen from these two figures the snow thickness retrieved shows the increasing and decreasing behavior as reported by the ground-truth.

![Figure 6.9 Snow thickness maps retrieved for DoYs 312, 330, 348 and 360.](image-url)
Figure 6.10 Snow thickness maps retrieved for DoYs 372, 384, 402 and 414.

Figure 6.11 shows some scatter plots of the snow retrieved at different areas of the field experiment versus the ground-truth.

As it can be seen, the correlation between retrievals and ground-truth at different areas is high, but there is some dispersion due to the different behavior of the snow at these different areas. The snow behaves differently depending on many factors. When it snows, some parts accumulate more snow than others, or some parts keep the snow during longer periods of time than others. Therefore Figure 6.11 shows the trend of snow being similar to the ground-truth values (high Pearson correlation coefficient, $\rho \approx 91\%$) and the expected dispersion (determination coefficient, $R^2 \approx 85\%$).
6.5 Conclusions

Due to the variability of the snow accumulation in the scenarios considered in this chapter (a mountain), the algorithm previously used, based on the inspection of notches (in terms of positions and the number of them) cannot be used. Therefore, a new semi-empirical algorithm, but more realistic in terms of applicability, has been implemented and tested in the MOSS field experiment, a long (~ 4 months) field experiment, retrieving snow thickness maps. During all this experiment the instrument operated autonomously, without human intervention, and in very hard meteorological conditions.

From the MOSS field experiment measurements and the algorithm implemented good results have been achieved, but also some aspects have been learnt about snow-covered surfaces:

- Due to the high variability of the field and the high number of notches that should be detected on the interference powers, the
SMIGOL-Reflectometer should be located at a higher position. As commented in previous chapters, as higher is the instrument location, faster is the speed of the oscillations. Then, the interference power envelope would be better defined and the notches’ detection would be easier and less sensitive to localization errors.

- Due to the low sensitivity (~1°/cm in mean) the algorithm based on notches gives more than one solution for the detected notch positions. To solve this uncertainty it is necessary to calibrate the measurements at the beginning of the experiment (for 5 cm ground-truth) and follow the snow thickness increase or decreases (weather depending, not predictable) using the measurement of an ultrasonic sensor. Then it assumes that in mean the observed area will increase or decrease following the ground-truth trend. So that, it is a semi-empirical algorithm (ground-truth dependent) that generates a snow-thickness map of the observed area. Note that although being ground-truth dependent the maps obtained show variability on the snow retrieval. When applying the algorithm although more than one solution is given only these solutions are possible, and the one selected is the one that in mean has a similar increase or decrease to the ground-truth.
This chapter makes use of the same GNSS-R techniques as in Chapter 4 and 5. After analysing the effects of the geophysical parameters on the interference patterns over land, some similarities with other surfaces as the ones called inland-waters, are easily found. This chapter shows the theoretical aspects and the GNSS-R Observations over Inland-water Surfaces (GOIS) field experiment performed to retrieve water level over reservoirs.
7.1 Theoretical Aspects

In [51] and [111] the classical altimetry approach with GNSS-R techniques was used for water level monitoring. Here the IPT is applied to perform a similar study. As explained before, the IPT consists of the simultaneous measurement of the direct GPS signal and the reflected one over the surface, which are coherently added at the receiving antenna (Figure 7.1).

![Diagram of SMIGOL-Reflectometer measuring over water while implementing the IPT.](image)

Due to the satellites’ movement, each sample corresponds to a different elevation angle of the GPS satellite position, so at the end the received power is observed as a function of the elevation angle. In Chapter 5 and [39] it was proven that over land surfaces, since the IPT is sensitive to phase differences, it is sensitive to the surface topography, as well. Indeed, a variation of the surface height can be translated into a variation in the height of the measurement instrument. This result is now directly translated to water surfaces in which same effect is observed: if the surface level of the water changes the instrument height with respect to the observed surface changes and it affects directly to the measurements. Figure 7.2 shows this effect on the received interference powers.
From Figure 7.2 it can be seen that when the instrument is closest to the surface the speed of the oscillations in terms of elevation angle is slower than when the instrument is at a higher height.

The algorithm developed for the water level retrieval splits the interference powers into windows containing one minimum and one maximum and computes the distance between them. Then, using an iterative process the corresponding instrument heights to these distances are determined. Finally, by subtracting the initial instrument height it is possible to monitor the variations of the water level.

### 7.2 The GNSS-R Observations over Inland-water Surfaces (GOIS) Field Experiment.

In order to test the theoretical considerations a field experiment has been performed at Palau d'Anglesola, Lleida, Spain, by deploying the instrument SMIGOL-Reflectometer on the shore line of a water reservoir, 41°40'12.22"N, 0°52'31.02"E. This field experiment has been named as GNSS-R Observations over Inland-water Surfaces (GOIS) field experiment. Figure 7.3 shows a Google map with the location of the instrument and the size of the reservoir.
Figure 7.3 The SMIGOL-Reflectometer location within the measurement site (41°40'12.22"N, 0°52'31.02"E) and the size of the water reservoir (181 m x 107 m).

Figure 7.4 shows two images of the instrument measuring in the reservoir.

Figure 7.4 SMIGOL-Reflectometer measuring at a water reservoir: (a) measurement emplacement and (b) instrument field of view.

The instrument was deployed into the measurement site two different days split in time to ensure that the water level of the reservoir had changed. The first measurements took place on October 30th, 2010 (Day of the Year (DoY) 303), and the ground-truth for the water level measured was 2.14 m with respect to the antenna phase center of the instrument, and the second measurements took place on December, 10th, 2010 (DoY 344), and the
ground-truth for the water level measured was 3 m. The ground-truth was measured with a laser distance sensor DLR130K BOSCH (beam diameter of 2 mm at 3 m distance), and averaging at least 10 consecutive measurements to get an accuracy +/- 1.5 millimeters.

7.3 Results

The SMIGOL-Reflectometer measurements during the GOIS field experiment have been processed and the algorithm to compute the equivalent instrument height has been applied to the two days of measurements.

Figure 7.5, shows the measured powers of four satellites (two satellites per each DoY) and the corresponding retrieved powers after applying the water level retrieval.

![Figure 7.5](image)

Figure 7.5 The SMIGOL-Reflectometer measured powers and the retrieved powers by applying the algorithm for DoY = 303 (a) satellite 16 and (b) satellite 32, and for DoY = 344, (c) satellite 22 and (d) satellite 31.
As it can be seen in Figure 7.5 the local maxima and local minima of measured and retrieved powers are in the same elevation angles, so the algorithm works properly. Note that the retrieved power does not take into account the antenna features: neither the gain nor the efficiency. So that there is a difference of 10 dB between the mean level of the measured and the retrieved powers and the amplitude of the oscillations is bigger in the theoretically retrieved power. Table 7.1 and Table 7.2 summarize the most important retrieval parameters.

Table 7.1 Main results for the retrieval performed on DoY = 303. Ground-truth for water level is 2.140 m.

<table>
<thead>
<tr>
<th>SAT</th>
<th>Mean level retrieved</th>
<th>σ</th>
<th>RMSE</th>
<th>Δh</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>2.133 m</td>
<td>0.6 cm</td>
<td>0.9 cm</td>
<td>0.7 cm</td>
</tr>
<tr>
<td>32</td>
<td>2.127 m</td>
<td>0.6 cm</td>
<td>1.4 cm</td>
<td>1.3 cm</td>
</tr>
</tbody>
</table>

Table 7.2 Main results for the retrieval performed on DoY = 344. Ground-truth for water level is 3.000 m.

<table>
<thead>
<tr>
<th>SAT</th>
<th>Mean level retrieved</th>
<th>σ</th>
<th>RMSE</th>
<th>Δh</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>2.982 m</td>
<td>6.7 cm</td>
<td>8.8 cm</td>
<td>1.8 cm</td>
</tr>
<tr>
<td>31</td>
<td>2.991 m</td>
<td>0.9 cm</td>
<td>1.3 cm</td>
<td>0.9 cm</td>
</tr>
</tbody>
</table>

As it can be seen in the results shown in Table 7.1 and Table 7.2, the instrument measurements can detect the water level changes from DoY 303 to DoY = 344. Note that mean level refers to the distance from the phase center of the antenna to the water top. So as higher is the mean level retrieved less is the water amount in the reservoir. In order to determine, the minimum level variation that can be monitored by the IPT and the SMIGOL-Reflectometer has been studied by artificially varying the instrument height. Table 7.3 summarizes the results obtained.

Table 7.3 IPT sensitivity study performed on DoY = 344.

<table>
<thead>
<tr>
<th>Ground truth</th>
<th>SAT</th>
<th>Mean level retrieved</th>
<th>Δh</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.000 m</td>
<td>22</td>
<td>2.982 m</td>
<td>1.8 cm</td>
</tr>
<tr>
<td></td>
<td>31</td>
<td>2.991 m</td>
<td>0.9 cm</td>
</tr>
<tr>
<td>3.006 m</td>
<td>28</td>
<td>2.997 m</td>
<td>0.9 cm</td>
</tr>
<tr>
<td>3.012 m</td>
<td>19</td>
<td>3.002 m</td>
<td>1.0 cm</td>
</tr>
<tr>
<td></td>
<td>23</td>
<td>3.003 m</td>
<td>0.9 cm</td>
</tr>
<tr>
<td>3.024 m</td>
<td>24</td>
<td>3.017 m</td>
<td>0.7 cm</td>
</tr>
<tr>
<td>3.036 m</td>
<td>13</td>
<td>3.022 m</td>
<td>1.4 cm</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>3.028 m</td>
<td>0.8 cm</td>
</tr>
<tr>
<td>3.048 m</td>
<td>17</td>
<td>3.052 m</td>
<td>0.5 cm</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>3.032 m</td>
<td>1.6 cm</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>3.037 m</td>
<td>1.1 cm</td>
</tr>
</tbody>
</table>
In Figure 7.6 the results on Table 7.3 are presented in a graphical form. The main parameters that describe the fitting between measured ground-truth and retrieved water level are shown in the title and the caption of Figure 7.6. The computed Pearson correlation coefficient (\( \rho \)) between retrievals and ground-truth is around 97% with a probability of error in its computation (Pe) of \( 1.33 \cdot 10^{-2} \). As Pe is less than 5%, the correlation given by \( \rho \) is trustable. The computed value for the determination coefficient of the statistic model (\( R^2 \)) is 93%, and that is describing the quality of the values to be a line and not a cloud of points, which is high.

![Graph showing water level retrieved vs ground-truth](image)

Figure 7.6 The water level retrieved vs the ground-truth measured. \( \rho = 97\% \), Pe = \( 1.33 \cdot 10^{-2} \) and \( R^2 = 93\% \).

### 7.4 Conclusions

The Interference Pattern Technique and the SMIGOL-Reflectometer have also proven to be powerful tools to monitor the water level of reservoirs and lakes. The developed algorithm, based on the speed of the oscillations of the interference powers, retrieves the water level with centimeter accuracy.
This chapter is the result of the Ph.D. Stay at the Earth System Research Laboratory (ERSL) in the National Oceanographic and Atmospheric Administration (NOAA), Boulder, Colorado, USA, during March – July, 2011. The Delay Doppler Maps (DDM) obtained as a result of processing the data collected by the GPS software receiver onboard the NOAA Gulfstream-IV jet aircraft are analyzed. Thereafter, the DDMs are used to retrieve surface wind speed using several different algorithms. In contrast to previous works where winds were retrieved by fitting the theoretically modeled curves into measured correlation waveforms, here no model is used. Instead, the DDMs characteristics are linked to the winds obtained by simultaneous GPS dropsonde measurements.
8.1 Introduction

The GNSS-R technique as a tool for remote sensing has been in a progress since it was first suggested for altimetric applications by Martin-Neira [29]. During the last decade a number of airborne experiments have been performed to study feasibility of GNSS reflection technique to measure ocean surface winds [20], [23], [112], [114]. Significant progress was made during this period in designing and testing various types of GPS reflection receivers which are appropriate to be seen as GPS multistatic radars [15], [35], [65] and [115].

