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IENAC 20 SAT

Rapport de stage d'insertion professionnelle

Acquisition d'un signal GPS L5 et d'un signal GALILEO E5

Réalisé du 06 juin au 09 septembre 2022 par

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à

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Acknowledgement

I wanted to thanks Boris PERVAN, the Head of Mechanical and Aerospace Engineering (MMAE) Department, to giving me the opportunity to do my internship in his department and who integrated me into an exciting project during a period of 14 weeks.

I would like to thank especially Sahil AHMED with whom I have worked closely, for his support, advice, mentoring and also the precious and varied knowledge he has given me.

And finally, I would also like to thank all the members of the navigation laboratory for welcoming me in their team and particularly Elisa GALLON for the precious advice about Chicago.

Contents

Introduction

The Illinois Institute of Technology is one of the 29 universities of Chicago specialized in science, technology and engineering. This university is also composed of several research laboratories. I had the chance to do my internship in the navigation research laboratory directed by Dr. Boris PERVAN and helped by Dr. Samer KHANAFSEH. The navigation laboratory is composed of four PhD students and of two master students. My internship involves helping one of the PhD students over the summer.

The student with I worked with was Sahil AHMED. His thesis consists in the detection of the spoofing in a GNSS signal. For now, he is primarily working on the detection on the GPS L1 and the GALILEO E1C signal. My goal was to compute the acquisition of the GPS L5 and Galileo E5 signal to extent the spoofing detection on all the constellation of GNSS. And due to the specificity of the four signals mentioned is this introduction, the acquisition of all four will allow the acquisition of all the GNSS signal.

So, as during 14 weeks I integrated the research team of the navigation laboratory, this internship report is written as a research report. The first part of the report states the understanding required in order to perform the acquisitions demanded. And the second part presents the results of the acquisition of the two signals.

Chapter 1

State of the Art of the acquisition of a GNSS signal

The aim of this Chapter is to describe the several signals use today of two of the main GNSS system, GPS and GALILEO, and to understand how this signal are received.

1.1 The creation and the acquisition of GPS L1 Band signal

The GNSS signals are generated to be singular among all the other signals a receiver can get. First, all GNSS signals include a very high frequency about hundreds of MHz. This very high frequency allows the receiver to search the signal in a particular bandwidth where few signals are emitted. Secondarily, these signals are generated with a code called the PRN code or Pseudo-Random Noise code. These signals are specific because they look like random signals. The aim is to prevent the signal from interfering with other similar signals which could lead to the destruction of the emitted GNSS signal. Finally, the GNSS signal also carries data.

The differences between all the GNSS signals is how this two or three components are modulated together to be properly received and process by the receiver.

1.1.1 A GPS L1 Band signal

General presentation

Global Positioning system known as GPS is one of the first navigation satellite system to become operational with GLONASS, its Russian homologue. Both these GNSS had been developed in a first place for a military use during the Cold War. It began having a civil use in the late 1980s [1].

The GPS L1 band has a center frequency of 1575.42 MHz and provides various services where the two main are P(Y), only for a military use and C/A which also has an military use but the essential use of it is for a civil application. The L1 band has three main components: a carrier emitted at the center frequency, a navigation data signal and a spreading code signal which is called the C/A code.

For the rest of the rapport, the L1 band will focus exclusively on the study of civil part C/A because it is the only one which is open-source.

The carrier of the signal is merely a sine wave at the center frequency of 1575.42 MHz.

For a GNSS use, the navigation data contains the ephemeride of the satellite sending them which mean its position and its velocity. This signal represents a sequence of bits that can take the value +1 or -1. This navigation data is unknown for the receiver because the satellite is continuously moving around the Earth [1]. All the data signal emitted in the GPS L1 band has a data rate of 50 symbols per second (bps) and a data symbol duration of 20 ms [2].

A spread spectrum code is unique and known for each satellite and enables the authentication of this one. They are the Pseudorandom Noise codes. These codes are a row of +1 and -1, that are called chip, and the sequence is design so that the probability of the sign is $\frac{1}{2}$. Each chip is set randomly and independently of all the other chips [1]. This specific way to design the codes has benefits detailed in the section 1.1.3. All the spreading codes of the L1 band have a duration of 1 ms and a length of 1023 chips [2]. The chips represent the bits of the code. The convention is to call these bits, chips so it is clear that they don't carry any data.

All the information about the L1 band is presented in the Table 1.1 page 19.

BPSK Modulation

The modulation is a way to link the different parts of the signal together in order to send it as one signal from the satellite.

The modulation of the C/A service of the L1 band is Binary phase-shift keying modulation 1 or BPSK(1). This means the different parts of the signal are modulated as in the following Figure.

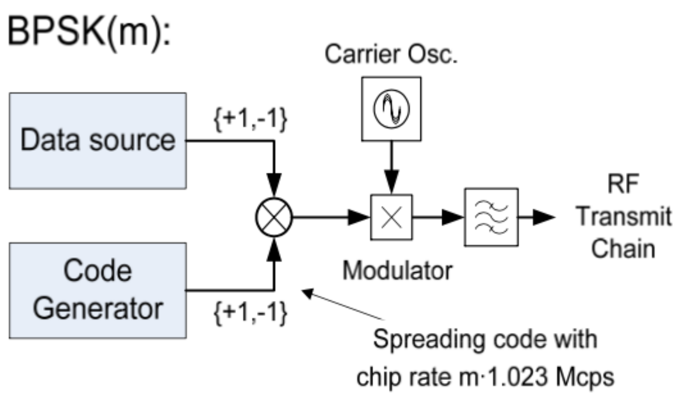

Figure 1.1: Schematic of a modulation BPSK-R(m) [3]

The Figure 1.1 represent the schematic of a BPSK(m) modulator. The navigation data signal and the spreading code are first generated by their respective generator to be then multiply together. Finally, this multiplication modulates the carrier sine wave generated by an oscillator. The value of m indicate the ratio between the chip rate of the spreading code and the reference frequency $f_0 = 1.023MHz$. In the case of a C/A code, $m = 1$ so its chips rate is equal to 1.023 Mcps.

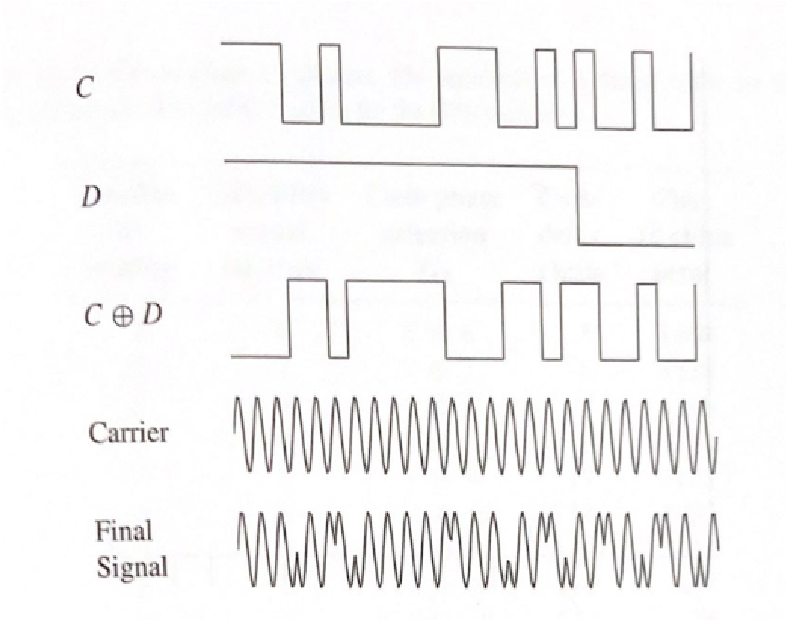

Figure 1.2: Visualisation of the effect of the BPSK modulation on the L1 carrier with the C/A code and the navigation data [4]

This Figure 1.2 shows the signal C which represents the spreading code and the signal D which represent the navigation data. These two signal can only take the value of ± 1, so they are square waves. The signal $C \oplus D$ represents the multiplication of the two previous signals. Then the obtained signal is used to modulate the carrier sine wave and this forms the last curve of the Figure 1.2. All the curves are not at their real frequency, the Figure 1.2 only represents the influence of each component on the signal.

When the curves of the Figure 1.2 are passed in the frequency domain, the square signal become a sinc function and the modulation with the carrier shifts this sinc function at the carrier frequency. So when passing in the frequency domain, the spectrum of the L1 band is easily obtained and it is represented in the Figure 1.3.

With this BPSK(1) modulation, the signal broadcast by the GPS L1 band satellites can be express as [1]:

$$s_{L1} = \sqrt{2P_{CA,T}}D(t)x(t)cos(2\pi f_{L1}t + \theta_{L1,T}), \tag{1.1}$$

where,

- $\sqrt{2P_{CA,T}}$ is the amplitude and $P_{CA,T}$ the average power at transmission in Watt,
- $D(t)$ is the navigation data,
- $x(t)$ is the spread spectrum code,
- f_{L1} the frequency carrier in Hz and
- $cos(2\pi f_{L1}t + \theta_{L1})$ is the radio frequency carrier.

The power of the transmitted signal is around 500 W.

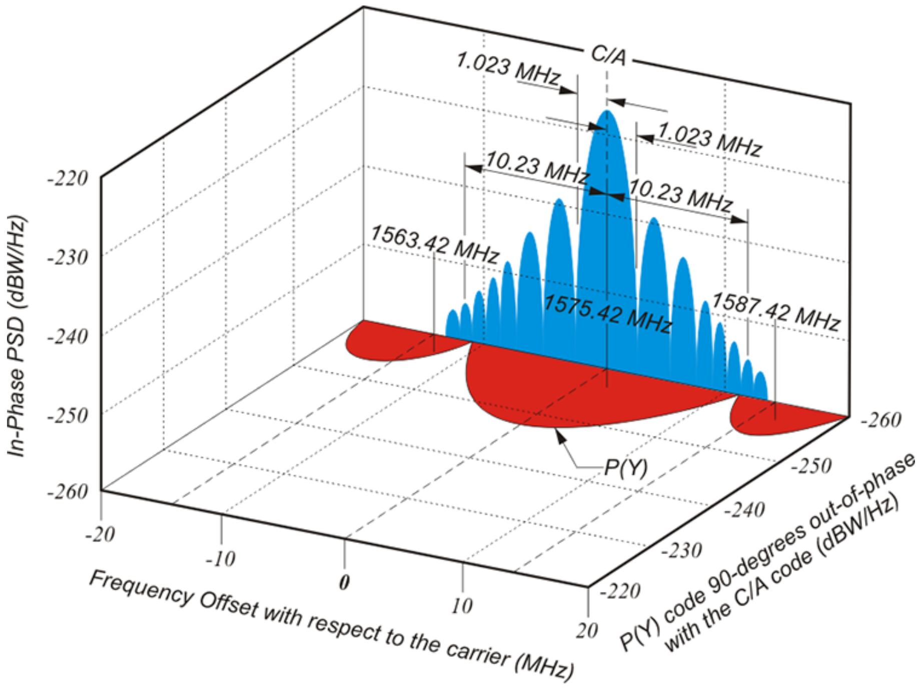

Figure 1.3: Frequency spectra of the L1 band [5].

