2 INTRODUCTION TO GNSS REFLECTOMERY

2.1 Introduction

The use of Global Navigation Satellite Systems (GNSS) signals reflected by the sea surface for altimetry applications was first suggested by Martín-Neira [12]. Since then, several applications based on a GNSS-R have been developed taking advantage of the high availability, stability and precision of GNSS signals. These retrievals have been performed using ground-based [13], airborne [14] and stratospheric sensors [15]. The GNSS-R approach has also been used to perform soil moisture retrieval [16] and ice characterization [17]. Other techniques than GNSS-R have also been tested for soil moisture purposes [6-10].

In this chapter, the basic concepts of GNSS-R are explained. First, a brief explanation of GNSS is given, followed by examples of the major existing systems. Later on, focus is given to the GPS (Global Positioning System) since it is the only navigation system currently being used in the context of this PFC. The understanding of the previous elements should give the reader enough material for the comprehension of reflectometry. At the end of the chapter, the Interference Pattern technique is briefly introduced.

2.2 Global Navigation Satellite System

Global Navigation Satellite System (GNSS) is the general name given to navigation systems making use of satellites for providing geo-localisation services to civilians and military. What makes it global is the fact that GNSS signals can be picked up anywhere on the surface of the planet as well as in the air and even in the highest layers of the atmosphere. GNSS satellites are deployed in geocentric medium Earth orbits – 2000 km to 35786 km – with large inclinations (with respect to the equatorial plane) to cover most of the planet.

Today, there is only one fully operational GNSS: the US-developed GPS system. It is the world’s most utilized system. Other systems are either in the process of being deployed or are in maintenance. Examples are GLONASS, developed by Russia and GALILEO, developed by Europe. Future GNSS receivers are supposed to be able to combine signals from all of the above system, giving an even better localisation precision. Table 2-1 below compares GPS, GLONASS and GALILEO:

	Operational by	**Inclination (°)**	**Number of planes**	**Altitude (km)**	**Number of satellites**
GPS	Now	55	6	20 200	32
GLONASS	2011 (plan)	64.8	3	19 140	24
GALILEO	2013 (plan)	56	3	23 222	30

Table 2-1 Comparison between GPS, GLONASS and GALILEO

Currently, GPS is the only system providing global coverage for free civilian use. Also, as it has been operational since 1993, GPS receivers are readily available on the market. Hence, it is the preferred GNSS for carrying out GNSS-R experiments worldwide. From this point onwards, the document will focus on the GPS.

2.3 Global Positioning System

2.3.1 Constellation

The GPS system is supported by a constellation of navigation satellites called the NAVSTAR. Those transmit precise microwave signals at L-band, which allow GPS receivers to determine their current location, the time, and their velocity.

The GPS orbit configuration was originally designed for 24 navigation satellites in 6 orbital planes. The *inclination* of such planes is 55° from the Equatorial plane ($\theta = 0°$). These orbits are equally spaced by 60° *right ascension of the ascending node* (RAAN). Figure 2-3 below depicts the parameters involved in describing the orbit. Inclination is the tilt of the orbital plane with respect to the Equatorial plane (containing the Equator). The ascending node is one of the two intersection nodes between the orbital plane and the Equatorial plane. It is the one node where the satellite is rising (moving North). The RAAN is the angle between the origin of longitude and the ascending node.