The reflected signal originates from the ocean surface area, known as a glistening zone which extent depends on wind speed. Different portions of the glistening zone contribute into the total received signal according to different time delays and Doppler frequencies around the specular point [20], [113], forming a Delay-Doppler Map (DDM) (see Figure 8.1).

![Figure 8.1 Geometry of the GPS signals scattered over the ocean surface [116].](image)

Therefore, the shape of the DDM can characterize the surface roughness conditions (wave slopes RMS): the higher is the wind speed the larger is the surface roughness, and the wider is the DDM in the time-delay/frequency domain. The most obvious and direct way to measure sea roughness using GPS reflected signals is to produce the 1-D delay waveform which is the
correlation power for a fixed center Doppler frequency. Analysis of the behavior of the trailing edge depending on the wind speed was presented in a number of papers [23], [34] and [112]. The effect of wind direction on waveforms is more subtle, not much works were done in that direction [112]. The delay waveform is, in fact, a result of integration of the DDM in Doppler domain over the entire expanse of the DDM, or over only a part of it, depending on the coherent integration time. At the same time, the DDM itself can be used for measuring surface roughness, or wind speed [37], [42], and [45].

In order to investigate the latter option in more detail an airborne experiment with the CU multistatic GPS software radar was conducted in January 2010 over the Northern Pacific Ocean. Overall, 26 hours of reflection data were obtained during four flights. As a result of processing of the I and Q data collected by the GPS software receiver onboard the NOAA Gulfstream-IV jet aircraft a set of the DDMs of the GPS reflected signal from several available satellites were obtained. These maps were used to retrieve surface wind speeds employing several different algorithms. The retrieval algorithms did not use any theoretical models of the signal scattering but rather relied on wind speed calibration and validation opportunity provided by the dropsondes deployed from the same aircraft.

**8.2 Theoretical Modeling of the Delay-Doppler Maps (DDM)**

Even though we do not use here any theoretical models of the DDM for the retrieval of the surface wind it is always helpful to have a general idea of how the DDM will look like for the conditions of the experiment. The first step in producing the DDM is despreading, or cross-correlating of the recorded signal’s I and Q data with a replica of the PRN code of the available GPS satellite for a set of different time lags and different carrier frequency offsets (see, e.g. [20], [113], [117]). This cross-correlation, $Y$, is achieved by integration of the product of the signal with the replica over the coherent integration time ($T_i$), short enough to preserve the coherence of the signal. The mean DDM is obtained by averaging a sufficiently large number of absolute value squared cross-correlations $|Y(\tau, f_d)|^2$. The simulations of the mean DDM follow a well-known bistatic equation model from [20] which describes the averaged correlation power of the reflected GPS signal at a given time delay $\delta \tau$ and at a given frequency offset $\delta f_d$ with respect to propagation time and Doppler frequency shift both associated with the nominal specular point on the ocean surface (Figure 8.1):
\( \langle |Y(\delta\tau, \delta f_d)|^2 \rangle = \cdots \)

\[ \ldots = \frac{T_t^2 P_T G_T L_{atm} L^2}{(4\pi)^3} \int \int \frac{G_{\delta}(\rho) \Lambda^2(\delta\tau - \tau(\rho)) |S(\delta f_d - f_d(\rho))|^2}{R_0^2(\rho) R^2(\rho)} \pi |\Gamma|^2 \cdot \frac{q^4(\rho)}{a^2(\rho)} \cdot P_{\delta} \left(-\frac{\delta L}{q^2}\right) \cdot d^2\rho, \quad (8.1) \]

Where:

- \( T_t \) is the coherent integration time,
- \( P_T G_T \) is the transmitter effective isotropic radiated power (ERIP),
- \( L_{atm} \) is the atmospheric attenuation,
- \( G_R \) is the receiver’s antenna gain.
- \( \Lambda \) is the PRN code correlation function defined as \( \Lambda(\tau) = 1 - |\tau|/\tau_c \) if \(|\tau|/\tau_c < 1\) and 0 elsewhere, with \( \tau_c \) being the length of a chip of the C/A code defined as 1 ms/1023;
- \( S(f) \) is the sinc-shaped function defined as \( S(f) = \sin(\pi f)/\pi f \),
- \( \tau(\rho) \) and \( f_d(\rho) \), are, respectively, the time delay, and the Doppler frequency shift for the signal traveling between the transmitter, arbitrary surface point \( \rho \), and the receiver, relatively to the same values associated with the nominal specular point on the mean ocean surface. The shapes of the equi-range annulus zones described by the equation \( \tau(\rho) = \text{const} \) and the equi-Doppler zones described by equation \( f_d(\rho) = \text{const} \) are shown schematically in Figure 8.1.
- \( R_0 \) is the distance from the GPS transmitter to the scattering point \( \rho \),
- \( R \) is the distance from \( \rho \) to the receiver,
- \( \Gamma \) is the Fresnel reflection coefficient for the ocean surface,
- \( \vec{q} \) is the scattering vector which depends on \( \rho \) and is defined as \( \vec{q} = k \cdot (\hat{n}_s - \hat{n}_i) = \vec{q}_x + q_x \hat{z} \) with \( \hat{n}_i \) and \( \hat{n}_s \) being unit vectors, respectively, of the incident and scattered waves, with \( k = 2\pi/\lambda \) and \( q = |\vec{q}| \); and,
- \( P_{\delta} \) denotes here the probability density function (PDF) of the ocean surface slopes \( \vec{v} \).

The double integral in Eqn. (8.1) is performed over the spatial extent of the glistening zone, i.e., over the surface area that scatters the GNSS signal towards the receiver. The surface roughness in this region is described by
PDF $P_{\vec{v}}$. The spatial coordinates are entering $P_{\vec{v}}$ through scattering vector $\vec{q}$. Note, that there is another formulation of Eqn. (8.1) [46] where surface integration is replaced by integration in a delay–Doppler domain.

Modeling of the average DDMs using Eqn. (8.1) requires knowledge of transmitter and receiver positions and velocity vectors, as well as the PDF of surface slopes. The GPS satellites positions and velocities are generally available. The position and velocity of the NOAA Gulfstream-IV jet aircraft during the 2010 experiment were measured onboard. The PDF of surface slopes was assumed to be Gaussian thus reducing the problem to calculating variances of two orthogonal components of L-band limited surface slopes, as well as their cross-correlation. These parameters of the PDF were obtained by employing the Eloufahily spectrum [118] - [120] that allows calculations of those variances as a function wind speed, wind direction and inverse wave age. Figure 8.2 shows a simulated average DDM obtained for positions and velocities of the GPS satellite with PRN9 and the NOAA aircraft at 10:15 UTC on January 24, 2010.

The wind information was obtained from dropsondes measurements. As one can see further, the comparison with the experimentally measured DDM (Figure 8.7) shows that the modeling reproduces the DDM shape quite closely.

However, knowledge of an average DDM often is not enough to understand and interpret the results of the measurements. The presence of noise, both additive thermal noise and speckle self-noise of the scattered signal which is accompanied by its decorrelation can limit accuracy of measurements. The effect of thermal noise due of its additive nature can be, in a large extent, suppressed by subtracting the noise power floor from the total correlation power. At the same time, the fluctuating behavior of the scattered signal represents a greater challenge.
In the treatment of the GPS scattered signal statistics, it will be assumed that the scattered signal $u$ (as well the voltage of the de-spread signal) is stationary and obeys circular Gaussian probability distribution with a zero mean [34], [121], [122]. Such a random field can be fully described by the second statistical moment of this field, i.e., by the spatio-temporal auto-correlation function $B_u(\hat{\rho}, \tau) = \langle u(\hat{r}, t) u^*(\hat{r} + \hat{\rho}, t + \tau) \rangle$ of the scattered field [103], [123]. Another reasonable assumption can be made that this function has a single characteristic scale, and that its spatio-temporal dependence can be reduced to only a temporal dependence because of the relatively fast movement of the receiver with respect to quasi-frozen random sea surface, i.e., $B_u(\hat{\rho}, \tau) \approx B_u(\hat{\rho} \approx \hat{v} \tau, 0)$. Under these assumptions only two parameters are required to fully describe the statistics of the scattered signal, namely, the variance of the signal (the scattered power) and its correlation time. The correlation time can be estimated by calculating directly the auto-correlation function $B_u(\tau)$ or a corresponding power spectrum which width is inversely proportional to the signal’s correlation time, $\tau_{\text{cor}}$ [121].

A crude estimate of $\tau_{\text{cor}} = \rho_{\text{cor}} / v$ can be obtained by use of the Van Cittert-Zernike theorem [122] from which it follows that $\rho_{\text{cor}} \propto R \lambda / r_0$, where $R$ is a distance between the receiver and the effective surface footprint of bistatic radar, and $r_0$ is the radius of that footprint. From here one can conclude that $\rho_{\text{cor}}$ of the signal that represents a certain pixel of the DDM depends on the transmitter-receiver geometry, and also on a spatial extent of the footprint scattering from which contributes into that pixel. From Figure 8.1 it is seen that such a footprint can be a pair of patches formed by intersection of the annulus zone with the Doppler zone. The signal correlation time ($\tau_{\text{cor}}$), is an important statistical parameter which set limitations on the coherent integration time ($T_{\text{coh}}$), and on the number of statistically independent samples ($N_s = T_{av} / T_{\text{coh}}$) used in the process of incoherent averaging of the signal ($T_{av}$is total averaging time).

### 8.3 Experiment Description

#### 8.3.1 Instrumentation and Measurement Technique

The current version of CU bistatic GNSS-R radar utilizes dual isolated GPS L1 radio ASIC components which have been clock synchronized to capture the raw IF streams from a nadir and zenith antennas. The bandwidth of the captured data is approximate 2.2 MHz centered about a 4.092 MHz intermediate frequency, translated from the 1575.42 MHz carrier frequency.
The sampling frequency is 16.3676 MHz and 2 bit data is collected from both channels. The block-diagram of the system is presented in Figure 8.3.

![Block Diagram of the CU GNSS Bistatic Radar](image)

Figure 8.3 Block diagram of the CU GNSS bistatic radar.

The basic parameters of the system are shown in Table 8.1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>2.2 MHz</td>
</tr>
<tr>
<td>Mass</td>
<td>1.68 Kg</td>
</tr>
<tr>
<td>Dimensions (without memory storage)</td>
<td>17.8cm x 14cm x 12.7cm</td>
</tr>
<tr>
<td>Power</td>
<td>18 W</td>
</tr>
<tr>
<td>Runtime (with 500 GB hard drive)</td>
<td>8 hr</td>
</tr>
</tbody>
</table>

### 8.3.2 Aircraft Experiment and Data Collection

In January 2010 NOAA has dispatched a high-altitude twin-engine Gulfstream IV-SP (G-IV) jet aircraft to collect information such as wind speed and direction, pressure, temperature and humidity over the North Pacific Ocean to enhance forecasts of winter storms for the entire North American continent. It was a part of annual Winter Storms Reconnaissance program. The aircraft was stationed at Yokota Air Force Base in Japan through February before repositioning to Honolulu, Hawaii in March. The CU GNSS bistatic radar was installed on board of the G-IV aircraft according to a collaborative plan between NOAA Aircraft Operations Center, NOAA Earth System Research Laboratory, and Colorado University at Boulder.
The flight of the NOAA G-IV jet aircraft on January 24, 2010 originated from Yokota Air Force Base in Japan to Honolulu, Hawaii (Figure 8.4a).

![Aircraft trajectory and wind speed](image)

**Figure 8.4** Experiment details: (a) Aircraft trajectory and (b) ground-truth for wind speed and wind direction obtained from dropsondes.

The aircraft took off at 08:09:28 UTC, flew at flight altitudes of about 12-13 km and velocities between 800-1000 km/h, and landed 6 hours 17 minutes later. The GPS reflection data was collected most of that time. Here results of data processing over a period between 9:00 and 13:00 UTC on that day are presented. The ground-truth data (wind speed and wind direction, Figure 8.4) was obtained from the dropsondes deployed from the aircraft at different times ($t_{gt}$), during the flight on January 24. The near-surface wind conditions were between 5 and 25 m/s with the wind direction between Northern to Eastern (Figure 8.4b). These conditions provided an opportunity to test the system for a large variety of sea surface conditions during a single flight. After the flights the hard drives with data have been sent to the lab for post-processing, and the correlation waveforms for both direct and reflected signals were retrieved from the raw data for all available satellites.

