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TRABAJO FINAL DE GRADO

GPS Transmitter Implementention through a Software Defined Radio Platform

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Abstract

The current project consists in a simple GPS transmission system design that imitate a satellite one and it is based on LabVIEW. Moreover, this technology objectives are related to education and it offers a required introduction about the Global Positioning System in order to understand all the variables that are sent by the transmitter in the GPS packet. The platform permits the configuration of the GPS messages and simulation, taking into account a receptor developed that has been developed at the same time. The tool objective is to be an test-bench and an intuitive and easy to use demonstration tool.

It will be seen that this project is very interesting in terms of specific education and even for students with a little curriculum in order to understand the protocol and grow in some important skills as critical thinking and decision-making. It will be seen also that a GPS satellite can be done with LabVIEW's USRP technology in some way.

Resumen

El presente proyecto consiste en el diseño de un sistema de transmisión GPS simple (imitando uno satelital, pero limitándolo) usando LabVIEW. Además, esta tecnología cuyos fines están relacionados con la educación ofrece una necesaria introducción al Sistema de Posicionamiento Global en pos de la comprensión de los parámetros mandados por el transmisor en el mensaje GPS. La plataforma permite la configuración de mensajes GPS y la simulación, a vista de un receptor preparado. La herramienta busca ser un área de pruebas y demostraciones de uso fácil e intuitivo para el usuario.

Se podrá observar que éste es un proyecto interesante en términos tanto de educacion específica como para estudiantes con una base educacional más baja pues permite entender bien el protodolo e incluso desarrollar capacidades en pensamiento crítico o en toma de decisiones. Se podrá ver, finalmente, que, de alguna forma, se puede desarrollar un satélite GPS a partir de la tecnología USRP de LabVIEW.

Acknowledgements

The time for doing this project has been very little. Because of it, the result of the project could not be better than what they are. And it could be less if I would not have been count on your help.

Mom and Dad, for giving me everything I have needed.

Sister, for spending very good times with me. Times that gave me the strength to continue.

Classmates, for helping me to grow up.

Friends, for letting me understand what life is about.

Roommates, for replacing me in my housework and for taking care of me in these hard days.

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Chapter 1

Introduction

This chapter serves as an introduction to understand the whole project thesis and motive. The objectives of this project are the creation of an USRP based system (using LabVIEW) that imitates as possible[1] the behaviour of an actual satellite but for educational porposes.

It gives a more extensive view of the system and protocol for telecommunications engineering students, even simple modulation and radiation demonstrations could be achieved. But, also, it is a powerful way of exhibiting the passionate world of the telecommunications realm for younger students without the required basis to understand the complex GPS system. So, in a schematic way the objectives are to build a prototype:

- as similar as possible to the actual one.

- that would be easy to use for demonstrations or for "playing" with it.

- that could monitor its "insides", to understand how the protocol works.

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[1]Some exceptions should be set in order to not surpass the normal amount of work in a end of career project like it is. These exceptions are the satellite clock corrections and the ionospheric delay effects.

1.1 Thesis's Structure

Satellite's gone

Up to the skies

Thing like that drive

Out of my mind

Lou Reed, *Satellite of Love*

(Transformer)

In this section the intention of every chapter will be explained:

The chapter 2 illustrates the origin, protocol and all the mathematics behind the Global Positioning System in order to understand the rest of the project.

The chapter 3 explains the process of development of the project. First, it set the specifications and requirements and then show the insides of the project.

The chapter 4 show the results of proceed like this project does. Split the project in two testing parts, the emitter part and the message creating part.

Finally in chapter 5 the project is concluded discussing about the objectives, the biggest problems in the project, the evolution that this project could create and the possibilities of more development inside it.

1.2 Socioeconomic Context

Satellite's gone

Way up to Mars

Soon it will be filled

With parking cars

Lou Reed, *Satellite of Love*

(Transformer)

So as to depict our socioeconomic context three ideas should be remarked. We live

in a society that tends more and more to the **technological progress**. Evermore, our economic system needs constant technological advances in order to manufacture newer products and, therefore, generate new customers or recover them. The second one, our world is **militarised**, all states invest hugely in warfare. The third object is that some of the **biggest businesses** are related to the telecommunications world, what means that these kind of advances attract investments.

So, once these ideas have been introduced, the answer for the question "why GPS in this context? Which sense have maintaining GPS in this era?" can be achieved. First, the changes that matter to us. It is significant to mention the **social benefits** that GPS has brought to mankind. From cars navigation, to a faster emergencies arrival, passing through leisure sports such as trekking, the GPS is everywhere. It has revolutionised our way of living. Nowadays, it is required by humanity because the advantages have been so big that we cannot conceive a planet without this technology anymore.

Second, GPS represents an **economy revolution**. Since the very beginning of mercantilism, the travel for goods interchange is a needed source of wealth. Since the end of the Middle Ages (after America's discovery), the capitalism starts one of its considerable expressions, global mercantilism. Therefore, the problem of navigation was a key point for traders in order to bring the merchandise to the destiny, fast, secured and with integrity. Compasses, sextants, astrolabes, maps, celestial navigation system and other navigational instruments were solutions back in those days but none of them were as precise as the GPS's Standard Positioning System is. Besides the navigation advances, other developments such as cargo location to avoid losses or simply, to notify clients of a package arrival, have induced an enormous progress and it have saved loads of money to businesses.

Third, the ability of knowing the exact location of something is a very big power and, also it is the capability of make computers understand that location. The newest weapons that are known contain a GPS chip in order to work properly, for example guided missiles or autopilot controlled aeroplanes/drones. This power, in its origin, was imagined and then developed by **military forces**. U.S.A now have the GPS, but also Russia has it's own version called *GLONASS*, China has it's *Beidou* and E.U. will have the *Galileo*

System. Geo-positioning is a revolutionary weapon.

1.3   Legal Framework

> Americans could be killed
>
> By a shotgun, by a drone
>
> By a flamethrower, in your home
>
> By the NSA
>
> Calm down, sir
>
> Americans could be killed, by a
>
> left-wing website
>
> _____
>
> schmoyoho, *Flying Robots (Songify the news 3)*

When transmitting power, some healthy issues should be taken into account. An excess of energy could kill. For that reason the governments and telecommunications organisations like ITU work for establishing the limits of radiated power. As can be read in [6]:

A safety margin, (which may also be called a public safety factor), is critical for safety-of-life applications in order to account for risk of loss of life due to radio-frequency interference that is real but not quantifiable. To support safety of life applications, all interference sources must be accounted for.

[...]

The utilisation of safety margins in navigation systems is well established. ICAO Annex 10 (Attachment G, Table G-2) specifies a safety margin for the microwave landing system (MLS) of 6dB. The instrument landing system (ILS) applies a safety margin of 8dB (see Recommendation ITUR SM.1009, Appendix 3 to Annex 2). In each case the margin is defined with respect to the navigation system carrier power.

For satellite systems, this magnitude of power is very low, because the signal from space needs a high energy to arrive the earth and be readable by not complex system with cheap antennas.

In [6], they continue saying that

> For Category I precision approach SBAS air navigation receivers (see Annex 1) the interference threshold is 140.5dB(W/MHz). The components of the interference threshold include: receiver thermal noise and satellite intrasystem interference based on random code analysis. A safety margin is then included to account for aeronautical design uncertainties; future GNSS selfinterference (e.g. pseudolites); unknown interference sources (e.g. industrial RF interference (RFI)); and intra-system based on analysis of specific codes.

Therefore, as this project should work in terms of -130dBm/-155dBm, the safety margin is not exceeded.

Chapter 2

State of the Art

> Whoa! Algebraic!
>
> Finn, *Adventure Time*

2.1 Global Positioning System

2.1.1 GPS Brief Story

Since the humans existed we have had a desire to explore and know our world, our reality. The compass was discovered and used in wars early in human history, before recorded history, according to Chinese storytelling. The discovery of navigation seems to be another field of knowledge that actually belongs to humans. The science of navigation advanced along the centuries. Earth studies, poles, latitude, longitude, rules, maps. . . And nowadays, the GPS, a system for everybody to know effortlessly where, exactly, they are.

As some of the revolutionaries inventions of the past century, the Global Positioning System was an army project of the U.S.A. In fact, in the early 1970s there was even three approaches of the GPS project. Two from the Navy (Transit and Timation) and one from the Air Force (project 621B). Finally, the GPS program was approved in December 1973, then the first satellite was launched in 1978 and in August 1993, GPS had the basic 24

satellites in orbit ready to work.

2.1.2 Standard Positioning System (SPS) Overview

As the definition of [5, p.3]:

> The SPS is a positioning and timing service provided by way of ranging signals broadcast at the GPS L1 frequency. The L1 frequency, transmitted by all satellites, contains a coarse/acquisition (C/A) code ranging signal, with a navigation data message, that is available for peaceful civil, commercial, and scientific use.

Space Segment

The space segment is defined by the **satellite constellation** and, therefore, the satellite system of **generation and transmission** of the GPS signal. The satellite constellation is comprised of **24 slots**, properly spaced, where each slot contains at least one satellite[1]. Also this slots are **grouped in six orbital planes**, what it means that there are six possible satellite's orbits around the Earth and, therefore, every satellite's orbit is divided in 4 slots that may contain one or more satellites.

The generation and transmission process follows the next steps, as it is represented in Figure 2.1. First, the data/code frequency is achieved from an **atomic clock** with a high accuracy. Later in this thesis, the importance of this high precision clock will be demonstrated. Next step is to acquire the **telemetry data** from the Control Stations and from the satellite's own calculations, and then the NAV (navigation) message should be constructed. Finally, in order to properly send the message, it should be modulated and then radiated in the appropriate frequency band.

It should be known that C/A means **coarse/acquisition** and P(Y) are two codes, the **precision** one (P) and the code when anti-spoofing mode is activated (Y). Since

---

[1]Only three of the 24 slots are expandable. Anyway, only the non-expandable baseline 24-slot constellation will be considered.

P(Y)-code is not accessible for common use, in this research from now on, only C/A is going to be shown.
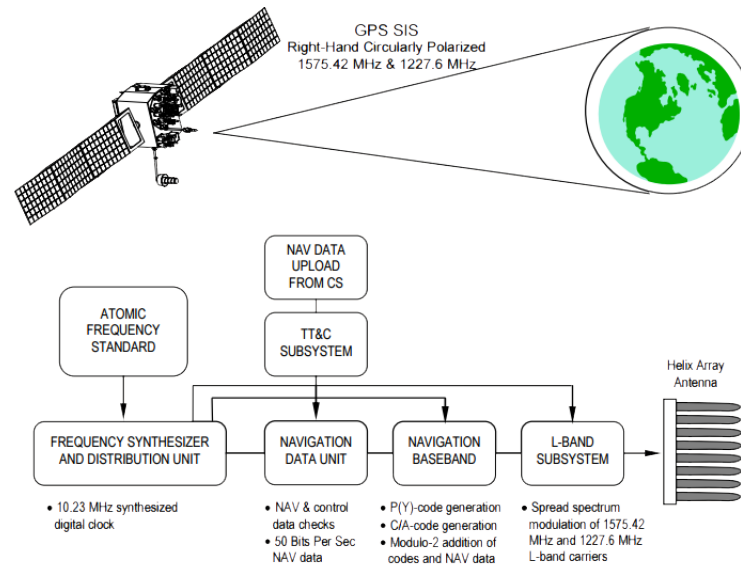

Figure 2.1: Space Segment Scheme[5]

Control Segment

A GPS satellite not only sends navigation messages, but also it has a link to receive and send messages to **Control Stations**. This stations take care about satellites health, about correction of certain constant parameters (that are important in order to send accurate ephemeris data[2], every some periods of time) and even about sending commands to correct the satellite's orbit. As soon as a base station is a fixed point in Earth, they are important in the calculation of satellites position that it is achieved from themselves. In Figure 2.2 the process of communication with all the stages between the Control Stations and a satellite can be seen.

Receiver Segment

GPS is considered, in an allegorical way, a "global utility". As a power company, but with no bill to pay. This is because of, the satellites broadcast the civil signal for

---

[2]The ephemeris data is a set of variables which permits the GPS location
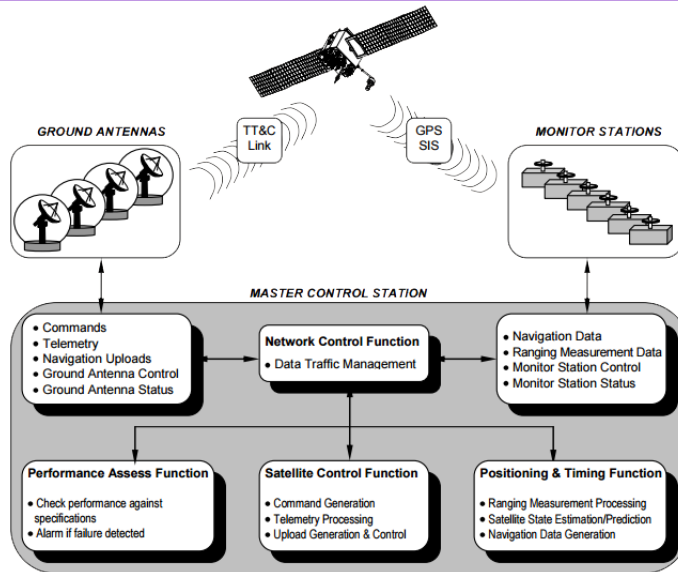
Figure 2.2: Control Segment Scheme[5]

everybody, everywhere. Moreover, a GPS device only have to receive the data from the visible and available satellites and then it have to make some calculation in order to achieve the user's position coordinates.
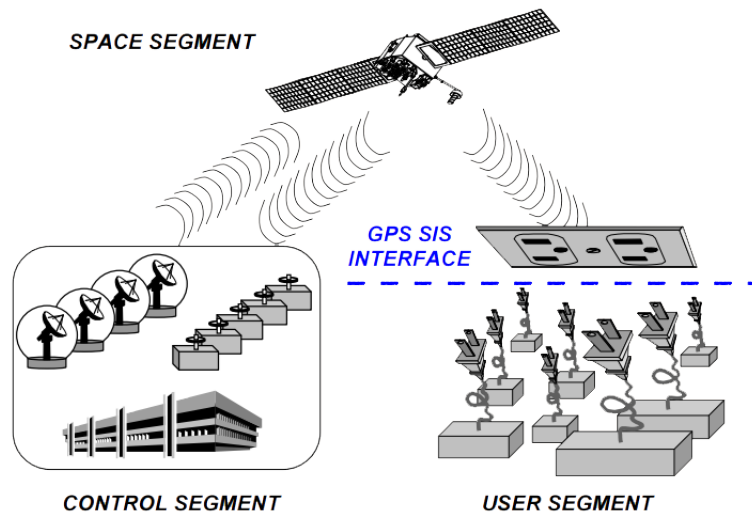

Figure 2.3: User Segment Scheme[5]

2.1.3   Introduction to GPS Mathematics

This section is very important, and therefore all the calculations and mathematics that contain lay the foundations of why the GPS NAV message, that will be discussed in the thesis's project description, includes all the parameters that it includes.

