E1 GALILEO SIGNAL RECEIVER

A Degree Thesis Submitted to the Faculty of Escola Tècnica d’Enginyeria de Telecomunicació de Barcelona

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by

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supervised by

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Abstract

E1 GALILEO Signal Receiver

Navigation is defined as the science of finding the position of a craft or person and getting them from one place to another. During the last times in a world in constant motion, a system capable of dealing with positioning and localization in any part of the globe with an accurate precision is indispensable. Global Navigation Satellite System (GNSS) refers to artificial satellite constellations providing signals from space allowing specific receivers to determine the requested position within a global coverage.

This is a project for the new GALILEO system created by the European Union. The study designs and implements a receiver that focuses on E1 signals, obtained all of them from European Space Agency and CTTC. For the development of this receiver, acquisition, tracking, demodulation and position performance parts have been taken into account, being these last two parts the specific subject of study of this project.
Resum

E1 GALILEO Signal Receiver

La navegació es defineix com la ciència de trobar la posició d’una persona o vehicle i guiar-los d’un lloc a un altre. Durant aquests anys en un món que es regeix pel constant moviment, un sistema capaç de tractar el posicionament i la localització en qualsevol lloc del món amb una precisió exacta és indispensables. El Sistema de Navegació Global per Satèl·lit (GNSS) fa referència a les constel·lacions de satèl·lits artificials que proporcionen senyals des de l’espai permitint als receptors dissenyats per tal fi determinar la posició requerida dins d’una cobertura global.

Aquest és un projecte pel nou sistema GALILEO creat per la Unió Europea. L’estudi dissenya i implementa un receptor que treballa amb els senyals E1, obtinguts tots ells a través de l’Agència Espacial Europea i del Centre Tecnològic de Telecomunicacions de Catalunya. Pel desenvolupament d’aquest receptor s’han tingut en compte les parts d’adquisició, seguiment, desmodulació i càlcul de la posició, sent aquestes dues últimes parts l’objecte d’estudi d’aquest projecte.
Resumen

E1 GALILEO Signal Receiver

La navegación se define como la ciencia de encontrar la posición de una persona o un vehículo y guiarlos de un lugar a otro. Durante los últimos tiempos en un mundo en constante movimiento, un sistema capaz de tratar el posicionamiento y la localización en cualquier parte del mundo con una precisión exacta es indispensable. El Sistema de Navegación Global por Satélite (GNSS) hace referencia a las constelaciones de satélites artificiales que proporcionan señales desde el espacio permitiendo a los receptores diseñados con tal fin determinar la posición requerida dentro de una cobertura global.

Éste es un proyecto para el nuevo sistema GALILEO creado por la Unión Europea. El estudio diseña e implementa un receptor que trabaja con las señales E1, obtenidas todas ellas a través de la Agencia Espacial Europea y del CTTC. Para el desarrollo de este receptor se han tenido en cuenta las partes de adquisición, rastreo, demodulación y cálculo de la posición, siendo estas dos últimas partes el objeto de estudio de este proyecto.
Acknowledgments

First of all, I would like to express my gratitude to my advisor, Prof. Juan Antonio Fernández Rubio, for all his complete dedication to this project and for transmitting to me the passion he really feels for this area.

I would like to thank Dr. Carles Fernández-Prades, member of CTTC (Centre Tecnològic de Telecomunicacions de Catalunya) for manifesting so much interest in the project and providing us his knowledge about the matter, particularly with real Galileo signals.

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Chapter 1

Introduction

In this section we will overview the different operational Global Navigation Satellite Systems. (GPS, GLONASS and GALILEO) together with the systems in development (BeiDou-2). It has been considered the Regional satellite navigation systems (BeiDou-1, NAVIC and QZSS, the last one in development). A concise comparison of the systems is implemented, focusing the rest of the project on the new GNSS European system GALILEO.

The objectives and methods used during this project are presented as well.

1.1 Global Navigation Satellite Systems

Global Positioning System (GPS)

In the early 1960s, several U.S. government organizations, including National Aeronautic and Space Administration (NASA), were interested in satellite systems for position determination. It was required global coverage, continuous weather operation, serve high-dynamic platforms and high accuracy as main attributes. After developing satellite navigation systems as Transit or 621B by the Air Force and their corresponding enhancement projects, the Office of the Secretary of Defense (OSD) established the Navigation Satellite Executive Steering Group to develop a Defense Navigation Satellite System (DNSS) program to consolidate the independent development works. From this effort, NAVSTAR GPS system concept was formed and developed by the GPS Joint Program Office (JPO).[1]

GPS constellation was designed originally to operate with 24 satellites in 6 orbital planes, four satellites per plane. The orbital planes have an inclination of 55º and they are separated by 60º right ascension of the ascending node (RAAN) at an altitude of approximately 20200 km (Medium Earth Orbit). It utilizes the concept of one-way
time of arrival (TOA) ranging. The transmission is referenced to highly accurate atomic frequency standards onboard the satellites in synchronism with an internal GPS system time base. GPS uses the code division multiple access (CDMA) technique and two only frequencies are used by the system: L1 (1575.42 MHz) and L2 (1227.6 MHz). There are 31 satellites in use in the GPS constellation. The additional ones allow a better receiver calculations.

**Global Navigation Satellite System (GLONASS)**

GLONASS is the Russian space-based radionavigation system operated by Russia’s Ministry of Defense. It is the most expensive program of the Russian Federal Space Agency. Like GPS the program began in the mid-1970s with military design goals. Both programs are quite similar. GLONASS achieved its full orbital constellation of 24 satellites in 2011. It employs three orbital planes at an altitude of 19,100 km. The satellite transmissions differ from GPS. GLONASS uses frequency division multiple access (FDMA), and each satellite broadcasts the same ranging codes and transmits on a different frequency.

**GALILEO**

GALILEO is the European global navigation system carried out by the European Union and the European Space Agency. It provides a highly accurate and global positioning service and it is interoperable with the other current global satellite navigation systems (GPS at USA and GLONASS under Russian control). It provides its own independence at any time, although the coordinated utilization brings great advantages in terms of precision and security.

GALILEO is based on the same technology as GPS yet it provides a similar or higher degree of precision and it is more reliable as it includes an integrity message signal that will warn of errors. Although the system is designed to be available to civil and military users, it is intended primarily for civilian use, reserving military use for extreme circumstances.

GALILEO will provide new services such as search and rescue among others. The first GALILEO satellite to be part of the operational system was launched in October 2011 and the complete system, consisted of 30 satellites, is expected by 2020.
BeiDou-2

The Chinese satellite navigation system is called BeiDou. BeiDou-2, also known as COMPASS, is the second generation of the system and it will have global coverage upon 2020 using 35 satellites, including 5 geostationary orbit satellites, 27 in Medium Earth Orbit and 3 in inclined geosynchronous orbit. The system is in development since January 2015 but in December 2011, with the use of 10 satellites, it became operational in China. It is expected to enhance the accuracy of GPS. BeiDou employs CDMA and its signals structure is similar to GALILEO or modernized GPS offering open and military service.

The frequencies are located in four bands: E1, E2, E5B and E6. These bands overlap with GALILEO bands. It could cause interferences, especially within E1 and E2, bands used for GALILEO’s public service. China start transmitting in these bands before Europe’s GALILEO and thus have primary rights according to International Telecommunication Union (ITU) policies.

BeiDou-1

BeiDou-1 is the China first satellite navigation system launched between 2000 and 2003. It consists of three working satellites and one backup satellite, and offers regional coverage for Chinese costumers since 2000. The used orbit, instead of being Medium Earth Orbit, is geostationary, so the system does not require a large number of satellites in its constellation but the coverage is limited. The frequency used by the system is 2491.75 MHz.
NAVigation with Indian Constellation (NAVIC)

NAVIC, previously known as IRNSS is a regional satellite navigation system developed by Indian Space Research Organization (ISRO). It was developed to guarantee the access to navigation satellite systems in hostile situations since during the Kargil war (1999) the Indian military was dependent on the American GPS.

It will be an independent regional system over India and 1500 km around it. NAVIC structure consists of 3 geostationary satellites and 4 other satellites in a geosynchronous orbit. They were successfully launched between 2013 and April 2016. The system will provide standard positioning service for civilian use and restricted service for authorized users. Both services will be carried on L5 (1176.45 MHz) and S band (2492.028 MHz). In 2017 it has been announced a failure with the atomic clocks of the first launched satellite (IRNSS-1A) belonging to geosynchronous orbit and IRSO is going to replace it in the second half of 2017.

Quasi-Zenith Satellite System (QZSS)

The Quasi-Zenith Satellite System (QZSS), is a regional navigation system and enhancement project for GPS signals receivable in Japan. Initially 3 geosynchronous satellites were proposed, but in March 2013, Japan’s Cabinet Office announced the expansion to 4 satellites. The first satellite was launched in September 2010 and the construction of the rest is planned to be launched before the end of 2017, being slated the operational system by 2018.