### 8.4 The Data Processing

#### 8.4.1 I-Q Data Processing

The I and Q raw data collected with the multistatic GPS radar on board the NOAA Gulfstream-IV jet aircraft was processed to obtain DDMs of the observed surface. The first step in such a processing is de-spreading or cross-correlating of the recorded I and Q raw data with a replica of the PRN code of the available GPS satellite for a set of different time lags and
different carrier frequency offsets. This cross-correlation is achieved by performing a coherent integration over a short enough time interval, called a coherent integration time ($T_i$). In order to have a resolution of the DDMs fine enough over a Doppler frequency domain a large $T_i$ is desired. At the same time, in order to successfully perform the cross-correlation, $T_i$ should be smaller than the correlation time ($\tau_{cor}$, usually on the order of several milliseconds) related to the possible random variation of the recorded I and Q components acquired due to propagation or scattering processes. Signal-to-noise ratio (SNR) of a single cross-correlator power per DDM cell is too low. To increase the SNR of the DDM it is necessary to incoherently average them in two steps. The first step of incoherent averaging is based on the assumption that over times from 200 ms to 500 ms the geometry of the measurement such as arrival/scattering angles, the receiver altitude, surface wind conditions do not appreciably change. A longer averaging time is not feasible because the migration of DDM’s position would lead to its smearing. At the same time, an accurate averaging even over such short intervals requires a properly tracking of the carrier and the code frequency. It has been achieved using a secondary order filter loop and estimators of the carrier and the code frequency [115]. Figure 8.5 shows the block diagram of the tracking channel.

![Block diagram of the tracking channel](image.png)

Figure 8.5 Block diagram of the tracking channel, [115].
When there is a phase error on the local carrier wave, the signal will be noisy, making it difficult to keep locked on the code. The design in Figure 8.5 has the advantage that it is independent of the phase on the local carrier wave. If the local carrier wave is in phase with the input signal, all the energy will be in the in-phase arm. But if the local carrier phase drifts compared to the input signal, the energy will switch between the in-phase and the quadrature arm. So, if the code tracking loop performance has to be independent of the performance of the phase lock loop, the tracking loop has to use both the in-phase and quadrature arms to track the code. Figure 8.5 shows how the tracking of the incoming signal is performed using early (\(E\)), prompt (\(P\)) and late (\(L\)) PRN codes, and how the loops are closed using two different discriminators, one for the code loop (the normalized early minus late power discriminator: \(\left(\sqrt{I_E^2 + Q_E^2} - \sqrt{I_L^2 + Q_L^2}\right)/\left(\sqrt{I_E^2 + Q_E^2} + \sqrt{I_L^2 + Q_L^2}\right)\)) and another for the carrier loop (Costas loop discriminator: \(\tan^{-1}\left(\frac{Q_E}{I_E}\right)\)). The normalized early minus late power discriminator is independent of the performance of the phase lock loop (PLL) as it uses both the in-phase and quadrature arms. The normalization of the discriminator causes that the discriminator can be used with signals with different signal-to-noise ratios and different signal strengths. The Costas loop discriminator is selected for being the most precise carrier tracking loop in GPS receivers sensitive for phase transitions due to navigation bit.

After applying the tracking over each millisecond of data, the output is a continuous 500-ms block of the cross-correlation power data which can be averaged under the assumption that the corresponding DDM does not significantly evolve due to changes in transmitter-receiver geometry over a half-second time interval. In order to retrieve the ocean surface roughness for moments \(t_{GT}\) when the wind ground truth from dropsondes became available 20 seconds of data has been processed as described above forming 40 continuous blocks of 500-ms averaged DDM cross-correlation power for each of three high-elevation satellites PRN 9, PRN 15, and PRN 27. The result is 40 blocks per each PRN at each \(t_{GT}\), and it is what is called a dataset in what follows.

The procedure of a second-step averaging was applied to each dataset. This averaging cannot be performed by simply adding up 500-ms averaged DDM and dividing them by 40, the number of blocks in each dataset. The reason is that the altitude of the aircraft is changing over the 20-second interval, so the DDM might change its position both over the delay and Doppler axes. The effect of position migration can be mitigated. For this, the time delay and Doppler offset positions of the DDM maximum were computed for each 500-ms block (see Figure 8.6).
Figure 8.6 5th order polynomial fit applied to the delay and Doppler variation of the maximum value of the DDM: PRN 9 (a) delay and (b) Doppler evolution (blue) and 5th order polynomial fitted values (red).

The estimated maximum positions vary appreciably due to noise in the DDMs. Those variations cannot be caused by the actual altitude changes of the aircraft, so the corresponding changes in maximum position should be much smoother. Taking this fact into account, the realistic position evolution was fitted using a 5th order polynomial (red curves in Figure 8.6) into the estimated maximum positions in both delay and Doppler dimensions. Using the filtered delay and Doppler values of the DDM maxima the DDMs for each block were aligned to a single maximum position. After that, the aligned DDMs can be averaged through each dataset. Prior to averaging, the noise floor must be subtracted from all DDMs. The noise floor was calculated according to this expression:

$$\text{Noise} = \frac{\sum_{i=1}^{f_{d_2}} \sum_{d_{d_1}} \Delta t DDM(i, f_d) \Delta f_d}{N},$$

(8.2)

Where $\tau_1$, $\tau_2$, $f_{d_1}$ and $f_{d_2}$ are the pixel limits for the zone of the DDM free of signal and $N$ is the number of pixels.

Once the noise floor has been subtracted the 40 blocks of 500 ms are averaged and normalized by the DDM peak value for each dataset which is characterized by the PRN and time $t_{GT}$. For example Figure 8.7 shows the DDM of the dataset that corresponds to PRN 9 at $t_{GT} = 10:15$ UTC in a linear (a) and a logarithmic (b) scale.
Figure 8.7 Normalized DDMs of one of the datasets ($t_{CT}$ expressed as UTC time), corresponding to PRN 9 at 10:15 UTC: (a) linear plot and (b) logarithmic plot.

Every dataset was used to retrieve wind speed at the location of the nominal specular point originated from positions of the aircraft and the GPS satellite with a specific PRN. Since the elevation angles for chosen triplets of satellite were between 45° and 90° the distance between specular points was of the order of the aircraft altitude. For fully-developed seas in the open ocean the average wind speed or surface roughness in those three locations should be rather close. Therefore, any differences in wind retrievals for these three points should be attributed to retrieval errors which can be reduced by applying an additional averaging over these three estimates.

### 8.4.2 Coherent Integration Time

As it was stated above, $\tau_{cor}$ of the signal that represents a certain pixel of the DDM depends on the transmitter-receiver geometry, and also on the spatial extent of the footprint from which scattering contributes into that pixel. Therefore, $T_{coh}$ which should be smaller than $\tau_{cor}$ might be chosen uniquely for each pixel. However, it would be difficult to do it technically. It is simpler to set a fixed minimal coherent integration time, $T_{coh}$, which would satisfy condition $T_{coh} < \min[\tau_{coh}(\delta r_n, \delta f_n)]$, where $n$ is a running index of the pixel. The specific value for $T_{coh}$ was chosen empirically by running the de-spreading code for a set of various $T_{coh}$ (specifically, for 1 ms, 2 ms and 5 ms) and making a comparison between resulting waveforms. If $T_{coh}$ exceeds $\tau_{cor}$ it will result in a reduction of the correlation power of the de-spread signal.
To demonstrate in Figure 8.8 how various $T_{coh}$ affect the shape of the normalized DDM we have chosen three values of coherent integration time, (a) $T_{coh} = 1$ ms, (b) $T_{coh} = 2$ ms, and (c) $T_{coh} = 5$ ms for 20 s of data from PRN9 at 10:15 UTC (wind speed 15 m/s). One can see that the DDM for $T_{coh} = 2$ ms is narrower than that for $T_{coh} = 1$ ms, and the DDM for $T_{coh} = 5$ ms is narrower than that for $T_{coh} = 2$ ms. Therefore, increasing of the coherent integration time $T_{coh}$ above the $\tau_{cor}$ causes the DDM to reduce its extent over the time delay axis, whereas the DDM extent over the Doppler frequency axis is not changing. In principle, this effect could be tolerated if the DDM would remain sensitive to the wind speed changes. Figure 8.9a, b, and c show that it is not the case.
Figure 8.9 Waveforms, DDMs integration over Doppler domain, of 4 different datasets for 
(a) $T_{coh} = 1$ ms, (b) $T_{coh} = 2$ ms, and (c) $T_{coh} = 5$ ms.

In this figure, the correlation power waveforms are plotted for three different wind speeds and three $T_{coh}$ as a function of the time delay only. They are obtained by integrating the corresponding DDMs over their Doppler frequency argument. From Figure 8.9 it can be seen that when using 1 ms integration time the trailing edge of the waveform is sensitive to wind speed variations and when using 5 ms the trailing edge loses that sensitivity. For example, the black curve in Figure 8.9a is lower than the blue and green ones (which have almost the same wind speed) and these are lower than the red curve (which is the one with the highest wind speed). However, in Figure 8.9c, the black, the blue and the green plots do not show any significant difference in the trailing edge, i.e. for wind speeds in the order of 6 m/s or 16 m/s the trailing edge do not show sensitivity. This means that coherently integrating longer than the correlation time of the ocean surface will reduce the sensitivity to the wind speed information. For that reason, the coherent integration time used in the post-processing to implement the wind speed retrieval was chosen 1 ms.
8.5 Wind Speed Retrieval Algorithms

Four different algorithms to retrieve the wind speed are presented in this section: firstly the weighted area, secondly the second order Euclidean distance (from now on distance) from the center of mass to the maximum value of the DDM, the distance from the geometric center to the maximum value of the DDM and the first order Euclidean distance (from now on taxicab distance) from the center of mass to the maximum value of the DDM. The algorithms have been applied to the DDM image resulting from:

\[ \mathcal{S}(\tau, \nu) = 10 \log_{10}(\text{DDM}_{\text{norm}}(\tau, \nu)) \]

with \( x \) being a minimum value considered (the threshold), defined as:

\[ x = 10 \log_{10}(e^{-1}). \]  

Therefore the function \( \mathcal{S} \) is treated as an image composed by pixels with a fix size \((d\tau, df_d)\) and a certain value defined by Eqn. (8.3).

8.5.1 Weighted-Area Algorithm

A very similar algorithm was proposed in [42] and tested during a ground-based field experiment in [44] and [67]. In that case the volume under normalized DDM was computed. Here the weighted area algorithm is presented. It is based on the double summation (delay and Doppler domain) of the image \( I(\tau, f_d) \) (Eqn.(8.3)), weighted by the value at each pair delay-Doppler Note that this is different from the definition used in [16]. Using all the available datasets the weighted area of the image, \( S_{\text{DDM}} \), has been processed as:

\[ S_{\text{DDM}} = \sum_{\tau} \sum_{f_d} I(\tau, f_d) \cdot d\tau \cdot df_d. \]  

The \( S_{\text{DDM}} \) for three PRN (9, 15 and 27) has been averaged for each dataset, and the result has been plotted against the ground-truth wind speed corresponding to each dataset (Figure 8.10a).
8.5.2 Center-of-Mass Algorithm

A center-of-mass algorithm is a novel algorithm proposed here. This algorithm is based on the computation of the distance $\Delta d_1$ from the maximum position, $\text{MAX}(\tau, f_d)$ to the center of mass, $\text{CM}(\tau, f_d)$ of the image $I(\tau, f_d)$, computed in Eqn.(8.3). The $\Delta d_1$ of the DDMs has been computed using all the available datasets as follows:

- Computation of the maximum position of the DDM, obtaining the $\tau$ and $f_d$ coordinates of the peak of the logarithmic normalized DDM ($\text{MAX}_\tau$ and $\text{MAX}_{f_d}$).