Basic GPS Concept. The location problem

The basic GPS principle is based on the idea of **trilateration**. In geometry, trilateration is a technique that answer the problem of how define a point (U) in the space with some other points $(S_1, S_2, S_3, ...)$ and measurements of distance $(x_1, x_2, x_3, ...)$. In a three-dimensional case, three points will be needed at least to locate the uncertain point without taking into account the height. The spot where three spheres, centred at all the three known points with radius equals the distances, meet is the point to locate.

In GPS the known points are the satellites, the known distances are calculated with the ephemeris data sent by the satellite and the unknown spot is the user location. In next sections and exactly way to calculate *satellite location* will be discussed.
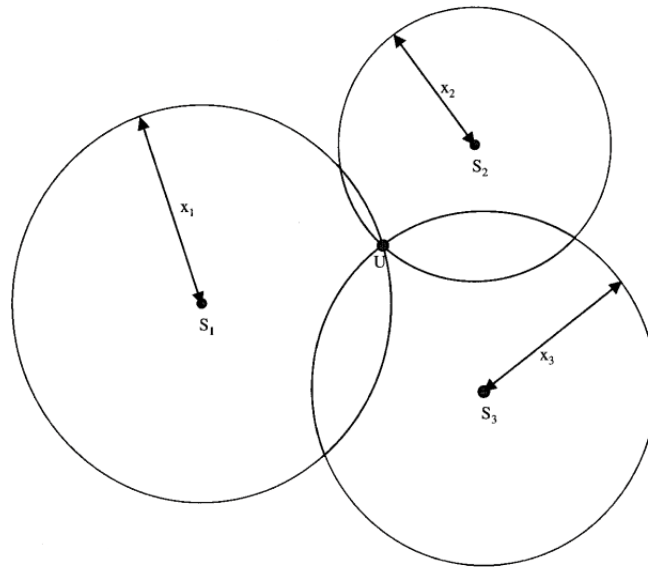

Figure 2.4: Two-dimensional trilateration example [1]

The distance between user and satellite is calculated considering that the wave the satellite sends travels at speed of light (c). Therefore, if the times of sending (t_s) and

receiving (t_u) would be registered, the user's distance to the satellite i could be known. So for any satellite, the **pseudorange's** equation will be:

$$\rho_{i_T} = c(t_u - t_{s_i}) \tag{2.1}$$

also the distance in *Cartesian* coordinate system is the *Euclidean* distance:

$$\rho_i = \sqrt{(x_i - x_u)^2 + (y_i - y_u)^2 + (z_i - z_u)^2} \tag{2.2}$$

so, in order to know the values x_u, y_u and z_u three equation-system is needed or in other words three different satellites radiating the same point.

But in real life, things do not go easy. The fact of obtaining the exact correct time is near impossible, so errors should be considered:

$$t'_{s_i} = t_{s_i} + \Delta b_i \tag{2.3}$$

$$t'_u = t_u + b_{u_t} \tag{2.4}$$

where the t' represent the actual time without error, Δb_i is the satellite clock error and b_{u_t} is the user clock **bias** error. Besides the clock error, there are some other factors affecting the pseudorange measurement but all can be corrected easily with information from the satellite, even the satellite clock error. But the user clock error cannot be corrected through received information. Therefore, Equation 2.1 must be modified as

$$\rho_i = \sqrt{(x_i - x_u)^2 + (y_i - y_u)^2 + (z_i - z_u)^2} + b_u \tag{2.5}$$

knowing that $b_u = cb_{u_t}$.

It should be noticed that with a new variable in the equations system, in order to solve it, should come another equation. So, the four equation-system only means that, actually, **GPS needs four satellites** to make the position solution with time correction. This is not a problem as soon as, nowadays, it is kind of strange to not "see" more than

six satellites. Also, it is possible to do the location math with more than four satellites choosing a nominal position that it is recalculated with the extra equations, looking for more accurate results.

As the every-day maps use the latitude-longitude-altitude notation, it should be consider the **spherical coordinate system** in the calculations instead of *Cartesian coordinates*. Therefore, the distance from the centre of the Earth to the user is:

$$r = \sqrt{x_u^2 + y_u^2 + z_u^2} \tag{2.6}$$

the **latitude**[3] is:

$$L_c = tg^{-1}\left(\frac{z_u}{\sqrt{x_u^2 + y_u^2}}\right) \tag{2.7}$$

longitude is:

$$l = tg^{-1}\left(\frac{y_u}{x_u}\right) \tag{2.8}$$

and finally **altitude** is:

$$h = r - r_e \tag{2.9}$$

All these previous calculations do not consider that the Earth is not ideally spherical. There are some relations to change from spherical to ellipsoidal Earth, but the explanation of them exceeds the goal of this just introductory chapter. Here the relations are[4]:

$$L \approx L_c + e_p sin(2L) \tag{2.10}$$

This nonlinear equation should be solved through the *iteration method* in the form as:

---

[3]**Geocentric latitude**, that is **not** the same as **geodetic latitude** often used in maps

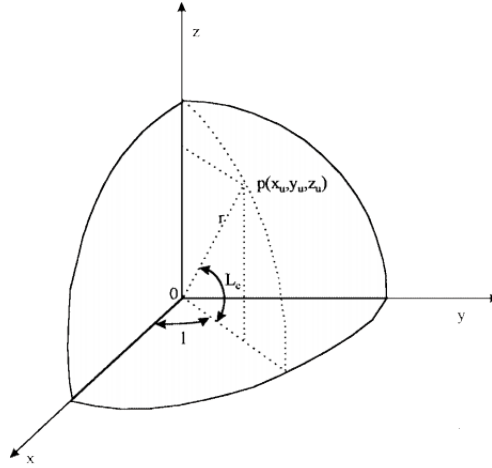[4]In this case this latitude L is the **geodetic latitude**

Figure 2.5: Spherical Coordinate Example in an ideal spherical Earth[1]

$L_{i+1} = L_c + e_p sin(2L_i)$. L_c is often used as L_0.

$$r_0 \approx a_e(1 - e_p sin^2(L)) \tag{2.11}$$

$$h \approx r - r_0 \tag{2.12}$$

where e_p is the ellipticity of the Earth ($e_p = 0.00335281066474$) and a_e is the semi-major axis of the planet ($a_e = 6378137 \pm 2$ m). It is also important to take into account that the longitude do not change as soon as the Earth is flattened at the poles.

Finally, the position of the satellite can be found by knowing some Kepler's equation. They will not be explained in detail because it surpasses the goal of this whole thesis. First, the eccentricity of an orbit is defined as:

$$e_s = \frac{\sqrt{a_s^2 - b_s^2}}{a_s} \tag{2.13}$$

Being, a_s and b_s the **semi-major** and **semi-minor axis**, respectively. Also, the E angle is important in the satellite's position calculations, that is known as the **eccentric anomaly**, the angle between the semi-major axis of the elliptical orbit and the projection of the satellite from the elliptical to the circular fictitious orbit. This point is represented as Q in the Figure 2.6.
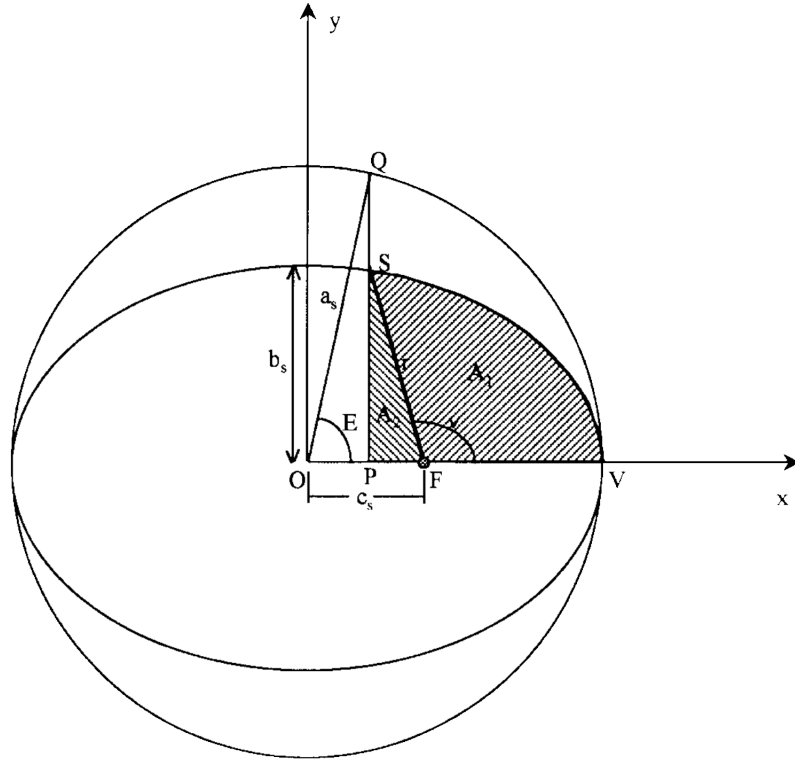
Figure 2.6: Satellite's elliptical orbit. [1]

In order to compute the E the **mean anomaly** M is used in this iteration equation:

$$E_{i+1} = M + e_s sin(E_i) \qquad (2.14)$$

defining the mean anomaly as

$$M = n(t - tp) \qquad (2.15)$$

being $n = \sqrt{\frac{\mu}{a_s^3}}$ the **mean motion**. The distance from the satellite to the centre of the earth, considered flattened at the poles, is

$$r = \frac{a_s(1 - e_s^2)}{1 + e_s cos(\nu)} \qquad (2.16)$$

where ν is an angle characterised in the Figure 2.6. The $cos(\nu)$ can be obtained as:

$$cos(\nu) = \frac{cos(E) - e_s}{1 - e_s cos(E)} \tag{2.17}$$

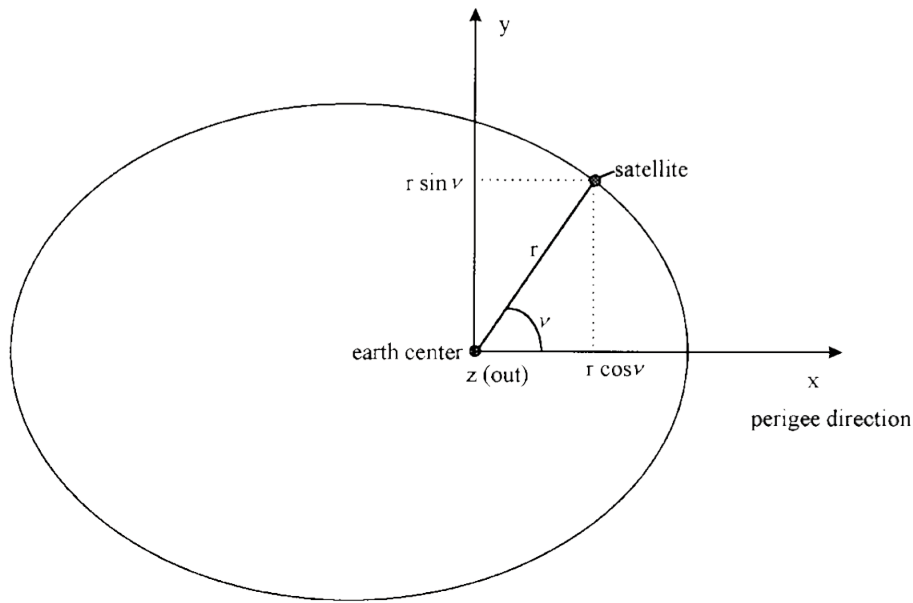then, substituting in Equation 2.16

$$r = a_s(1 - e_s cos(E)) \tag{2.18}$$

Figure 2.7: Satellite location[1]

Bearing in mind the scheme Figure 2.7, the position of the satellite can be found as:

$$
\begin{aligned}
x &= rcos(\nu) \\
y &= rsin(\nu) \\
z &= 0
\end{aligned}
\tag{2.19}
$$

From Satellite's to User's coordinate system

In the previous section, all calculations needed in order to find a GPS user were discussed, but considering a coordinate system centred on Earth and without taking into

account the movement of the Earth. Besides, a satellite, to achieve its own calculations to fill the NAV message, use a coordinate system centred in its orbit, as seen before. Thus, a coordinate system transform is needed. First the **direction cosine matrix** will be used, to accomplish the coordinate system transform. Then, some variables that appear in the NAV message will be explained and also used. The inclination (i) and perigee (w) angles.