1.1.2 Receive a L1 band signal

After being modulated, the L1 signal is sent toward the surface of the Earth where several receiver will receive and process it. For every receiver the signal need to be conditioned so that the receiver can properly handled it.

The signal, after being emitted by the satellite, crosses the space and the atmosphere to reach the antenna of the receiver. Hence, the signal transmitted is affected by the weather conditions of the atmosphere and also by the environment near the antenna of the receiver, like buildings, radio transmitter devices, etc. So the expression of the signal s_{L1} is not the same at the receiver. First, because of the loss during the propagation, the power of the received signal is about 10^{-16} W, so the signal is buried in the noise. Then, the propagation also introduces a delay and the motion of the satellite and the possible motion of the receiver implies a Doppler frequency.

The expression of the received signal if the satellite broadcasts the signal with the equation (1.1) is then [1]:

$$s_{L1} = \sqrt{2P_{CA,R}}D(t-\tau)x(t-\tau)cos(2\pi(f_{L1}+f_D)t+\theta_{L1,R})+n(t), \tag{1.2}$$

where,

- τ is the delay of the propagation in s,
- $P_{CA,R}$ is the average power at reception in Watt,
- $\theta_{L1,R}$ is the phase induces by the propagation in radian,
- f_D is the Doppler frequency in Hertz.

Signal conditioning

The signal conditioning is a succession of processes to make the signal fit several conditions in order to be easily process.

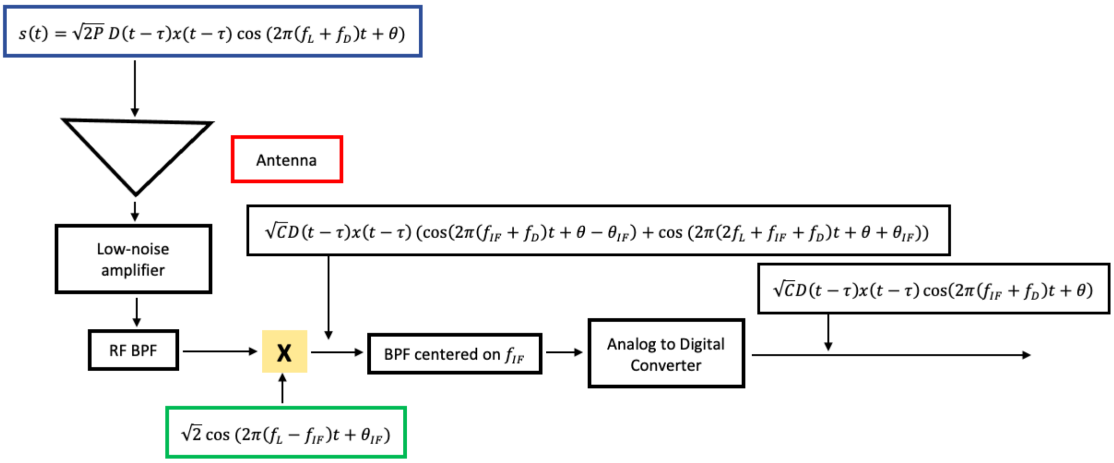

Figure 1.4: Head of a receiver [1]

The Figure 1.4 represents the conditioning of the signal after the antenna gets it. The received signal is buried in the noise. The signal is process through a low-noise amplifier (LNA) which amplifies the power of the low-power signal by 10 orders of magnitude without degrading its signal-to-noise ratio, so the power of both the signal and the noise is amplified. The LNA also add some noise because it is an active component. After passing through the LNA, the signal passes through a radio-frequency pass-band filter (RF BPF) with a center frequency equals to f_{L1}.

The following process is the frequency down conversion. As explain previously, the frequency of a GNSS signal contains a very high frequency to avoid any confusion with other signals emitted by other radio frequency devices. Completing the rest of the signal process at the high frequency f_{L1} is theoretically possible but it requires an extremely thoughtful design of the receiver hardware. In fact it would involve the co-existence of a strong and a weak signal at one frequency and if the strong output leaks back to the input, the amplification will be applied to the stray signal and the receiver would not longer be an amplifier but an oscillator [1]. This is the reason why most receivers have one or more intermediate frequency stages.

The frequency down conversion is based on the trigonometric identity :

$$Acos(\alpha)Bcos(\beta) = \frac{AB}{2}(cos(\alpha+\beta)+cos(\alpha-\beta)) \tag{1.3}$$

Therefore, as we can see on the Figure 1.4, the input signal is multiplied with a cosine wave carrier at the frequency $f_{L1} - f_{IF}$, where f_{IF} is the intermediate frequency. This process adds a random phase to the signal θ_{IF}. Then, the part of the equation with the higher frequency is wiped off by the band-pass filter centered on f_{IF}. The process of multiplying and filtering is called mixing.

The signal after the filter is written as :

$$s_{L1}(t) = \sqrt{C}D(t-\tau)x(t-\tau)cos(2\pi(f_{IF}+f_D)t+\theta)+n(t), \tag{1.4}$$

where C is the received power and θ represent the phase of the signal.

Sampling

In the head of the antenna, the input signal is an analog signal, in other words the signal takes a continuum of amplitude values and it is defined for all instant of time. But to reduce the cost and the complexity of the receiver, the input signal is converted through an analog-digital converter (ADC). A digital signal accepts a limited value of amplitude and is discrete in time. The signal needs to be digitized as fast as possible because the digital components are not subject to humidity and to the environment as the analog ones are. And a digital receiver cost less because the signal is process through a software that can be easily modified unlike the design of the analog receiver have to be rebuilt if any change is desired.

To do the discretization, the choice of a sampling frequency has to be made and is significant to faithfully reconstruct $s_{L1}(t)$. For GPS signal, the sampling frequency is chosen with the uniform sampling theorem for low-pass signal. This theorem establishes the sampling frequency has to be twice higher than the upper frequency of the input signal [1].

To make easier the understanding of the steps of the acquisition part and as the sampling frequency is chosen in order to faithfully reconstruct this signal, the expression of the sampling coming signal will be written as a continuous signal for the rest of the report.

1.1.3 The acquisition of an L1 band signal

Once the signal is conditioning, the GNSS treatment can begin. The process of a GNSS signal is in three key phases. First, the acquisition which aim is to known which satellites are currently visible through their unique PRN code and to make a first approximate estimation of the delay and the Doppler frequency. Then, the tracking which goal is to accurately estimate the code phase τ and the Doppler frequency f_D and to tracks changes into the future. Finally, the data demodulation which allows the receiver to know the ephemerides of the satellite.

There are two possible starts. A cold start which is a start with no a priori information. The receiver does not know which satellites are in the sky. Consequently, it starts researching for satellites randomly and process to an almanac so the receiver now identifies the satellites to seek in the sky. The second start is a warm start when the receiver possesses data on which satellites are visible [1].

The correlation

The correlation between two signals is an operation to see how likely they are. The formula of the correlation between two continuous signals, $x(t)$ and $y(t)$ is

$$R_{x,y}(\tau) = \int_0^{T_c} x(t)y^*(t-\tau)dt, \tag{1.5}$$

with T_c the period of the C/A code.

Here, the signal are digitized so the auto-correlation become,

$$R_x(n) = \sum_{i=1}^{N} x(i)x(i-n), \tag{1.6}$$

where N is the number of samples during the time T_C [6].

For signals like the C/A code which accepts only the values of ± 1, the correlation product with is a sum the products of the individuals ± 1 of the two signals. Remember when both are $+1$ or both -1, the result of the product is $+1$ and when one is $+1$ and the other -1 the result is -1. If the signal is exactly the same, the result of the auto-correlation is a sum of a thousands of $+1$ so the results of the auto-correlation gives a very strong peak [7].

The C/A codes are especially generated to possess particular properties. As mention earlier, these codes are PRN codes, so the probability of each chip to be ± 1 is $\frac{1}{2}$ and each chip is independent from the others. As the PRN codes are generated as pseudo-random noise, the correlation of a PRN code with all other signals is 0. Furthermore, the auto-correlation of a PRN code with a itself delayed is also 0 [7].

The auto-correlation of the C/A code of a L1 signal is represented in the Figure 1.5.

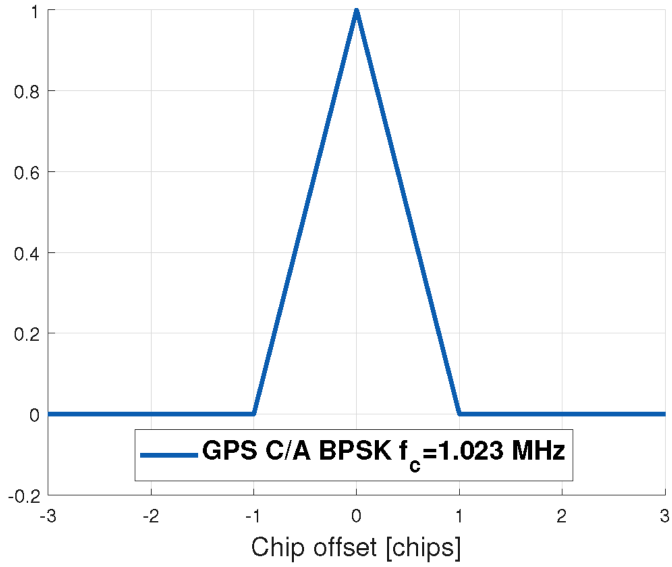

Figure 1.5: Auto-correlation function of the received code with a local replica with the right delay τ. [8]

As one can see on the Figure 1.5, the correlation of the C/A code with a replica is different of zero only if the delay τ between the two signals is smaller than a chip.

The aim of the acquisition is to create a local C/A code for all the delay τ value and for all the Doppler frequency f_D possible and to correlate it with the coming code. When the local C/A code is aligned with the coming one, so when both the delay and the Doppler frequency are good estimator, the auto-correlation peak will be strong and so the receiver knows that this satellite is visible.