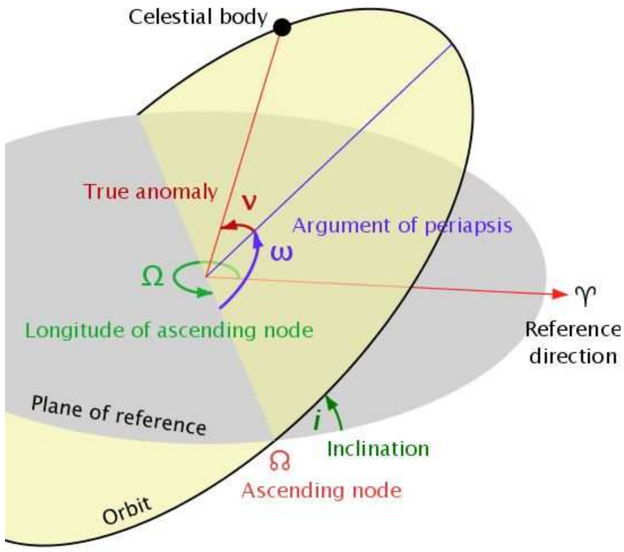

Figure 2-1 Parameters describing an orbit

In every orbital plane, there are four different transmitter satellites, non-equally spaced. Each satellite makes two complete orbits each sidereal day (23h56min) so that a user at any fixed point on Earth's surface sees exactly the same pattern of satellites everyday with a time-shift of 4 minutes (because the pattern is periodical in the sidereal time rather in the mean solar time, where a day lasts exactly 24 hours). This combined with the rotation of the Earth draws a fixed pattern of 24 ground tracks maintained within 2° from their normal values by the GPS control segment.

The orbits are nearly circular (eccentricity < 0.02) with a semi-major axis of approximately 26600 km, that is an altitude of about 20200 km above the Equator. The velocity of the craft is around 3.87 km/s.

The visibility of the constellation from the Earth depends on the latitude of the observer. Figure 2-1 shows the statistics of the visibility of the operational GPS-24 configuration from various user latitudes. A 5° elevation mask angle has been assumed. It is the angle below which satellites should not be tracked (normally set to 15 degrees to avoid interference problems caused by buildings and trees, but can be lower in an open field). Note that there are always at least 5 satellites in view with the GPS-24 configuration.