- Center of mass computation:

  \[
  \text{CM} = (\text{CM}_\tau, \text{CM}_{f_d}),
  \]

  where $\text{CM}_\tau$ and $\text{CM}_{f_d}$ are the $\tau$ and $f_d$ coordinates of the center of mass, which are defined as:

  \[
  \text{CM}_{f_d} = I_0^{-1} \iint f_d F(\tau, f_d) d\tau df_d,
  \]

  \[
  \text{CM}_\tau = I_0^{-1} \iint \tau F(\tau, f_d) d\tau df_d,
  \]

  where:

  \[
  F(\tau, f_d) = I(\tau, f_d),
  \]

  \[
  I_0 = \iint F(\tau, f_d) d\tau df_d.
  \]

- Then, the $\Delta d_1$ is computed. The distance between two points, $p = (x_1, y_1)$ and $q = (x_2, y_2)$, is defined as:

  \[
  d = \|p - q\|_2 = (\sum_{i=1}^{2} |x_i - y_i|^2)^{1/2}.
  \]

- Then, $\Delta d_1$ expressed in delay and Doppler coordinates takes the form:

  \[
  \Delta d_1 = \Delta_\tau \Delta_{f_d} \sqrt{\left(\frac{\text{MAX}_\tau - \text{CM}_\tau}{\Delta_\tau}\right)^2 + \left(\frac{\text{MAX}_{f_d} - \text{CM}_{f_d}}{\Delta_{f_d}}\right)^2},
  \]

  where $\Delta_\tau$ and $\Delta_{f_d}$ correspond to the delay and Doppler steps in the DDM.

After that, $\Delta d_1$ of the three PRN (9, 15 and 27) has been averaged for each dataset and the result has been plotted against the ground-truth wind speed corresponding to each dataset (Figure 8.10b).
8.5.3 Geometrical Center Algorithm

The geometrical center algorithm is also a novel algorithm proposed in this work. This algorithm is based on the computation of the distance $\Delta d_2$ from the maximum position of the DDM ($\text{MAX}(\tau, f_d)$), to the geometric center of the image $l(\tau, f_d)$ ($\text{GC}(\tau, f_d)$, computed in Eqn.(8.3)). Using all the available datasets the $\Delta d_2$ of the DDMs have been computed as follows:

- Computation of the maximum position of the DDM, obtaining the $\tau$ and $f_d$ coordinates of the peak of the logarithmic normalized DDM ($\text{MAX}_\tau$ and $\text{MAX}_{f_d}$).
- Geometrical center computation:

$$\text{GC} = \left(\text{GC}_\tau, \text{GC}_{f_d}\right).$$

(8.13)

where $\text{GC}_\tau$ and $\text{GC}_{f_d}$ are the $\tau$ and $f_d$ coordinates of the geometrical center, which can be found using:

$$\text{GC}_\tau = \frac{\int \tau g(\tau) d\tau}{\int g(\tau) d\tau},$$

(8.14)

$$\text{GC}_{f_d} = \frac{\int f_d g(f_d) d\tau}{\int g(f_d) d\tau},$$

(8.15)

where $g(x)$ is the characteristic function of the subset of values, which is 1 inside the representative contour of the image $l(\tau, f_d)$, computed in Eqn.(8.3), and 0 outside it.

- Then, the $\Delta d_2$ is computed using eqn.(8.11) as follows:

$$\Delta d_2 = \Delta_\tau \Delta_{f_d} \sqrt{\left(\frac{\text{MAX}_\tau - \text{GC}_\tau}{\Delta_\tau}\right)^2 + \left(\frac{\text{MAX}_{f_d} - \text{GC}_{f_d}}{\Delta_{f_d}}\right)^2},$$

(8.16)

where $\Delta_\tau$ and $\Delta_{f_d}$ correspond to the delay and Doppler steps in the DDM.

The $\Delta d_2$ of the three PRNs (9, 15 and 27) have been averaged for each dataset and the results have been plotted against the ground-truth wind speed corresponding to each dataset (Figure 8.10c).
8.5.4 Taxicab Center of Mass Algorithm

The taxicab center of mass algorithm is also a novel algorithm proposed in this work. This algorithm is based on the computation of the taxicab distance $\Delta d_3$ [124] from the maximum position ($\text{MAX}(\tau, f_d)$), to the center of mass ($\text{CM}(\tau, f_d)$) of the image $I(\tau, f_d)$ (computed in Eqn.(8.3)). Using all the available datasets the Taxicab distance $\Delta d_3$ of the DDMs has been obtained by performing the following steps:

- Computation of the maximum position of the DDM by obtaining the $\tau$ and $f_d$ coordinates of the peak of the logarithmic normalized DDM, ($\text{MAX}_\tau$ and $\text{MAX}_{f_d}$).

- Center of mass computation. The center of mass is computed following Eqn. (8.6) – Eqn. (8.10).

- Then, the Taxicab distance $\Delta d_3$ is computed. The taxicab distance between two points $p = (x_1, y_1)$ and $q = (x_2, y_2)$, is defined as:

$$d = ||p - q||_1 = \sum_{i=1}^{2} |x_i - y_i| ,$$

(8.17)

- After that, expressed in delay and Doppler coordinates the Taxicab distance $\Delta d_3$ takes the form:

$$\Delta d_3 = \Delta_\tau \Delta_{f_d} \left( \frac{|\text{MAX}_\tau - \text{CM}_\tau|}{\Delta_\tau} + \frac{|\text{MAX}_{f_d} - \text{CM}_{f_d}|}{\Delta_{f_d}} \right) ,$$

(8.18)

where $\Delta_\tau$ and $\Delta_{f_d}$ correspond to the delay and Doppler steps in the DDM.

The Taxicab distance $\Delta d_3$ of the three PRN (9, 15 and 27), has been averaged for each dataset and the result has been plotted against the ground-truth wind speed corresponding to each dataset (Figure 8.10d).
8.5.5 Comparison of the Four Algorithms.

All four algorithms proposed show that wind speed can be retrieved from the DDM measurements using any of them, however, the accuracy of these retrievals varies (Figure 8.10). Let us compare them with each other by calculating some descriptor values for every method: $\rho$, that is the Pearson correlation coefficient and defines the correlation between retrievals and ground-truth, $P_e$, that is the probability of error in the $\rho$ computation, and
finally $R^2$, the coefficient of determination which determines the tendency of the values to be a line instead of a cloud of points.

- The method presented in subsection 5.1 is different from the following three because it relies on the DDM’s extent over both variables, namely, weighted area observable $S_{DDM}$. One can see that it is affected by the wind conditions as the descriptor values, $\rho$, $P_e$ and $R^2$ in Figure 8.10a, indicate. Although this method gives a high correlation value, $\rho$, at the same time, $R^2$ is around 67.2 %, which implies a large error in the retrievals. Indeed, the error by using this retrieval is up to $\sim 8$ m/s.

- The observable $\Delta d_1$, presented in subsection 5.2, gives higher descriptor values ($\rho$, $P_e$ and $R^2$ in Figure 8.10b) than observable SDDM, and they are highly affected by the wind speed. This method demonstrates high values for the correlation, $\rho$, and for the determination coefficient, $R^2$. The $R^2$ reaches value of 92.6 %, which translates into the wind retrieval error $\sim 3$ m/s for this range of winds.

- Observable $\Delta d_2$ presented in subsection 5.3 also produces higher descriptor values ($\rho$, $P_e$ and $R^2$ in Figure 8.10c) than observable SDDM, but these descriptor values are lower than those produced by observable $\Delta d_2$. Value $R^2$ is 81.3 % which translates into the wind retrieval error $\sim 5$ m/s for the same range of winds as above.

- The observable from the Taxicab method, $\Delta d_3$, presented in subsection 5.4, demonstrates even higher descriptor values ($\rho$, $P_e$ and $R^2$ in Figure 8.10d) than the other three previous observables, being highly affected by the wind speed. Value $R^2$ reaches 96.2% which indicates the high probability of the points to be concentrated along the line rather than being a cloud of points, reducing the error in the wind retrieval to $\sim 2$ m/s.

The above analysis shows that, with the available ground-truth information, the best algorithm to implement for wind speed retrieval is the Taxicab center of mass algorithm.

8.5.6 Assumptions

Two assumptions have been made in the wind speed retrieval algorithms, and their validity should be proven.
- Use of 1 ms coherent integration time leads to better retrieval results than 5 ms. This statement can be verified by producing similar plots to Figure 8.10, and applying the above algorithms to data obtained with 5 ms integration time. The combined plot that depicts such output for all four algorithms is presented in Figure 8.11.

![Figure 8.11](image)

Figure 8.11 5ms coherent integration time processing for the averaged DDM versus the wind speed ground-truth available for each dataset at 10 m: (a) \( S_{\text{DDM}} \), \( \rho = 75.9\% \), \( Pe = 1.8\% \) and \( R^2 = 57.5\% \), (b) \( \Delta d_1 \), \( \rho = 30\% \), \( Pe = 47\% \) and \( R^2 = 9\% \), (c) \( \Delta d_2 \), \( \rho = 27.9\% \), \( Pe = 50\% \) and \( R^2 = 7.8\% \), and (d) \( \Delta d_3 \), \( \rho = 33.3\% \), \( Pe = 42.1\% \) and \( R^2 = 11.1\% \).

It can be seen that plots in Figure 8.11a-d represent a degraded version of Figure 8.10a-d, respectively. The most degraded algorithms turned out to be those that demonstrated the highest accuracy for 1 ms coherently integrated data, namely, those which are based on any sort of distance, between the maximum of the DDM and the center of mass or the geometric center. Interestingly enough, the weighted area
observable, although degraded, appears to be the most robust descriptor when longer integration times are considered.

- Threshold \((x)\). All discussed above wind retrieval algorithms use a threshold \(x\) defined in (8.4). In order to estimate the goodness of this choice what happens to the retrieval algorithms (specifically the center of mass algorithm) is analyzed when the DDM is subject to a lower threshold. The theoretical model for a completely averaged DDM predicts a better sensitivity for increasingly lower thresholds. But that is the case when the noise is completely averaged out. Figure 8.12 shows the result of considering a lower threshold when noise is the factor.

![Figure 8.12 Threshold study: (a) Waveform cut at different thresholds and (b) results obtained at each one of these thresholds.](image)

As it can be seen, the lower the threshold is the noisier is the processed DDM is, and the lower becomes the correlation between the wind speed and the observable \(\Delta d_1\). The conclusion is that the best strategy for choosing the threshold \(x\) is a tradeoff between a high enough threshold to minimize the effect of noise and a low enough threshold to still get sensitivity to wind speed. We should mention here that because of the high altitude of the aircraft and the low-gain antenna, the signal-to-noise ratio was not enough to sense the wind direction which affects mostly the periphery of the DDM where noise might dominate the signal.
8.6 The Wind Speed Retrieval

Once it has been confirmed that a coherent integration time of $T_{coh} = 1$ ms and a threshold $x = 10 \log(e^{-1}) = -4.34 \ dB$ are suitable values, the error budget of each algorithms was analyzed and the wind retrieval for long time series has been performed.

8.6.1 Wind Speed and Observable Relationships

First, the numerical relationship between the observable of each algorithm and the wind speed from the ground truth were defined.

- From Figure 8.10a, the regression relationship $S_{DDM} = 34.2 \times WS + 1670.7$ is obtained. Therefore, $WS = \frac{S_{DDM} - 1670.7}{34.2}$ is the relationship used in the following wind speed retrieval based on observable $S_{DDM}$.

- From Figure 8.10b, the regression relationship $\Delta d_1 = 0.50 \times WS + 7.495$ is obtained. $WS = \frac{\Delta d_1 - 7.49}{0.50}$ is the relationship used in the following wind speed retrieval based on observable $\Delta d_1$.

- From Figure 8.10c, the regression relationship $\Delta d_2 = 0.46 \times WS + 4.32$ is obtained. $WS = \frac{\Delta d_2 - 4.32}{0.46}$ is the relationship used in the following wind speed retrieval based on observable $\Delta d_2$.

- From Figure 8.10d, the regression relationship $\Delta d_3 = 0.75 \times WS + 6.44$ is obtained. $WS = \frac{\Delta d_3 - 6.44}{0.75}$ is the relationship used in the following wind speed retrieval based on observable $\Delta d_3$.