1.2 Objectives and Methods

The purpose of this project is the design and the implementation of E1 Galileo signal receiver. The Galileo receiver consists of four main parts: acquisition, satellites tracking, decoding and finally the positioning performance. The research group has focused his tasks on acquisition and tracking parts, whereas this project is focused on decoding and satellites position parts. After the implementation, it is allowed to obtain an accurate position of the receiver by using real Galileo signals.

The receiver is fully performed using MATLAB algorithms. Some of the decoding algorithms were previously developed for GPS technology, so it has had to adapt everything, not only the concepts but also the Galileo navigation message. Yet, the major part were newly developed.

The European Space Agency has provided real Galileo signals. These signals were useful to understand how is the navigation message structure and they were able to obtain
the first parameters carried by Galileo signals.

Then, so as to compute the satellites position, a new signal was provided. This time it was courtesy of CTTC (Centre Tecnològic de Telecomunicacions de Catalunya). First, a signal just with one satellite navigation data and then, a new signal with navigation messages coming from several satellites. To obtain this last signal, it was necessary to install an open source Global Navigation Satellite Systems software-defined receiver (GNSS SDR) on Linux and adapt the parameters of the receiver to Galileo receiver. The software GNSS SDR is developed by a group of researchers at CTTC for educational and research purposes.

To obtain satellites position new algorithms were coded. Initially, there were some problems with the satellite signal and the expected results were not obtained, since some parameters gave an erroneous value. Fixed the incident, the position of the satellites was performed.

The satellites position together with the pseudo-range provided by the tracking tasks allow to calculate the position of the receiver.

Throughout the project some roadblocks have been encountered due to the scarce information that still exists of the Galileo system. Although there is a lot of information and books on GPS system, GALILEO is in full development process and some specifications are not fully defined or have been left for future work. Due to this fact, some problems have appeared due to the lack of information that exists in this field.

The project is carried out in the framework of the Signal Theory in Communications department at Universitat Politècnica de Catalunya.

Below it is presented the Gantt diagram of the final project where the title and duration of the packages are specified.

![Gantt Diagram](image)

Figure 1.2: Gantt Diagram.
Chapter 2

Galileo System Overview

2.1 System Description

The Galileo system consists of 30 satellites (24 operational and up to 6 active spares). They are positioned in three Medium Earth Orbit planes with an inclination of 56° with reference to the equatorial plane (8 operational satellites and 2 active spares per plane) and separated by 120° right ascension of the ascending node (RAAN) at an altitude of approximately 23222 km.[2]

2.1.1 Galileo Control Centers (GCC)

The performance of two Galileo Control Centers (GCC), located in Oberpfaffenhofen and Fucino, controls the satellite constellation, the synchronization of the satellite atomic clocks, the processing of the integrity signal and the data handling of all internal and external elements. These GCC’s consists of: Orbit Synchronization and Processing Facilities (OSPF), Precision Timing Facilities (PTF), Integrity Processing Facilities (IPF), Mission Control Facilities (MCF), Satellite Control Facilities (SCF) and Services Product Facilities (SPF).

The GCC are supported by a worldwide network of five Telemetry, Tracking and Control (TT&C) stations. Data transfer to and from the satellites is performed through a global network of Galileo Uplink Stations (GUS). Each GUS combines a TT&C and a Mission Uplink Station (MUS). Galileo Sensor stations (GSS) are distributed around the globe. They sense the quality of the satellite navigation signal, as known as Signal In Space (SIS). The information on the SIS quality, called Integrity Information, is the major differentiator of GALILEO compared to other GNSS. The Integrity Information will be transmitted globally together with the navigation signal and thus allows the Galileo system to be certified for safety-of-Life applications.
2.2 Services

Galileo system will provide four navigation services and one service to support Search and Rescue. The following services will be independent from other systems and they will be available worldwide.

- **Open Service (OS):** This service will be free of charge. It will provide position, down to one meter, and simple timing. It is a combination of open signals.

- **Safety of Life navigation (SoL):** It is an enhancement of the open service as it provides timely warnings to the user when it is out of a certain accuracy margin. This service is suitable for applications that need a guaranteed precision.

- **Commercial Service (CS):** In order to obtain higher data rates, this service provides access to two additional signals. It also enables users to improve their accuracy. It is a guaranteed and encrypted service.

- **Public regulated Service (PRS):** Service for government authorized users that require better continuity of service and controlled access. The signals involved use encrypted ranging codes.

- **Search and Rescue service (SAR):** Galileo signals will be able to pick up signals from emergency beacons carried by ships, planes or individuals and relay them to national rescue centers. In this type of situation is very important to know the precise position and this Galileo service allows at least one Galileo satellite to be visible of any point on Earth at any times. It is a flattering factor because it permits real-time distress alerts. It also contributes to improve the international COSPAS-SARSAT Search and Rescue System, taking part in the MEO Search and Rescue system (MEOSAR).

2.3 Frequency Plan

The Galileo navigation signals are transmitted in L-band (1-2 GHz) spectrum. These signals occupy four different frequency bands indicated in figure 2.1. The four frequency bands are: E5a, E5b, E6 and E1. Galileo satellites share the E1 band (1575.42 MHz) with GPS.

These frequency bands are allocated in the spectrum for Radio Navigation Satellite Services (RNSS). In addition, E5a, E5b and E1 bands are included in the spectrum for Aeronautical Radio Navigation Services (ARNS) as well. This allocated spectrum is employed by Civil-Aviation users and is defined as a radionavigation service intended for the
benefit and for the safe operation of aircraft [3]. This service enables specific applications such as the so-called Safety of Life service.

Figure 2.1: Galileo Frequency Plan where it is shown the frequency bands allocation of the different GNSS systems.

2.4 Modulation Schemes

In table 2.1 it is shown the Galileo carrier frequencies for each band.

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<td>1575.420</td>
</tr>
<tr>
<td>E6</td>
<td>1278.750</td>
</tr>
<tr>
<td>E5</td>
<td>1191.795</td>
</tr>
<tr>
<td>E5a</td>
<td>1176.450</td>
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<tr>
<td>E5b</td>
<td>1207.140</td>
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Table 2.1: Carrier frequencies of Galileo bands

The E5 carrier is subdivided into two subbands: E5a and E5b. This carrier is modulated through a modified BOC called AltBOC. E5a and E5b signals can be processed independently by the receiver as they are two separate QPSK signals with a carrier frequency of 1176.45 MHz and 1207.14 MHz respectively, as shown in figure 2.1.

The E6 signal is formed by components B and C. The component B contains data stream modulated with the encrypted ranging code and the component C is a pilot component. Both pilot and data components are combined on the same carrier component E6.
This study will focus on the E1 signal. In figure 2.2 it is presented the modulation scheme for this signal generation. This modulation is the so-called composite binary offset carrier CBOC(6,1,11).

The Galileo E1 band is centered at $f_c = 1575.42$ MHz and its receiver reference bandwidth is 24.552 MHz.

The E1-B component contains the bit sequence of the Integrity Navigation Message, $D_{I/NAV}$ and Safety-of-Life (SoL) services.

The E1-C component is a pilot signal with a secondary code.

The signals involved are $e_{E1-B}$ and $e_{E1-C}$:

- $e_{E1-B}$: I/NAV navigation data stream $D_{E1-B}$ and the ranging code $C_{E1-B}$. Then it is modulated with the sub-carriers $sc_{E1-B,a}$ and $sc_{E1-B,b}$.
- $e_{E1-C}$: pilot component from the ranging code $C_{E1-C}$ including its secondary code.
  Then it is modulated with the sub-carriers $sc_{E1-C,a}$ and $sc_{E1-C,b}$.

In table 2.2 there is a description with the chip rates and sub-carrier rates of the ranging signals for the E1 signal transmitted by Galileo. The symbol rate of the navigation data stream component, $R_{D,E1-B}$, is 250 symbols/s.
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<th>Ranging Code Chip-Rate $R_{C,E1-Y}$ (Mcps)</th>
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<td>CBOC, anti-phase</td>
<td>1.023</td>
<td>6.138</td>
<td>1.023</td>
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Table 2.2: E1 CBOC Chip Rates and Sub-carrier Rates

The E1-B/C composite signal in baseband is then generated according to equation 2.1.

$$s_{E1}(t) = \frac{1}{\sqrt{2}}(e_{E1-B}(t)(\alpha s_{E1-B,a}(t)+\beta s_{E1-B,b}(t))-e_{E1-C}(t)(\alpha s_{E1-C,a}(t)-\beta s_{E1-C,b}(t)))$$

(2.1)

Where

$$s_{E1-X,a}(t) = \text{sgn}(\sin(2\pi R_{s,E1-X,a}t))$$

$$R_{s,E1-X,a}(t) = 1.023 \text{ MHz}.$$  

$$s_{E1-X,b}(t) = \text{sgn}(\sin(2\pi R_{s,E1-X,b}t))$$

$$R_{s,E1-X,b}(t) = 6.138 \text{ MHz}.$$  

The parameters $\alpha$ and $\beta$ are chosen such that the combined power of signal $s_{E1-B,b}$ and the $s_{E1-C,b}$ sub carrier components equals of the 1/11 of the total power of $e_{E1-B}$ plus $e_{E1-C}$, before application of any bandwidth limitation.

$$\alpha = \sqrt{\frac{10}{11}} \text{ and } \beta = \sqrt{\frac{1}{11}}$$

2.5 Transmitted and Received Signals

To compute the receiver position, two parameters are necessary: the satellite position and its clock error. The satellites convey this information to the receiver.