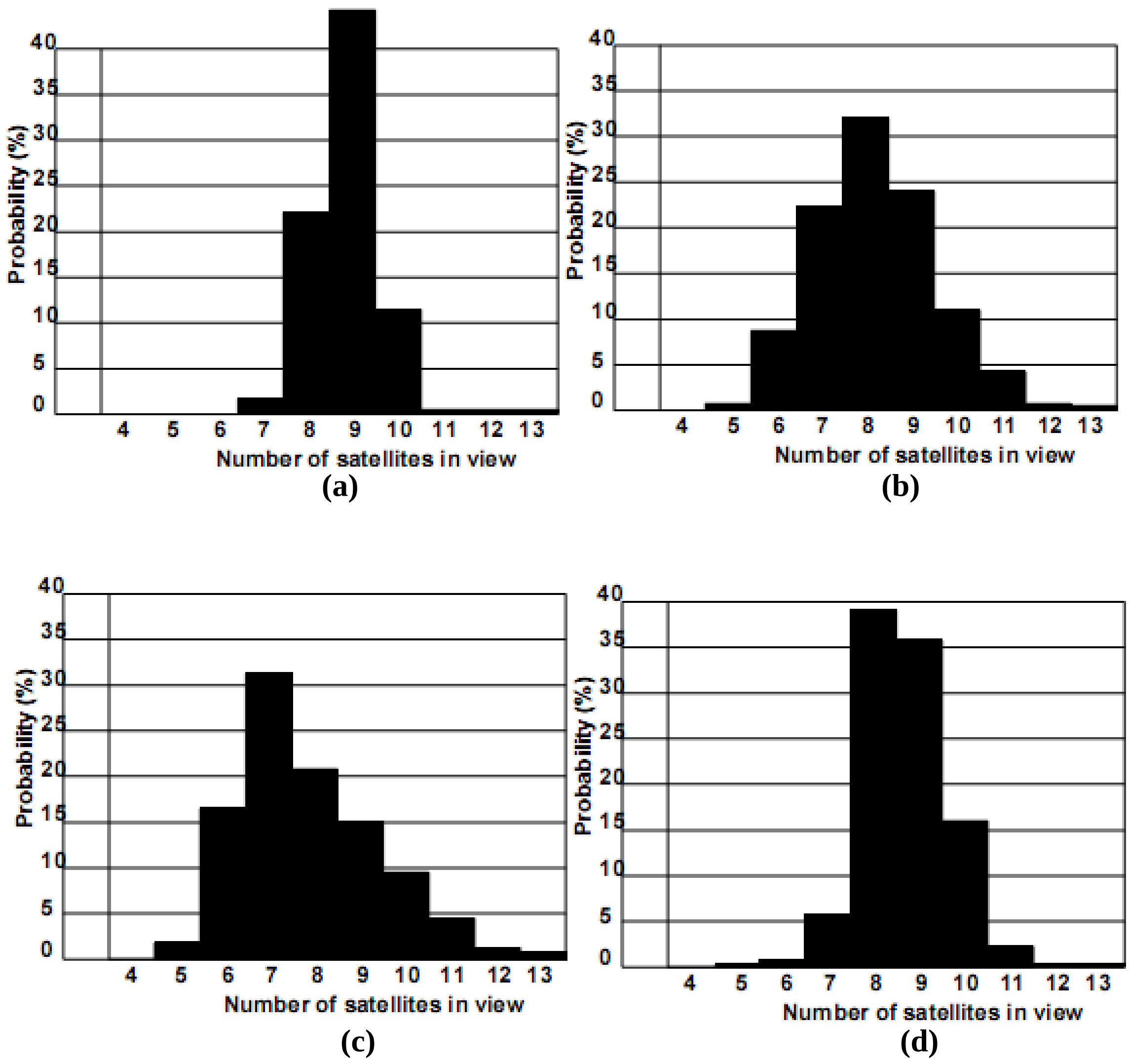

Figure 2-2 Statistics of the visibility of the operational GPS-24 configuration: (a) 0° (Equator) (b) 35° (c) 40° (d) 90° (Pole) – data from [Parkinson and Spilker Eds., 1996]

Note: Since March 2008, there are 31 actively broadcasting satellites in the GPS constellation, so that at least six satellites are always within line of sight from almost everywhere on Earth's surface.

2.3.2 Navigation signals

Satellites in the NAVSTAR constellation broadcast navigations signals in the L-band (390MHz – 1.55GHz), a spectrum band normally used for satellite communications and for terrestrial communications between satellite equipment. Currently, messages are broadcasted on two distinct carrier frequencies: 1.57542 GHz (L1 signal) and 1.2276 GHz (L2 signal).

The receiver can distinguish the signals from different satellites because GPS uses a code division multiple access (CDMA) spread-spectrum technique where the low-bitrate message data, i.e. the navigation message, is encoded with a high-rate pseudo-random noise (PRN) sequence that is different for each satellite. The receiver knows the PRN codes for each satellite and can use them to reconstruct the actual message data. The message data is transmitted at 50 bits per second.

Two distinct CDMA encodings are used: the Coarse / Acquisition (C/A) code, a 1023-bit long PRN at 1.023 million chips per second, and the Precise (P) code, a 6.1871×10^{12} bit-long PRN at 10.23 million chips per second. The L1 carrier is modulated by both the C/A and P codes, while the L2 carrier is only modulated by the P code. The C/A code is public and used by civilian GPS receivers, while the P code can be encrypted ton generate the P(Y) code which is only available to military equipment with a proper decryption key. Besides the redundancy and military purpose, a critical benefit of having two frequencies transmitted from one satellite is the ability to directly measure, and therefore remove, the ionospheric delay error for that satellite.

In this study, the signal used for investigation is the civilian one, i.e. the L1 signal. Figure 2-2 shows a block diagram representing the modulation of this signal.