The direction cosine matrix method permits also to do the coordinate change in different steps. For example, suppose one wants to transform in n steps (from coordinate system 1 to n), then the following relation can be used:

$$C_1^n = C_{n-1}^n ... C_2^3 C_1^2 \tag{2.20}$$

This cascade method is useful in order to facilitate the understanding of the total transformation as a few little transformations. The first of this little transformations is the alignment between the **perigee**[5] axis and the **ascending node**[6], from x_1 to x_2. The angle between them is w, so the required rotation is described as:

$$C_1^2 = \begin{bmatrix} cos(w) & -sin(w) & 0 \\ sin(w) & cos(w) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2.21}$$

Next step is to move from the **orbit plane** to the **equator plane**, from z_3 to z_3. In this case, the angle between them is i, so the rotation will be described as:

$$C_2^3 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos(i) & -sin(i) \\ 0 & sin(i) & cos(i) \end{bmatrix} \tag{2.22}$$

The last rotation achieves two things. The first one is the change from the equator plane to the **Earth's orbit plane**, to the vernal equinox[7] exactly. The second one is

---

[5]The perigee is the nearest point to the earth in the satellite orbit.

[6]It is the line where converges the satellite orbit plane and the equator plane. It is considered the positive of the axis the part where the satellite "ascends"

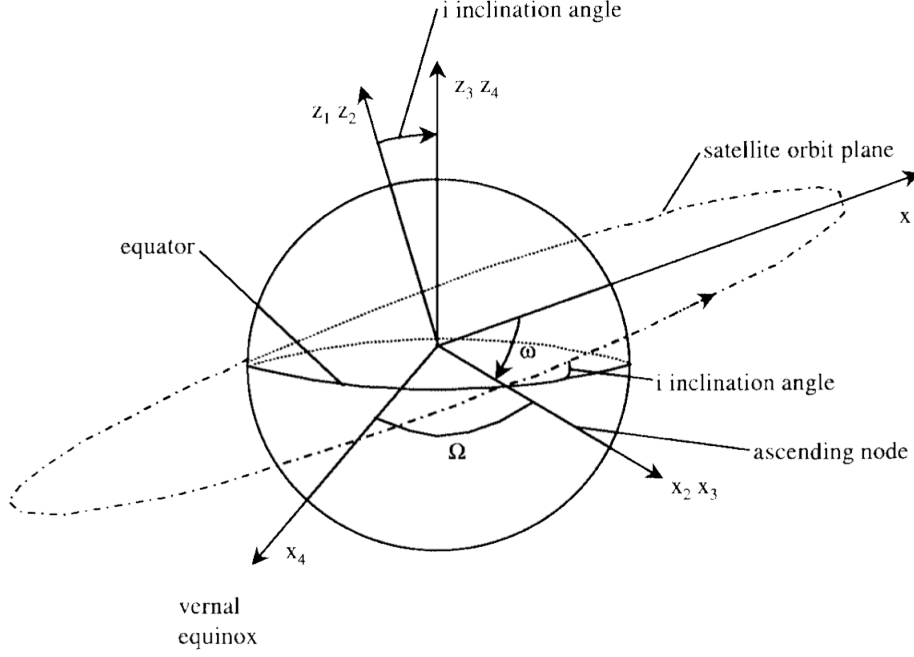[7]It is the line where converges the equator plane and the plane of the Earth's movement

Figure 2.8: Some coordinate transformation[1]

to take into account the rotation of the planet. For the first goal, the right ascension angle (Ω) will be used. For the second, the angle between the ascending node and the Greenwich meridian (Ω_{er}) will be used, that changes every time and is define as follows

$$\Omega_{er} = \Omega - \dot{\Omega}_{er}t_{er} \qquad (2.23)$$

where $\dot{\Omega}_{er} = 7.2921151467 \times 10^{-5}$ rad/s that is the earth rotation rate and t_{er} is the time of rotation, that should be changed into the GPS time (t) as $t_{er} = t + \Delta t$. So finally

$$\Omega_{er} = \Omega - \dot{\Omega}_{er}t - \dot{\Omega}_{er}\Delta t \qquad (2.24)$$

So the final transform is

$$C_3^4 = \begin{bmatrix} cos(\Omega_{er}) & -sin(\Omega_{er}) & 0 \\ sin(\Omega_{er}) & cos(\Omega_{er}) & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad (2.25)$$
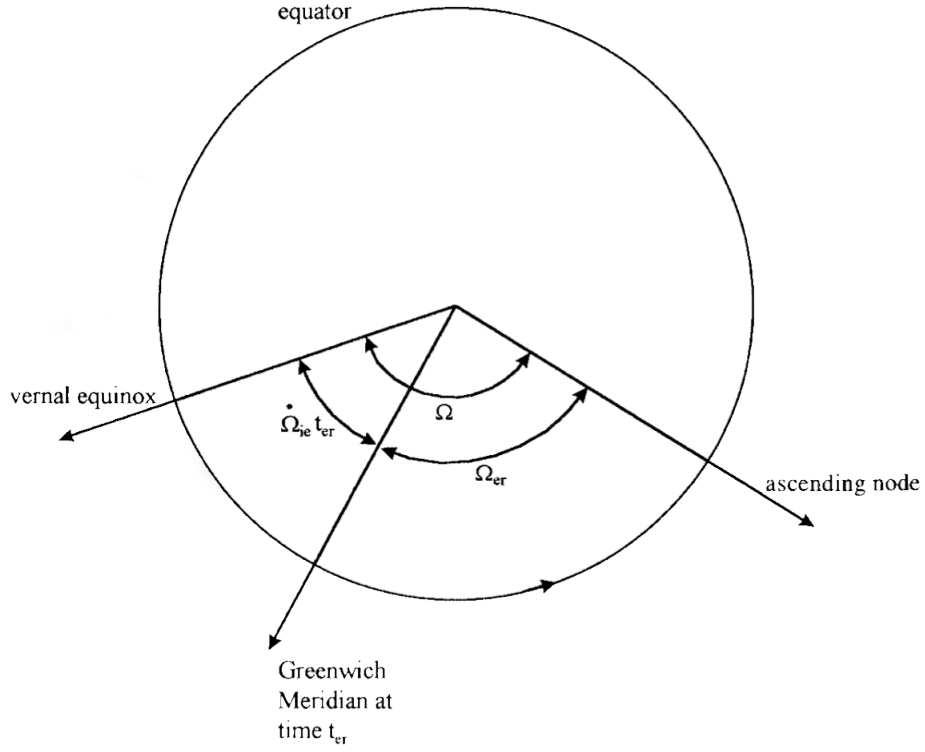
Figure 2.9: The right ascension angle and the rotation of the planet[1]

And, thus, the overall transformation is represented as

$$
\begin{bmatrix} x_4 \\ y_4 \\ z_4 \end{bmatrix} = C_3^4 C_2^3 C_1^2 \begin{bmatrix} rcos(\nu) \\ rsin(\nu) \\ 0 \end{bmatrix} =
$$

$$
= \begin{bmatrix} cos(\Omega_{er}) & -sin(\Omega_{er}) & 0 \\ sin(\Omega_{er}) & cos(\Omega_{er}) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos(i) & -sin(i) \\ 0 & sin(i) & cos(i) \end{bmatrix} \begin{bmatrix} cos(w) & -sin(w) & 0 \\ sin(w) & cos(w) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} rcos(\nu) \\ rsin(\nu) \\ 0 \end{bmatrix} =
$$

$$
= \begin{bmatrix} r(cos(\Omega_{er})cos(\nu + w) - sin(\Omega_{er})cos(i)sin(\nu + w)) \\ r(sin(\Omega_{er})cos(\nu + w) + cos(\Omega_{er})cos(i)sin(\nu + w)) \\ rsin(i)sin(\nu + w) \end{bmatrix}
$$

$$(2.26)$$

Several corrections to be aware of

This section gives a little bit of knowledge about **variables needed in the NAV message** in order to correct errors in calculations. As it is said before, the deep explanation for this variables surpass the whole thesis intention.

The GPS time with errors is represented as t_c and the time correction term is

$$\Delta t = a_{f_0} + a_{f_1}(t_c - t_{oc}) + a_{f_2}(t_c - t_{oc})^2 + \Delta t_r - T_{GD} \tag{2.27}$$

where all the unknown values are time correction parameters set by the Control Segment and can be found in the ephemeris part of NAV message. The GPS time t can be corrected as

$$t = t_c - \Delta t \tag{2.28}$$

In Equation 2.24 the right ascension will be corrected as

$$\Omega \rightarrow \Omega + \dot{\Omega}(t - t_{oe}) \tag{2.29}$$

where t is the GPS time, t_{oe} is the **reference time for the ephemeris** and $\dot{\Omega}$ is the **rate of change** of the right ascension.

The mean motion will be as

$$n \rightarrow n + \Delta n \tag{2.30}$$

being Δn a correction term inside the data sent by the satellite. Also, the mean anomaly changes

$$M = M_0 + n(t - t_{oe}) \tag{2.31}$$

where M_0 is the **mean anomaly at reference time**. The correction term to $\nu + w$ is

$$\delta(\nu + w) = C_{us}sin(2(\nu + w)) + C_{uc}cos(2(\nu + w)) \tag{2.32}$$

and the new $\nu + w$ is

$$\nu + w \rightarrow \nu + w + \delta(\nu + w) \tag{2.33}$$

The correction to r is

$$\delta r = C_{rs}sin(2(\nu + w)) + C_{rc}cos(2(\nu + w)) \tag{2.34}$$

and the r corrected is

$$r \rightarrow r + \delta r \tag{2.35}$$

And, finally the inclination i is

$$i \rightarrow i + \delta i + idot(t - t_{oe}) \tag{2.36}$$

where *idot* can be obtained from ephemeris in NAV message and

$$\delta i = C_{is}sin(2(\nu + w)) + C_{ic}cos(2(\nu + w)) \tag{2.37}$$

The correction constants C_us, C_uc, C_rs, C_rc, C_is and C_ic are known as the amplitudes of sine and cosine harmonic correction and they can be known looking at the ephemeris parameters.

Chapter 3

Project Development

I just wondered how things were put
together

_____

Claude Shannon

The requirements of the project, the way to transmit the information and the package needed to be sent will be described in this chapter. After the general description of the developed system a deep description of the project, from the requirements and limits of the GPS system through the modulation-transmission of the signal and ending in the C/A code and NAV message, will be offered.

3.1   General description

The designed system consist in a LabVIEW's test-bench with an auto-generated interface by the software that makes easy the understanding of itself and the GPS protocol which is the main objective of this whole project. As an implementation decision it could be noticed that to organise the circuit that a modulated scheme is used. Little boxes/systems that contains some other and so and so. From the generation of the message bits, through the configuration of the USRP and the modulation boxes to the final emission, the signals flows and it is sent to the receiver.
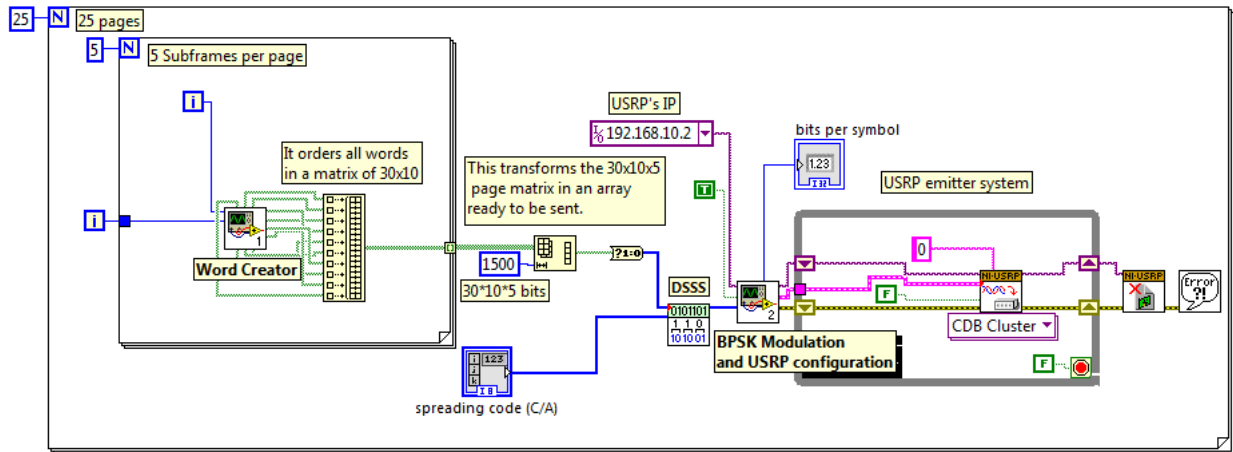
Figure 3.1: Whole project

3.2 Specifications

As soon as the objective is to imitate as exactly as possible the actual GPS system, the requirements come directly from it. The main specifications will be explained first and then the message values requirements and the message structure will be described.

In this section just the needed requirements of the GPS protocol will be explained but the all actual specifications of GPS will not be described as soon as it would exceed the project's goal. Neither the **ionospheric losses** nor the **clock correction**

3.2.1 Modulation

The Space Segment clock signal is generated by an Atomic Frequency Standard (AFS) with a frequency of **10,23 MHz**. The GPS signal uses two links but one for public use, the L1, that is at **1575,42 MHz**. This value is not trivial, it can be figured that $1575,42MHz = 154 \times 10,23MHz$. About the power level of the signal, what we receive in the surface of the Earth it is **-130dBm/-155dBm** but it seems to not work properly in the LabVIEW software, so a *decision* is to increase it just for the demonstration. The data rate is **50 Hz**.