8.6.2 Error Analysis

The issue of wind retrieval errors was briefly mentioned before. Now, a more detailed error analysis is presented in Figure 8.13 by making a comparison between wind speed retrieved from GPS reflection measurements and the wind speed ground-truth values.
Figure 8.13 Retrieval performed using (a) $S_{DDM}$ observable, (b) $\Delta d_1$ observable, (c) $\Delta d_2$ observable and (d) $\Delta d_3$ observable. Plots on the left: retrieved wind speed vs wind speed ground-truth ($U_{10}$), and plots on the right: computed error between retrievals and ground-truth values.
On the right-hand side of Figure 8.13 the retrieved values and the ground-truth values for wind speed are plotted as a function of time. On the left-hand side of Figure 8.13 the error between these values are also plotted as a function of time. The mean error and the standard deviation of the error were also computed, and they are shown in the figures as well. Figure 8.13 clearly demonstrates an improvement that the use of observable $\Delta d_3$ (the Taxicab distance) represents versus the use of other observables.

### 8.6.3 Wind Speed Retrieval

As stated before, wind speed ground-truth information was available over the flight segment between 10:00 UTC and 12:15 UTC on January 24 2010. The I and Q data has been processed every 5 minutes within this period, as explained in Section II. Figure 8.14 shows the selected points for the wind speed retrieval and the points where the ground truth was available.

![Figure 8.14 Selected points in the aircraft trajectory](image)

In order to implement the most accurate wind retrieval the taxicab center of mass algorithm was chosen, which was applied to DDMs obtained with the most suitable coherent integration time, $T_{coh} = 1$ ms, and with threshold, $x = 10 \times \log(e^{-1}) = -4.34$ dB. Figure 8.15 shows the wind speed retrieval achieved using the Taxicab observable $\Delta d_3$ and the relationship from Figure 8.10d, $WS = \frac{\Delta d_3 - 6.44}{0.75}$.
Figure 8.15 Retrieval performed between UTC 10:00 and UTC 12:15. Black dots correspond to dropsondes measurements and red dots to retrieved values using observable $\Delta d_3$.

Figure 8.15 shows wind speed retrievals for every 5 minutes. It shows that the trend of the wind speed retrieved is the same as the ground-truth measured. The values retrieved are not a perfect curve following the ground-truth, but this curve is within the intrinsic error bars of the method ($\mu_{\text{mean}} = 0.76 \, \text{m/s}$ and stdmean $= 0.79 \, \text{m/s}$) and follows the real surface wind speed variations.

Figure 8.16 give an idea about the geometry of the surface footprints associated with these three GPS satellites, and the size of the spot that embraces these three footprints.

Figure 8.16 Geometry of the effective spot over the surface.

The spot is a circle of radius $d = 1.5 \times \max(d_1, d_2, d_3)$. Radii $d_1$, $d_2$, and $d_3$ being the distances between the reflection points from PRN9, PRN15, and PRN 27 and the aircraft position, respectively. The maximum of these three distances, multiplied by 1.5 (in order to roughly take into account the size of the first annulus zone for the furthest PRN) gives the radius of the equivalent area from which measurements were combined to provide the
wind speed values assigned to this area. This wind speed retrieval can be mapped into latitude-longitude map.

Figure 8.17 Wind speed retrieved values in the aircraft trajectory: (a) World map and (b) zoom of the area where retrieval has been performed (wind speed is represented by the color scale set at the right-hand side).

Figure 8.17 shows the wind retrieval mapped over latitude and longitude map with spots on the surface whose shape and size account for the geometry of the footprints.

8.7 Conclusions

The results of the work which was conducted with the CU GNSS multistatic radar onboard the NOAA Gulfstream-IV jet aircraft, and obtain Delay-Doppler Maps (DDMs) suitable for wind speed retrievals. The DDMs were obtained because of the relatively high altitude and speed of the aircraft. To some extent, this experiment can be regarded as a proxy for space-borne
GNSS multistatic radar. The DDMs have been post-processed and analyzed by means of four different wind speed retrieval algorithms based on four DDM observables: weighted area, distance from the center of mass to the maximum position, distance from the geometrical center to the maximum position and taxicab distance from the center of mass to the maximum position. After choosing the most suitable coherent integration time (1 ms) and the threshold (-4.34 dB), the error of each algorithm has been estimated. Table 8.2 summarizes the performance of the algorithms.

Table 8.2 Performance of the algorithms, $T_{coh} = 1$ ms and $x = -4.34$ dB.

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Relationship</th>
<th>$\rho (P_e)$</th>
<th>$R^2$</th>
<th>$\mu_{error}$</th>
<th>$\sigma_{error}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pondered area (obs = $S_{DDM}$)</td>
<td>$WS = \frac{obs - 1670.7}{34.2}$</td>
<td>82.0% (1.30%)</td>
<td>67.2%</td>
<td>3.43 m/s</td>
<td>1.82 m/s</td>
</tr>
<tr>
<td>Center of mass (obs = $\Delta d_4$)</td>
<td>$WS = \frac{obs - 7.49}{0.50}$</td>
<td>96.2% (1.3e-2%)</td>
<td>92.6%</td>
<td>1.32 m/s</td>
<td>0.89 m/s</td>
</tr>
<tr>
<td>Geometric center (obs = $\Delta d_2$)</td>
<td>$WS = \frac{obs - 4.32}{0.46}$</td>
<td>90.2% (2.2e-1%)</td>
<td>81.3%</td>
<td>2.20 m/s</td>
<td>1.49 m/s</td>
</tr>
<tr>
<td>Taxicab center of mass (obs = Taxicab $\Delta d_3$)</td>
<td>$WS = \frac{obs - 6.44}{0.75}$</td>
<td>98.1% (2.0e-3%)</td>
<td>96.2%</td>
<td>0.76 m/s</td>
<td>0.79 m/s</td>
</tr>
</tbody>
</table>

The most suitable one was found the taxicab distance from the center of mass to the maximum position, whose mean error and standard deviation are the lowest, and it gives the highest correlation with the ground truth. This algorithm has been used to further retrieve the wind speed during 2 hours and 15 minutes of flight producing wind speed data sampled at 5 minutes rate.

Overall, the wind speed retrieval based on dela-Doppler maps should provide more accurate wind speed estimates compared to the retrieval from 1-D delay waveform. Accuracy of retrievals is limited by the residual partially-averaged speckle noise which still present in the DDM due to averaging over a limited number of samples. However, after computing the DDM center of mass position the remaining noise becomes lower than corresponding noise in retrievals based on 1D delay waveforms. The total accuracy gain would depend on how the width of the DDM along Doppler axis is larger than the Doppler filtering zone, which is inversely proportional to the coherent integration time. Further studies will be required to address absolute accuracy issues of the DDM retrieval method, especially for the satellite based GNSS bistatic radars. Overall, good performance of this approach for the aircraft platform motivates continued consideration of the DDM retrieval method for remote sensing applications.
This chapter focuses on the main space-borne GNSS-R advances. The four space missions performing GNSS-R measurements are introduced here and some modest contributions of this Ph.D. Thesis are explained.
9.1 GNSS-R Spaceborne Missions

Only two space missions have performed GNSS-R measurements from space and other two may be launched in a mid-term future:

- Spaceborne Imaging Radar-C (SIR-C) mission (two flights in 1994).
- United Kingdom Disaster Monitoring Constellation (UK-DMC), (September 2003 to present).
- The PARIS In Orbit Demonstrator (PARIS IoD), (undergoing Phase A).
- PAU/INTA μsat-1, (undergoing Phase C/D).

These four missions are explained in next sections and some contributions developed during the present PhD Thesis are added. These contributions are related to the UK-DMC, the PARIS IoD and the PAU/INTA μsat-1 missions.

9.1.1 Spaceborne Imaging Radar-C/X-Band Synthetic Aperture Radar (SIR-C/X-SAR)

The Spaceborne Imaging Radar-C/X-Band Synthetic Aperture Radar (SIR-C/X-SAR) is a joint US-German-Italian project that uses a highly sophisticated imaging radar to capture images of Earth that are useful to scientists across a great range of disciplines. The first spaceborne observations of a GPS signal reflected over the Earth surface took place during the SIR-C/X-SAR mission [125]. All the work developed to process the data was carried out by the Jet Propulsion Laboratory (JPL), California Institute of Technology, under contract with the National Aeronautics and Space Administration (NASA).
Figure 9.1 SIR-C (a) Photo of the Space Shuttle Endeavour on the launch pad and (b) photo of the SIR-C/X-SAR payload in the Shuttle bay (images credit: NASA)

Because the data were collected for radar imaging, it was considered unlikely that a data set containing GPS reflection could be found. Most data were taken over land and there the reflected signal is much weaker than over ocean. Despite the low probability a search was performed into the SIR-C data looking for a favorable geometry where GPS signal was measured over ocean. Fortunately, one of the specular reflections for one of the GPS in the scene was found to be very close to the radar mapping region for the entire track. Finally these data were processed and a GPS reflection was found, Figure 9.2.

Figure 9.2 4-s GPS reflected signal (stars) with the expected signal for the direct, scaled to have the same peak, for PRN 39, [125].
9.1.2 United Kingdom – Disaster Monitoring Constellation (UK-DMC)

The Disaster Monitoring Constellation (DMC) is an international program initially proposed in 1996 and led by SSTL (Surrey Satellite Technology Ltd), Surrey, UK, to construct a network of five affordable Low Earth Orbit (LEO) microsatellites. The objective is to provide a daily global imaging capability at medium resolution (30-40 m), in 3-4 spectral bands, for rapid-response disaster monitoring and mitigation.

![Image of UK-DMC satellite](image)

Figure 9.3 UK-DMC for Earth observation, contractor SSTL.

A spaceborne GNSS reflectometry experiment was undertaken by Surrey Satellite Technology Limited with support from the British National Space Centre (BNSC) to investigate the reception of reflected GPS signals off the ocean for oceanographic applications. The GPS receiver on the UK-DMC satellite has been modified to accommodate a downward (nadir) pointing moderate-gain antenna, to send sampled data to a solid-state data recorder and to process reflected signals. This instrument has been used to search for signals reflected off the ocean and when detected, characterize their relationship with the sea state. This experiment has proven to be the first step towards a constellation of low cost small satellites that could make real-time measurements of the sea state around the globe.

Some works have been performed related to UK-DMC, [35]-[37]. One of the first results obtained can be seen in Figure 9.3, [36].
The publicly available data from the GPS bistatic remote sensing experiment onboard the UK Disaster Monitoring Constellation satellite (UK-DMC) [126] have been analyzed. These data correspond to three different types of scenarios: 12 s over ocean, 20 s over land, and 7 s over ice. The UK-DMC uses the Surrey Satellite Technology Limited’s Space GPS Receiver [36]. The Daaxa software, developed by Scott Gleason under GNU GPL Surrey Satellite Technology Limited [36], is a Borland-C code that processes the raw data providing DDMs products. Daaxa code has been carefully analyzed and some improvements have been implemented.

9.1.2.1.1 UK-DMC Raw Data Analysis

The DDMs are defined as the power distribution of the reflected signal coming from the GPS satellites represented over a two-dimensional space of delay offsets (in chips) and Doppler shifts (in Hz) with respect to those at the specular reflection point. For this purpose, it is necessary to determine the basic DDM unit, or the minimum number of incoherent integrations needed to obtain a good-quality DDM, (Figure 9.5).
Figure 9.5 Two DDMs measured over the ocean, (a) with a coherent integration time of 1 ms and (b) with 2000 incoherent integrations 1 ms basic coherent integrations.

In Figure 9.5, two DDMs with 1 ms coherent integration time, but different incoherent integration times are shown. As it can be seen in Figure 9.5a no DDM can be seen, while in Figure 9.5b, a DDM clearly appears. The basic DDM unit will be between this two integration times.

Three criteria have been established to found the basic unit that defines a DDM as a “good-quality” DDM:

- the study of the evolution of the DDM volume vs. time,
- analysis of the DDM’s SNR, and
performing histograms and analyzing the statistics of significative DDM pixels.

The main objective of this section is to conduct these three studies directly from the DDMs and conclude which is the best method.