The satellites position is known by the receiver using the ephemeris information transmitted by different satellites. The GNNS receiver measures its distance to the satellites, knowing the time the signal takes to arrive, and it uses this information to compute its position. Every satellite denotes the receiver is located in a point of the sphere surface which is centered in the corresponding satellite and it has the total distance to the receiver as radius. The concept known as trilateration is helpful in this cases and it is shown in figure 2.3. With only 3 points, the receiver position could be computed. Yet, when talking about 4 dimensions 4 points are necessary due to receiver clock error. Considering the spatial intersection between the three spheres and the temporal intersection with the
fourth one, two points are obtained. One of them is located outside the globe, and the other one is the point related to the receiver.

![Diagram of Trilateration concept](image)

**Figure 2.3: Trilateration concept.** Whether the satellites clocks are not synchronized with the receiver’s clock, some error is made in the measurement of time, and the three spheres do not intersect at the correct point.

**Time**

Introducing UTC (Universal Time Coordinated), it is the main hour standard around the world. It is based on second jumping, which is a one-second adjustment that is occasionally applied to UTC in the sense of keeping the time of day closer to the solar time.

Galileo Time and UTC do not indicate the same time. Unlike UTC, Galileo timing is constantly continuous. This phenomenon causes a gap between both timing systems, and Galileo displays which is this difference.

Galileo satellites transmit the navigation message at the same instant of time, since all of them are synchronized with very accurate clocks. Nevertheless, the received signals do not arrive at the same time. That is when the concept of pseudo-range arises: importance is taken by the relative times. The first received signal is set to 0 (Offset) and then it is computed several time increments with the receiving of the rest of the signals. In Chapter 5: Positioning Performance, this concept is widely explained. In order to anticipate this, figure 2.4 presents a scheme with 4 satellites and the 4 equations belonging to the calculation of its 4 pseudo-ranges.
Figure 2.4: Position determination. At least 4 satellites are necessary so as to obtain the receiver position.

\[ \rho_1 = \sqrt{(x_{s1} - x_u)^2 + (y_{s1} - y_u)^2 + (z_{s1} - z_u)^2 + c\Delta t} \] (2.2)

\[ \rho_2 = \sqrt{(x_{s2} - x_u)^2 + (y_{s2} - y_u)^2 + (z_{s2} - z_u)^2 + c\Delta t} \] (2.3)

\[ \rho_3 = \sqrt{(x_{s3} - x_u)^2 + (y_{s3} - y_u)^2 + (z_{s3} - z_u)^2 + c\Delta t} \] (2.4)

\[ \rho_4 = \sqrt{(x_{s4} - x_u)^2 + (y_{s4} - y_u)^2 + (z_{s4} - z_u)^2 + c\Delta t} \] (2.5)
Chapter 3

GNSS Receiver

In this section it is presented the main parts of which a Galileo E1 signal receiver consists. A GNSS receiver is composed of the following blocks: RF front-ends, RF system, Signal source, Signal conditioner, Acquisition, Tracking and Decoding of the navigation message.

In figure 3.1 it is presented an overview of a proposed GNSS software receiver, where the input are raw bits coming from the RF front-end’s ADC and they can be read from a file or directly in real time from a hardware device. At its output there is an amplified, downconverted, decimated, filtered and digitized version of the received signal. The signal conditioner consists of adapting the sample bit depth to a data type tractable at the host computer running the software receiver, and it can intermediate frequency to baseband conversion.

Figure 3.1: Proposed Galileo signal receiver. Notice its main parts such as Acquisition, Tracking and Telemetry Decoder [4].

So as to delve into these main parts, their general purposes are described in the next sections. [4]
3.1 Acquisition

This block is in charge of the detection of presence/absence of signals coming from a GNSS satellite. When the receiver obtains a positive detection, it should provide estimations of the code phase $\hat{\tau}$ and the Doppler shift $\hat{f}_d$ in order to initialize the delay and phase tracking loops.

The maximum likelihood (ML) estimators of $\tau$ and $f_d$ are obtained by maximizing the function:

$$\hat{f}_{d,ML}, \hat{\tau}_{ML} = \arg \max_{f_d,\tau} \{|\hat{R}_{xd}(f_d,\tau)|^2\}$$

(3.1)

Where:

$$\hat{R}_{xd}(f_d,\tau) = \frac{1}{N} \sum_{n=0}^{N-1} x_{IN}[n]d[nT_s - \tau]e^{-j2\pi f_d nT_s}$$

(3.2)

Where 

- $x_{IN}[n] = $ complex vector containing I&Q samples of the received signal.
- $T_s = $ sampling period.
- $\tau = $ code phase of the received signal with respect to a local reference.
- $f_d = $ Doppler shift.
- $N = $ number of samples in a spreading code.
- $d[n] = $ locally generated reference.

Obtaining the optimum estimators implies the maximization of the correlation function of the incoming signal with its matched filter.

A two-dimensional search from a multiplication-and-sum of N complex samples is required for the maximization of equation 3.1. To make this process easier, it is used the FFT-based circular convolution, which exchanges the expensive multiplication-and-sum operation by a discrete Fourier transform. [5]

3.2 Tracking

This block receives the data stream $x_{IN}[n]$ and proceeds to do its function when it obtains a 'positive acquisition' message from the control plane, along with the estimations $\tau_{acq}$ and $\hat{f}_{acq}$. Once obtained, its role is to refine the estimations and track their changes along the time.

To attain signal tracking there are three relevant parameters: evolution of the code phase $\tau$, Doppler shift $f_d$ and carrier phase $\phi$.

So as to obtain the optimum estimators it is commonly used closed-loop structures designed to minimize the difference between the code phase, the carrier phase and the frequency of the incoming signal with respect to a replica generated locally.
3.3 Decoding

As it is explained in section 2.4, the E1-B signal component carries the I/NAV navigation message. This message, once decodified provides the following specifications: space vehicle identification (SVID), Issue of Data, ephemeris data, signal-in-space accuracy indicator (SISA), clock correction parameters, ionospheric correction, Broadcast Group Delay (BDG), signal health and data validity status, Galileo System Time (GST), GST-UTC and GST-GPS time conversion parameters, almanacs and Search and Rescue service data (SAR).

The next chapter titled Galileo Message Structure goes deeper into this type of content and the description of the I/NAV message.
Chapter 4

Galileo Message Structure

There are three different types of navigation message: F/NAV provided by E5a-I for open service, I/NAV provided by E5b and E1-B corresponding to both open and commercial service and C/NAV provided by E6-B signal supporting commercial service. The subject of this chapter is the study of the I/NAV message since it is carried by E1-B component, the interested signal.

4.1 I/NAV Message Description

The general structure of the I/NAV message is represented in figure 4.1. The complete navigation message data are transmitted as a sequence of frames. The frame duration is 720 seconds and it is composed by 24 subframes of 30 seconds of duration each of them. The subframes contain 15 nominal pages, having a duration of 2 seconds transmitted sequentially in time in two parts of duration 1 second each of them. These two parts are named even and odd. There is another type of I/NAV page known as alert page. In order to differentiate both pages there is a 1 bit field equal to 0 or 1 to indicate the nominal or alert page type, correspondingly.

The I/NAV nominal page, even or odd, is composed by 120 bits: 114 bits for I/NAV Page Part and 6 tail bits consisting of 6 zeros.
4.2 Error coding

To avoid errors during data transmission, three methods of error coding are applied to the Galileo message data stream.

4.2.1 Cyclic Redundancy Check (CRC)

The CRC technique is used in Galileo system to detect the reception of corrupted data. For the I/NAV page, a CRC of 24 parity bits is computed on the even/odd fields but it does not include the Reserved 2 field. The CRC is generated from the generator polynomial $G(X)$ described below.

$$G(X) = (1 + X)P(X) \quad (4.1)$$

And $P(X)$ is primitive and irreducible polynomial given by equation 4.2.

$$P(X) = X^{23} + X^{17} + X^{13} + X^{12} + X^{11} + X^9 + X^8 + X^7 + X^5 + X^3 + 1 \quad (4.2)$$

The primitive polynomial in binary is $[1 0 0 0 0 0 1 0 0 0 1 1 1 0 1 1 0 1 0 1 0 0 1]$ and the resulting generator polynomial is $[1 1 0 0 0 1 1 0 0 1 0 0 1 1 0 0 1 1 1 1 0 1 1]$.
4.2.2 Forward Error Correction (FEC)

The type of FEC used by Galileo is the convolutional codes encoding. In order to decoding convolutional codes, several algorithms exist, yet the Viterbi algorithm has been chosen in this study as it is commonly used for the given specifications and it provides maximum likelihood performance.