BPSK

Moreover, a BPSK modulation is used. This means that, summing the DSSS, a CDMA will be the complete design. Finally the signal is following, the equation:

$$Asin(2\pi ft + \phi) \tag{3.1}$$

Direct Sequence Spread Spectrum

In order to satisfy a large amount of **multiple users** and to avoid noise or losses centred on an exact frequency in some zones, GPS protocol uses DSSS. The DSSS generates a wider spectrum signal repeating some code that in this case it is called the C/A code. The C/A code signal has a chip frequency of $f_c = 1,023$ MHz.

The C/A codes belong to the family of Pseudo-random noise (PRN) codes. Its length is of 1023 bits and it is generated by the sum of two sub-sequences called G1 and G2 that are generated by a 10 stages linear shift register that could be seen in Figure 3.2. Every satellite has its own code, that it is generated just changing the cells of G2 that are summing G1.
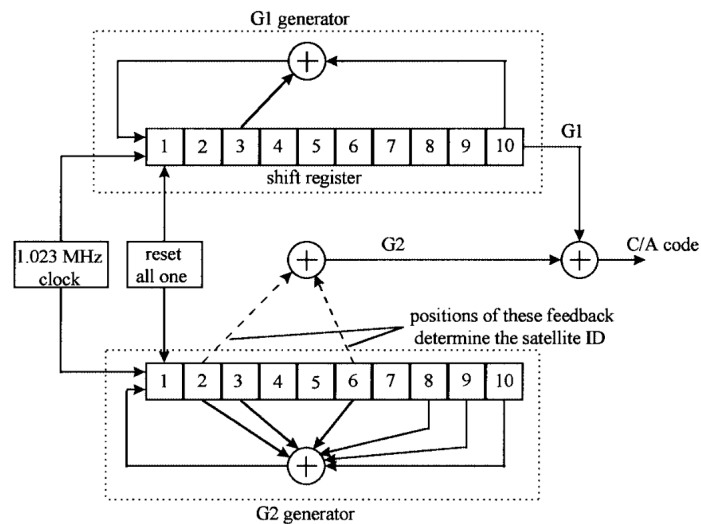
Figure 3.2: C/A code generator[1]

After doing the DSSS with the message, the chip will be $1/1,023MHz = 977,5$ ns

long. Also, as soon as the C/A code is a bi-phase modulated signal, the bandwidth after the DSSS step will be of 2,046 MHz.
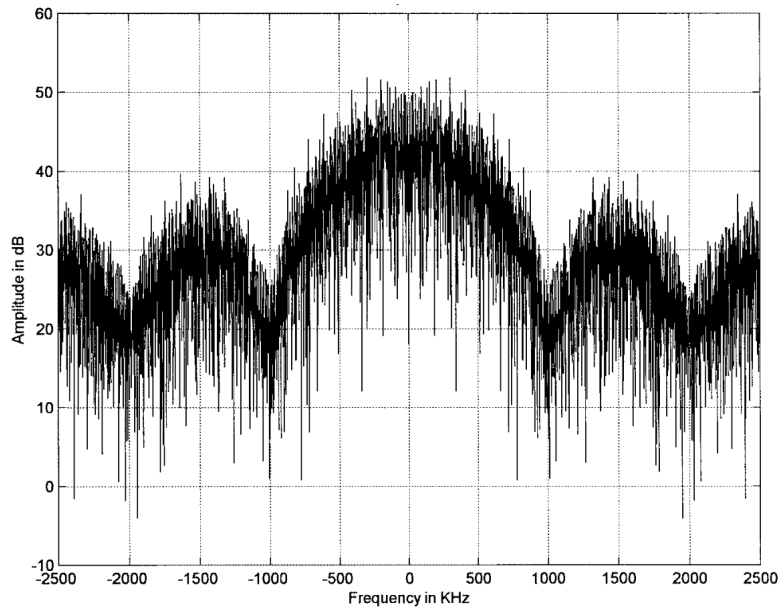
Figure 3.3: Frequency spectrum of the C/A code sampled from satellite 12[1]

3.2.2 NAV Message

Each message is composed of **25 "pages"** with **5 sub-frames each**, but just two frames (4 and 5) change along the transmission of all pages. In addition, it is important to take into account that each word ends with a set of 6-8 **parity** bits in order to detect transmission errors. Every sub-frame is composed of **10 words** that are **30 bits long each**. As it will be calculated in the next sections, the duration of sending a full NAV message last **12 minutes and a half**. So, in order to have a fast communication system, GPS protocol sends every page (that can be sent every **30 seconds**) without waiting for the others.

Headers

Each sub-frame has its own header that it is formed with two words, the **telemetry word (TLM)** and the **hand over word (HOW)**. The TLM starts with a **preamble**
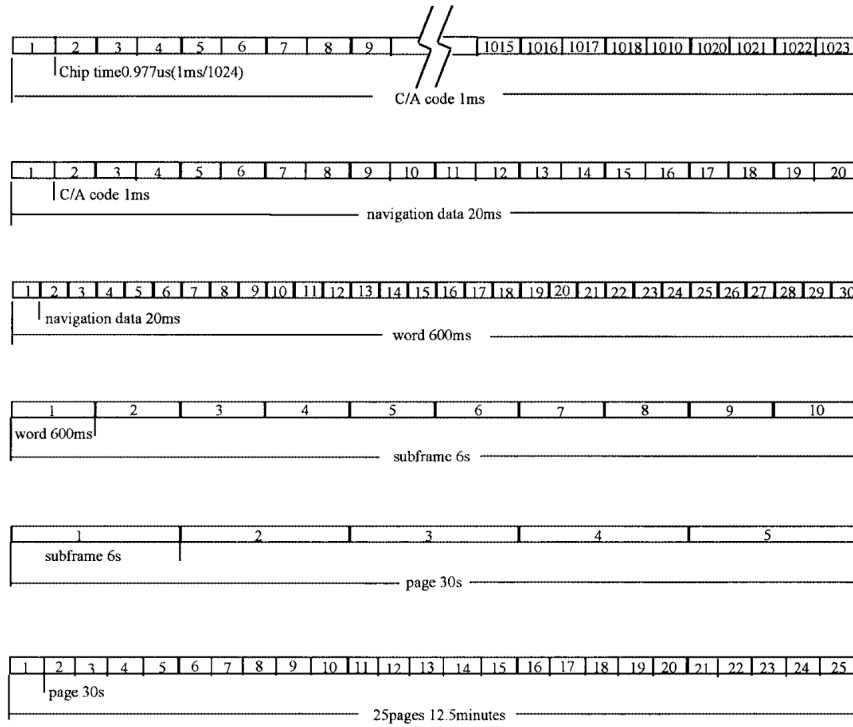
Figure 3.4: Data format[1]
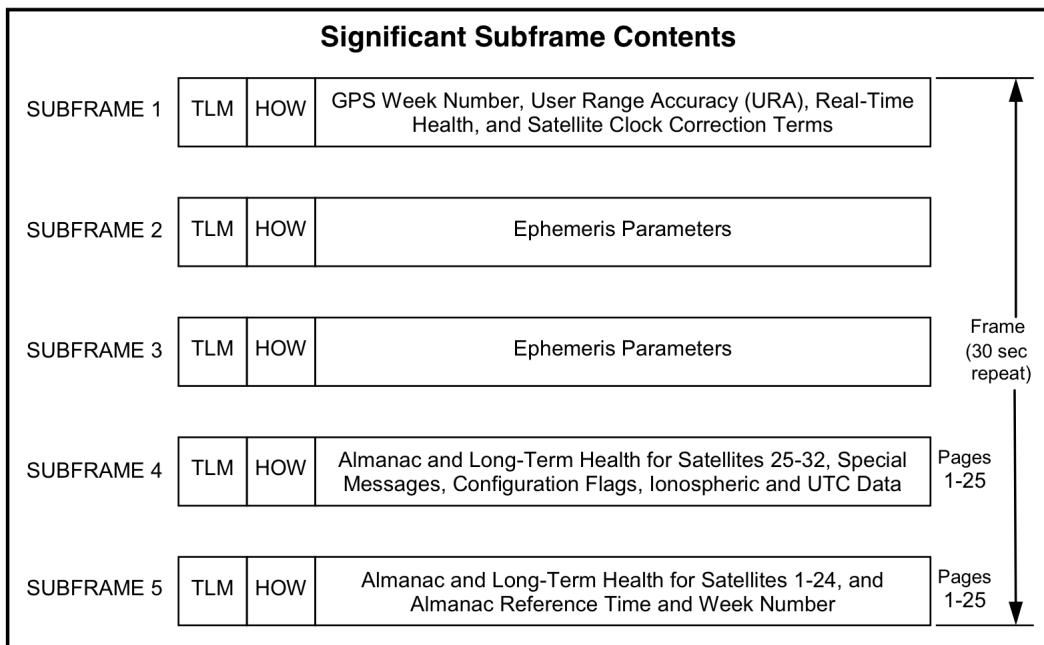
Figure 3.5: Page Format[5]

10001011, it continues with some reserved bits and it ends with the parity bits. The HOW needs the **Time Of the Week (TOW)**, the **sub-frame ID** and parity.
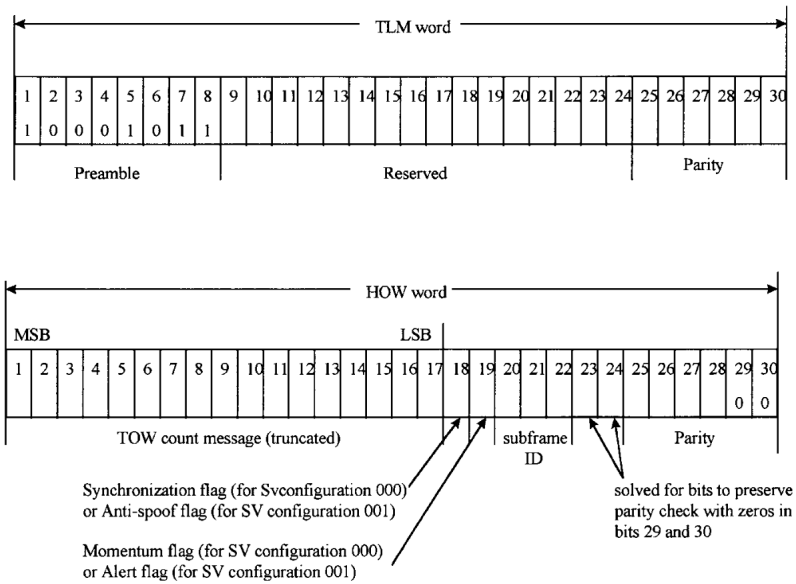

Figure 3.6: TLM and HOW[1]

The TOW is just a number that represents the present day of the week since midnight of January 5, 1980 but truncated. The time unit, then, is 6 seconds.
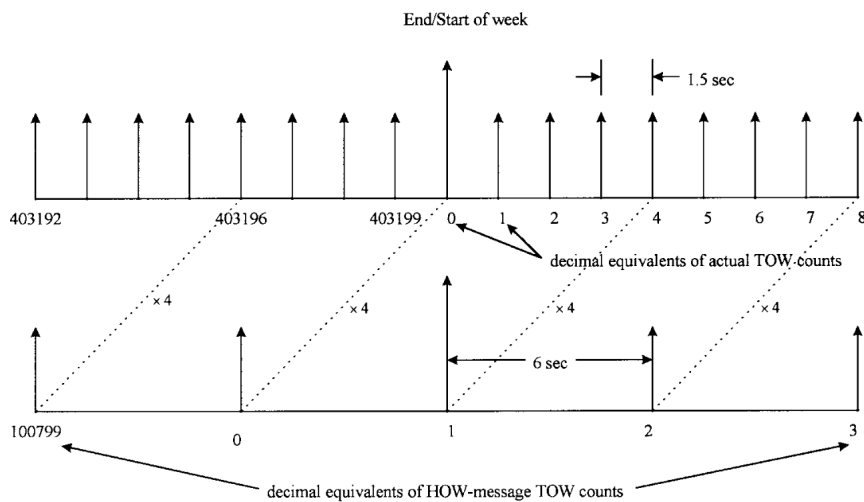

Figure 3.7: TOW calculation[1]