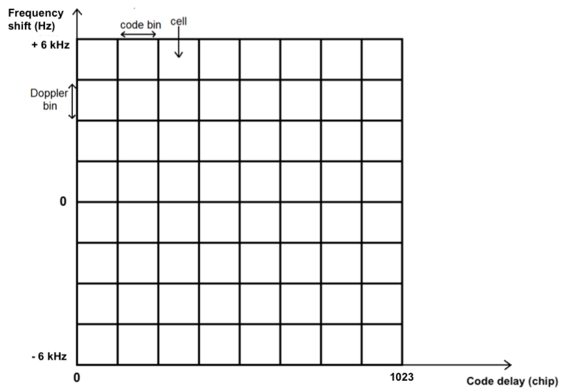

Figure 1.6: Schema of the search area of the acquisition [7].

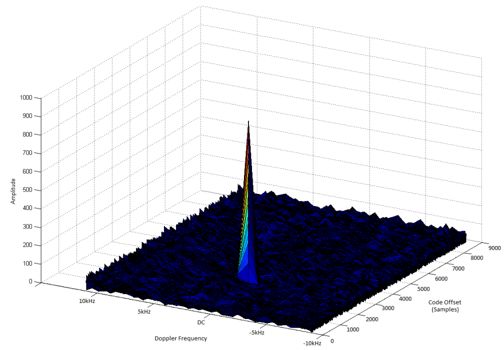

Figure 1.7: Example of a peak in the 2D search area[7]

The search area

Until we found the auto-correlation peak, there are two unknowns, the actual frequency offset f_D and the actual delay τ. As we have two unknowns the search is in 2D. The acquisition search space is to search f_D on one axis and τ on another as described in the Figure 1.6.

Therefore, the receiver looks for all the possible values of the Doppler frequency and the time delay.

For the possible value of the time delay, the receiver search for the time delay that align the local PRN code with the coming PRN code. Therefore, the receiver tests the auto-correlation for all the chip of the code. As a C/A code is 1023 chips long that means that the axis of the Figure 1.6 goes from 0 to 1023 chips.

The value of the frequency offset is more complex to find because several effects influence its value. First, there is the TCXO or the Temperature Compensated Crystal Oscillator, because the frequency of the carrier is made on the satellite by an atomic clock may be not at the exact frequency of the wanted GPS frequency. That can add an offset up to ±1.575 kHz. Furthermore, the satellites are in motion, so it is either moving forward or moving backward and so it implies a Doppler effect with changes the frequency. But the speed of the satellites is limited to 3.3 km/s, hence the frequency offset is also limited to ±4.200 kHz. Finally, the receiver can be also moving, but it speed is smaller than the speed of the satellites, so its motion can add up to ±0.146 kHz. In most cases, the search band of the frequency goes from -6 kHz to +6 kHz [7].

The serial search acquisition

The serial acquisition is the most basic algorithm used to do the acquisition of a signal.

The serial search acquisition is made in the time domain. During the acquisition method, each cell of the search area is examined to find the unknown values of τ and f_D. For each cell, the income digitized signal is correlated with the local PRN code generate with a Doppler frequency value and the time delay value. The delay and Doppler frequency values of the test signal are changed step by step within the search space range. If a peak is not present or it is smaller than a defined threshold, the search continue in the next cell. If a peak is detected and it is above the threshold, the satellite is acquired and then the receiver transitions to the tracking mode [1].

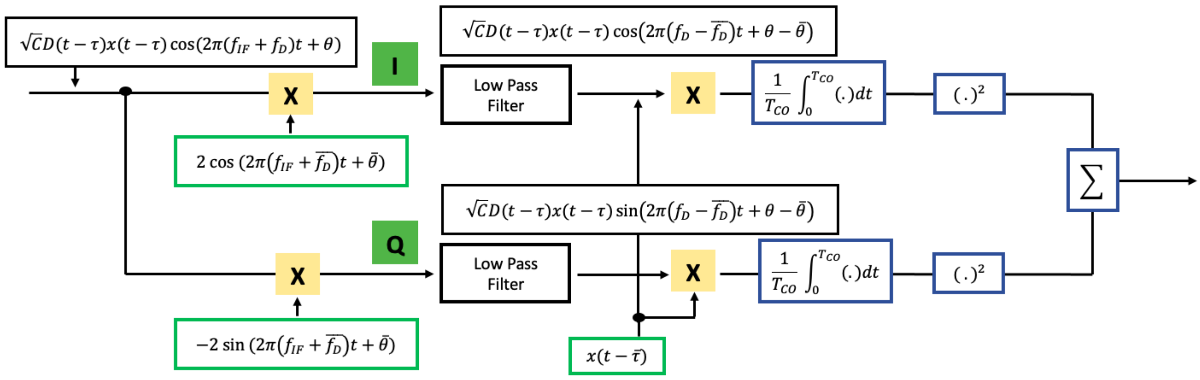

Figure 1.8: Schema of the serial search acquisition algorithm [1].

The Figure 1.8 shows the step of the serial search acquisition method. First, the digitized coming signal is multiplied by two reference signals:

$$\begin{aligned}&\sqrt{2}cos(2\pi(f_{IF}+\bar{f_D})t+\bar{\theta})\\&\sqrt{2}sin(2\pi(f_{IF}+\bar{f_D})t+\bar{\theta})\end{aligned} \tag{1.7}$$

These signals are called the in-phase and quadrature reference signals. Afterwards, the results are passing through a low-pass filter. As in the conditioning part, the purpose of this mixing is to wipe off the intermediate frequency and to only keep the Doppler frequency and its estimator. The signal is multiplied by both an in-phase and a quadrature reference signals because this enables the receiver to estimate f_D without any real control over $\theta-\bar{\theta}$. This I/Q process also enable the receiver to identify if the Doppler shifts are positive or negative thus if the satellite approaches or moves away from the receiver.

The second step of acquisition is to be correlated with the local generate PRN code. These two signal are correlated during a time T_{CO} called coherent integration time. This time need to be shorter than 20 ms because it is the duration of a data bit. If the data bit shifts during the correlation, the sign of the signal change and the signal energy will be partially lost and the acquisition performance will suffer [1].

The square is then taken of the real, I and imaginary, Q values of product and then they are added together. Finally, the amplitude of the auto-correlation function is check for the specific threshold value.

The drawback of this method is all the cells of the search area are checked one by one, so it takes time. Or, the performance of a receiver is based on its acquisition time. Other methods exist where one parameter, either the delay or the Doppler frequency is eliminated from search procedure, which reduce the acquisition time considerably [9].

The parallel code phase search algorithm

The parallel code phase search algorithm is an improvement of the previous algorithm as it passed the signal into the frequency domain by the fast Fourier transform (FFT) to do the correlation product.

The Fourier Transform is a mathematical operation which is used in signal processing to pass time domain function in the frequency domain. For an analog signal, the Fourier transform is the following expression :

$$S(f) = \int_{-\infty}^{+\infty} s(t)e^{-i2\pi ft}dt. \tag{1.8}$$

For a digitized signal, the Fourier transform, which is called the discrete Fourier transform, become

$$S(\tilde{f}) = \sum_{-\infty}^{+\infty} s(k)e^{-2i\pi\tilde{f}k}, \tag{1.9}$$

with $\tilde{f} = \frac{f}{f_s}$ the reduce frequency [10].

To pass from the Fourier domain to the time domain, the inverse of the discrete Fourier transform is expressed as

$$s(k) = \sum_{-\infty}^{+\infty} S(\tilde{f})e^{2i\pi\tilde{f}k}. \tag{1.10}$$

This conversion in the frequency domain eliminates one parameter, which is the time delay τ. Consequently, the algorithm checks all the delay values in one step for a particular Doppler frequency value over the search space.

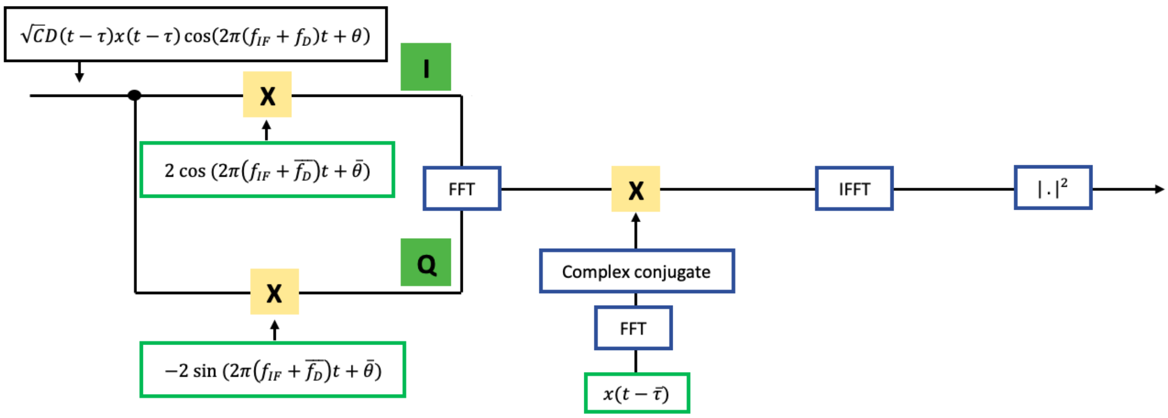

Figure 1.9: Schema of the parallel code phase search algorithm [9].

The scheme of this acquisition is shown in Figure 1.9. After the intermediate frequency wipe off, both I and Q signal are added and then passed in the frequency domain with the FFT. Next, it is multiplied with the complex conjugate of the Fourier transform of the local code. The correlation product is then obtained by taking the inverse of the FFT of the resultant signal. At that point, the square of the signal is completed and compared to a threshold to detect the correlation peak [9].

This method is the easiest one to implement.

Summary of the characteristic of a L5-GPS signal

	GPS L1 band
Center frequency (MHz)	1575.42
Transmit bandwidth (MHz)	30.69
Component name	L1 C/A
Component	Data
Service	C/A
Modulation	BPSK-R(1)
Primary PRN duration (ms)	1
Primary PRN length (bits)	1023
Primary PRN rate (Mcps)	1.023
PRN code repetition (ms)	1
Data fraction power (%)	100
Data symbol duration (ms)	20
Data rate (sps)	50
Data rate (bps)	50

Table 1.1: Table of the component of GPS L5-band signal [2]

1.2 New GNSS band

In the 1990s, with the rise of the use of the GPS, governments decided to define modern bands of GPS use for military and civil application. These alternative bands have been developed to modernize GNSS.