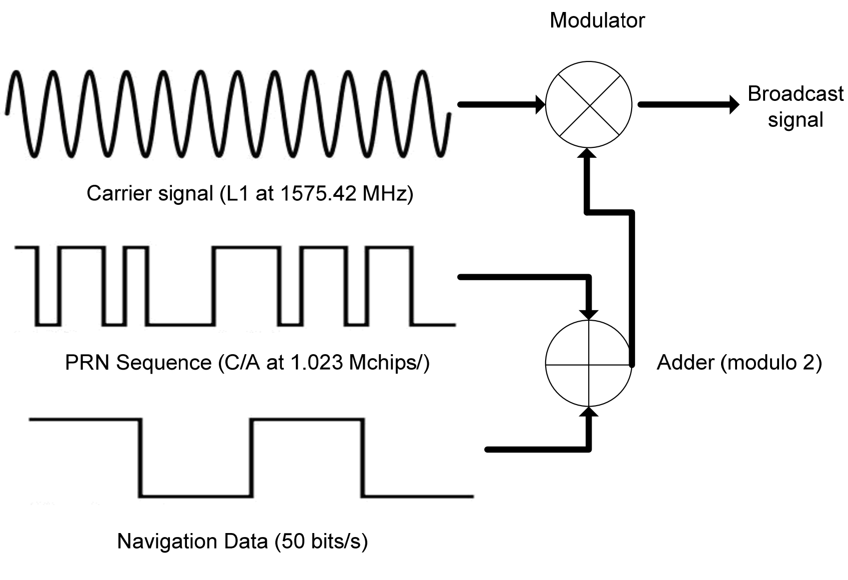

Figure 2-3 Modulation of L1 signal (1575.42 MHz)

2.3.3 Detection of the GPS signal

The GPS signal structure and constellation is designed to provide a positioning solution without any previous knowledge of neither the receiver location nor the constellation status. Since all of the satellite signals (civilian) are modulated onto the same L1 carrier frequency, there is a need to separate the signals after demodulation. The receiver produces the C/A code sequence for a specific satellite with some form of a C/A code generator. It then uses correlation to find a peak with a clean replica of a PRN C/A code. Once a peak is found, the receiver is able to track the C/A signal and thus decode the navigation data message. This quickly permits to locate the other satellite in view, and estimate their delay and frequency offsets to appropriately adjust the PRN C/A replicas. Therefore, the whole set of C/A signals gathered by the receiver antenna can be demodulated and the carriers locked: the primary GPS observables are tracked. The functional block diagram for the GPS receiver is shown in Figure 2-4.