Sub-frames

In order to end with this section properly, an enumeration and plot of the different sub-frames is proffered. It should be reminded that some of the variables that are shown in the sub-frames are not going to be used later on in the project as one of the main decisions of the project is to imitate the protocol but as simple as possible. The project objective is the education.
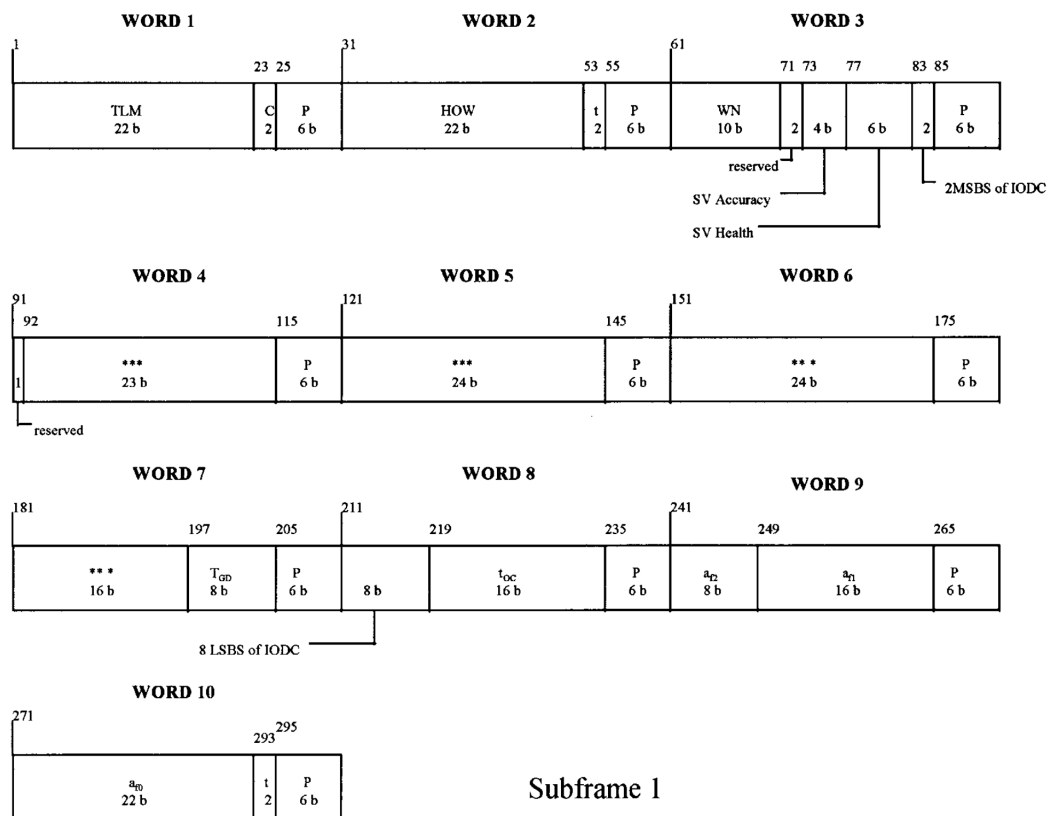
Figure 3.8: Sub-frame 1[1]

The sub-frames that change with every page are the 4Th and 5Th. Not every page has a proper content, sometimes they are reserved bits for future applications and others simply contains extra information that makes difficult the understanding of the GPS protocol and are not needed in order to work. For this reason, just the following plots are shown:
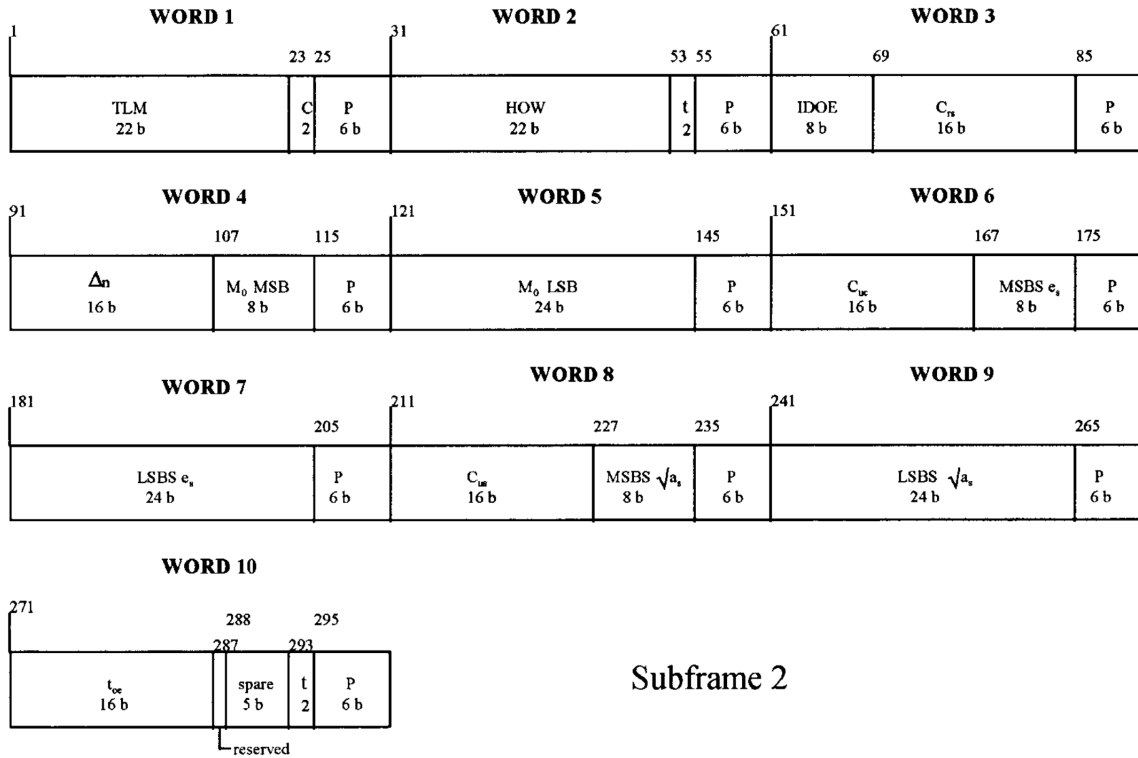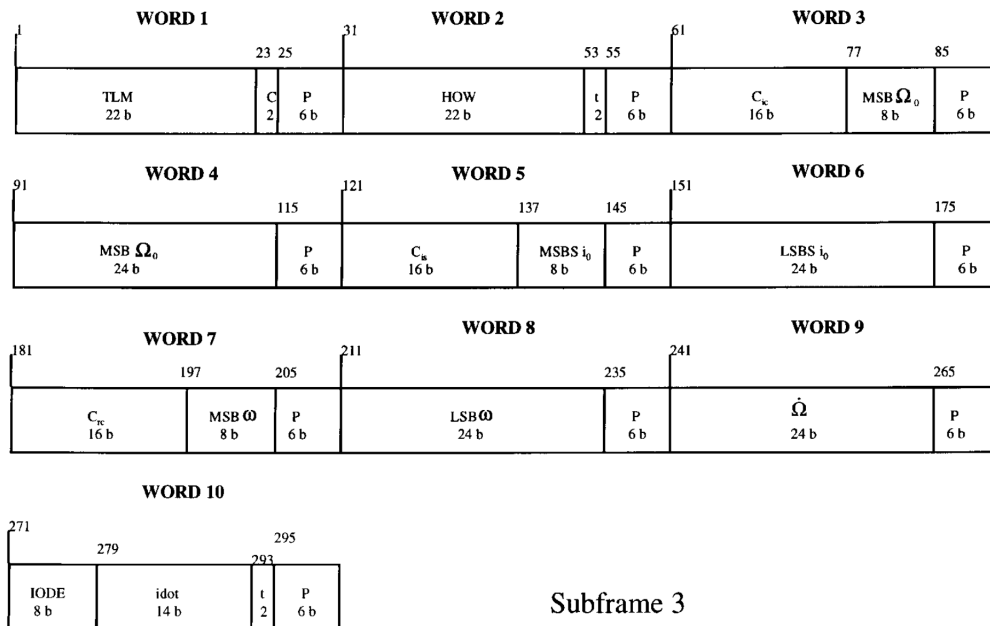
Figure 3.9: Sub-frame 2[1]
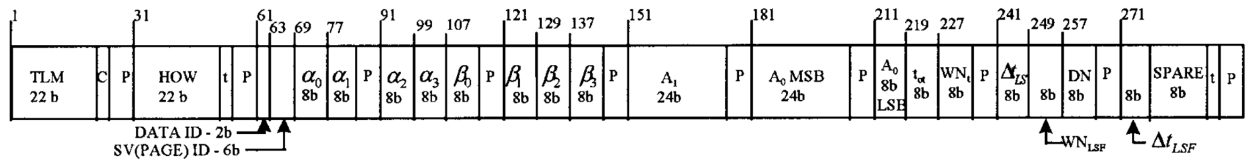

Figure 3.10: Sub-frame 3[1]
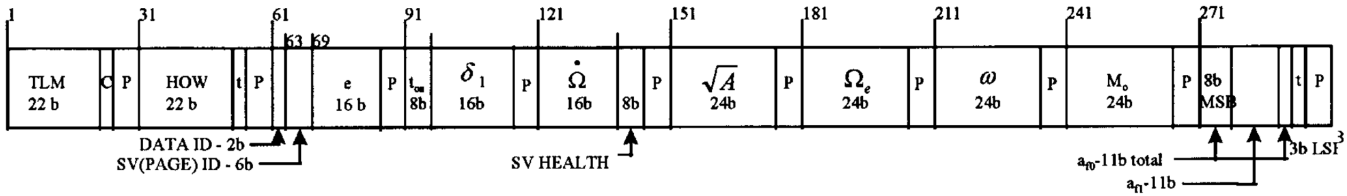
Figure 3.11: Sub-frame 4 in the 18 page[1]

Figure 3.12: Sub-frame 4 in pages 2, 3, 4, 5, 7, 8, 9 and 10 and sub-frame 5 in pages 1-24[1]

3.3 Modulation and transmission

In this section, the development of the modulation and transmission systems inside the project will be discussed. First, the configuration of the USRP and the antenna's transmission will be explained. Then, the modulation part will be exposed.

3.3.1 USRP's Transmission

Before achieve the emission, the antenna has to be configured. First a transmit session should be opened with the *niUSRP Open Tx Session VI* tool, then signal is configured with *niUSRP Configure Signal VI*. In order to do this, the needed parameters are:

- The **IVI Refnum** is the place for the IP of the USRP.

- The **reset** is constantly set to boolean True, in order to be on.

- The **symbol rate** of the data is 50 Hz.

- The **carrier frequency** is the L1 link centred frequency.

- The **gain** is set as -155 dB after the decision of putting a higher gain, because LabVIEW do not work with so little power.

- The **channel** is set to 0 as the antenna will not have multiple channels.

- The **activate antenna** is the selection between the USRP antenna TX1 o TX2.

- The **error** is generated from a previous step.

The output of this first step will be attached to the BPSK modulation box by the variables of **coerced IQ rate**, that it is the proper rate for the specific configuration, and **IVI Refnum out**, that contain the IP of the USRP if it was correct and accepted by the configurator. Also the **error out** that is error propagator signal.
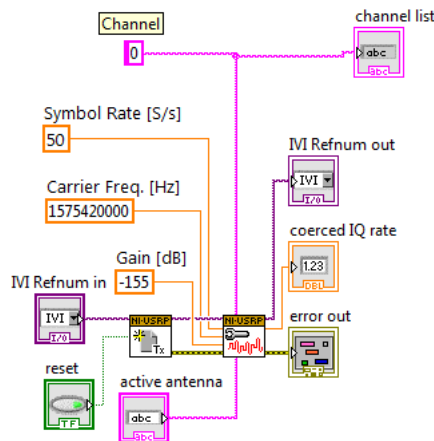

Figure 3.13: USRP's configuration

Once the configuration is set and after DSSS and BPSK modulation (that will be explained in the next sections), the **data** arrives in the pink link to the USRP emitter called *niUSRP Write Tx Data (poly) VI*. It also needs:

- The **channel list**,that is 0 as explained before.

- The **end of data** link, that is set as a boolean false because in a satellite the emission never stops.

- The **error**.

It can be noticed that this emission system is closed in a grey rectangular *structure*. This kind of rectangles in LabVIEW are called *structures* and this one is equivalent to a `while` in some programming languages.
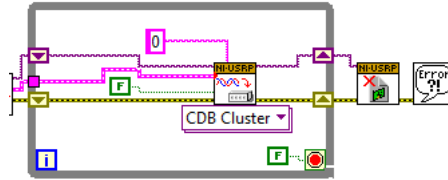

Figure 3.14: LabVIEW's transmission structure for the USRP

Finally the session handle should be closed with the *niUSRP Close Session VI* that requires the IP direction of the USRP that is related to the **session** and the **error** link. In case that an error occurred, after the *niUSRP Close Session VI* the error link is connected to the *Simple Error Handler VI* that prompts a message with the error.

3.3.2 BPSK Modulation

Three systems are going to be used in order to reach the whole BPSK modulation system; *MT Generate System Parameters VI* as BPSK configurator, *MT Generate Filter Coefficients VI* as the filter $g(t)$ and *MT Modulate PSK VI* as the PSK modulator. It should be seen that the modulation circuit is inside a green rectangular *structure* that in this case is equivalent to an `event trigger` to avoid the modulation process if an error appears.

BPSK Configurator

In order to prepare the **PSK system parameters** that outputs in the proper way to be understood by the PSK modulator this parameters should be introduced:

- **PSK type** and **differential PSK** that are set as `normal` and `disable` respectively because an usual BPSK is needed.

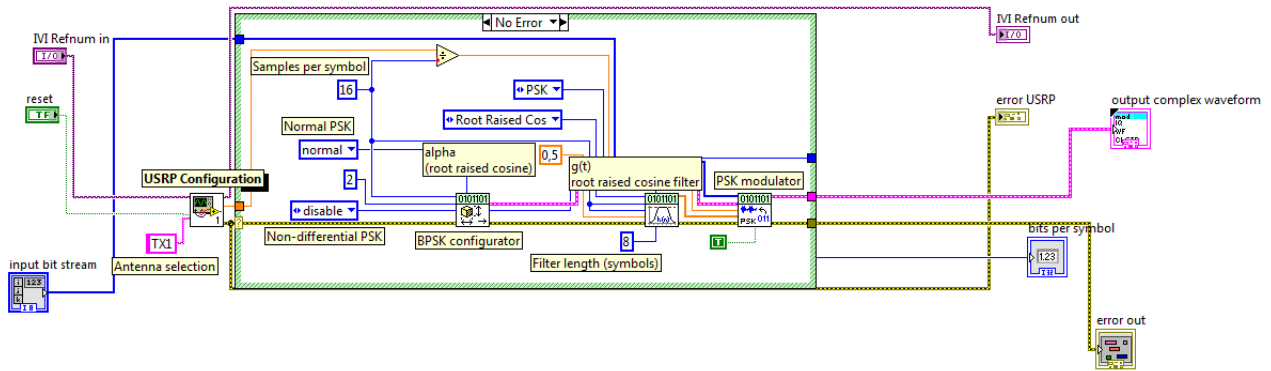- **M-PSK** that is 2 as soon as it is a BPSK modulation.