1.2.1 L5-GPS signal

The L5 band is in the frequencies which are only use by the aviation safety services. The aim of this band is to meet the requirement of safety-to-life transportation. This band is used with L1 C/A band to increase the accuracy and the robustness of services [11].

General presentation

The GPS L5 band provides a center frequency of 1176.45 MHz and the width of the center lobe is 20.46 MHz. As one can see in the Figure 1.10, that is ten times wider than the civil L1 band with C/A code of 2.046 MHz.

The L5 signals contain two channels, an in-phase one which contains the navigation data, the PRN spreading code and the second code. The second channel is the quadrature one called the pilot component and it contains the PRN spreading code and the secondary code. Indeed, the L5 signals are made of two codes. The primary code is the PRN code and is used to recognize the in view satellite and the secondary code is the Neuman-Hoffman code and it is used to synchronize the in-phase and the quadrature channels of the L5 signal [12].

The primary code has a rate of 10.23 Mcps and a length of 10,230 chips. The rate is ten times the PRN code rate of the L1 C/A signal, which induce more accurate measurements. The in-phase and quadrature channels have the different PRN codes.

The secondary code is not the same in the in-phase channel and in the quadrature one. In the in-phase channel, the NH code is 10 chips long and each chip is 1 ms long. In the quadrature channel, the NH code is 20 chips long and each chip is 1 ms long. Every full cycle of the quadrature NH code exactly aligns with two in-phases NH code cycles. The secondary codes of the in-phase channel and of the quadrature one are the same for all the satellites of the GPS constellation.

The data navigation message has a rate of 100 sps and a data duration of 20 ms. It is similar to the data navigation message of the L1 C/A, but it has a process called forward error correction (FEC) encoding which prevents the incorrect translation of data bits [12].

All the information about the L5 band is presented in the Table 1.2 in page 23.

The Figure 1.10 represents the spectrum of the L5 band. This spectrum is composed of a large main center lobe and is similar to the one of the military one of the L1 band in the Figure 1.3. This wider main lobe involves a better accuracy and robustness in the processing of the signal.

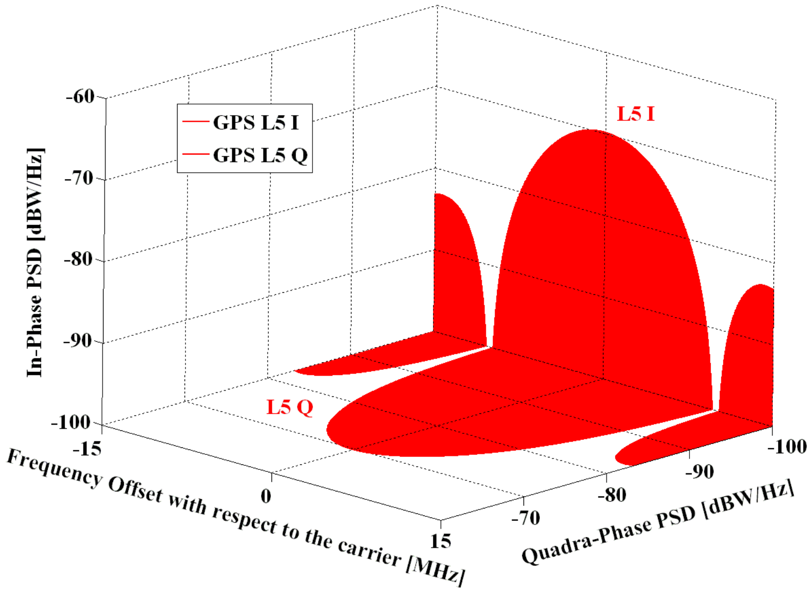

Figure 1.10: Frequency spectrum of the L5 band [5].

QPSK(10) modulation

The modulation of the L5 signal is described in the Figure 1.11. The I5 signal is modulated by the data and the spreading code, but there is also another difference due to the presence of the secondary code. As shows in the Figure 1.11, the secondary code modulate the data signal before being added to the primary code. And in the quadrature signal, the PRN code is added to the NH code before being modulated with the carrier. Then the signal $s(t)$ of the Figure 1.11 is obtained by performing the QPSK modulation of the I5 and Q5 signal at the frequency of 1176.45 MHz.

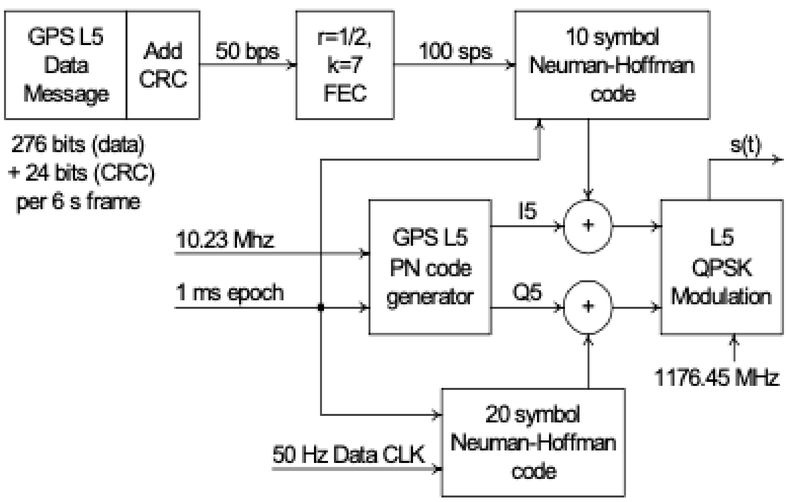

Figure 1.11: Schematic of the modulation BPSK(10) of the GPS L5 signal [13].

The QPSK or Quadrature Phase Shift Keying modulation is similar to the modulation of the L1 C/A signal which is a BPSK(n) modulation describe in the Figure 1.1. The principal difference is in a BPSK the symbol of the signal represents one bit which can be 0 or +1. In a QPSK modulation, a symbol is equal to two bits 00, 01, 10 or 11. Hence, it exists in four states of the signal, so four possibly phase-shift 45°, 135°, 225° and 315°. The L5 signals have a better bandwidth efficiency because instead of transmitted 1 bit per symbol, it transmits two bits during each symbol period [14]. The QPSK modulator is represented in the Figure 1.12.

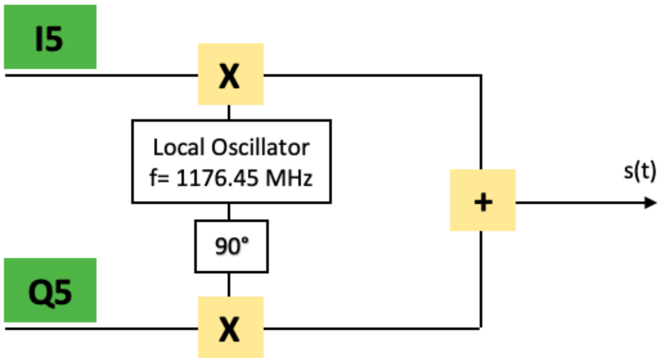

Figure 1.12: Schematic of a modulation QPSK [14].

At the end of the modulation, the transmitted L5 signal can be expressed as

$$s_{L5}(t) = \sqrt{2P_{L5I}}D(t)NH_{10}(t)C_I(t)cos(2\pi f_{L5}t) + \sqrt{2P_{L5Q}}NH_{20}(t)C_Q(t)sin(2\pi f_{L5}t), \quad (1.11)$$

where P_{L5I} is the signal power, $D(t)$ is the data bit value, $C_x(t)$ is the PRN code bit value, NH_x is the Neuman-Hoffman code bit value and f_{L5} the center frequency of the L5 band.

Auto-correlation function

The primary codes of L5 band are very similar to the C/A ones and they also have extremely specific properties of auto-correlation. The result is null if the code time delay between the two signals is higher than one chip.

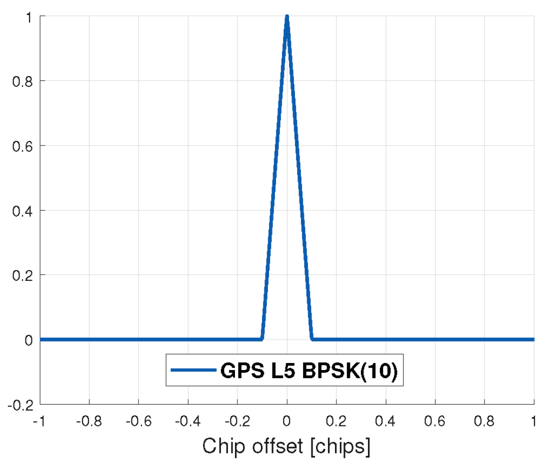

Figure 1.13: The auto-correlation function of the PRN code of the L5 signals [8].

The peak of the auto-correlation function of the Figure 1.13 is sharper than the peak of the auto-correlation function of the C/A code, so the precision during the acquisition is more exact for an L5 signal.

Summary of the characteristic of a L5-GPS signal

	GPS L5 band	
Center frequency (MHz)	1176.45	
Transmit bandwidth (MHz)	24	
Component name	L5I	L5Q
Component	DATA	PILOT
I/Q	I	Q
Service	SoL	
Modulation	BPSK-R10	BPSK-R10
Primary PRN duration (ms)	1	1
Primary PRN lenght (bits)	10230	10230
Primary PRN rate (Mcps)	10.23	10.23
Secondary PRN lenght (bits)	10	20
Secondary PRN rate (Hz)	1000	1000
PRN code repetition (ms)	1	1
Data fraction power (%)	50	/
Data symbole duration (ms)	20	/
Data rate (sps)	100	/
Data rate (bps)	50	/

Table 1.2: Table of the component of GPS L5-band signal [2]

1.2.2 E5-Galileo signal

The E5 band have the same purpose as the L5 band. They have both been design to respond to the demand of the safety-to-life transportation especially in the aviation domain.

General presentation

The Galileo E5 band provides a center frequency of 1191.795 MHz and the width of the main lobes is 20.46 MHz as for L5 band.

The E5 signals are divided in two parts, $E5a$ and $E5b$. Both parts have two channel, an in-phase I one, called the data channel, which as for a L5 signal contains the navigation data, the PRN spreading code and a secondary code. The second channel is the quadrature called the pilot channel which contains the PRN spreading code and the secondary code. As the L5 band, E5 signals are made with a second code which aim is to synchronize the in-phase and quadrature channels.