Following, both systems are widely described.

**Convolutional Code**

Convolutional encoding consists of generating parity symbols. They are characterized by the Coding Rate (n/k) and the Constraint Length (K). In table 4.1 the Galileo parameters for convolutional encoded data are specified.

<table>
<thead>
<tr>
<th>Code Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coding Rate</td>
<td>1/2</td>
</tr>
<tr>
<td>Constraint Length</td>
<td>7</td>
</tr>
<tr>
<td>Generator Polynomials</td>
<td>G1=171o</td>
</tr>
<tr>
<td></td>
<td>G2=133o</td>
</tr>
<tr>
<td>Encoding Sequence</td>
<td>G1 then G2</td>
</tr>
</tbody>
</table>

Table 4.1: Galileo Data Coding Parameters

The convolutional encoding is a system with memory and it is generated with the current bits and with the previous information in time. Constraint Length (K) states the output is a function of the current input as well as the previous K-1 inputs. This method is depicted in figure 4.2, where each memory register holds an input bit.

![Figure 4.2: Galileo Non-Recursive Convolutional Coding Scheme. Note the negation symbol on the lower branch. It describes an encoder where the lower branch is inverted at the end. This novelty of Galileo system caused a modification on the ordinary FEC code.](image)

Due to this convolutional encoding, the 120 bits of the I/NAV nominal page are converted into 240 symbols.
Viterbi Algorithm

Viterbi decoder is based on a simple calculation of distances, yet it needs a great storage capability. Viterbi algorithm utilizes a trellis diagram where all possible transitions of the input bits are shown. Each branch of the trellis diagram has a tag associated with the distance between the received bits by the channel and the output encoded bits corresponding to that branch. To compute the Viterbi path it is necessary to add the tags branch by branch. For each state it is calculated the accumulated distance for every possible path. The branch associated to the path with minimum distance is selected. The algorithm stores the path of minimum distance that reaches each state, so that it makes the decision at the end of the sequence.

To obtain the decoded data, it has been taken advantage of a MATLAB function that consists of convolutionally decoding binary data using the Viterbi algorithm. In this function the trellis is required and it is previously obtained through another function that uses the Constraint Length, that specifies the delay for each of the input bit streams, and the Generator Polynomials. These parameters are specifically indicated in table 4.1.

4.2.3 Interleaving

Usually, bit errors will not accustom to appear in isolation, but bursts will appear with many consecutive erroneous bits. The solution is interleaving, which modifies the order of bits at the output of the encoder so that consecutive bits are affected by independent channel conditions.

The block interleaver used by Galileo system consists of 30 columns and 8 rows. The 240 data symbols are written in columns and once the matrix is filled, data is read by rows and sent to the channel.

<table>
<thead>
<tr>
<th>Interleaved Symbols</th>
<th>Columns</th>
<th>Rows</th>
</tr>
</thead>
<tbody>
<tr>
<td>240</td>
<td>30</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 4.2: Interleaving Parameters

4.3 I/NAV Page Part

The I/NAV page part (even or odd) is codified as follows: 120 bits binary string of data, included 6 zero-value tail bits, is the input to the convolutional encoder, obtaining 240 symbols binary string. The encoded symbols of the string are given as input to the I/NAV block interleaver obtaining 240 interleaved symbols. At the beginning of the binary string there is added a synchronization pattern that is not encoded.
This pattern is \([0 \ 1 \ 0 \ 1 \ 1 \ 0 \ 0 \ 0 \ 0 \ 0]\).

In figure 4.3 it is shown the structure of the nominal I/NAV pages (even is the first part of a page and odd is the second one). Both parts are transmitted sequentially over the same frequency.

![Figure 4.3: I/NAV Nominal Page Structure and Bits distribution \([2]\).](image)

The structure of the Nominal Page, whose duration is 2 seconds, is highly important; therefore, a more detailed explanation of the different fields is given:

- **Even/Odd**: This bit indicates whether the part of the page is even (0) or odd (1).
- **Page Type**: This bit is set to 0 to indicate the page is a Nominal Page. In case the page is an Alert Page, this bit will be set to 1.
- **Data**: It is composed of a nominal word of 128 bits distributed into two page parts: 112 bits (1/2) and 16 bits (2/2).
- **SAR data**: Search and Rescue (SAR) Return Link Message (RLM) 22 Bits of data.
- **CRC**: These 24 Bits are computed on the following even and odd fields: Page Type, Data, Spare, SAR and Reserved 1 fields. It is always broadcast on the odd part.
- **Tail**: This field consists on 6 zeros, as mentioned before, and it is not protected by the CRC.

Yet, the field that contains the most important information so as to calculate afterwards the satellite position is the 128 bits data field. As it has been described, nominal words set up this field.
4.3.1 I/NAV Word Types

There are 11 different word types that carry the navigation data. Each of them contains all the parameters required to compute the position, velocity and time.

Following there is a specific scheme of how are these parameters distributed in the different nominal words. Besides, there are several examples obtained from the parameters extraction from a real Galileo satellite signal. It should be considered that the values given below refer to a particular Galileo signal and they are not standard. This has been accomplished using a MATLAB script that has been adapted to the requirements of this system.

![Figure 4.4: I/NAV Word Type 1 [2].](image)

Where
\[ t_0e[n] = \text{Ephemeris reference time.} \]
\[ t_0e[n]_{\text{Galileo}} = 421800 \text{ s} \]
\[ M_0[n] = \text{Mean anomaly at reference time.} \]
\[ M_0[n]_{\text{Galileo}} = 0.2388 \text{ semi-circles} = 0.75 \text{ rad} \]
\[ e = \text{Eccentricity.} \]
\[ e_{\text{Galileo}} = 0.0090 \]
\[ A^{1/2} = \text{Square root of the semi-major axis.} \]
\[ A^{1/2}_{\text{Galileo}} = 5.4407 \times 10^3 \text{ meter}^{1/2} \]

![Figure 4.5: I/NAV Word Type 2 [2].](image)

Where
\[ \Omega_0 = \text{Longitude of ascending node of orbital plane at weekly epoch.} \]
\[ \Omega_{0\text{Galileo}} = 1.8782 \text{ semi-circles} = 5.9 \text{ rad} \]
\[ i_0 = \text{Inclination angle at reference time.} \]
\[ i_{0\text{Galileo}} = 0.3107 \text{ semi-circles} = 0.976 \text{ rad} = 55.928^\circ \]
\[ \omega = \text{Argument of perigee.} \]
\( \omega_{\text{Galileo}} = 0 \) semi-circles

\( \dot{i} \) = Rate of change of inclination angle.

\( \dot{i}_{\text{Galileo}} = 1.8608 \cdot 10^{-9} \) semi-circles = \( 5.846 \cdot 10^{-9} \) rad

<table>
<thead>
<tr>
<th>Type</th>
<th>10DOE</th>
<th>SVID</th>
<th>( \cdot \Omega )</th>
<th>( \Delta n )</th>
<th>( C_{UC} )</th>
<th>( C_{US} )</th>
<th>( C_{RC} )</th>
<th>( C_{RS} )</th>
<th>SVID/4E50</th>
<th>Total (bits)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>10</td>
<td>24</td>
<td>16</td>
<td>16</td>
<td>16</td>
<td>16</td>
<td>16</td>
<td>16</td>
<td>8</td>
<td>128</td>
</tr>
</tbody>
</table>

Figure 4.6: I/NAV Word Type 3 [2].

Where \( \dot{\Omega} \) = Rate of change of right ascension.

\( \dot{\Omega}_{\text{Galileo}} = 1.9057 \cdot 10^{-6} \) semi-circles = \( 5.987 \cdot 10^{-6} \) rad

\( \Delta n \) = Mean motion difference from computed value.

\( \Delta n_{\text{Galileo}} = 7.4488 \cdot 10^{-9} \) semi-circles = \( 2.34 \cdot 10^{-8} \) rad

\( C_{UC} \) = Amplitude of the \( \cosh \) correction term to the argument of latitude.

\( C_{UC_{\text{Galileo}}} = 1.2206 \cdot 10^{-4} \) semi-circles = \( 3.83 \cdot 10^{-4} \) rad

\( C_{US} \) = Amplitude of the \( \sinh \) correction term to the argument of latitude.

\( C_{US_{\text{Galileo}}} = 1.2206 \cdot 10^{-4} \) semi-circles = \( 3.83 \cdot 10^{-4} \) rad

\( C_{RC} \) = Amplitude of the \( \cosh \) correction term to the orbit radius.

\( C_{RC_{\text{Galileo}}} = 2.0475 \cdot 10^{3} \) semi-circles = \( 6.43 \cdot 10^{3} \) rad

\( C_{RS} \) = Amplitude of the \( \sinh \) correction term to the orbit radius.