Figure 3.15: USRP configuration and BPSK modulation in LabVIEW

- **samples per symbol** that was decided to be 16 samples/symbol, because of its very common use.

- **error**

It returns the defined **PSK system parameters**, the **bits per symbol** and the **error**.

Root Raised cosine filter g(t)

The next step is to transform the discrete data in to analog signals, quite common issue in Digital Communications. First step is to make some decisions. As soon as this is a project with educational aspirations, a very studied and good working signal will be used. The root raised cosine. An $\alpha = 0, 5$ is used in order to not change the BW so much and for a good ISI avoidance. Then, the input parameters for *MT Generate Filter Coefficients VI* will be:

- **modulation type** that is PSK.

- **pulse shaping filter** that is the Root Raised Cosine.

- **pulse shaping samples per symbol** and **matched samples per symbol** that should be equal as the 16 samples per symbol.

- **filter parameter** that is the $\alpha = 0, 5$.

- **filter length** in symbols that should be 8.

- **error**

The outputs will be the error as a ever and the **pulse shaping filter coefficients**, an ordered array of filter coefficients corresponding to the root raised cosine filter and it passes the **error**.

PSK Modulator

Finally, the inputs of the modulation:

- **input bit stream** that is the data ready to be modulated.

- **PSK system parameters**, the output from the BPSK configurator.

- **symbol rate** that is $\frac{IQrate}{samples/symbol}$.

- **pulse shaping filter coefficients**, the output from the filter.

- **reset** set to a boolean constant as true in order to make it work without stop.

- **error**

And the outputs are the **output complex waveform** that is going to be emitted and the **error** link.

3.3.3 Direct Sequence Spread Spectrum

In order to spread the data sequence from the *Word Creator* the system called *MT Spread Symbols VI* whose inputs are:

- **input bit stream** that is the data sequence.

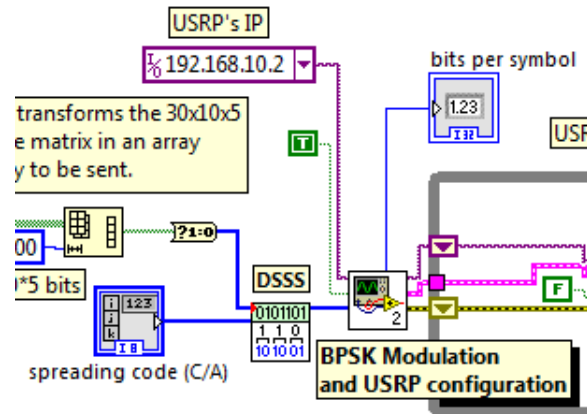- **spreading code** that is the C/A code.

- **error**

Figure 3.16: Modulation system in LabVIEW

It is important to take into account some transformation that appears here, just between the page creation and the DSSS, that is that the full message is done in a boolean format, but in order to modulate the signal it should be a bit based array. Finally, it returns the **output chip stream** or the spread data sequence and the **error**.

3.4 NAV Message

In this section, the construction of the NAV message will be explained. Again, it is warmed that just the needed variables and parts will be explicated. The construction of every page is done inside a `for` loop that is the rectangle structure that surrounds the *Word Creator*. This structure is also surrounded by another `for` loop that, in this case, encloses all the project systems as soon as the same process should be done for each of the 25 pages, with few differences as shown before.
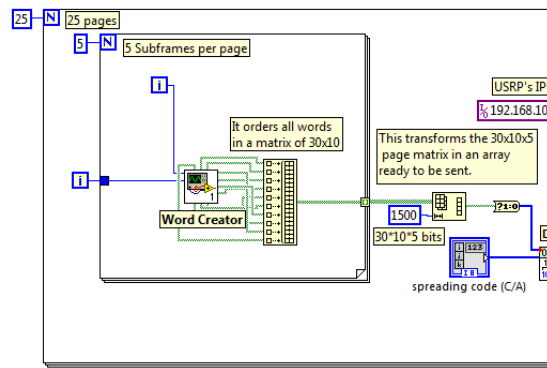
Figure 3.17: NAV Message overview

3.4.1 Headers TLM and HOW

Here not just the TLM and HOW words are going to be unmounted but also here an example of a word construction based in the specification idea will be illustrated. All the protocol words are constructed by same pattern, for that reason just this ones are going to be shown. What changes all along the rest of the words is the variable an its position in the message.

For the matrix construction the *Replace Array Subset Function* is needed. From now on it will be used every time in this section. Its function is to insert a little array inside a bigger one, or as in the case of this project to insert the information into an empty array. The needed inputs are:

- **n-dimension array**. The empty array.

- **index**. It is the position in the empty array where the content will be inserted.

- **new element/sub-array**. The new content.

Every word in the message ends with a parity array in order to checkout at the receiver if there has been errors in the transmission. Although the actual parity algorithm works in a different way, this non-proper approximation could be a simpler way to denote errors. The parity algorithm used in this design fill all the parity section of the word with 1's or 0's depending on the previous bit. If it is a 1 then all the parity space will be filled of 1's, if it is a 0 then otherwise.

TLM

In the TLM it is just interesting the *preamble*, the rest is either reserved space or the parity.
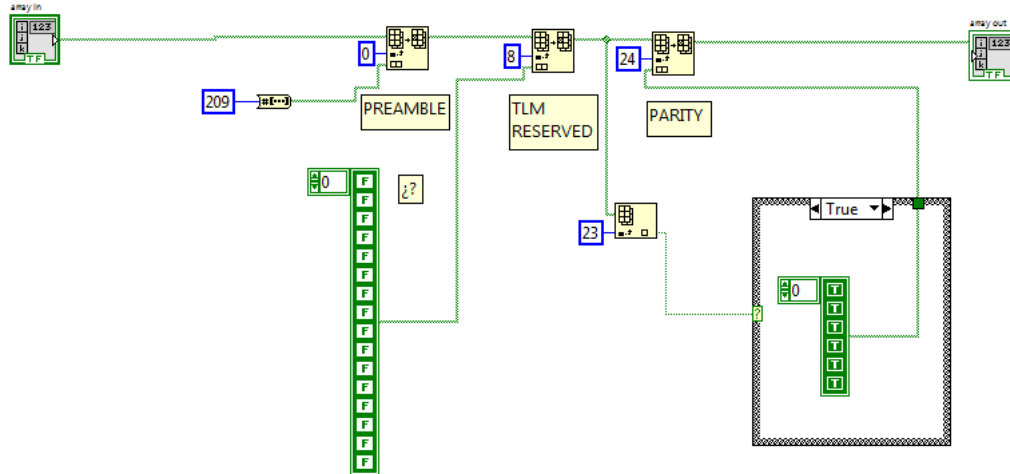

Figure 3.18: TLM circuit

HOW

In the other hand, in the HOW word, the important sections are *TOW*, *user range warming* and *anti-spoofing* (without taking into account the parity). The TOW concept is a complex one because, although it is divided by six in order to make it a little number, the calculation of the moment of the week since the launched date is a tricky issue. As it can be seen in the next image, the solution comes by entering the date of the week's first day and the current day in the LabVIEW's box that outputs the time in seconds since the 01/01/1970. Then, a substraction between them is done and a division by 6.

3.4.2   Sub-frames

To achieve the sub-frames creation a complex structure is needed. Full of conditions inside conditions, because every subframe should be different in every page and also between themselves. In order to do it, a condition structure is used and it can be
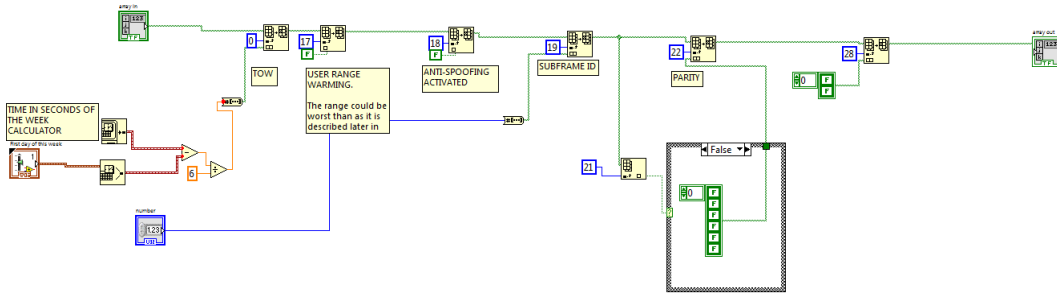
Figure 3.19: HOW design

recognized in the next pictures as the grey box that can be or true or false (although it could be filled with other cases as it will be seen). This boxes check the page and the subframe in order to complete the words with a variable or another.
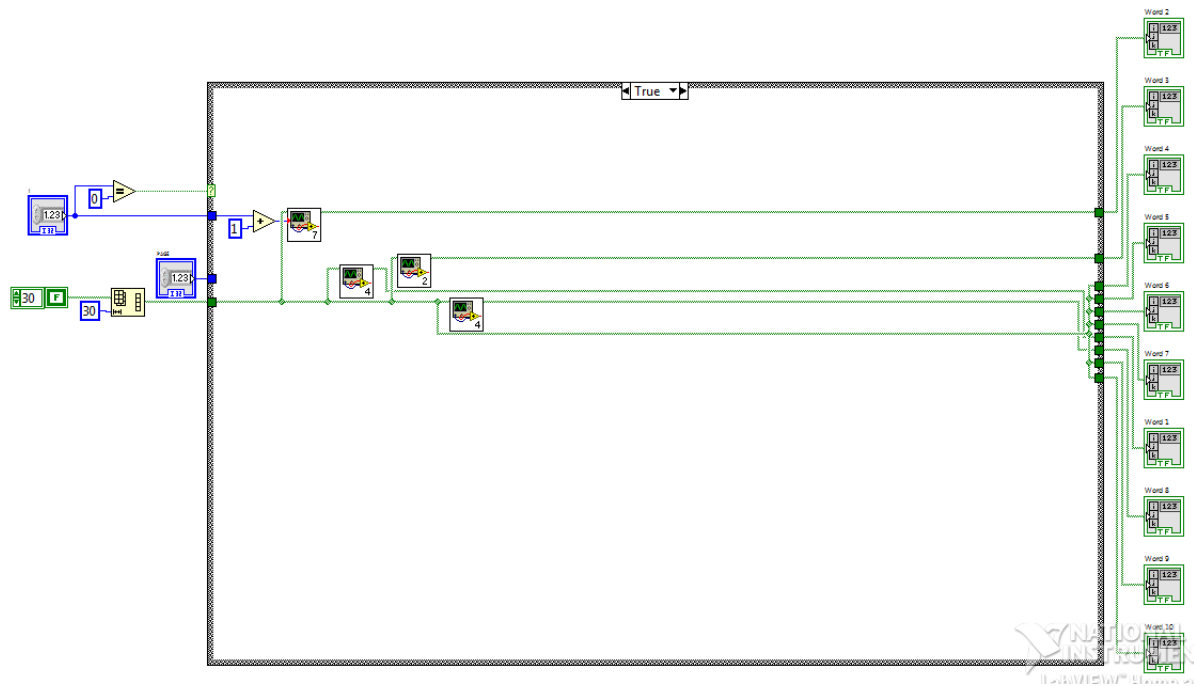

Figure 3.20: Sub-frame 1 scheme

In the fifth and fourth sub-frames there will be an additional structure inside that permits the page selection, because they are the sub-frames that change the most every page.