**SNR analysis**

As previously said, the analysis is performed directly from the DDM. For this reason it is necessary to define the SNR as in modern imaging techniques. Traditionally, the SNR has been defined as the ratio of the average signal value to the standard deviation of the signal value:

$$\text{SNR} = \frac{\mu_{\text{Signal}}}{\sigma_{\text{Signal}}}. \quad (9.1)$$

However, in image processing the standard deviation of the signal value approaches zero and thus, SNR approaches infinity; which is physically meaningless in this kind of analysis. Therefore, a new definition of SNR yields a meaningful value. SNR is thus defined as the ratio of the mean signal value to the RMS noise.

$$\text{SNR} = \frac{\mu_{\text{Signal}}}{\sigma_{\text{RMSNoise}}}, \quad (9.2)$$

where:

$$\text{Signal} = \mu_{\text{Signal}} - \mu_{\text{Background}}. \quad (9.3)$$

The Rose criterion [127] states that an SNR of at least 5 is needed to be able to distinguish image features. An SNR less than 5 means less certainty in identifying image details.

Figure 9.6 shows the result of processing DDM’s SNR with each criterion.
Figure 9.6 SNR vs integration time calculated with (a) the classical form eqn. 1, and (b) the image processing criteria eqn. 2.

As it can be easily seen, comparing Figure 9.6a and Figure 9.6b, the image processing criteria is more suitable for this kind of study. So that, the SNR of each data set, which corresponds to different scenarios, has been processed using Eqn. (9.2). Figure 9.7 shows the results.

Figure 9.7 DDM SNR over three surfaces vs incoherent integration time: (a) ocean, (b) land and (c) ice.
The DDM over the ocean (Figure 9.7a) reaches the Rose criteria for $T_i > 90$ ms, so the $T_i$ required to obtain a basic DDM unit is 90 ms. For the DDM over land (Figure 9.7b) the SNR analysis is not conclusive because the values fluctuate too much which is probably due to the multiple reflections and topography. From the ice data (Figure 9.7c), neither the SNR analysis contributes relevant information about the basic DDM unit, because its values are always better than 5.

**Volume analysis**

In order to study the normalized DDM volume it is necessary to establish different thresholds. A threshold is defined as a function of the maximum value of the DDM in %. Lower thresholds correspond to 10% of the maximum value of the DDM and higher thresholds to 60%. Then, the normalized DDM volume is defined as the area (chip x Hz) multiplied by the normalized power of the DDM overcoming these thresholds.

Theoretically with increasing integration time, the difference between the signal peak and the average noise value increases too. If a certain threshold is selected, for low integration times the difference between the signal peak and the noise floor is small, and the noise floor overcomes the threshold. In this case, when computing the volume, it will be higher than the expected one. But if the integration time increases, only useful signal will be over the threshold, and the volume falls down. Then, with a progressively increasing of the integration time, the volume also increases and tends to stabilize.

Figure 9.8 shows the volume analysis of each DDM versus the value of the integration time. Observing the ice raw data processing (Figure 9.8c) makes evident that in practice the behavior of this study is exactly the expected one: from a certain integration time, the volume of the figure that overcomes any of the thresholds defined is kept practically constant. Before this minimal integration time, which defines the basic DDM unit, the volume of the figure that overcomes each threshold has a certain fluctuation due to a high level of noise that is still over the marked threshold.
Figure 9.8 DDM volume vs. incoherent integration time for different threshold values over each surface type: (a) ocean, (b) land and (c) ice.
From Figure 9.8 it can be inferred that over ice and over land the volume is a good criteria to determine the basic DDM unit, because the volume stabilizes from one set integration time for each surface type. So, a basic DDM unit should be defined over ice around 7-8 ms (Figure 9.8c), while over land the basic DDM unit will be set around 45 ms (Figure 9.8b). Doing the same analysis over ocean surface, the basic DDM unit stabilizes around 90 ms (see Figure 9.8a), although the results are not as clear as in both other surfaces, probably because of ocean surfaces are more dynamic than land and ice surface in terms of dispersion, and the DDM power fluctuates.

Statistical analysis

The third way proposed to determine the basic DDM unit is by means of a statistical study of one point in the DDM (in this work the study has been done in two points, the one closest to the maximum, and one of noisy zone). The main idea is departing from the entire strip of information to obtain the DDM corresponding to every millisecond and then accumulate them in groups with lengths defined by the integration time.

If the real and imaginary parts of the received signal correspond to two independent Gaussian distributions, the received signal amplitude will be a Rayleigh. The mean and variance of a Rayleigh random variable may be expressed as:

\[
\mu(x) = \sigma \frac{\pi}{\sqrt{2}}, \hspace{1cm} (9.4)
\]

\[
var(x) = \frac{4 - \pi}{2} \sigma^2. \hspace{1cm} (9.5)
\]

The Rayleigh distribution is a particular case of the Rice distribution, when no signal is present, and there is only Gaussian noise. Therefore, in theory, when the integration time corresponds to the lowest value (1 ms coherent integration), the expected distribution is a Rayleigh probability density function (pdf). As the integration time approaches the DDM’s basic unit, the probability density function will progressively behave as a Rice distribution.
Figure 9.9 Histograms of the DDM over three surfaces: (a) ocean with $T_i = 1$ ms, (b) ocean with $T_i = 20$ ms, (c) land with $T_i = 1$ ms, (d) land with $T_i = 20$ ms and (e) ice with $T_i = 1$ ms, (f) ice with $T_i = 20$ ms.

From the statistical analysis it is very difficult to determine the basic DDM unit, but based on it a quality map (based on the dominant distribution) for the DDM can be obtained. It can be determined if the resulting DDMs too
noisy or a real DDM is present. The main drawback of this analysis comes from the fact of the pdf changes do not occur instantaneously.

Conclusions

The analysis of the DDM's volume is the clearest of all the proposed ones to determine the basic DDM unit (minimum incoherent integration needed to obtain meaningful information). From these results, it can be stated that its value becomes stable from 8 ms over ice, from 45 ms over land, and 90 ms over ocean. The statistical analysis does not provide any significant information except to monitor the presence or not of a DDM in the noise. More data is needed to be processed to generalize this study, but SSTL has not agreed to release it.

9.1.3 PAssive Reflectometry and Interferometry System (PARIS) In-orbit Demonstrator (PARIS IoD)

9.1.3.1 The Concept

The passive reflectometry and interferometry system (PARIS) concept was originated by Martin-Neira in 1993 in the European Space Agency (ESA), Noordwijk, The Netherlands, in 1993 as a novel method to perform mesoscale ocean altimetry. The PARIS concept [15] uses signals of opportunity such as the signals from the global navigation satellite systems (GNSS), which are reflected off the ocean surface to perform mesoscale ocean altimetry. Opposed to classical GNSS-R, where signals are cross-correlated with locally generated replicas of the C/A code, in PARIS IoD the direct and the reflected signals are cross-correlated. Essentially, the relative delay between the direct and the reflected signals received from a Low Earth Orbit satellite providing information about sea surface height.

In order to test the feasibility of the PARIS concept some experiments have been carried out. The first one was performed off the 5022-m-long Zeeland bridge [30] on the Dutch coast - the longest in the Netherlands - in July 2010.
The two-sided antenna picked up the signals coming from the GNSS satellites from above and their reflected counterparts from below. Correlating the two together turned out to give a measure of sea surface height to an accuracy of 5 cm. One of the first results obtained can be seen in Figure 9.11, [30].

9.1.3.2 Contribution to Altimetry Study: Experiment from Aircraft Measurements (AirborneGNSS-Reflectometer)

A lot of work has been carried out in altimetry applications of GNSS-R [29], [31]. This section presents another contribution to the altimetry retrieval using GNSS-R techniques but from a small remote control aircraft. First, the structure and characteristics of the developed GNSS-R Reflectometer are explained. Then, the classical approach for altimetry is explained using
the measurements obtained with a vector signal generator in order to validate the system, and the ones obtained on an experimental field campaign. The PARIS IoD approach in considered to be applied to the measurements and the feasibility is studied. Finally, the conclusions are presented.

9.1.3.2.1 The GNSS-R Reflectometer Onboard

The GNSS-Reflectometer is mainly composed of two antennas, one antenna for the direct signal and one antenna for the reflected signal. These two antenna signals are combined, amplified, downconverted and sampled at 8.18 MHz. The GNSS-Reflectometer is a small instrument suitable for airborne applications, such as a radio control aircraft (Figure 9.12) developed and piloted by the UPC’s professor Albert Aguasca.

![Image of a radio control aircraft with antennas labeled RHCP and LHCP, and a circle around the electronics of the aircraft.](image)

Figure 9.12 GNSS-Reflectometer over the Radio control aircraft platform.

The raw GPS data is collected using an USB interface and stored into a binary file in the on-board computer.

Then, applying GNSS-R signal processing techniques, the measured direct and reflected signals are simultaneously correlated with a local replica of the PRN code, to compute the Delay-Doppler Map (DDM) [20]. This DDM has two peaks (one is due to the direct signal and the other to the reflected signal). In order to visualize them, the radio control aircraft must fly high
enough to separate in delay samples the reflected signal from the direct signal, avoiding that the direct signal masks the less intense reflected signal.

9.1.3.2.2 Classic Approach

9.1.3.2.2.1 Theoretical simulations

The expected product given by the GNSS-Reflectometer is two DDM peaks coming from the same satellite, but one delayed with respect to the other, due to the differences in the paths covered, and one has a smaller amplitude than the other, due to the reflectivity of the surface over which the GPS signal is scattering. In order to emulate these measurements a vector signal generator has been used, SMU 200A Vector Signal Generator from ROHDE SCHWARZ [128].

*Signal levels and incoherent integration time*

The level of the two signals is different due to the fact that the reflected signal comes from the surface over which has been scattered and affected by their reflectivity. So, that the reflected signals is expected to be powerless than the direct signal.

In order to consider the received signals as quality enough signals, the minimum SNR that must be reached is 5, following the Rose criterion [127], Eqn. (9.2). The weaker the reflected signals is, the larger is the incoherent integration time needed to achieve a SNR >5.

In Figure 9.13 a number of measurements with synthetic data has been performed considering the reflected signal some dB lower than the direct one and the corresponding SNRs has been computed by increasing the incoherent integration time. As it can be seen when reflected signal is attenuated 2 dB respect to the direct one the required coherence integration time is 1 ms, but in the extreme case where reflected signal is 15 dB lower than the direct one, 16 ms incoherent integration is needed.
Figure 9.13 Simulated direct signal SNR and espascular reflection signal SNR considering: reflected signal (a) 2 dB, (b) 4 dB, (c) 6 dB, (d) 9 dB, (e) 12 dB and (f) 15 dB lower than direct signal.

**Instrument height and DDMs separation**

Depending on the aircraft altitude and the surface topography the distance covered by the reflected signal can be greater or smaller. The path difference
(\Delta y) between the direct and the reflected signals translates in a delay difference ($N_{\text{samples}}$) in the DDM obtained, eqn. (9.6).

\[
\Delta y = \frac{c}{f_s} \cdot N_{\text{samples}} = \frac{c}{f_s} \cdot \left(\frac{N_{\text{chips}}}{1023}\right) f_s,
\]

where $c$ is the light speed and $f_s$ is the sampling frequency of the GNSS-Reflectometer, and $N_{\text{chips}}$ is the number of chips in one period.

Figure 9.14 Simulated direct signal and specular reflection signal by introducing a delay in the reflected signal of (a) 0.5 chips, (b) 1 chip, (c) 1.5 chips, (d) 2 chips, (e) 2.5 chips and (f) 3 chips.

Figure 9.14 shows the simulation of the two peaks (direct and reflected) splitting as a function of the number of chips introduced. As it can be seen,
reflected signal must be at least 2 chips apart to be able to avoid overlapping between direct and reflected signals. Since \( f_s = 8183.86 \, MHz \) and computing Eqn. (9.6), a path difference of \( \Delta y = 582 \, m \) is achieved, which is equivalent to a flight height of \( h_{\text{flight}} = \Delta y/2 = 293 \, m \). Therefore the minimum flight height required is 293 m.

The resolution of the system is 1 sample, which is equivalent to 18.33 m height. This resolution obtained from the delay of the DDM peaks could be improved using the phase of the DDM peaks.