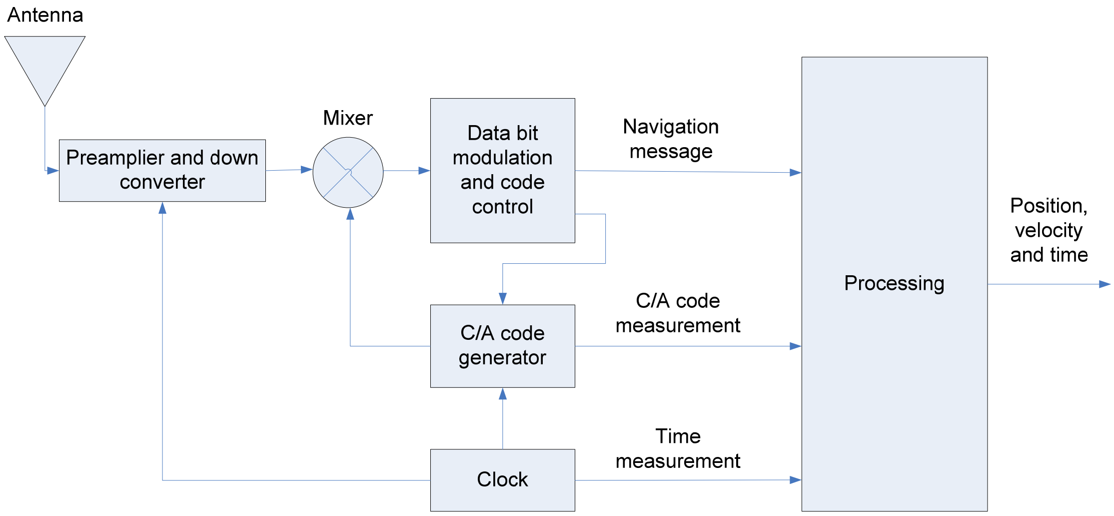

Figure 2-4 GPS receiver block diagram

To simplify, the emitted signal s(t) by a given satellite is composed of the following three components: the carriage frequency, the spreading code CA(t) and the navigation message N(t). After down conversion, we can describe the received signal in complex form by Eqn. 2-1:

$$s(t) = N(t) \cdot CA(t) \cdot e^{i2\pi \cdot f \cdot t} \tag{2-1}$$

By 2010, around fifty satellites will be orbiting Earth emitting navigation signals in the L-band, the spectrum band offering maximum sensitivity to soil moisture. More satellite coverage means creating larger soil moisture topography, thereby having a more precise model for climatic prediction.

2.4 GNSS Reflectometry

Traditional bistatic radar has been the dominating technique for remote sensing for many years. Today, a high number of GNSS satellites orbit our planet and many more are to come in the future such as those of the GALILEO constellation. These satellites provide a new kind of bistatic radar concept: the GNSS Reflectometry. Figure 2-5 below shows a configuration making use of this concept.

Figure 2-5 GNSS bistatic radar with the GPS satellite as emitter and the receiver onboard a plane

The use of GNSS-R for oceanography is very extensive since Martín-Neira has brought this technique to light [11]. Since then, there have been many investigations in this field [14, 18-21].

The use of GNSS-R over land is becoming more and more common and there are studies which have validated this technique for the retrieval of soil moisture [6-10]. Within those studies, the GNSS-R techniques have been implemented through various forms:

1. Retrieval from waveforms [6, 8, 10]
2. Retrieval from Delay Doppler Maps [7, 9]

2.4.1 Waveforms

Soil moisture retrieval by waveforms consists in measuring the direct GPS signal with a right-hand circularly polarized (RHCP) antenna connected to a GPS receiver and the reflected GPS signal by a left-hand circularly polarized (LHCP) antenna connected to another GPS. The reflected signal is then normalized with the direct signal. The mean power of the normalized reflected signal is directly related to the soil moisture. This is because the dielectric constant of the surface changes with soil moisture and therefore changes the characteristics of the reflected signal. By correlating mean power of the normalized reflected signal and the soil moisture in-situ, it is possible to determine the relationship between them and estimate soil moisture from power measures.

2.4.2 Delay Doppler Maps

The GPS signal is transmitted using a RHCP electromagnetic wave that, when scattered over wet surface, becomes left-hand elliptically polarized. Over flat land, the scattered signal comes from the specular reflection point, determined by the shortest distance between the transmitting GPS satellite and the receiver. However, when the soil is rough, the scattered signals come from a wider region that enlarges with increasing roughness. If the scattering surface is a plane, the loci of constant delay (isorange) are a set of ellipses, and the loci of constant Doppler shift (isoDoppler) are a set of hyperbolae. Therefore each point over the surface has a particular delay and Doppler (actually there are two points with the same delay and Doppler). Figure 2-6 below shows the geometry described.