For the rest of the pages the circuit design will be equal as the design of the fifth
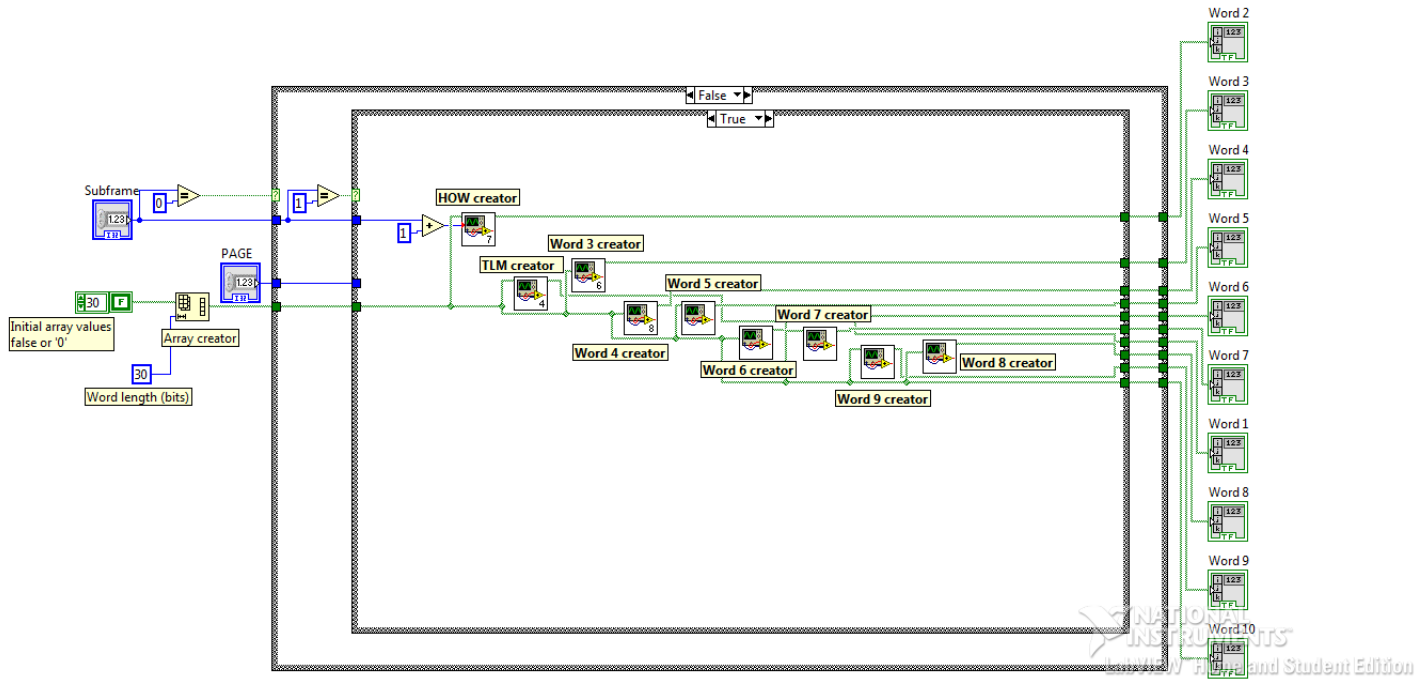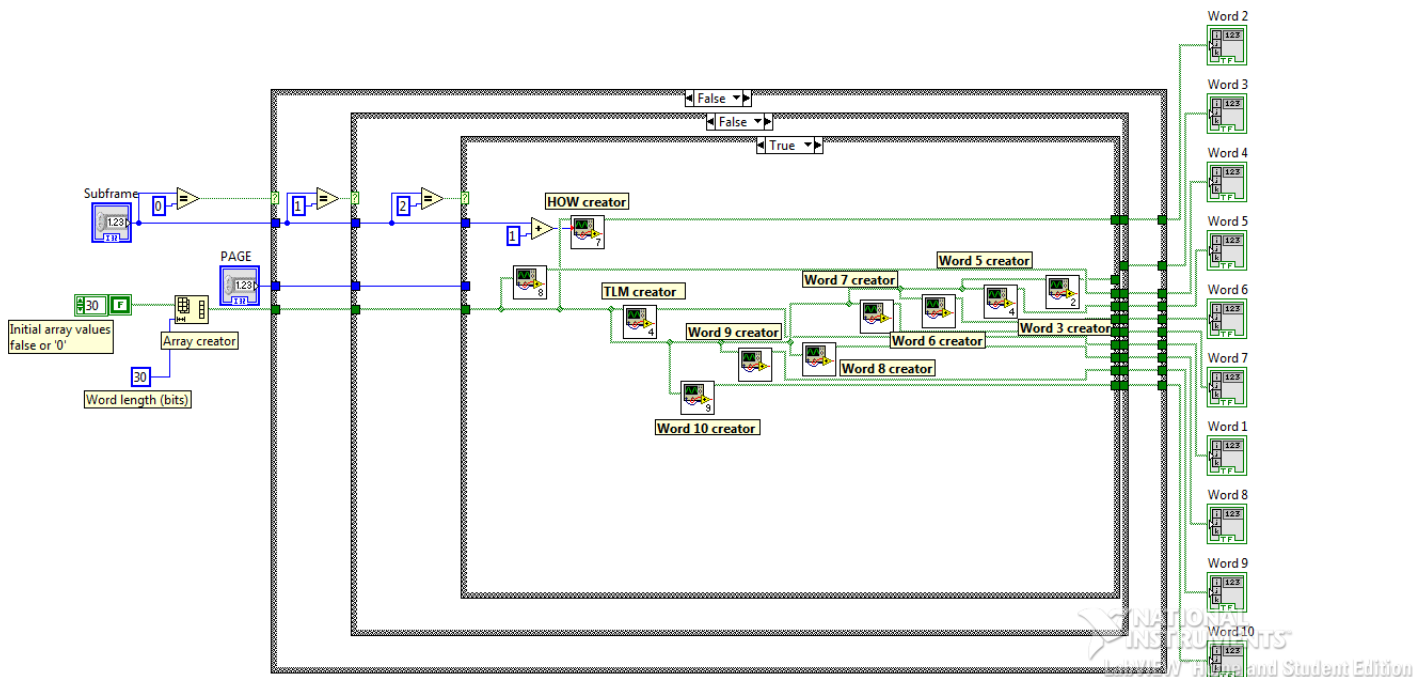
Figure 3.21: Sub-frame 2 scheme
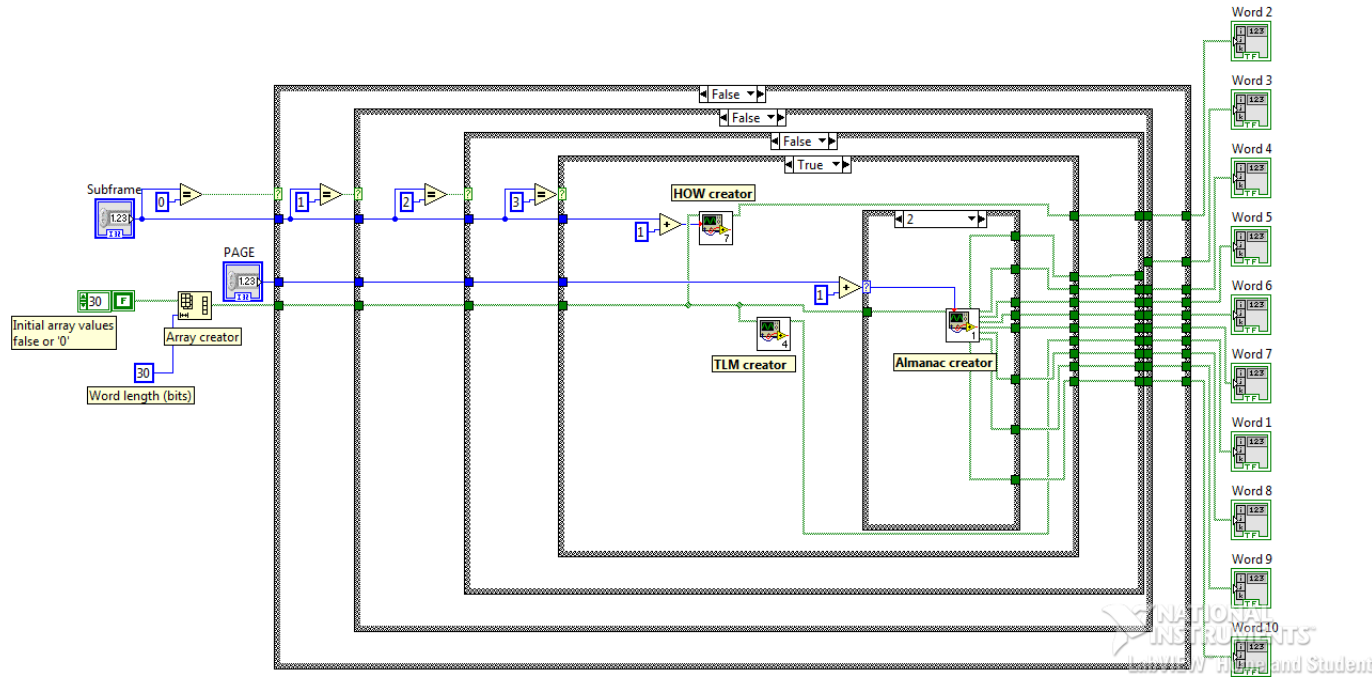

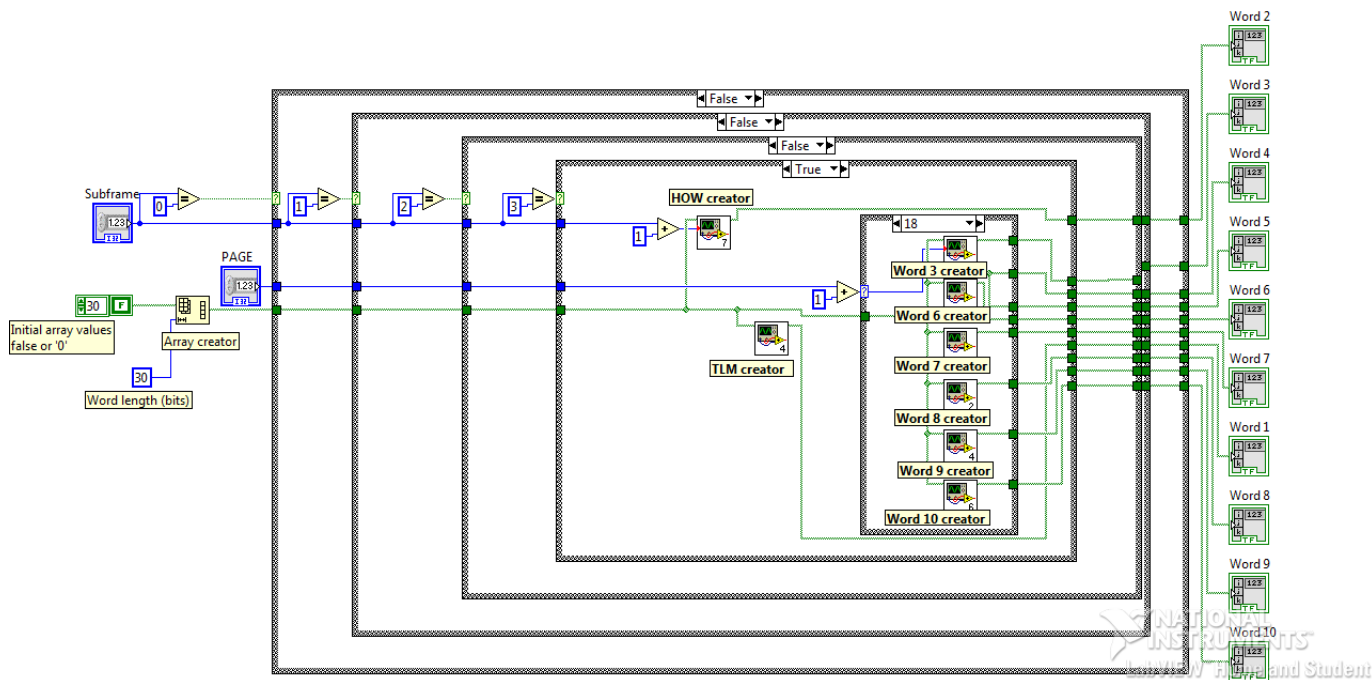Figure 3.22: Sub-frame 3 scheme

Figure 3.23: Sub-frame 4 scheme

Figure 3.24: Sub-frame 4 scheme

sub-frame in the twenty fifth page that will be shown in the next section.
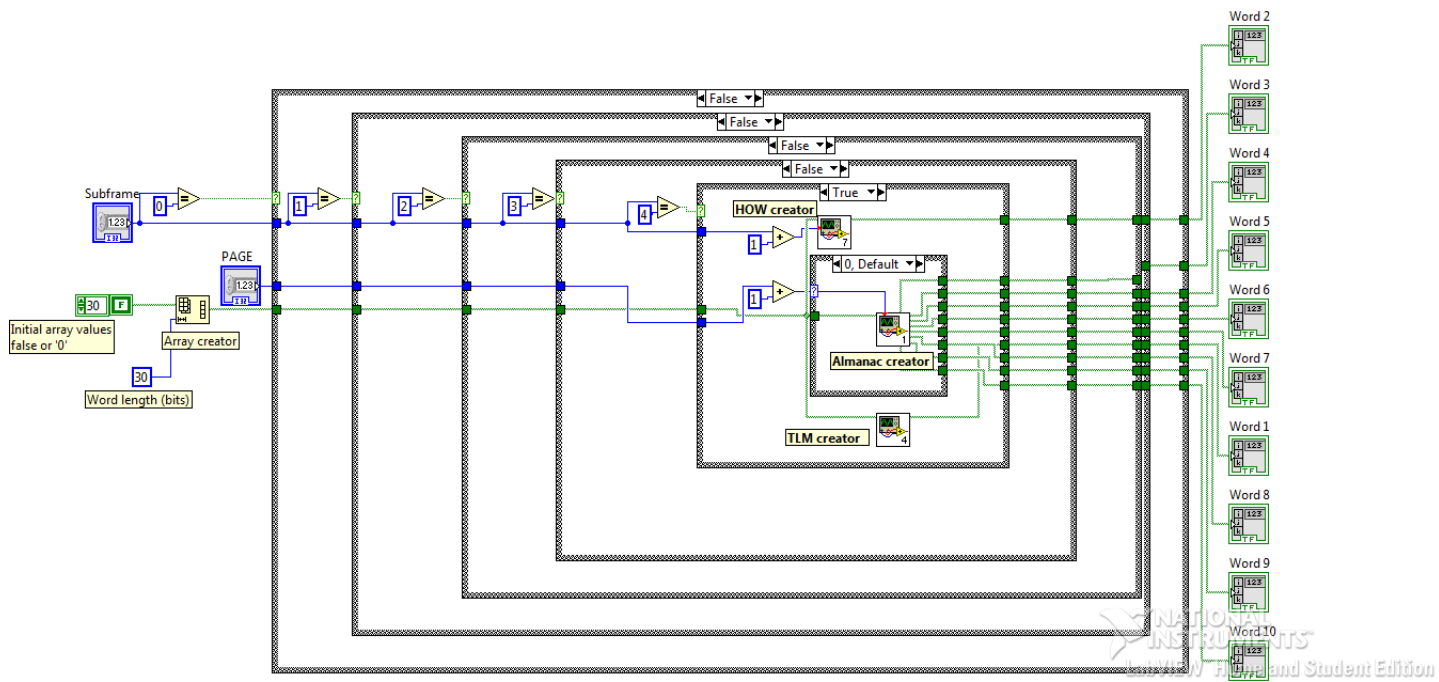