9.1.3.2.2 Experimental Results

Field Experiment Setup

In order to acquire some raw data a field campaign was performed over an airfield at Ripollet, Spain, on June 29\(^{th} \), 2009. Figure 9.15 shows the aircraft trajectory (blue dots) and the GNSS-Reflectometer successful measurements in which both peaks are present (named as “shots” and marked in yellow colour).

![Figure 9.15 Aircraft trajectory (blue dots) and the SiGe-based reflectometer successfully shots (yellow dots)](image)

The main data for the aircraft attitude and altitude has been acquired using X-sens MTi-G sensor [129], a unitat GPS Inertial Measurement Unit (GPS-
IMU) that gives the aircraft attitude, from now on X-sens. The attitude (roll and pitch angles) are shown in Figure 9.16, and also an image of the aircraft during the flight.

![Aircraft attitude for GNSS-Reflectometer shots](image)

**Figure 9.16.** (a) Attitude (roll and pitch angles), (b) aircraft image in flight

**Results**

Some of the successful shots are shown in Figure 9.17. Each one of the measurements has required a different incoherent integration time in order to achieve enough SNR (see Figure 9.17 plot headers). The number of samples between the direct and reflected signals has been obtained and the equivalent flight height has been computed using the rationale explained before (Figure 9.18). The differences are due to the following reasons:

- X-sens gives altitude in WGS-84 (World Geodetic System, respect to the geoid) while GNSS-Reflectometer gives the topographical distance (respect to the ground surface).

- X-sens gives the altitude respect to the gravity vector while GNSS-Reflectometer gives the distance to the point where signal is reflected. It means that, due to the elevation and azimuth angles of the satellites, the reflectometer measurement does not have to match the X-sens data point. This difference can be corrected by knowing the satellites position, but this information was not available in the field experiment.

Pitch and roll angles must be as close to zero as possible to avoid undesirable antenna effects.
Figure 9.17 Two peaks DDMs obtained in shot number (a) 1, (b) 6, (c) 7, (d) 12, (e) 17 and (f) 19.
Figure 9.18 X-sens ground truth vs GNSS-Reflectometer retrieved heights.

9.1.3.2.2.3 Conclusions

The main conclusions extracted from theoretical simulations have been summarized using Figure 9.19.

Figure 9.19 Main conclusions obtained: (a) Required incoherent integration time as a function of the power difference between direct and reflected signals, and (b) equivalent receiver altitude as a function of the distance between direct and reflected peaks.

Figure 9.19a shows the relationship between the power difference and the incoherent integration time needed to obtain quality DDMs. This relationship follows a third order polynomial approximation. Figure 9.19b shows the linear relationship between altitude as a function of the distance between direct and reflected peaks.
From the experimental results it is concluded that topography retrieval can be achieved using the GNSS-Reflectometer, but some improvements must be done to the experimental setup in order to give accurate results: as knowing the topography, to validate the retrieval, and having information about satellite elevation and azimuth, to better assign the retrieved heights to surface location.

9.1.3.2.3 PARIS IoD Approach

The PARIS IoD approach was thought to be applied to the measurements obtained from aircraft. Instead of using direct signal to correlate with reflected signals, as in PARIS concept, it was proposed to autocorrelate the signal measured from aircraft, containing both the direct and the reflected. The expected result is a high peak centered at 0, due to the direct signal, and two replicas at $\pm \tau_d$, the distance between direct and reflected signals due to the path difference. Two replicas appear because autocorrelation is a symmetric function.

Figure 9.20 shows the result of the autocorrelation of the measured signal (the PARIS IoD approach, Figure 9.20a) and the correlation of the measured signal with the corresponding CA code (classical approach, Figure 9.20b).

![Figure 9.20](image)

Figure 9.20 DDM obtained from real measurements for (a) the correlation with CA code and (b) the autocorrelation.

Any replica can be observed in Figure 9.20a, but from Figure 9.20b it is clear that the reflected signal is present. Same simulation is made using synthetic signal instead of real measurements, Figure 9.21. Recall that synthetic signal was created using the vector signal generator [128].
Figure 9.20 and Figure 9.21 prove that the concept cannot be applied. In order to understand the reason for that and since it is impossible to deduce anything from the real/synthetic data, a new signal has been constructed based on a C/A code to emulate that signals and to have the control over the different components.

\[ s(t) = CA_{id_29}(t) + \beta \cdot CA_{id_29}(t - \tau_d) + \alpha \cdot n(t) \quad (9.7) \]

where \( \tau_d \) is the delay between both, the direct and the reflected signals. \( \beta \) and \( \alpha \) are two coefficients that accounts for the reflected signal coefficient and the noise level, respectively. The noise has been constructed using \( CA_{id_1} \) with no delay to ensure that the noise has the same bandwidth than the signal. It is not taken into account any Doppler since the signal is going to be autocorrelated. The optimal situation is when \( \beta = 1 \) and \( \alpha = 0 \). In Figure 9.22 the autocorrelation is computed for no noise \( (\alpha = 0) \), and varying the power of the reflected respect to the direct \( (\beta) \).

Figure 9.22 Autocorrelation considering no noise \( (\alpha = 0) \) at eqn. (9.7) for different values of \( \beta \).

As it can be seen from Figure 9.22, when there is no noise considered, and the reflected signal has the same power than the direct signal \( (\beta = 1) \), the
replica due to the reflected signal can be perfectly detected at $\pm r_d$, exactly what was expected to get from real measurements autocorrelation. But, as the power of the reflected signal decreases, the replicas loose power. When the reflected signal power is 10% of the direct power, the replicas are under the noise and cannot be detected.

Now let us consider noise ($\alpha \neq 0$) (Figure 9.23).

![Figure 9.23](image1)

**Figure 9.23** Autocorrelation considering different levels of noise ($\alpha$) at (9.7) for (a) $\beta = 1$, (b) $\beta = 0.5$ and (c) $\beta = 0.1$

As it can be seen in Figure 9.23, when noise increases the reflected peak decreases. For example, when $\beta = 1$ the peaks can be detected up to $\alpha = 3$ (SNR $= -9$ dB), but when $\beta$ decreases even low noise causes the no detection of the peaks ($\alpha = 2$, SNR $= -12$ dB).

Figure 9.24 shows a comparison between the different autocorrelations.

![Figure 9.24](image2)

**Figure 9.24** Comparison between the autocorrelation of the real signal and a clear CA code.
As it can be seen in Figure 9.24, the acquired signal has more bandwidth since it decorrelates faster than the C/A replica.

Due to the low SNR of the acquired signal ($\alpha$) and the relationship between the direct and the reflected signal ($\beta$) it will not be possible to observe two peaks on those signals, unless the SNR of the acquired signal is increased. Figure 9.25 shows the autocorrelation of the signal $s(t)$ at (9.7) and the correlation of the signal $s(t)$ with the clean C/A code, considering a noisy signal ($\alpha = 4$) and relationship between direct and reflected signal levels of the 50 % ($\beta = 0.5$).

![Figure 9.25 Simulation performed using $\alpha = 4$ and $\beta = 0.5$ for the autocorrelation of the signal $s(t)$ at (9.7) and the correlation of the signal $s(t)$ with the clean C/A code.](image)

As it can be seen in Figure 9.25, when correlating with a clean code for the same PRN, both peaks, the direct and the reflected, are observed (as it was shown in Figure 9.20b and Figure 9.21b), but when performing the autocorrelation only the peak due to the direct can be seen over the noise (as it was shown in Figure 9.20a and Figure 9.21a).

### 9.1.4 Passive Advanced Unit / National Institute for Aerospace Technology $\mu$satellite-1 (PAU/INTA $\mu$sat-1)

On December 2006 a simplified version of the griPAU instrument [65] (Figure 2.6), (with only one receiver front-end) was submitted to the Call for Ideas for Secondary Payloads aboard the SeoSat satellite (now renamed as INGENIO) [126]. It was selected for Phase A study, which was carried out by Mier Comunicaciones, EADS-CASA Espacio and NTE (Spain), but due to accommodation problems, it did not undergo in Phase B. During 2009, INTA offered a launch of opportunity in INTA’s MicroSat-1 satellite and a second Phase A was conducted by AD Telecom (Spain) to analyze the feasibility of
fitting an even more simplified version of the PAU-instrument concept (Figure 9.26).

Figure 9.26 INTA MicroSat-1 artist’s view showing PAU’s nadir-looking 8-element LHCP antenna.

The radiometer is operated as a Total Power Radiometer (instead of a pseudo-correlation radiometer) with frequent calibration, and the GNSS-Reflectometer is operated while the receiver is connected to the antenna. PAU in INTA MicroSat-1 includes two redundant receivers and two digital processing boards based on Virtex-4 FPGAs for on-board quasi real-time processing of full DDMs, in-orbit reconfigurability and reprogramming capabilities [130]. The combination of the up-looking antenna channel in the down-looking one through a coupler not only saves one receiving chain, but allows to perform amplitude absolute calibration, relative measurements of scattering coefficients, altimetric measurements etc. It is foreseen to finalize the integration and testing of the Engineering Model (EM) by the end of 2011, and the Flight Model (FM) by the first half of 2012. The EM will then be available for ground-based, airborne or eventually space-borne (e.g. from the International Space Station(ISS)).

9.1.4.1 Contribution to PAU/INTA μsat-1 Data Analysis.

This Ph.D. Thesis was actually inizited in the frame of SeoSAT/INGENIO and focused during the first year on the study the GNSS-R techniques from space in order to understand the main concepts related to them. As mentioned before, due to accommodation problems, it did not undergo in
Phase B and this Ph.D. Thesis had to change the topic focusing on the IPT and the SMIGOL-Reflectometer, explained in all previous chapters, and leaving the initial spaceborne GNSS-R studies performed as a small contribution inside the amount of works and advances that were and are being made. The main contribution here was the development of a simulator that was the tool to perform the study, [42], presented in the J.F. Marchan-Hernandez's Ph. D. Thesis. Here the simulator is shortly presented.

The simulator was implemented in MATLAB, and allows to create an Earth scenario composed of GPS satellites broadcasting over the Earth and another satellite (SeoSAT/INGENIO or in the present PAU/INTA μsat-1) receiving the reflections and computing the DDMs for the different GPS satellites. The SeoSAT satellite's orbit was not yet determined at the time of performing the study, but a polar (inclination = 98.9°) circular orbit with a height of 681 km (v = 7.5 km/s) was assumed. The orbital elements of the GPS satellites were obtained from data given by “Center for Space, Standard and Innovation” and the GPS satellites and SeoSAT relative geometry was computed in 20 seconds steps. PAU’s antenna consists of a 7 patch hexagonal array with a beamwidth (-3dB) of ~25°, providing a footprint of ~260 km, that best matches the glistening zone at medium wind speeds. The main parts of the simulators to obtain the DDMs are the follow ones:

- Search of the visible GPS satellites in an Earth-observation satellite geometry and the GPS satellites position into the constellation (Figure 9.27 and Figure 9.28).

![GPS Satellites found at arbitrary position of an Earth-observation satellite](image)

Figure 9.27 GPS satellite in the field of view of the Earth-observation satellite.
Figure 9.28 GPS satellites in the field of view of the Earth-observation satellite.

- Incidence and reflection geometry study in the full Earth observation area of an Earth-observation satellite.

Figure 9.29 Scattering geometry and definition of variables.

- GPS signals power distribution above the Earth’s observation area, obtaining the Delay-Doppler-Maps (DDM) using the convolution method [42], the delay and Doppler distribution of the signals coming from the GPS satellites that are detected by the antenna of the instrument on board of the Earth-observation satellite (Figure 9.30).
In order to relate the DDM with the brightness temperature change induced by the sea state ($\Delta T_{B,p}(\theta, \phi)$), it is important to extract from the DDM some physically meaningful parameters that can be linked to this change. As was presented in [42], a good descriptor is the volume under the normalized DDM, which increases with increasing roughness, since the region from which the signals are scattered enlarges:

$$V_{\text{DDM}} = \int_{\tau_{\text{min}}}^{\tau_{\text{max}}} \int_{f_{d_{\text{min}}}}^{f_{d_{\text{max}}}} \overline{\text{DDM}}(\tau, f_d) \cdot d\tau \cdot df_d,$$

(9.8)

where $\tau_{\text{min}}, \tau_{\text{max}}, f_{d_{\text{min}}}, f_{d_{\text{max}}}$ are the minimum and maximum values for the code offset and Doppler shift respectively, and $\overline{\text{DDM}}(\tau, f_d)$ is the normalized DDM.