\( C_{RS_{\text{Galileo}}} = 2.0475 \cdot 10^{3} \) semi-circles = \( 6.43 \cdot 10^{3} \) rad

<table>
<thead>
<tr>
<th>Type</th>
<th>10DOE</th>
<th>SVID</th>
<th>( C_{ic} )</th>
<th>( C_{is} )</th>
<th>( t_{0e} )</th>
<th>( \dot{t}_{0e} )</th>
<th>( \dot{t}_{0e} )</th>
<th>( \dot{t}_{0e} )</th>
<th>( \dot{t}_{0e} )</th>
<th>Space</th>
<th>Total (bits)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>10</td>
<td>6</td>
<td>16</td>
<td>16</td>
<td>14</td>
<td>31</td>
<td>21</td>
<td>6</td>
<td>2</td>
<td></td>
<td>128</td>
</tr>
</tbody>
</table>

Figure 4.7: I/NAV Word Type 4 [2].

Where \( SVID \) = Satellite identification.

\( C_{ic} \) = Amplitude of the \( \cosh \) correction term to the angle of inclination.

\( C_{ic_{\text{Galileo}}} = 1.2206 \cdot 10^{-4} \) semi-circles = \( 3.83 \cdot 10^{-4} \) rad

\( C_{is} \) = Amplitude of the \( \sinh \) correction term to the argument of latitude.

\( C_{is_{\text{Galileo}}} = 1.2206 \cdot 10^{-4} \) semi-circles = \( 3.83 \cdot 10^{-4} \) rad

\( t_{0e} \) = Clock correction data reference Time of Week.
\[ t_{0_{\text{Galileo}}} = 421800 \text{ s} \]

\( a_{f_0} = \text{SV clock bias correction coefficient.} \)

\[ a_{f_0_{\text{Galileo}}} = 0.1249 \text{ s} \]

\( a_{f_1} = \text{SV clock drift correction coefficient.} \)

\[ a_{f_1_{\text{Galileo}}} = 2.9802 \cdot 10^{-8} \text{ s/s} \]

\( a_{f_2} = \text{SV clock drift rate correction coefficient.} \)

\[ a_{f_2_{\text{Galileo}}} = 0 \text{ s/s}^2 \]

---

**Figure 4.8: I/NAV Word Type 5 [2].**

<table>
<thead>
<tr>
<th>Ionospheric correction</th>
<th>Az</th>
<th>Ionospheric disturbance flag</th>
<th>GST</th>
<th>Total (bits)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type-5</td>
<td>6</td>
<td>11</td>
<td>11</td>
<td>14</td>
</tr>
</tbody>
</table>

Where

\( a_{i_0} = \text{Effective Ionisation Level 1}\text{st order parameter.} \)

\( a_{i_1} = \text{Effective Ionisation Level 2}\text{nd order parameter.} \)

\( a_{i_2} = \text{Effective Ionisation Level 3}\text{rd order parameter.} \)

\( \text{BGD(E1,E5a)} = \text{E1-E5a Broadcast Group Delay (F/NAV)}. \)

\( \text{BGD(E1,E5b)} = \text{E1-E5b Broadcast Group Delay (I/NAV)}. \)

Ionospheric disturbance flag

\( E5b_{HS} = \text{E5b Signal Health Status.} \)

\( E1B_{HS} = \text{E1-B/C Signal Health Status.} \)

\( E5b_{DVS} = \text{E5b Data Validity Status.} \)

\( E1B_{DVS} = \text{E1-B Data Validity Status.} \)

\( WN = \text{Week Number.} \)

\[ WN_{\text{Galileo}} = \text{week 734} \]

\( TOW = \text{Time of Week.} \)

\[ TOW_{\text{Galileo}} = 421735 \text{ s} \]
Figure 4.9: I/NAV Word Type 6 [2].

Where

\[ A_0 = \text{Constant term of polynomial.} \]

\[ A_1 = 1^{st} \text{ order term of polynomial.} \]

\[ \Delta t_L S = \text{Leap Second count before leap second adjustment.} \]

\[ t_{0L} = \text{UTC data reference Time of Week.} \]

\[ WN_{0L} = \text{UTC data reference Week Number.} \]

\[ WN_{LSF} = \text{Week Number of leap second adjustment.} \]

\[ DN = \text{Day Number end leap second adjustment becomes effective.} \]

\[ \Delta t_{LSF} = \text{Leap Second count after leap second adjustment.} \]

Figure 4.10: I/NAV Word Type 7 [2].

Where

\[ IOD_a = \text{Almanac Issue Of Data.} \]

\[ WN_a = \text{Almanac reference Week Number.} \]

\[ \Delta t_L S = \text{Leap Second count before leap second adjustment.} \]

\[ t_{0a} = \text{Almanac reference time.} \]

Almanac for SVID1 (1/2).

Figure 4.11: I/NAV Word Type 8 [2].

Almanac for SVID1 (2/2) and SVID2 (1/2).
Figure 4.12: I/NAV Word Type 9 [2].

Almanac for SVID2 (2/2) and SVID3 (1/2).

Figure 4.13: I/NAV Word Type 10 [2].

Where 
\[ A_{0G} \] = Constant term of polynomial describing offset \( \Delta t_{system} \).

\[ A_{1G} \] = Rate of change of the offset \( \Delta t_{system} \).

\[ t_{0G} \] = Reference Time for GGTO data.

\( WN_{0G} \) = Week Number of GGTO reference.

Almanac for SVID13 (2/2).

Figure 4.14: I/NAV Word Type 0 [2].

I/NAV Spare word, \( WN \) and \( TOW \).

When the field \( Time \) is not set to 10, \( WN \) and \( TOW \) do not contain valid data.
4.3.2 I/NAV Nominal Sub-Frame Layout

In Galileo system, a sub-frame is composed of 15 Nominal Pages, so its duration is 30 seconds.

Using a MATLAB script with a Galileo real signal, it has been verified that the order that is carried out by the nominal words within a sub-frame is as follows:

<table>
<thead>
<tr>
<th>time (s)</th>
<th>Word</th>
<th>time (s)</th>
<th>Word</th>
<th>time (s)</th>
<th>Word</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2</td>
<td>12</td>
<td>Reserved</td>
<td>22</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>14</td>
<td>Reserved</td>
<td>24</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>16</td>
<td>Reserved</td>
<td>26</td>
<td>5</td>
</tr>
<tr>
<td>8</td>
<td>7 or 9</td>
<td>18</td>
<td>Reserved</td>
<td>28</td>
<td>Spare</td>
</tr>
<tr>
<td>10</td>
<td>8 or 10</td>
<td>20</td>
<td>Reserved</td>
<td>30</td>
<td>Spare</td>
</tr>
</tbody>
</table>

Table 4.3: I/NAV Nominal Sub-Frame Structure

4.3.3 I/NAV Nominal Frame Layout

The Galileo frame is composed of 24 sub-frames of 30 seconds of duration, so the total duration of a Galileo frame is 720 seconds.

Almanac data, i.e. data corresponding to nominal words 7,8,9 and 10, are sequenced in a nominal frame depending on the sub-frame, as it has been seen in table 4.3. Table 4.4 introduces an example of how it is implemented:

<table>
<thead>
<tr>
<th>Sub-Frame ID</th>
<th>Words</th>
<th>Sub-Frame ID</th>
<th>Words</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7 and 8</td>
<td>3</td>
<td>7 and 8</td>
</tr>
<tr>
<td>2</td>
<td>9 and 10</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

Table 4.4: I/NAV Sub-Frame sequencing

4.4 SAR Data

Search and Rescue data is transmitted within the Galileo navigation message. It is an European contribution on humanitarian Search and Rescue activities, since the satellites will pick up emergency signals from beacons carried on transport or people. Then these signals will be sent back to national rescue centers which will be able to know the accurate location of an accident. Reducing the required time to locate a distress and provide assistance increases the probability of survival. [7]

SAR messages can be transmitted within short or long Rescue Link Message structure
Chapter 5

Positioning Performance

The navigation data contain the 4 types of data needed to perform positioning: ephemeris parameters to indicate the position of the satellite to the receiver, time and clock correction parameters to compute pseudo-range, service parameters to identify satellites and signal health and almanac parameters to indicate the position of other satellites.

Once ephemeris, service and almanac parameters have been presented, it is time to go deeper into time and clock correction parameters so as to compute the so-called pseudo-range.

Then, it will be the time to indicate the equations used to find the satellite positions.

5.1 Pseudo-range

The relative pseudo-range is the distance (or time) between two reference points. In GNSS there is no absolute time reference. The only time reference is the sampling frequency and the clock bias of the receiver is unknown.