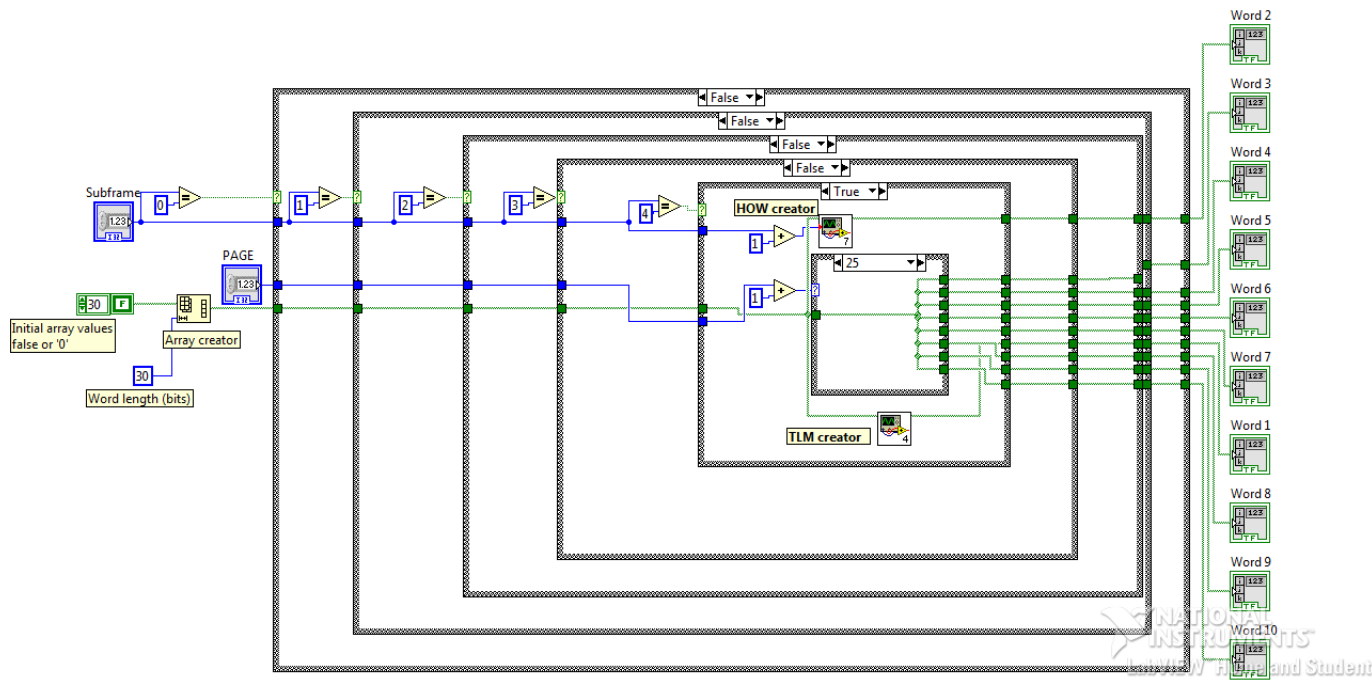Figure 3.25: Sub-frame 5 for pages 1-24 scheme

Figure 3.26: Sub-frame 5 for page number 25 scheme

Chapter 4

Results and validation

Mommy's in the kitchen, cooking up
something good
And daddy's on the sofa, pride of the
neighbourhood
My brother's in the ballet, it seems
he's got it set
And I'll be up at midnight with my
cigarette

Mac DeMarco, *Cooking Up Something*
Good (2)

In this chapter the results of the project are going to be reviewed. It is not possible to demonstrate all the inspections that have been done because it would require a demonstration video but, anyway, some pictures will be offered in order to show what is working.

4.1   Modulation layer results

In order to test the modulation system of the project, a transmitter and a receptor are established. Both of them are USRPs mounted with a LabVIEW project. In the transmitter, this project is mounted and, in the receptor, a predefined project is also

installed. This predefined project that comes as an example in LabVIEW can demodulate BPSK but in order to invert the DSSS and to observe the results in a proper way, some other things should be added. These things are the DSSS demodulator, called *MT Despread Symbols VI*, and a simple screen print to check that the received data is the same that the one that was sent.
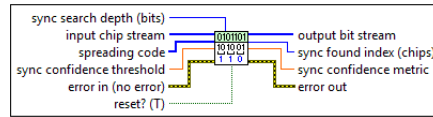

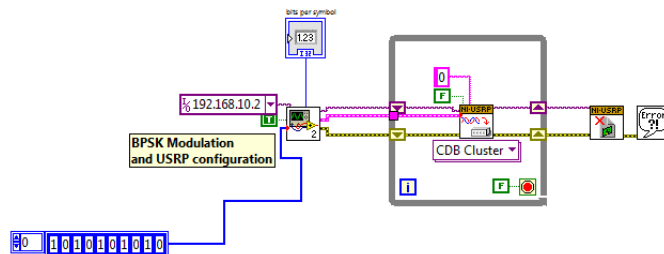Figure 4.1: DSSS demodulator from LabVIEW

Figure 4.2: Example of testing the sender

After the testing process, repeated several times with different sequences of bits, the 100% of bits are received without error.

4.2 Acquisition layer results

For testing if the packet algorithm is working well, just a screen printer is needed after the sub-frame creator. The process will start with all the packets empty except for the headers or other mandatory bits depending on the sub-frame. A set of results are offered, of the first of the 25 pages. It should be known that every green light is a bit. If the light is on it represents a 1, 0 otherwise.
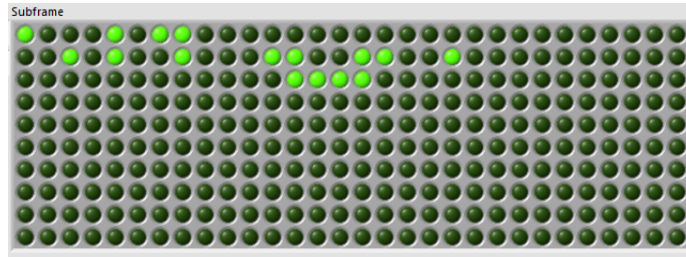
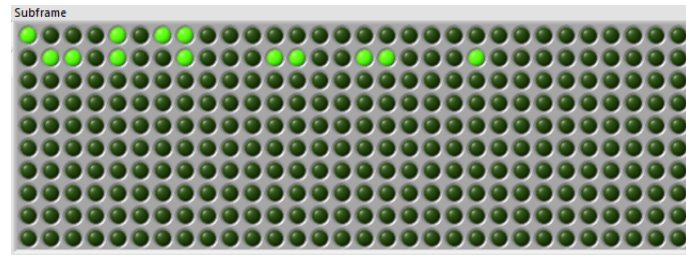Figure 4.3: Page 1 Sub-frame 1

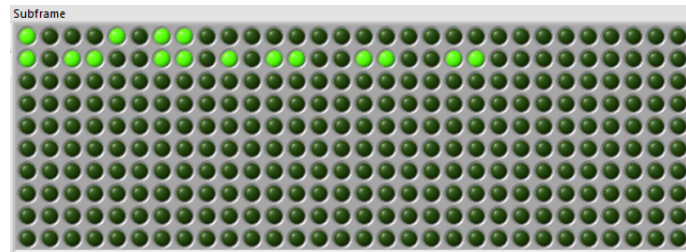Figure 4.4: Page 1 Sub-frame 2

Figure 4.5: Page 1 Sub-frame 3
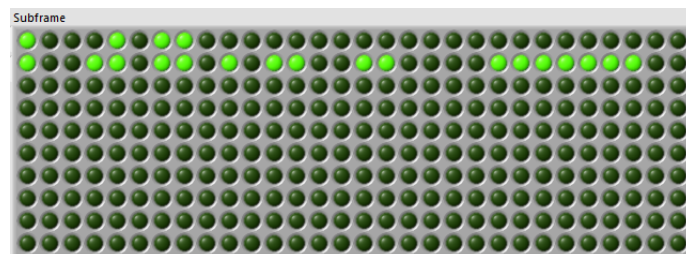
Figure 4.6: Page 1 Sub-frame 4
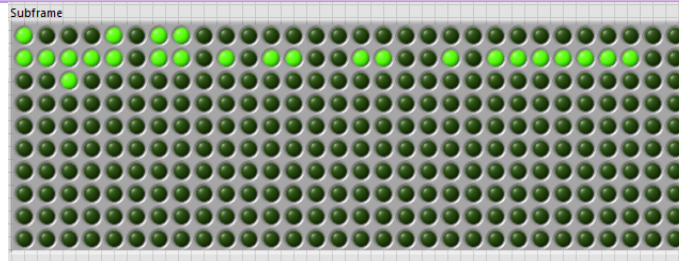
Figure 4.7: Page 1 Sub-frame 5

It can be seen in the results that the TOW changes every time and that every bit of different words or variables are respected. The message algorithm is working, the message could be completed with the variables values.

4.3 Total results

The total results of the project cannot be shown as soon as I got a place at the UPC (Barcelona) and I had to move to Barcelona the firsts days of September. Therefore, I lose the possibility of continuing my work with the USRP transmitter. For this reason I could not create another test system for checking the full results.

Chapter 5

Conclusions

> This is the end, my only friend
>
> The end of our elaborate plans
>
> ———————————————
>
> The Doors, *The End (The Doors)*

As described in the chapter 4 the objectives that have been completely reached were: to build a system as similar as possible to the actual one and that could be monitorized in order to understand the protocol. But, is it possible to do a satellite GPS with USRP technology?

The answer is complex, because the USRP has some "cons" and some "pros". In the cons it could be said that the USRP has a normal processor that can not reach easily the computational speed that is required, in order to be completely equal as a real satellite. In the pros, the LabVIEW support that makes easier the prototyped process appears. So, the final response is that could be done but without demanding so much processing load.

The most difficult part of the development of this project has been the NAV message development, because it has a lot of different cases that are not trivial for doing them in LabVIEW as it can be seen in chapter 3. Also it needs all the mathematical knowledge about GPS location algorithm for knowing which variable is important and which one overtake the limits of this project. This knowledge is also important for knowing which type of variable is it and, therefore, to know how to treat it.

Although it was not a complete mess, the learning of how to work with LabVIEW

should be mentioned, because the time used into learn how to work with it is not insignificant. And, finally, to find good and verified bibliography was very difficult as soon as it is not a topic which requires a deep knowledge as this is for working with it nowadays. Most of the information about GPS was how to implement software using already created libraries or API's.

This project has its other coin face, a receptor, that has been developed in parallel to this one. With five USRP's, four as satellites and one as a receptor, a demonstration could be done, indeed. This educative demonstration also could illustrate which is the meaning of every needed variable as soon as they could be manually changed. Even the radiated waves could be monitored in order to understand better the modulation and the changes in time of the data. As in this emitter the receptor could also show step by step

A future telecommunications student could be more interested in GPS as this tool helps to be passionate about the protocol and it will help, for sure, in its understanding. But this is even an interesting way of motivational learning even for a younger high-school student that could encourage skills like critical thinking and decision-making, and can serve as an excellent way for this kind of students to learn where data comes from and how to collect it. This kind thesis could be found in an interesting article of a educational researcher [2].

Finally, about the possible improvements of the project, it could be seen that the C/A code creation was not developed inside this project. This is a possibility that could help the project being more realistic. Moreover, an algorithm that calculates the value of some of the shown GPS variables in order to decide a fake place to transmit and, then, receive this coordinates would be very helpful in order to achieve the objective of making easy demonstrations. Of course, the development of an exact copy of the GPS signal could be done as an improvement. If this is done, even an USRP's receptor could be avoided because any other usual receptor could be use. This kind of improvements would do the project more powerful when demonstrating the passionate telecommunications world to young students or future engineering students.

Bibliography

[1]   James Bao-Yen Tsui. *Fundamentals of Global Positioning System Receivers. A Software Approach.* John Wiley and Sons, 2000.

[2]   L. Briggs. "Here, There, and Everywhere". In: *T H E journal* 34(5) (2007), pp. 50–51.

[3]   Michael J. Dunn. *Global Positioning Systems Directorate. Systems engineering and integration.* Performance Standard. GPS NAVSTAR, 2013.

[4]   John G. Grimes. *Global Positioning System. Precise Positioning Service Performance Standard.* Performance Standard. GPS NAVSTAR - USA Department of Defense, 2007.

[5]   John G. Grimes. *Global Positioning System. Standard Positioning Service Performance Standard.* Performance Standard. GPS NAVSTAR - USA Department of Defense, 2008.

[6]   ITU-R. *Technical and performance characteristics of current and planned radionavigation-satellite service (space-to-Earth) and aeronautical radionavigation service receivers to be considered in interference studies in the band 1559-1610 MHz.* 2008.

[7]   Thomas J. Nagle. *GPS Civil Monitoring Performance Specification.* Performance Standard. USA Department of Transportation, 2009.

[8]   Colegio Oficial de Ingenieros de Telecomunicación (COIT). *Emisiones Radioeléctricas: Normativa, Técnicas de Medida y Protocolos de Certificación.* 2008.

[9]   Steve Zaidman. *Global Positioning System. Wide Area Augmentation System (WAAS) Performance Standard.* Performance Standard. USA Department of Transportation - Federal Aviation Administration, 2008.