In order to study the relationship between the DDM volume and the sea state (in these set of simulations parameterized in terms of the wind speed only), a threshold at a given percentage of the maximum value has been defined, setting all points below it to zero. Figure 9.31 shows the results for wind speeds from 3 to 14 m/s, and different thresholds.
Figure 9.31 DDM volume related to the wind speed of the surface.

As expected, the volume decreases as the threshold increases, and the lower the threshold, the larger the sensitivity (largest output change for same input change) with respect to the wind speed. Similarly, the $\Delta T_{B,p}(\theta = 0^\circ, U_{10})$ (increase of the brightness temperature for the p polarization at nadir position as a function of the surface wind speed $U_{10}$) associated to the same roughness conditions was computed as described in [132]. It is then possible to link the DDM with the $\Delta T_{B,p}(\theta = 0^\circ, U_{10})$, which can be used to compensate for this term in the sea surface salinity retrieval algorithms. At present, this dependence is only empirically known with respect to the wind speed and/or the significant wave height [96], [131] or through models [133] that rely on the wind speed dependence (and eventually others such as the wave age [118] and other surface processes [134]). Even though $\Delta T_{B,p}(\theta, V_{\text{DDM}})$ will only be known when the DDMs and the brightness temperatures are measured simultaneously, an estimate can now be obtained by using the wind speed as intermediate variable $\Delta T_{B,p}(\theta, V_{\text{DDM}}(U_{10}))$. 

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Figure 9.32 DDM volume related to the $\Delta T_s$ of the surface.

This relationship is shown in Figure 9.32, which have been obtained by replacing in Figure 4 the wind speed dependence of the L-band brightness temperature at nadir derived using the Small Perturbation Method/Small Slope Approximation (SPM/SSA) [118], [135] (Figure 9.33).

Figure 9.33 $\Delta T_{Bp}(\theta = 0^\circ, U_{10})$ as a function of wind speed computed with the SPM/SSA method and Elfouhaily’s sea surface spectrum [118].
9.2 Conclusions

Global Navigation Satellite System Reflectometry (GNSS-R) has shown its potential to retrieve geophysical parameters over the ocean, mainly altimetry and sea state, and over land, mainly soil moisture. For that reason all these missions are important and relevant to keep on performing scientific studies at a global scale. The related studies of the present Ph.D Thesis are modest contributions to the work that has been or it is being performed for the RSLab and many other researching groups.
This chapter summarizes the main conclusions of the work developed during this Ph.D. Thesis. A general conclusion and the future research lines are also presented.
10.1 Summary

GNSS Reflectometry (GNSS-R) is nowadays a convenient tool for remote sensing of the Earth, which is receiving more and more interest. A lot of effort and work have been performed since it was first proposed for altimetric applications [29].

This Ph.D. Thesis has presented some contributions to Earth observation using GNSS opportunity signals. The innovation of the Ph.D. Thesis is mainly the development of a new ground-based instrument (the Soil Moisture GNSS Observations at L-band (SMIGOL) reflectometer) to apply an original and simple technique (the Interference Pattern Technique or IPT) over a number of different scenarios that, after performing some field experiments and acquiring real data, have produced very good results on the retrieval of geophysical parameters.

Although this is the main core of the Ph.D. Thesis, parallel studies have been performed to retrieve other geophysical parameters, as:

- the vegetation water content, that required a specific instrument also designed and developed during the Ph.D and a field experiment to validate the GNSS-Transmission (GNSS-T) technique, and

- the wind speed over the ocean that was part of an international collaboration at the Earth System Research Laboratory (ERSL) in the National Oceanographic and Atmospheric Administration, at Boulder, Colorado, USA.

The IPT has been presented as a new technique to measure the surface’s soil moisture based on the power variations of the interference signal between the direct and the reflected GPS signals:

- a simple soil moisture retrieval algorithm has been devised based on the position of the notch of the interference pattern at v-polarization and the amplitude of the oscillations of the pattern, and

- experimental data over a bare soil field has been presented to validate the technique, and

The effect of vegetation has also been studied, and the data processing of different field campaigns, including the vegetation growth stages and different crops, has been performed. New retrieval algorithms have been developed and topography, vegetation height, and soil moisture retrievals
over vegetation-covered soils have been validated using these experimental data.

The effect of vegetation water content has been also studied by implementing a different technique, the GNSS-T. Specifically, this technique has been used to retrieve the water content of the leaves of a walnut-tree field. This was accomplished by computing the differential attenuation of the signals received by two receivers (open sky and under vegetation). Then, the $b$-factor has been computed to relate $\tau$ and LWC. It has been demonstrated that this factor depends not only on the type of vegetation (different for trunks and branches), but also on the homogeneity of the observed area. In order to consider the whole range of measurements it would be necessary to get a more accurate ground-truth, not only for leaves, but also for the trunk and branches, and then compute the whole walnut-tree equivalent water content as a function of elevation angle.

The IPT and the SMIGOL-Reflectometer have been validated and are powerful tools to monitor the water level of reservoirs and lakes as well. The algorithm developed, based on the speed of the oscillations of the interference powers, retrieves the water level with centimeter accuracy.

Over snow-covered surfaces, the IPT can also retrieve the snow height. Due to the variability of the snow accumulation in scenarios as a mountain, the previously used algorithm based on the inspection of notches (in terms of positions and the number of them) cannot be directly used. Therefore a new semi-empirical algorithm, more realistic in terms of applicability, has been theoretically implemented and tested in a long field experiment retrieving snow thickness maps in the Pla de Beret at Comalada Mountains (Vall d’Aran, Lleida, Spain).

The IPT cannot be applied from an aircraft or over ocean surface which requires the use of techniques based on Delay-Doppler Maps (DDM) to retrieve ocean winds. The results of the work processing the I and Q data collected with CU GNSS multistatic radar onboard the NOAA Gulfstream-IV jet aircraft, are shown. The DDMs were possible to obtain because of the relatively high altitude and speed of the aircraft. To some extent, this experiment can be regarded as a test for space-borne GNSS-R. The DDMs have been post-processed and analyzed by means of four different wind speed retrieval algorithms based on four DDM observable: weighted area, distance from the center of mass to the maximum position, distance from the geometrical center to the maximum position and taxicab distance from the center of mass to the maximum position. After choosing the most suitable coherent integration time and the threshold, the error of each
algorithm has been estimated. The most suitable one was found the taxicab distance from the center of mass to the maximum position, whose mean error and standard deviation are the lowest, and it gave the highest correlation with the ground truth. This algorithm has been used to further retrieve the wind speed during 2 hours and 15 minutes of flight producing wind speed data sampled at 5 minutes rate.

10.2 Final Conclusions

At the beginning of this Ph.D. Thesis, when performing the simulator of a space-borne GNSS receiver, the theory and the main concepts of the GNSS-Reflectometry were assimilated and a general idea of the GPS signals main interactions with the Earth were understood. Then, when SeoSAT/INGENIO did not undergo into phase B and the project left with no sense for a Ph.D. Thesis, a new idea came into our minds and, as it fit into the Ph.D. Thesis title “Contribution to Earth observation using GNSS-R opportunity signals”, we decided to investigate in that new direction.

The Interference Pattern Technique (IPT) was initially though for soil moisture monitoring. To implement that technique it was necessary to develop an instrument, which was called Soil Moisture Interference-pattern GNSS Observations at L-band (SMIGOL) Reflectometer. By building the instrument a lot of hardware and technical issues, as circuit design and suitability of components for the design, have appeared. The IPT and the SMIGOL-Reflectometer were used into several field experiments, a total of 6 long field experiments with the corresponding ground-truth data acquisition were performed. The real data acquired was used to develop the retrieval algorithms, testing the technique for several applications. What initially was though to retrieve the soil moisture of land has ended into a very useful tool to retrieve many other parameters, as topography, vegetation height of different crops, water level into reservoirs, and snow thickness of snow covered surfaces. In order to get information about vegetation water content other complementary GNSS technique have been implemented building a simple instrument to get GPS signals above and under vegetation layer.

Thanks to the initial learning process related to Seosat/INGENIO it has been possible to process the data from an aircraft flying over the ocean and new algorithms have been applied for wind speed retrieval, complementing the initial goals of this Ph.D. Thesis.
The algorithms developed for the retrievals are the complementary software part, the field campaigns carried out fulfil the experimental part, and finally, the results obtained are the validation of the hypothesis introduced at the beginning of this Ph.D. Thesis.

10.3 Future Work

The future research lines opened by the work presented in this Ph.D. Thesis are:

- The instrument developed during the Ph.D. Thesis, which has been the necessary tool to demonstrate all algorithms and get all the results can be improved. Currently a wireless 4-faces SMIGOL is being implemented by a new Ph.D student and it will be fully operational during 2012. Thinking in soil moisture, the idea is to enlarge the covered area converting the SMIGOL-Reflectometer in one of the intermediate steps global soil moisture monitoring: soil moisture probes – wireless 4-faces SMIGOL – aircraft measurements – satellite.

- Regarding to vegetation water content it could be interesting to test the technique into a maize field, one of the most moisturized plants. It has been tested in this Ph.D. Thesis under a walnut area, but crops grow and combined with the IPT and the SMIGOL-Reflectometer to extract the plant height, it could give very nice results.

- Another interesting idea related to the previous one is to perform a polarimetric study using Right Hand Circularly Polarized (RHCP) and Left Hand Circularly Polarized (LHCP) with a cross-polar component of at least -35 dB. During this Ph.D Thesis it was also tested, but the patch antenna used was not good enough. We realized about the exigent characteristics required for the experiment, and as it was not the main goal of this Ph.D. Thesis, we decided to leave the idea for the future.

- Regarding to water level monitoring, a pending issue is to test this technique over dumps or lakes. During the Ph.D. thesis it has been tested into a small reservoir very clean of geographic accidentals and also the receiver was located very close to the surface (~3 m).
The results obtained convert all these applications into promising applications, but a lot of work can still be done. This Ph.D dissertation is another contribution to the GNSS-R field which is expanding more and more every day and has a lot of people of around the world making efforts in performing studies, developing instruments and carrying out field experiments to test and validate concepts.
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Appendices

APPENDIX 1: Main descriptors for data fit

The main descriptors considered for the fit of the data are described below.

The Pearson correlation coefficient $r$ is defined as:

$$r = \frac{\sigma_{XY}}{\sigma_X \sigma_Y}, \quad (A. 1)$$

where $\sigma_{XY}$ is the covariance of the measurements vector and the ground-truth data vector, $\sigma_X$ is the variance of the measurements vector and $\sigma_Y$ is the variance of the ground-truth data vector. $P_e$ is the probability of error in the computation of the Pearson correlation coefficient. If $P_e$ is less than 5% then the correlation given by $r$ is trustable.

$R^2$ is the coefficient of determination of the statistical model, describing the tendency of the values to be a line instead of a cloud of points, and is defined as:

$$R^2 = 1 - \frac{SS_e}{SS_{tot}}, \quad (A. 2)$$

where $SS_e$ is the sum of squares of residuals and $SS_{tot}$ is the total sum of squares defined as:

$$SS_e = \sum (\tau_{measured} - \tau_{regression})^2, \quad (A. 3)$$

where $\tau_{measured}$ is the vector of measurements and $\tau_{regression}$ is the regression line of the vector of measurements.

$$SS_{tot} = \sum (\tau_{measured} - \bar{\tau}_{measured})^2, \quad (A. 4)$$

where $\bar{\tau}_{measured}$ is the mean of the vector of measurements.

Finally, the RMS error (RMSE) is the root mean square error computed as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N} (\tau_{measured_i} - \tau_{regression_i})^2}{N}}. \quad (A. 5)$$
Published work

JOURNALS


CONFERENCES


Co-advised Master thesis


Patents


  [Advanced algorithms for the Delay Doppler Maps (DDM) computation.]


  [An airborne system for soil moisture and vegetation water content measurement and implementation method.]


  [A system for geophysical parameters retrieval using navigation satellites’ signals.]