All the channels of the E5 band have a primary PRN code which has a rate of 10.23 Mcps and a length of 10,230 chips. However, the characteristics of the secondary code are not the same in the four channels of the E5 band. Their values are summarized in the Table 1.3.

The characteristics of the data navigation are not the same in $E5a$ and $E5b$. The data navigation message of the $E5a$ in-phase channel has a rate of 50 sps and a duration of 20 ms whereas the in-phase channel of the $E5b$ has a data rate of 250 sps and a duration of 4 ms.

All the information about the E5 band is presented in the Table 1.3 in page 27.

AltBOC modulation

The E5 signal is modulated with the AltBOC(15,10) or Alternate Binary Offset Carrier modulation. This modulation is the most sophisticated of all the modulation of the GNSS signals. The Figure 1.14 shows the trivial schematic of the modulation of the E5 signal.

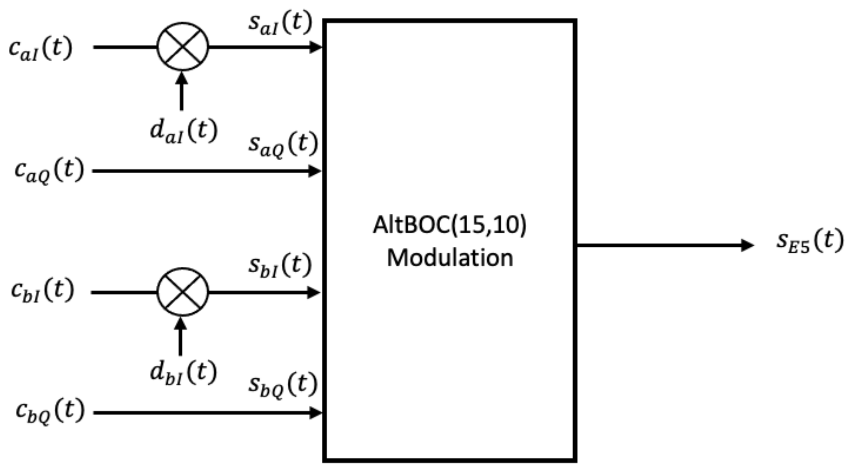

Figure 1.14: Schematic of the modulation AtlBOC(15,10) of the Galileo E5 signal [15].

The c_{kI} and c_{kQ} are the spreading code of each of the channel and d_{kI} is the data bits modulation of E5k. The detail of the AltBOC modulation is unshown in this figure, but the concept of it is detailed right after.

To understand the AltBOC modulation, it is sufficient to understand the AltLOC modulation or the Alternate Linear Offset Carrier modulation. The difference with the E5 modulation is that the subcarriers are linear signals and no discrete ones.

First, the E5 transmitted signal can be written as [15],

$$S_{E5}(t) = \Re s_{E5}(t)e^{j(\omega_C t+\phi_0)}, \tag{1.12}$$

where ϕ_0 is the phase at $t = 0$, $\omega_c = 2\pi f_c$ is the pulse of the carrier and $s_{E5}(t)$ is the baseband signal.

The baseband signal $s_{E5}(t)$ is made of the multiplication of the signal of each part $E5a$ and $E5b$ with the subcarrier. Thus, it can be writing as,

$$\begin{aligned} s_{E5}(t) &= s_b(t)e^{j\omega_{SC}t} + s_a(t)e^{-j\omega_{SC}t} &(1.13)\\ &= (s_{bI}(t) + js_{bQ}(t))e^{j\omega_{SC}t} + (s_{aI}(t) + js_{aQ}(t))e^{-j\omega_{SC}t} &(1.14)\end{aligned}$$

where the $s_{kI}(t) = d_{kI}(t)c_{kI}(t)$ is the E5k data signal and $s_{kQ}(t) = c_{kQ}(t)$ is the E5k pilot signal.

By inserting the equation (1.14) in the equation (1.12) and developing, the final expression of the signal of E5 can be expressed as,

$$S_{E5}(t) = s_{bI}(t)cos(\omega_b t) - s_{bQ}(t)sin(\omega_b t) + s_{aI}(t)cos(\omega_a t) - s_{aQ}(t)sin(\omega_a t), \tag{1.15}$$

where $\omega_b = (\omega_C + \omega_{SC})$ and $\omega_a = (\omega_C - \omega_{SC})$ are the pulsation of the E5b and E5a respectively.

The AltBOC modulation is based on the same reasoning but the subcarrier is discrete. So, final AltBOC modulation is similar to a 8-PSK modulation, but other operations are made after this process to make the envelope of the signal constant. These operations are described in the reference [15].

Spectrum of the E5 band

The subcarrier of the E5 signal, as the one of the E1 signal, splits the power of the signal in two on either side of the central frequency as one can see in the Figure 1.15.

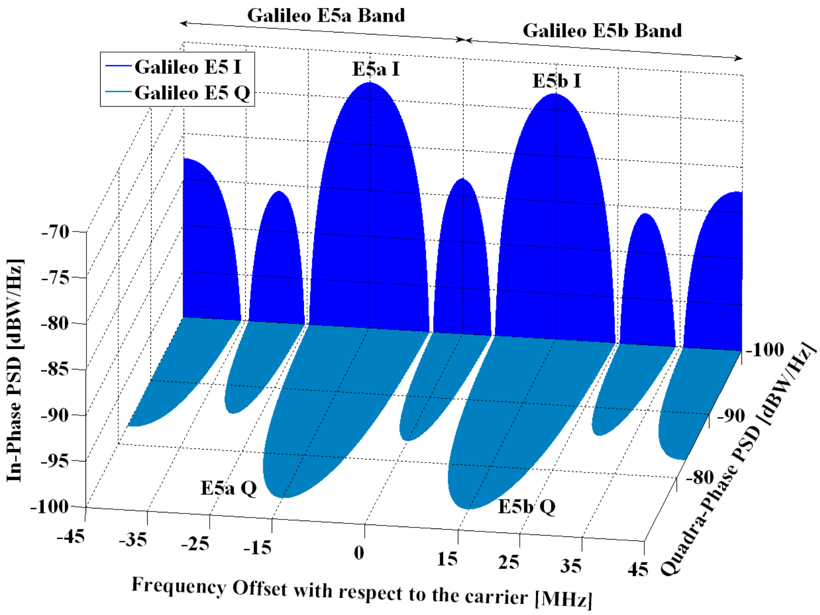

Figure 1.15: Frequency spectrum of the E5 band [16].

The Figure 1.15 represents the spectrum of the E5 band. This spectrum is similar to the one of L5 represented in Figure 1.10 with a shift by 15.345 MHz to the left an right of the carrier frequency of E5 band.

But there are some differences between the modulation of the E1 band and the E5 band. The sub-carrier of the E5 signal is a complex function and each side channel aI, aQ, bI, bQ has its own primary code.

Figure 1.16: Auto-correlation of the E5 spreading code [8]

The Auto-correlation of the E5 spreading code is represented in the Figure 1.16. As the auto-correlation function of the E1 band, the ACF of the E5 band is made of several peaks, and some of them are negatives. The central peak of the ACF is sharper than all the other peaks provide by the other modulation.

Summary of the characteristics of a E5-Galileo signal

The following table detailed the parameters of the E5 band.

	Galileo E5 band			
Center frequency (MHz)	1191.795			
Transmit bandwidth (MHz)	51.15			
Component name	E5a-I	E5a-Q	E5b-I	E5b-Q
Component	DATA	PILOT	DATA	PILOT
I/Q	I	Q	I	Q
Service	OS/CS		OS/SoL/CS	
Modulation	AltBOCs(15,10)			
Sub-carrier frequency (MHz)	15.345 MHz			
Primary PRN duration (ms)	1	1	1	1
Primary PRN lenght (bits)	10230	10230	10230	10230
Primary PRN rate (Mcps)	10.23	10.23	10.23	10.23
Secondary PRN lenght (bits)	20	100	4	100
Secondary PRN rate (Hz)	1000	1000	250	1000
PRN code repetition (ms)	20	100	4	100
Data fraction power (%)	50	/	50	/
Data symbole duration (ms)	20	/	4	/
Data rate (sps)	50	/	250	/
Data rate (bps)	25	/	125	/

Table 1.3: Table of the component of Galileo E5 band signal [17]

1.3 Conclusion

This chapter allows us to understand the structure of the signal used in the GPS and GALILEO constellations. It presents a good summary of their code, their modulation and gives a trail to design a digital receiver to complete the acquisition of the L1 signal. By knowing all this information one can develop a code to realise a digitized receiver for all this signal.

Chapter 2

Simulation of the acquisition of a GNSS signal

After the description of the different GNSS signal in the previous chapter, this chapter is describing the conception of the digital receiver in order to make the acquisition of the L1 C/A, L5 and E5 signals. In the first place, this chapter describes the code implemented to the acquisition of L1 C/A to understand the code. Next, it describes the steps I have achieved to extend the code to make the acquisition of L5 and E5 signals.

2.1 Context

After the analog conditioning, the signal is process in a digitized part of receiver. The strength of the digitized part of the receiver is that it can by change through a software. In the laboratory of the IIT, the acquisition, the tracking and the data processing are optimized with the Matlab software. The Matlab code which is elaborate in the research laboratory is based on the code of the book, *A Software-Defined GPS and Galileo Receiver: A Single-Frequency Approach* [4] which provides a code of the acquisition, the tracking and the data processing of a L1 band signal.

The signals used to do all the following acquisition are not real signal but they are generated in the laboratory with the Skydel software. In the record, the signal is already conditioned and sampled. Hence, the signal is already at the intermediate frequency of 0 Hz.

2.2 Acquisition of a GPS L1 band signal

As the acquisition code is taken from the software of the book, the aim of this simulation is to familiarize with the Matlab code and the acquisition of a signal. In the software [4], the method used to make the acquisition of the signal is the parallel code phase search algorithm because it is the most efficient acquisition algorithm for basic acquisition algorithm.

The parameters used in the L1 acquisition are summarised on the following Table 2.1.

The sampling frequency at 25 MHz is a generic value used in real GNSS receivers. This value respects the Nyquist–Shannon sampling theorem and allows a remarkably good sampling of most of the GNSS signals.

Parameters	**Values**
Code Frequency (MHz)	1.023
Code Length (Chips)	1023
Sampling Frequency (MHz)	25.0
Correlation time (ms)	1
Frequency search band (kHz)	14
Threshold	2.5

Table 2.1: Parameters used for the L1 acquisition

An important element of the acquisition is the time of correlation which determines the quality of the acquisition. For a L1 C/A signal, the spreading code is 1 ms long. This value settles the minimum value of the time of the correlation. But this time can not be too long because every 20 ms there is a data chip shift and this shift is very likely to damage the acquisition correlation. The initial time of correlation is 1 ms because it is a common value for a GPS L1 C/A receiver.