Considering it is taken as reference point the beginning point of sub-frame 1, for instance, all the beginning points of sub-frame 1 from different satellites are transmitted at the same time except for the clock correction terms of each satellite. As a result it can be considered that the sub-frames from different satellites are transmitted at the same time. Since the beginning of sub-frame 1 from different satellites are received at different times, this difference time represents the time (or distance) difference from the satellite to the receiver. Therefore, it represents the relative pseudo-range. [6]
**Ideal Case**

The ideal case to compute pseudo-ranges is when it does not exist errors with the transmitter and receiver clock, ionospheric, tropospheric or receiver noise errors.

\[ R_i(t_T, t_R) = |r_{si}(t_{Ti}) - r_{R}(t_R)| = \sqrt{(x_{si} - x_R)^2 + (y_{si} - y_R)^2 + (z_{si} - z_R)^2} \] (5.1)

Where \( R_i(t_T, t_R) = \) distance between the transmitter and the receiver.  
\( t_R = \) instant when the received signal arrives to the receiver.  
\( t_{Ti} = \) instant when the signal is transmitted by the satellite \( i \).

It can also be define the delay associated to the satellite \( i \) \( \tau_i \) as:

\[ \tau_i = \frac{R_i(t_T, t_R)}{c} = t_R - t_{Ti} \] (5.2)

To compute the position it is required at least 3 satellites so as to solve a non-linear system of 3 equations with 3 unknown quantities.

**Non-Ideal Case**

This is the real case, where errors are present. The transmission time of the satellite \( i \) is:

\[ t_{Ti} = t_{Galileo}^{Ti} + \Delta t_{Ti} \] (5.3)

Where \( \Delta t_{Ti} = \) satellite clock error.

The signals arrive to the receiver at the following instant:

\[ t_{R}^{Galileo} = t_{Ti}^{Galileo} + \tau_i - \Delta t_i^{rel} \] (5.4)

Where \( \Delta t_i^{rel} = \) relativistic correction.

And the instant measured by the receiver and replacing with equation 5.4 is:

\[ t_R = t_{R}^{Galileo} + \Delta t_R + \Delta t_n = t_{Ti}^{Galileo} + \tau_i - \Delta t_i^{rel} + \Delta t_R + \Delta t_n \] (5.5)

Where \( \Delta t_R = \) receiver clock error.  
\( \Delta t_n = \) delay due to receiver measurement error due to white noise. Random variable with the same statistical properties for each satellite.
Finally, replacing with equation 5.3 it is obtained:

\[ t_R = t_T + \tau_i - (\Delta t_T + \Delta t_i^{\text{rel}}) + \Delta t_R + \Delta t_n \]  

(5.6)

Note that \( \Delta t_R \) is common to all satellites.

The \( \tau_i \) delay is obtained by the sum of the geometric delay, ionospheric delay and tropospheric delay.

\[ \tau_i = \tau_i^{\text{geo}} + \Delta t_i^{\text{ion}} + \Delta t_i^{\text{trop}} \]  

(5.7)

The total delay between the transmitter and the receiver is:

\[ \tau_i^{\text{tot}} = t_R - t_T = \tau_i - (\Delta t_T + \Delta t_i^{\text{rel}}) + \Delta t_R + \Delta t_n \]  

(5.8)

Replacing \( \tau_i \) by equation 5.7 it is obtained:

\[ \tau_i^{\text{tot}} = \tau_i^{\text{geo}} + \Delta t_i^{\text{ion}} + \Delta t_i^{\text{trop}} - (\Delta t_T + \Delta t_i^{\text{rel}}) + \Delta t_R + \Delta t_n \]  

(5.9)

Once the total delay has been computed, it is possible to obtain the pseudo-range by multiplying it by the speed of light \( c \).

\[ \rho_i = c \tau_i^{\text{tot}} = R_i + c \Delta t_i^{\text{ion}} + c \Delta t_i^{\text{trop}} - c(\Delta t_T + \Delta t_i^{\text{rel}}) + c \Delta t_R + c \Delta t_n \]  

(5.10)

Where \( R_i \) = geometric distance and as it has been seen in equation 5.1 from the ideal case, the geometric distance is computed as follows:

\[ R_i \equiv R_i(t_{T_i}^\text{Galileo}, t_R^\text{Galileo}) = |r_s(t_{T_i}^\text{Galileo}) - r_R(t_R^\text{Galileo})| \]  

(5.11)

\[ R_i(t_{T_i}^\text{Gal}, t_R^\text{Gal}) = \sqrt{x_s(t_{T_i}^\text{Gal}) - x_R(t_R^\text{Gal})^2 + [y_s(t_{T_i}^\text{Gal}) - y_R(t_R^\text{Gal})]^2 + [z_s(t_{T_i}^\text{Gal}) - z_R(t_R^\text{Gal})]^2} \]  

(5.12)

Note from equation 5.10 that \( \Delta t_R \), and from equation 5.11 that \( r_R \) do not depend on satellites position. The parameter \( \Delta t_R \), that is the receiver clock error is not known so it can be treated as another unknown quantity.

Thus, 4 satellites are necessary to determine the receiver coordinates and its clock error.

**Linealization**

To solve the obtained equations system, it must be taken into account that it is non-linear. It should be linearized assuming that an approximate position and approximate clock error
are known. To that end, the pseudo-range is derived and it is obtained:

\[ \delta \rho_i = \frac{\delta \rho_i}{\delta x_R} \delta x_R + \frac{\delta \rho_i}{\delta y_R} \delta y_R + \frac{\delta \rho_i}{\delta z_R} \delta z_R + \frac{\delta \rho_i}{\delta w_R} \delta w_R \]  

(5.13)

Where \( w_R = c \Delta t_R \)

Partial derivatives can be written as:

\[ \frac{\delta \rho_i}{\delta x_R} = -\frac{x_{s_i} - x_{R_i}}{R_i}; \]  

(5.14)

\[ \frac{\delta \rho_i}{\delta y_R} = -\frac{y_{s_i} - y_{R_i}}{R_i}; \]  

(5.15)

\[ \frac{\delta \rho_i}{\delta z_R} = -\frac{z_{s_i} - z_{R_i}}{R_i}; \]  

(5.16)

\[ \frac{\delta \rho_i}{\delta w_R} = 1; \]  

(5.17)

Then, it is defined:

\[ \delta p = [\delta x_R \delta y_R \delta z_R \delta w_R]^T; \delta \rho = [\delta \rho_1 \delta \rho_2 \ldots \delta \rho_K]^T \]  

(5.18)

\[ A = \begin{pmatrix} a_{11} & a_{12} & a_{13} & 1 \\ a_{21} & a_{22} & a_{23} & 1 \\ \vdots & \vdots & \vdots & \vdots & 1 \\ a_{K1} & a_{K2} & a_{K3} & 1 \end{pmatrix} \]  

(5.19)

Where \( a_{i1} = -\frac{x_{s_i} - x_{R_i}}{R_i} \)
\( a_{i2} = -\frac{y_{s_i} - y_{R_i}}{R_i} \)
\( a_{i3} = -\frac{z_{s_i} - z_{R_i}}{R_i} \)

\[ p = [x_{R} y_{R} z_{R} w_{R}]^T = \text{extended position vector with receiver error.} \]

And it can be written that:

\[ \delta \rho = A \delta p \]  

(5.20)

The position of the receiver can be calculated iteratively. Whether an approximate extended position vector is available at a given time instant, the estimation may enhance as:

\[ p^{(k)} = p^{(k-1)} + \delta p^{(k)} \]  

(5.21)

Where \( \delta p^{(k)} = \text{linear system solution.} \)
As it is possible to use more equations than unknown quantities, the solution will be the so-called least squares:

\[
\delta p(k) = (A^{(k-1)T}A^{(k-1)})^{-1}A^{(k-1)T}\delta \rho^{(k-1)}
\]

(5.22)

Where \( \delta \rho^{(k)} = \hat{\rho} - \rho^k \)

The process will continue until norm of \( \delta p \) is small enough \( (< 10^{-12}) \).

### 5.2 Calculation of Satellite Position

In order to obtain the satellite position in the earth-centered, earth fixed system (ECEF), this section uses all the information from ephemeris data. These calculations require the data obtained from section 4.3.1 where the I/NAV word types and its carried information were presented.

The computed mean motion \( n_0 \) is the average angular velocity of the satellite

\[
n_0 = \frac{2\pi}{T} = \sqrt{\frac{\mu}{A^3}}
\]

(5.23)

Where \( \mu \) = geocentric gravitational constant.

\( A \) = Semi-major axis

Once obtained the mean motion in \((\text{rad/s})\) it can be computed the corrected mean motion

\[
n = n_0 + \Delta n
\]

(5.24)

Where \( \Delta n \) = mean motion difference from computed value.

The actual total time difference between the time \( t \) and the epoch time \( t_{0e} \) \((t_{0a} \text{ for the almanacs})\) is \( t_k \)

\[
t_k = t - t_{0e}
\]

(5.25)

Where \( t = \) Galileo System Time.

The mean anomaly can be found from

\[
M = M_0 + nt_k
\]

(5.26)
Where  \( M_0 \) = mean anomaly at reference time.