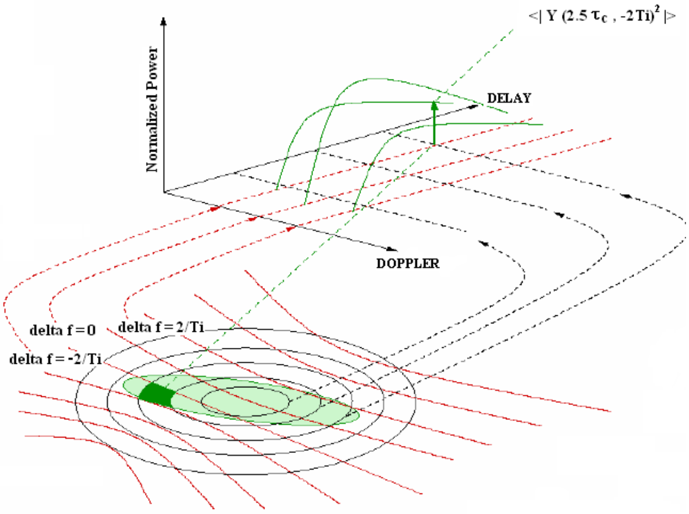

Figure 2-6 Each point over the surface is determined by isodopplers and isoranges.

In radar, the ambiguity function provides a measure of the similitude between a signal and a delayed version of it that may include a Doppler shift. It is a two-dimensional function of time delay and Doppler frequency $\chi(\tau,f)$ showing the distortion of an uncompensated matched filter due to the Doppler shift of the return from a moving target. For a given complex baseband pulse $s(t)$, the narrowband ambiguity function is given by Eqn. 2-2.

$$\chi(\tau, f) = \int_{-\infty}^{\infty} s(t)s^*(t-\tau)e^{-i2\pi ft}dt \qquad (2\text{-}2)$$

where * denotes the complex conjugate and i is the imaginary unit. Note that for zero Doppler shift ($f = 0$) this reduces to the autocorrelation of $s(t)$.

In GNSSR the equivalent to the ambiguity function in radar is known as a Delay Doppler Map (DDM), and consists of the power distribution of the reflected signal over the two-dimensional space of delay offsets and Doppler shifts. Therefore, the shape of the DDM is actually providing a measurement of the size of the area over which the GPS signals are scattered (also known as *glistening zone*). Thus, larger sizes mean that the received signal is composed by contributions from a wider range of propagation delays and Doppler shifts. The DDM of a rough surface is shown in Figure 2-7.

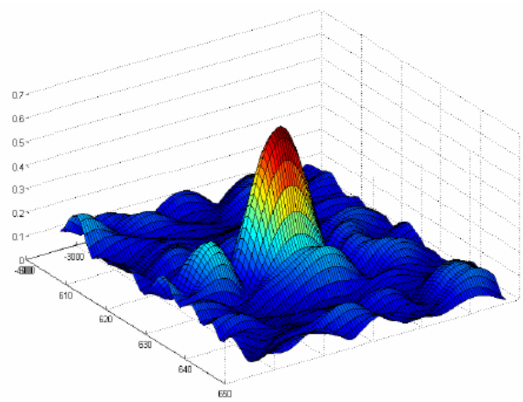

Figure 2-7 DDM of a roughed surface

DDM characteristics vary as a function of the geophysical parameters. If the DDM is not normalized the peak amplitude varies as function of soil moisture content and also the roughness of the surface. Tipically DDMs are normalized, so it can be retrieved the surface roughness (sea state or roughness of the soil) which mainly affects the width of the DDM.

2.4.3 Interference Pattern

In this PFC, the technique which will be used has been named as “Interference Pattern”. This technique has been validated previously although having other purposes and a slightly different configuration by Kavak [22-23], who mainly studied dielectric properties of soils. Furthermore, a recent study has been carried out for retrieving dielectric characteristics of materials such as polystyrene, styrofam and snow over a metal plane, following the Kavak work configuration [24]. The basic difference between those works and the ones developed by the RSLab [11] is the polarization of the antenna, which those works chose as a circular (LHCP) one and here is selected to be a linear polarization (V-pol and H-pol). Also, the final goal of the present work is the retrieval of the moisture by observing GPS satellites passing over a monitored site, so as to create a soil moisture map and secondly, generate simple topography maps of the site.