At the end of the acquisition, The results are shown in the bar chart in the Figure 2.1.

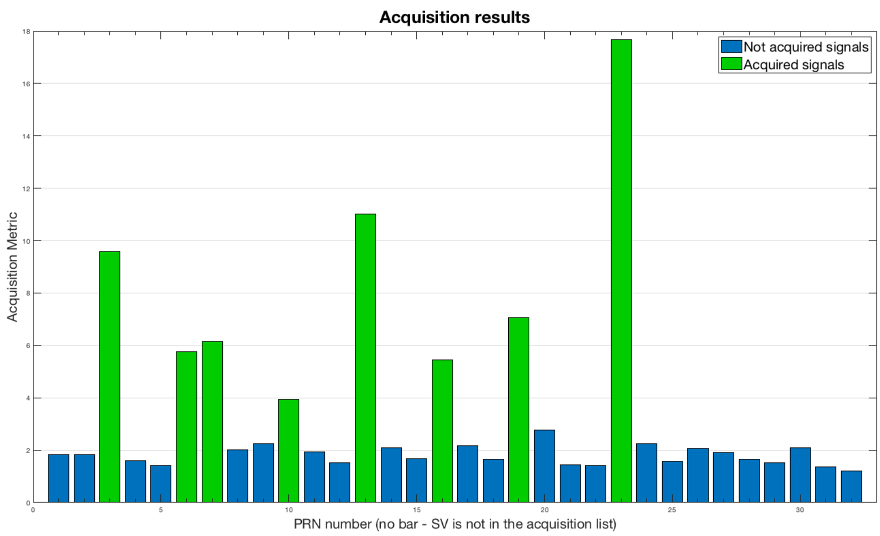

Figure 2.1: Bar chart of the acquisition of the L1 band signal

The bars on the Figure 2.1 represent the ratio the value of the peak of the auto-correlation function over the value of the second highest peak of each of the 32 satellites of the GPS constellation. The ones in green are those which exceed the threshold of 2.5 settled in the settings. The value of the threshold is typically set to achieve a desired false alarm rate. The eight satellites with a green bar are the satellites admitted as acquired. As the signals we are manipulating are not real signals but they are generated with a software, we already identify the list of the satellites in the sky. Thus, we can deduce from the acquired satellites if our acquisition is working. Here the satellites 3, 6, 7, 10, 13, 16, 19 and 23 are the ones that were generated by the software.

For each acquired satellites, the peak of the auto-correlation function (ACF) is drawn. In the Figure 2.2, the graphic on the left represents the ACF as the function of the Doppler frequency. The peak of the auto-correlation is unique and sharp as represented in the Figure 1.5. However,

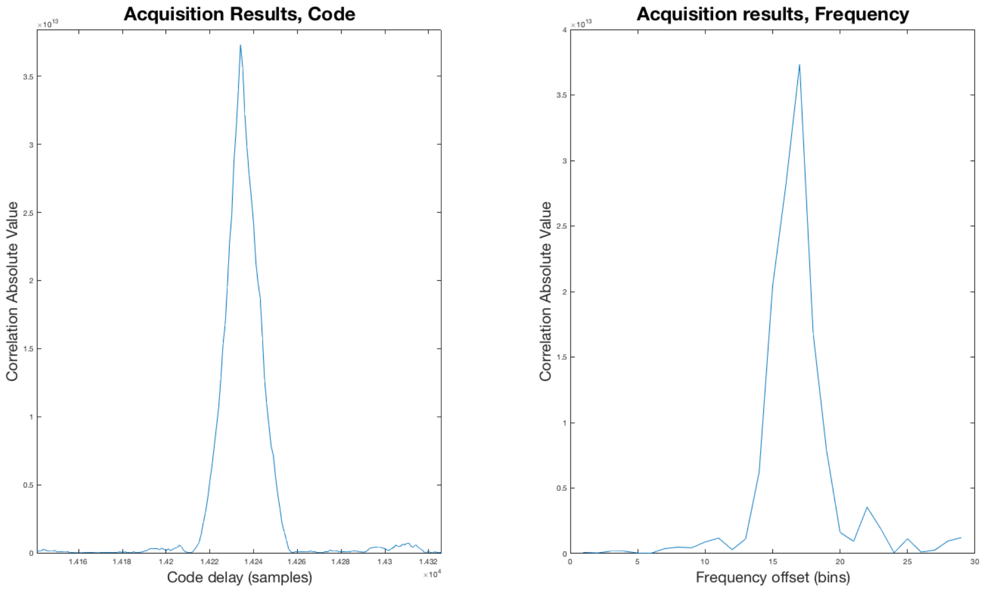

Figure 2.2: Values of the auto-correlation function of the satellites 3

the values around the peak are not exactly zero as in the theory. This is due to the random noise of the received signal. This noise present in the signal constitutes the reason why this is the ration between the maximum peak and the second maximum which is compared to the threshold.

The graphic on the right represents the ACF as a function of the code chip. The curve is supposed to be a sinc function, but as the signal has noise, all the sinc function except the central peak is buried in the noise.

2.3 Acquisition of a GPS L5 band signal

2.3.1 Basic acquisition of a L5 signal

Acquisition using only one of the channel

The GPS L5 band signals, as explain in the section 1.2.1, have a QPSK(10) modulation. But the QPSK modulation can be considered as the sum of two BPSK modulations. The signal on the in-phase channel I is modulated with the BPSK(10) modulation and so is the signal on the quadrature channel Q. Thus, to acquire the L5 signal, I took the same algorithm of acquisition that the one of the L1 band signals and I only changed the values of the characteristics of the L5 band. These values are detailed in the Table 2.2.

Parameters	**Values**
Code Frequency (MHz)	10.23
Code Length (Chips)	10230
Sampling Frequency (MHz)	25.0
Correlation time (ms)	1
Frequency search band (kHz)	14
Threshold	2.5

Table 2.2: Parameters used for the L5 acquisition

I maintain the threshold at the value 2.5 to keep the same probability of false alarm than the one of the L1 C/A acquisition and I also maintain the width of the bins at 500 Hz. The sampling frequency is still at 25 MHz because this value is enough to sample the L5 signal as it covers all the 20.46 MHz wide main lobe where the essential part of the power of the signal is located.

This acquisition only requires the I channel spreading code or the Q channel spreading code. Consequently, I made an acquisition with each channel spreading code. The results of the two acquisitions are illustrated in the Figures 2.3 and 2.4.

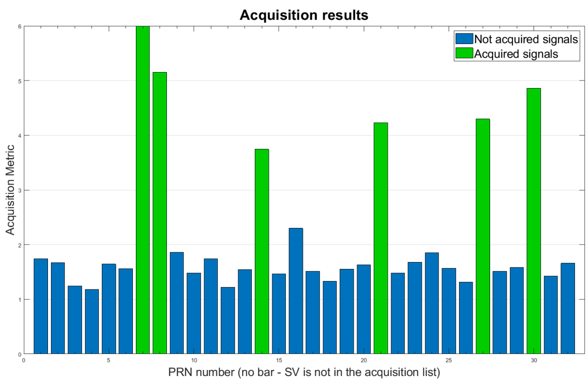

Figure 2.3: Bar chart of the acquisition of the in-phase channel I of the L5 band

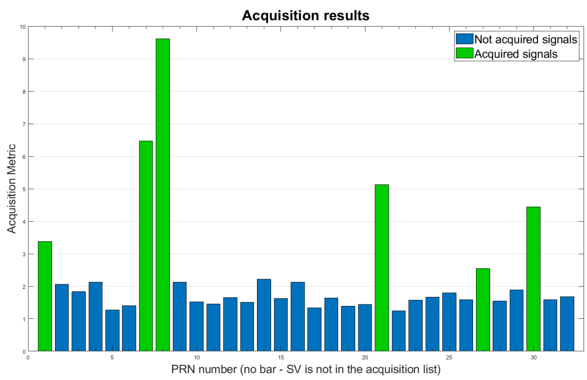

Figure 2.4: Bar chart of the acquisition of the quadrature channel Q of the L5 band

The acquisition with only the I channel spreading code shows the satellites with the number 7, 8, 14, 21, 27 and 30 and the acquisition with only the Q channel show the satellites 1, 7, 8, 21, 27 and 30. There is also a difference in the value of the ratio of the highest peak and the second highest peak. This difference is due to noise in the receiver. When we compare the number of the satellites acquired and the ones generated by the software, we noted that some of then where missing because the satellites generated are 1, 7, 8, 14, 16, 21, 27 and 30.

Acquisition using the simultaneously the two channels

By doing the acquisition on only one of the two channels of the L5 signal, we are losing some of the power of this signal. Indeed, the power of the L5 signal is divided equally between the two channel when the signal is generated. Therefore, to exploit the maximum of power during the acquisition, I decided to do the acquisition of the two channel simultaneously by sum up their results of the auto-correlation at the end as it is shown in the Figure 2.5.

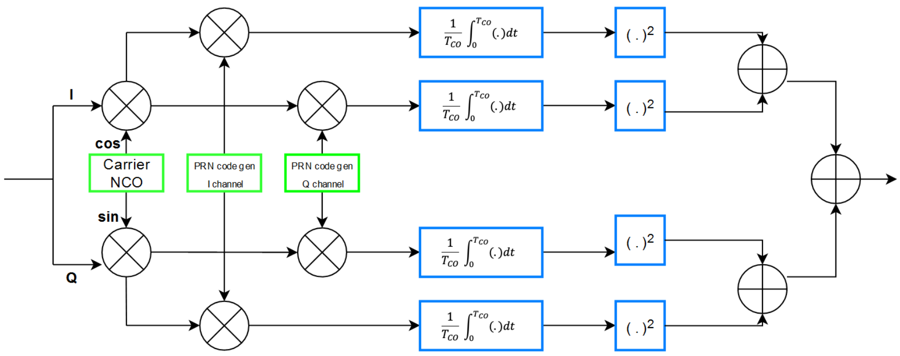

Figure 2.5: Schema of the acquisition algorithm using the two channels

The result of this acquisition is illustrated in the Figure 2.6.