Kepler’s equation for eccentric anomaly \( E \) (may be solved by iteration) is defined as

\[
M = E - e \sin(E)
\]  

(5.27)

Where  \( e \) = eccentricity.

The relativistic correction term can be obtained by

\[
\Delta t_r = F e A^{1/2} \sin(E)
\]  

(5.28)

Where  \( F = -2\mu^{3/2}/c^2 \) is a constant.

The satellite time correction (in seconds) is modelled through the following second order polynomial which defines a parabola

\[
\Delta t_{SV}(X) = a_{f0} + a_{f1}(X)[t - t_{0C}(X)] + a_{f2}(X)[t - t_{0C}(X)]^2 + \Delta t_r
\]  

(5.29)

Where  \( a_{f0}, a_{f1}, a_{f2} \) = SV clock correction coefficients.

\( t_{0C} \) = clock correction data reference Time of Week.

\( X = (f_1, f_2) \) dual frequency combination \( f_1 \) and \( f_2 \) used for the clock model.

The true anomaly is defined as

\[
\nu = \tan^{-1}\left\{ \frac{\sin(\nu)}{\cos(\nu)} \right\} = \tan^{-1}\left\{ \frac{\sqrt{1 - e^2} \sin(E)/(1 - e \cos(E))}{(\cos(E) - e)/(1 - e \cos(E))} \right\}
\]  

(5.30)

And argument of latitude can be found from

\[
\Phi = \nu + \omega
\]  

(5.31)

Argument of latitude correction is computed as follows

\[
\delta u = C_{us} \sin(2\Phi) + C_{uc} \cos(2\Phi)
\]  

(5.32)

The radius correction is given by

\[
\delta r = C_{rs} \sin(2\Phi) + C_{rc} \cos(2\Phi)
\]  

(5.33)
And inclination correction can be found from

\[ \delta i = C_{is} \sin(2\Phi) + C_{ic} \cos(2\Phi) \]  

(5.34)

The corrected argument of latitude, once obtained \( \Phi \) and \( \delta u \) is obtained by

\[ u = \Phi + \delta u \]  

(5.35)

The corrected radius, once obtained \( \delta r \) is

\[ r = A(1 - e \cos(E)) + \delta r \]  

(5.36)

And the corrected inclination is given by

\[ i = i_0 + \delta i + (\dot{i})t_k \]  

(5.37)

Then it can be computed the position in orbital plane as follows

\[ x' = r \cos u; y' = r \sin u \]  

(5.38)

The ascending node is computed on the following way

\[ \Omega = \Omega_0 + (\dot{\Omega})t_k \]  

(5.39)

But this result belongs to the eart-centered inercial system (ECI). Once obtained \( \Omega \), the next step is necessary to obtain this result in ECEF system

\[ \Omega = \Omega - \omega_E t_k - \omega_E t_{0e} \]  

(5.40)

Where \( \omega_E = \) mean angular velocity of the Earth.

Finally, to find the position of the satellite:

\[
\begin{pmatrix}
x' \\
y' \\
z'
\end{pmatrix} =
\begin{pmatrix}
x' \cos(\Omega) - y' \sin(\Omega) \cos(i) \\
x' \sin(\Omega) + y' \cos(\Omega) \cos(i) \\
y' \sin(i)
\end{pmatrix}
\]  

(5.41)
Chapter 6

Satellites and Receiver Position

The position of the satellites is obtained from the algorithm presented in section 5.2 of the previous chapter; however, in order to obtain the ephemeris from a real Galileo signal, it has to be pre-treated and decoded correctly.

6.1 Decoding Algorithms

Given a Galileo signal containing data from different satellites, the first step, once read the signal properly, is synchronizing the input sequence. This has been carried out through the use of a MATLAB function that obtained the synchronized sequence employing the synchronization pattern, presented in section 4.3. The synchronized sequence consists of codified Nominal Pages array with 250 symbols each of them.

So as to decode them it is applied a new function whose purpose is obtaining the 120 bits from every page part (even and odd) by using the convolutional code parameters, the interleaving parameters and the Cyclic Redundancy Check.

Once both page parts are decoded, Data, Reserved 1 and 2, SAR and Spare data fields are obtained. With the decoded data field it is necessary to obtain the word identification in order to identify the different I/NAV word types, presented in section 4.3.1.

Using a MATLAB algorithm and taking into account the different structure of the I/NAV word types, ephemeris data are obtained and prepared for the satellites position calculation.

In figure 6.1 there is a conceptual map where the MATLAB functions and the parameters involved are presented.
6.2 Satellites Position Algorithm

To compute the satellites position it is used a MATLAB function that with the input of ephemeris data and clock correction parameters and using exactly the same algorithm that the explained in section 5.2, it obtains the Galileo GTRF (Galileo Terrestrial Reference Frame) coordinates of the SV (Space Vehicle) antenna phase center position at a given time.

Figure 6.1: MATLAB functions Conceptual Map.
Chapter 7

Results, Conclusions and Future Work

7.1 Results

During this project, 3 different Galileo signals have been treated. The first one, from CTTC, contained information from a single satellite. With this signal the first indicative parameters of the ephemeris were obtained. These parameters are presented in section 4.3.1. The second signal, also from ESA, was a simulated Galileo signal. This means that the parameters were previously stipulated. For this reason, in parameters such as eccentricity, it was assigned a value of 0, although it is known that the orbits of Galileo system are not perfectly circular. The third signal contained all the correct parameters. The problem was that only 3 satellite information was available, and in order to calculate the position, a minimum of 4 satellites are required.

Finally the ESA simulated signal was chosen to calculate the position, although the result is an approximation due to the simulation that was done with the signal.

Obtaining the position of the satellites begins by synchronizing the satellite signal bits. In order to synchronize the signal and to detect where each nominal page starts, the synchronization pattern must be taken into account, since each nominal page, even or odd, takes this sequence as a preamble. A correlation is made between the signal bits and the synchronization pattern. Then, it has to be searched where are located the maximums of the correlation, which will be where a nominal page begins. Note that in figure 7.1 there are some maximums or minimums that have to be eliminated since they are incorrect. The maximums are +10 and the minimums are -10. In this last case, the signs of the bits are changed due to the phase ambiguity of $\pi$ radians that the PLL sets. To verify the obtained maximums of the correlation, the periodicity of the signal is taken into account. Correlation between the Satellite 1 signal and the Synchronization Pattern.
Once the signal has been synchronized, it is decoded. For this purpose, the parameters of the convolutional encoded data, interleaving parameters and CRC are considered. After decoding, even and odd nominal pages with 120 bits are obtained.

An example of an odd nominal page from satellite 1 is shown below. The 120 bits follow the structure that was introduced in figure 4.3 of section 4.3.

Note that the first bit is set to 1, as it refers to an odd nominal page. The first bit would be 0 if it was an even nominal page. The second bit is set to 0, since it is a nominal page. In the case of an alert page, the second bit would be 1. Note also that the last 6 bits are 0 as it refers to the tail bits field.

\[
1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0
\]

Then, the decoded parameters of the nominal pages are obtained: reserved fields, SAR data, Spare data, CRC, and word data.

The most important parameters that have been considered for this project have been the CRC fields and, obviously, the words data, since is there where all the information from ephemeris is stored.

The CRC field is very important to check whether the signal data is correct or not. The Galileo system, using the CRC technique has the ability to detect errors, but not to correct them. A function was created to detect when the CRC was incorrect and thus, discard the nominal page to which it belonged. To accomplish this, the function calculates the CRC that was emitted by the satellite, and then compares it with the CRC field that was obtained by decoding the nominal pages. In case the CRC fields do not match, the
function warns that there is an error. However, the CRC that has been obtained for all the nominal pages of all the satellites of this project has always been correct.

The word data field is the essence of this project. This field is transmitted divided into 2 parts. The first part is composed of 112 bits and it is transmitted within the even word. The second part, of 16 bits, is transmitted inside the odd word. The total data field is composed of a nominal word of 128 bits.

There are 11 different types of nominal words. Their types are indicated in the first 6 bits of each nominal word. Below, it is shown an example of nominal word. Its word type is 000010, which in decimal is 2.

\[000010\ 00000110000000000000000000000000000000000000000000000000001\] So as to obtain the satellite ephemeris, word types have to be considered. As it is explained in section 4.3.1, where all the I/NAV word types are presented, ephemeris are distributed following a certain structure. The created function in MATLAB takes this into account.

An example of the obtained ephemeris from the simulated ESA signal belonging to satellite 1 is presented in table 7.1. Note that several parameters are set to 0 due to the signal is simulated. This is the case of the eccentricity, that is simulated as the orbit was circular.