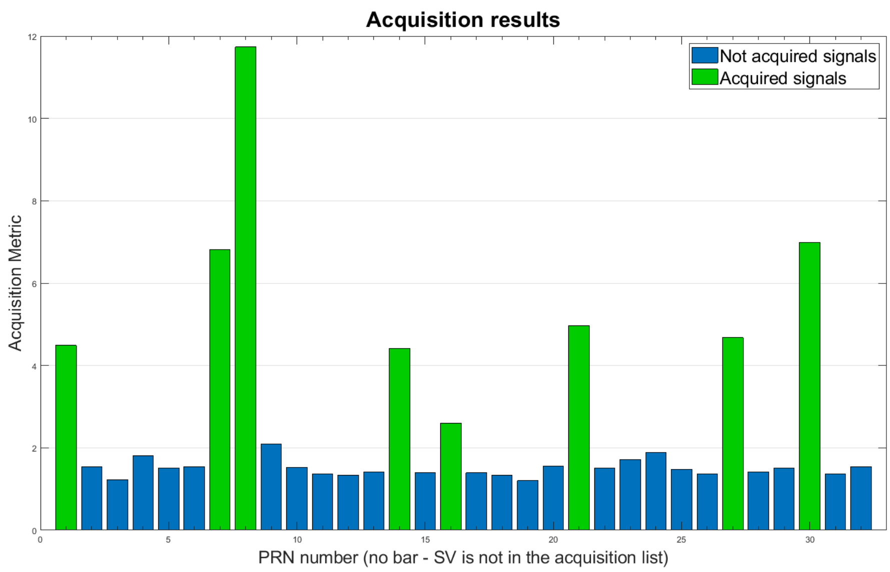

Figure 2.6: Bar chart of the acquisition of both channels I&Q of the L5 band

All the satellites acquired in the Figure 2.6 are the one generated by the software. In average the ratio of the auto-correlation peak is higher than when the acquisition is done only in one channel. Doing the acquisition simultaneously on the two channels provides a higher power of the signal and consequently allows the acquisition of more satellites.

2.3.2 The acquisition of a L5 signal implementing a longer coherent integration

As explains in the section 1.2.1, the quadrature channel is only made of the PRN code and of the secondary Neuman-Hoffman code. Therefore, this channel is completely deterministic. Longer coherent integration are possible using this channel.

Hence, I executed the acquisition of the L5Q channel with an integration of 20ms. For that I proceed as is the schema of the Figure 2.7.

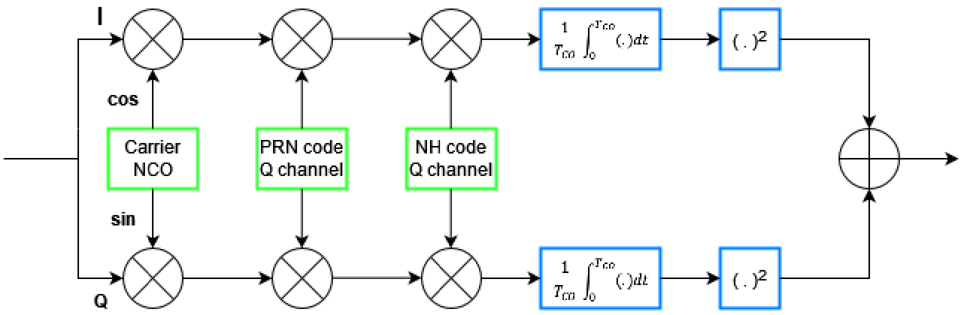

Figure 2.7: Schema of the acquisition algorithm using the secondary code

The goal is to make 20 acquisitions of 1ms each and to sum their search area. This method is also utilized to make the acquisition of weak signals, because, as it is illustrated in the Figure 2.8, when the sum is done, the value of the peaks are added but the mean of the noise is still zero.

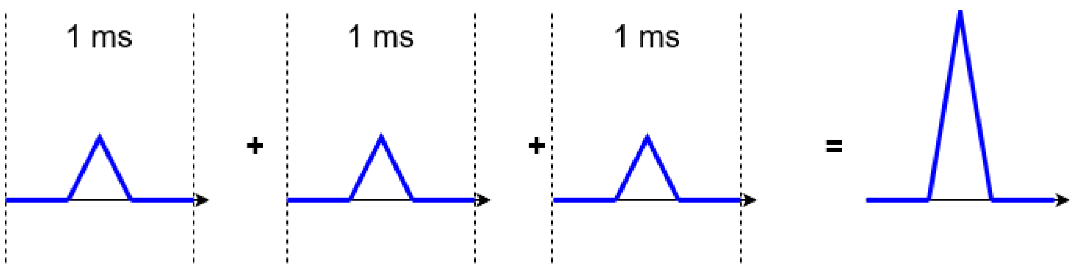

Figure 2.8: Description of the method of the 20 x 1 ms acquisition

The results of this acquisition are presented in the Figure 2.9.

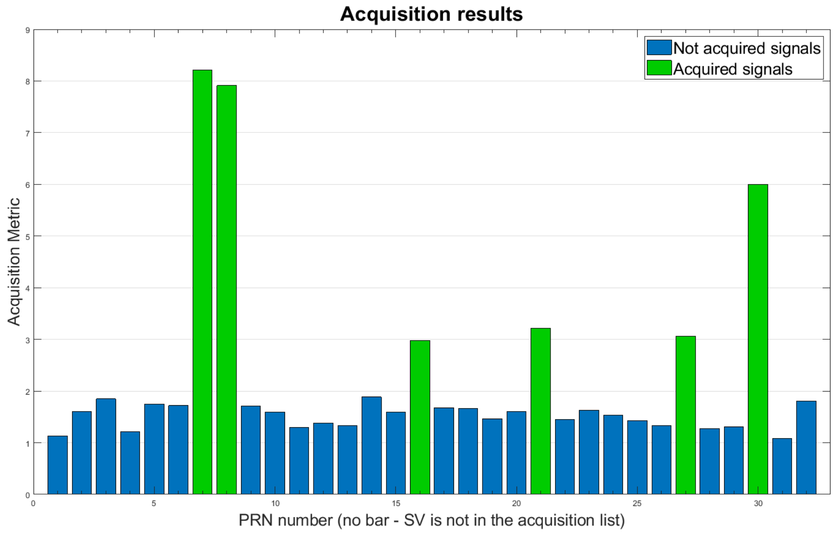

Figure 2.9: Bar chart of the 20 x 1 ms acquisition of the channel L5Q

There are some satellites missing in the acquisition and the power is the same rough size than a classic acquisition. This result can be explained by the Figure 2.10. The presence of the secondary code switch the direction of the peak and when their are added together, the sum is buried in the noise of the signal.

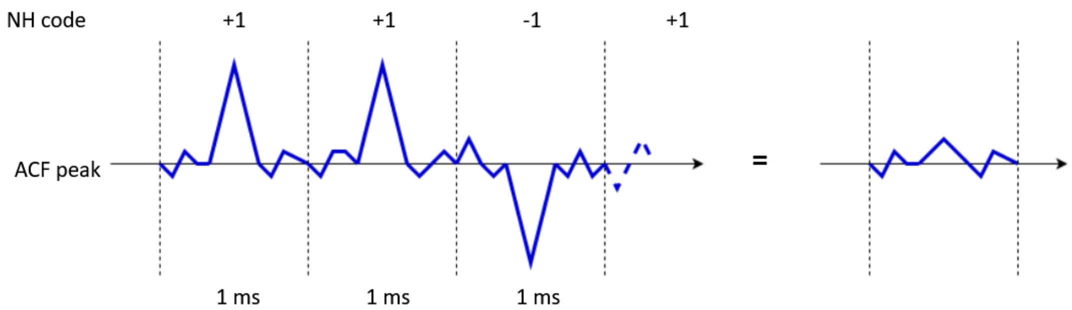

Figure 2.10: Description of the method of the 20 x 1 ms acquisition with the influence of the secondary code

To improve this acquisition, we had the idea to found the start of the secondary code, to align it with the beginning of the signal and to multiply the result of the auto-correlation with the secondary code. Like that all the peaks will be in the same direction.

Because of the lack of time, I could not complete the search of the secondary code. But, the method to achieve it is explained here.

To determine the beginning of the secondary code, we got inspire by the method used to detect the start of a data subframe. The correlation between the 100 first bits of the incoming signal and the 20 bits of the Neuman-Hoffman code should return a result as in the Figure 2.11.

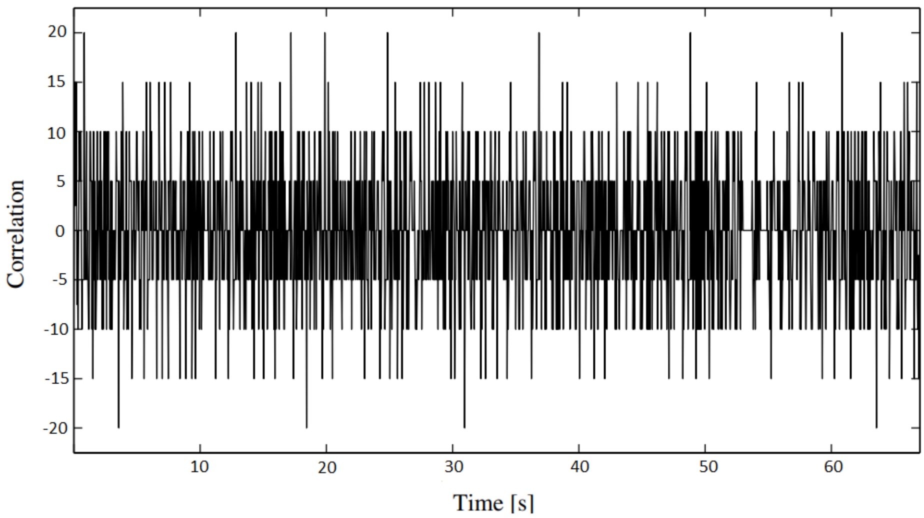

Figure 2.11: Auto-correlation function between the incoming signal and the Neuman-Hoffman code

The result of the auto-correlation should be 20 when the secondary code is located. To be sure the peak at 20 represents indeed a start of the secondary code, one has to check that the following peak is exactly 20 ms after.

Due to the resemblance between the L5 signal and the E5a and E5b signals, all the previous results on the acquisition of the L5Q are correct for the E5aQ and E5bQ channel.