<table>
<thead>
<tr>
<th>Type</th>
<th>(M_0)</th>
<th>(\Delta n)</th>
<th>(e)</th>
<th>(A^{1/2})</th>
<th>(\Omega_0)</th>
<th>(i_0)</th>
<th>(\omega)</th>
<th>(i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.2222</td>
<td>0</td>
<td>0</td>
<td>5.4406e+03</td>
<td>0.3111</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type</th>
<th>(\Omega)</th>
<th>(C_{uc})</th>
<th>(C_{us})</th>
<th>(C_{rc})</th>
<th>(C_{rs})</th>
<th>(C_{ic})</th>
<th>(C_{is})</th>
<th>SVID</th>
<th>(t_{0e})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>244800</td>
</tr>
</tbody>
</table>

Table 7.1: Ephemeris Satellite 1 ESA signal

In contrast to these results, the parameters obtained from the simulated CTTC signal are shown in table 7.2. Remind that this signal was not used because only 3 satellite information was available.

<table>
<thead>
<tr>
<th>Type</th>
<th>(M_0)</th>
<th>(\Delta n)</th>
<th>(e)</th>
<th>(A^{1/2})</th>
<th>(\Omega_0)</th>
<th>(i_0)</th>
<th>(\omega)</th>
<th>(i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.98</td>
<td>1.02e-09</td>
<td>4.22e-04</td>
<td>5.44e+03</td>
<td>0</td>
<td>0.305</td>
<td>-0.44</td>
<td>1.14e-11</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type</th>
<th>(\Omega)</th>
<th>(C_{uc})</th>
<th>(C_{us})</th>
<th>(C_{rc})</th>
<th>(C_{rs})</th>
<th>(C_{ic})</th>
<th>(C_{is})</th>
<th>SVID</th>
<th>(t_{0e})</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.79e-09</td>
<td>-5.74e-06</td>
<td>1.06e-05</td>
<td>111.5</td>
<td>-127.40</td>
<td>1.09e-05</td>
<td>1.09e-05</td>
<td>12</td>
<td>364200</td>
<td></td>
</tr>
</tbody>
</table>

Table 7.2: Ephemeris Satellite 1 CTTC signal
A part from ephemeris, other parameters can be obtained from nominal words. In table 7.3 the clock correction parameters from ESA signal are presented. In table 7.4 there are the parameters realted to CTTC signal.

\[
\begin{array}{|c|c|c|c|c|}
\hline
BGD & t_{0c} & a_{f0} & a_{f1} & a_{f2} \\
\hline
0 & 244800 & 0 & 0 & 0 \\
\hline
\end{array}
\]

Table 7.3: Clock Correction parameters ESA signal

\[
\begin{array}{|c|c|c|c|c|}
\hline
BGD & t_{0c} & a_{f0} & a_{f1} & a_{f2} \\
\hline
-1.82e-09 & 364200 & 5.28e-04 & 8.32e-11 & -1.73e-18 \\
\hline
\end{array}
\]

Table 7.4: Clock Correction parameters CTTC signal

Finally, the ionospheric correction parameters were obtained from ESA and CTTC siganl as it is presented in the table below.

\[
\begin{array}{|c|c|c|c|c|}
\hline
a_{i0} & a_{i1} & a_{i2} & a_{i0} & a_{i1} \\
\hline
0 & 0 & 0 & 65 & 0.1328 \\
\hline
\end{array}
\]

Table 7.5: Ionospheric Correction parameters ESA and CTTC signal

Obtaining the satellites position is conditioned by the reference system to be used. First, the ECEF system is chosen. The Earth-Centered, Earth-Fixed system represents positions as an X,Y and Z coordinate. To compute the position, 4 satellites from the ESA signal were selected. The obtained coordinates in ECEF system were converted to longitude, latitude and height. The results are presented in table 7.6.
<table>
<thead>
<tr>
<th>Satellite</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellite 1</td>
<td>69.34722056°</td>
<td>3.87413012°</td>
<td>23221268.097 m</td>
</tr>
<tr>
<td>Satellite 2</td>
<td>123.91384408°</td>
<td>8.73824091°</td>
<td>23222286.915 m</td>
</tr>
<tr>
<td>Satellite 3</td>
<td>136.44520668°</td>
<td>11.93834524°</td>
<td>23222917.060 m</td>
</tr>
<tr>
<td>Satellite 4</td>
<td>27.09450949°</td>
<td>2.59276764°</td>
<td>23222252.660 m</td>
</tr>
</tbody>
</table>

Table 7.6: Satellites Coordinates

Note that the height of each satellite coincides with the Galileo altitude, that is approximately 23222 km.

In figure 7.2 it is represented the position of the 4 selected satellites. It has been used Google Earth software so as to visualize them more clearly. To represent these coordinates, a KML file was created using the MATLAB software.

![Figure 7.2: Position of 4 GALILEO Satellites. Blue dots indicate the position point.](image)

Then, taking advantage of the coordinates in the ECEF system, the orbit was calculated for each one of the satellites. In figure (a) it is appreciated the satellite corresponding to channel 1, in figure (b) it is shown satellite orbit corresponding to channel 3, in figure (c) it is represented the satellite orbit corresponding to channel 4 and in figure (d) it is represented the satellite orbit corresponding to channel 6.

It is important to note that the orbits represented in figure 7.3 correspond to the orbit that is visualized when an observer is on Earth.
The coordinate system that can be used can also be inertial. This system is known as ECI. Earth-Centered Inertial coordinates remain fixed with respect to the surface of the Earth. In this case, the observer is quiet in the center of the Earth.

The orbits obtained are circular due to the simulated signal, as can be seen in figure 7.4. Only three orbits can be visualized since two of the satellites share the same orbital plane.

The orbits represented in figure 7.3 and figure 7.4 are obtained through a simultaion of the orbits and then it is generated a KML file with all the coordinates. The results are presented on Google Earth.

The receiver position is obtained from the measurements of the position of the satellites and the pseudo-ranges of each one of them.

Pseudo-ranges vary as the satellites move, for this reason, it is important to select the correct time. The values of pseudo-ranges are specified in a RINEX file where they vary respect to the time. So as to choose the correct pseudo-range, it was taken into account the TOW parameter from the navigation message.

In table 7.7 it is presented the chosen pseudo-range for each satellite.

The TOW had a value of 245045 s. These seconds correspond to day 2 of the week at 20:04:05.
Figure 7.4: Satellites Orbits represented in ECI System.

<table>
<thead>
<tr>
<th>Satellite 1</th>
<th>Satellite 2</th>
<th>Satellite 3</th>
<th>Satellite 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel 1, ID 2</td>
<td>Channel 3, ID 12</td>
<td>Channel 4, ID 13</td>
<td>Channel 6, ID 19</td>
</tr>
<tr>
<td>Pseudo-range</td>
<td>23745063.780 m</td>
<td>22626279.017 m</td>
<td>20626320.695 m</td>
</tr>
<tr>
<td></td>
<td>21953162.040 m</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7.7: Pseudo-Ranges of 4 GALILEO satellites.

Once all the required parameters are obtained, there are specific MATLAB functions for the calculation of the position. These functions are responsible for obtaining the position of the receiver using the method of least squares. Once the position is obtained in Cartesian coordinates, it is changed to geographic coordinates in the reference ellipsoid WGS84. A KML file with the computed coordinates was generated and represented on Google Earth as it shows figure 7.5.

### 7.2 Conclusions

This project works with GALILEO E1 signal. All the different parts of the receiver have been studied: acquisition, tracking, decoding and position calculation. Given the complexity of the entire receiver, the project has focused on implementing the decoding and positioning parts using the MATLAB software.

From the bits obtained from the tracking of the signal by the CTTC, a series of functions that treated the signal of GALILEO have been created in MATLAB. As the GALILEO system has only a short time in force, there are not many books specialized on this topic. Some functions that were used in this project existed for the GPS system, therefore, they have adapted to the new GALILEO system.

The first step was to synchronize the signal using the synchronization pattern. Once synchronized, the signal was decoded using the convolutional encoder parameters, the
interleaving parameters, and it was checked, nominal page to nominal page that the data were correct, taking into account the CRC emitted by the satellite and the received CRC.

All parameters contained within the nominal words were obtained. For the calculation of the position of the 4 satellites with which it has been worked, the ephemeris of each satellite have been used.

Once the position of the 4 satellites was obtained, an orbit was simulated for each one. The orbit was calculated in both ECEF and ECI coordinates. To visualize the orbits, the coordinates were changed to latitude, longitude and height. A KML file was created so as to perfectly visualize them on Google Earth software.

The pseudo-ranges were obtained from a RINEX file provided by the CTTC, since this part belongs to the tracking part. The CTTC has a C++ program and the results of this project can be checked. In fact, all the results, after comparing them with CTTC, were correct.

7.3 Future Work

The work team is currently working on the signal tracking part. It is interesting to implement this part on MATLAB. Since the navigation message of GALILEO is very different from the GPS navigation message and together with the little information that exists relating to GALILEO system, the process is not easy.

The next step would be to start working with other GALILEO signals, such as the E5 signal. The E5-a signal provides the F/NAV message and it supports Galileo Open Service. The E5-b signal provides the I/NAV message and it supports the Open Service and the Commercial Service.
Bibliography