2.4 Acquisition of a Galileo E5 band signal

The E5 signal as describes in the section 1.2.2, has a very specific modulation called AltBOC which allows the signal to achieve better performance of robustness that all the other GNSS signals. As one can notice in the Figure 1.15, the spectrum of the E5 signal looks like two spectra of QPSK modulated signals. In fact, there are two kind of receivers to process an E5 signal. The first one, which is withal the cheapest and easiest one, is to filter the two parts of the E5 signal and then to process separately the E5a part and the E5b part as QPSK(10) modulated signals but the performance are the same that the one of the L5 acquisition. The second one is to process the all signal as a AltBOC(15,10).

2.4.1 One-side band acquisition

First, I began by the acquisition of only one of the part of the E5 signal. The software that generate the signals can generate only a E5a or a E5b signal as if the E5 signal has been filtered be fore in the head of the receiver. As the signal is filtered, the bandwidth of the signal is only about 24 MHz. Whence the signal can be digitized with a sampling frequency of 25 MHz.

According to the Table 1.3, the duration of all the PRN codes of the channels is 1 ms and the shorter duration secondary codes symbol or of the data symbol of the four channels is 4 ms. So I chose to keep the correlation duration of 1 ms. The other factors of the acquisition, detailed in the Table 2.3, remain the same that for the acquisition of the L5 signal. I replaced the code of the different channels.

Parameters	**Values**
Code Frequency (MHz)	10.23
Code Length (Chips)	10230
Sampling Frequency (MHz)	25.0
Correlation time (ms)	1
Frequency search band (kHz)	14
Threshold	2.5

Table 2.3: Parameters used for the E5a or the E5b acquisition

The Figures 2.12 and 2.13 represent respectively the result of the acquisition of the E5a and E5b part. In both of these acquisitions, the code of the in-phase and quadrature channel are used. We can see in these results that the identical satellites are acquired in the E5a or E5b part and that only the value of the power ration differs from the two bar chart.

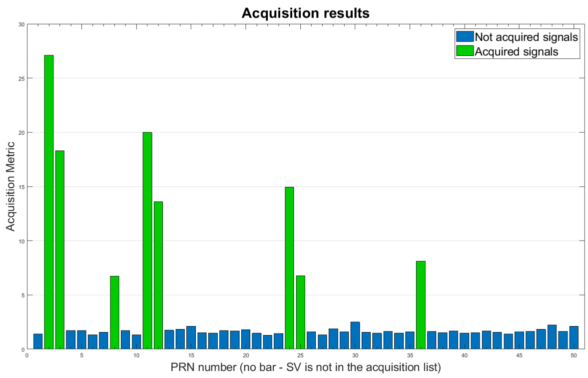

Figure 2.12: Bar chart of the acquisition of the E5a part

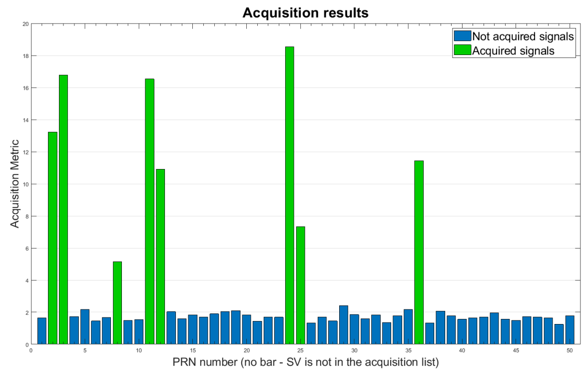

Figure 2.13: Bar chart of the acquisition of the E5b part

The two previous figures show the acquisition of the satellites 2, 3, 8, 11, 12, 24, 25 and 36. This satellites are effectively the ones use to generate the E5 signal is the simulator.

When seeing the ACFs in the Figure 2.14 and 2.15, one notices that the two ACF are the same. But as expected there are not of the form of the ACF of a E5 signal as shown in the Figure 1.16, but there look like the ACF of a QPSK(10) modulated signal. This is coherent because the part a and b are modulated as such.

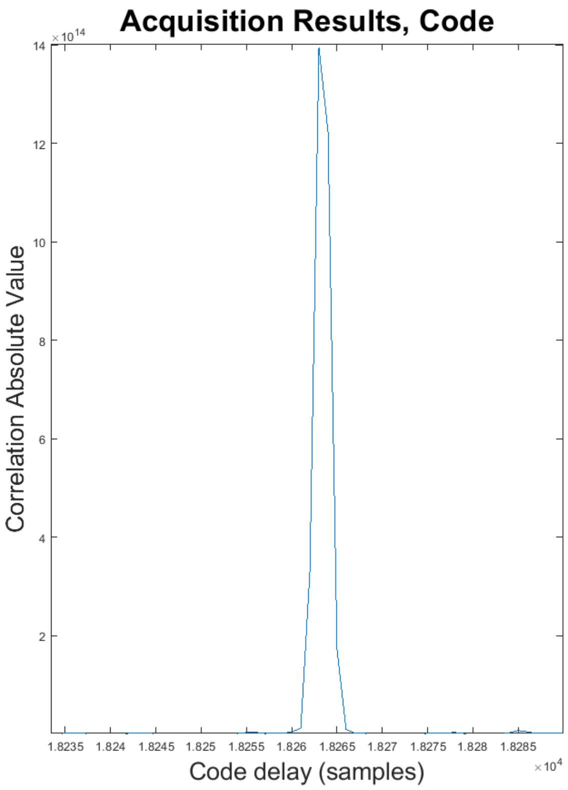

Figure 2.14: Auto-correlation peak of the acquisition of E5a of the 36^{th} satellite of the Galileo constellation

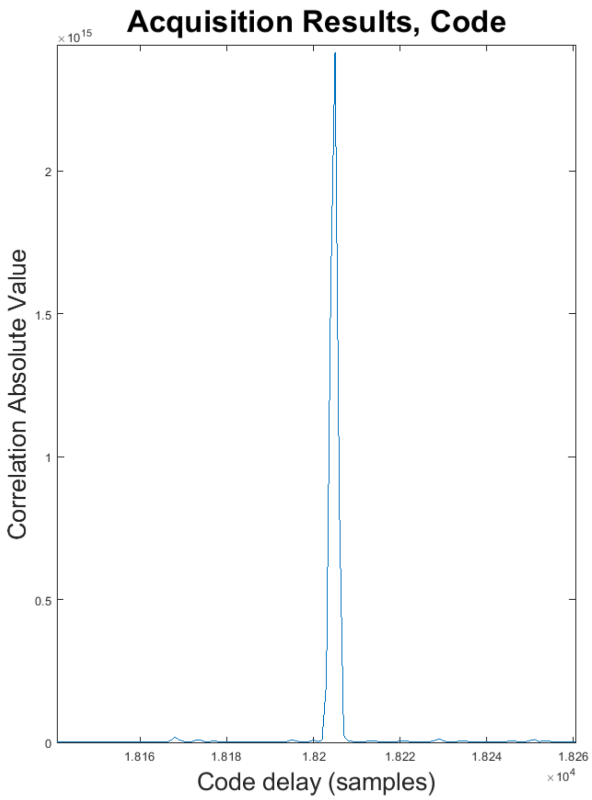

Figure 2.15: Auto-correlation peak of the acquisition of E5b of the 36^{th} satellite of the Galileo constellation

After succeeding to to the separate acquisition of the E5a and E5b signal, I had try to do the acquisition of all the E5 signal.

2.4.2 AtlBOC(15,10) acquisition

The principal difficulty with an E5 signal is its wide bandwidth of 51 MHz. Therefore, with this value of bandwidth, the sampling frequency must be increased. The parameters used for the acquisition are resumed in the following Table 2.4.

Parameters	**Values**
Code Frequency (MHz)	10.23
Code Length (Chips)	10230
Sampling Frequency (MHz)	66.0
Correlation time (ms)	1
Frequency search band (kHz)	14
Threshold	2.5

Table 2.4: Parameters used for the E5 acquisition

Unfortunately, the acquisition did not work. Even when we tried the former code to do the acquisition on only one of the two channels. We think the problem comes from the generation of the E5 signal by the software. In effect, the bandwidth required to generate all the E5 signal is the largest of all GNSS signal and have never be done in the navigation laboratory of the IIT before. Because of problems with the time and of the availability of the generator, we decided to call it quit and to study the tracking of the L5 signal.

2.5 Conclusion

This chapter presents the results of the acquisition of the signals L5 and E5. Unfortunately, because of the problem of the generation of all the E5 signal, this chapter does not expose the results of an AltBOC modulated signal acquisition. However, it presents a proper in-depth look of the acquisition of the L5 signal using its quadrature channel and its secondary code to obtain a better accuracy in the results of the acquisition than for a L1 signal.

Conclusion

The L5 band of the GPS and the E5 band of GALILEO are the new signal of the GNSS. They have been created to reach the performance wanted by the civil aviation requirements for the safety. These better performances are due to their conception. Indeed, the two L5 band signals differ from the L1 one because they have a more complex modulation which allows the signal to have an in-phase and a quadrature channel. The presence of the quadrature channel enables the receiver to track the signal with a longer time of coherent integration without dealing with the unknown data switch. This allows them to be more resilient to the spoofing. These two bands also have wider main lobes, so the signals are more resistant to interference.

The work that I performed during this three months is the prequel of the acquisition and processing of an L5 and E5 signal at it has been never done before in the navigation laboratory of the IIT. It will allow the PhD student who I worked with, Sahil AHMED, to continue my work and to extend his researches about spoofing detection on the new L5 band signals.

During these 14 weeks in the navigation research laboratory of the Illinois Institute of Technology, I had the chance to integrate the team of the laboratory. This internship was the opportunity to discover the field of the research and help students during their PhD. It was also the opportunity to concretely used my knowledge in signal theory collected during the past year at ENAC but also to increase it. I am very grateful that I had the chance to work in this laboratory.

Glossaire

ACF Auto-Correlation Function

ADC Analog to Digital Converter

AtlBOC Alternate Binary Offset Carrier

BOC Binary Offset Carrier

BPF Band Pass Filter

BPSK Binary Phase-Shift Keying

CBOC Composite Binary Offset Carrier

C/A Coarse Acquisition

DLL Delay Lock Loop

FFT Fast Fourier Transform

FLL Frequency Lock Loop

GNSS Global Navigation Satellite System

GPS Global Positioning System

IF Intermediate Frequency

IFFT Inverse Fast Fourier Transform

LNA Low Noise Amplifiers

NCO Numerically Controlled Oscillator

NH code Neuman-Hoffman code

PLL Phase Lock Loop

PRN Pseudo-Random Noise

QPSK Quadrature Phase-Shift Keying

RF Radio Frequency

TCXO Temperature Compensated Crystal Oscillator

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