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Development of a software SBAS receiving module for a GPS receiver

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Dedicated to my parents and my girlfriend...

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Resumo

Desde os primeiros tempos que a nossa localização e orientação tem sido uma preocupação. Vários métodos têm sido utilizados tais como as estrelas, Lua e o Sol. Com o aparecimento dos satélites, foi dado um enorme passo neste tema, permitindo usar o Sistema de Navegação Global por Satélite (GNSS) - qualquer sistema de navegação por satélite que possui a capacidade de oferecer posicionamento em qualquer ponto da superfície terrestre, adota-se esta nomenclatura - para obtermos a nossa localização actual de forma bastante precisa. Um dos sistemas GNSS mais conhecidos é o GPS (Global Positioning System), sistema da responsabilidade do governo dos EUA, que funciona em qualquer ponto do globo. O GPS foi desenvolvido pelo exército militar Americano no ano de 1973. Começou por se chamar Defense Navigation Satellite System (DNSS) com o objectivo de ser um sistema de navegação que fornece informação de localização e tempo em qualquer condição metereológica e em qualquer ponto do planeta. Mas só em 1983 é que o sistema passou a estar disponivel para uso civil.

Em 2005 a Comissão Europeia em conjunto com a Agencia Espacial Europeia e a EUROCONTROL começaram as operações do EGNOS (European Geostationary Navigation Overlay Service). O EGNOS é um sistema que que aumenta as capacidades dos sistema por satélite, em particular do GPS (SBAS - Satellite Based Augmentation System) com cobertura na Europa. A 1 de Outubro de 2009 ficou pronto para utilização civil

O âmbito deste trabalho é adicionar o receptor EGNOS a um receptor GPS implementado num SDR (Software-defined radio). Ao adicionar a funcionalidades do EGNOS ao receptor, vai ser possível obter localizações com uma maior precisão e adicionar um factor de erro e margem de confiança que não são possíveis de obter usando apenas o sistema GPS. O receptor, após a implementação, irá permitir escolher o modo de operação - usando apenas o sinal GPS ou usar as melhorias EGNOS.

Os resultados obtidos usando o módulo EGNOS desenvolvido sobre um programa open-source existente - SoftGNSS - comprovou que as localizações obtidas são sempre mais precisas quando comparadas com as calculadas somente usando o sistema GPS. Para além desta vantagem, foi possível obter sempre níveis de proteção e alarmistica, algo não possivel usando apenas o sistema GPS.

Todo o trabalho desenvolvido será explicado em detalhe e os resultados examinados de forma a perceber as melhorias aplicadas.

Palavras-chave: Global Navigation Satellite Systems (GNSS), Software-defined radio (SDR),EGNOS (European Geostationary Navigation Overlay Service), GPS (Global Positioning System), HPL (Horizontal Protection Level), VPL (Vertical Protection Level), SoftGNSS

Abstract

Since the begin of times that our location and orientation have been a constant object of study. Either the stars, the Moon or Even the sun were used to help our ancestors get information on location, however it was only centuries later with the appearance of satellites that we would be able to be more precise on our location definition. One of the most known GNSS – Global Navigation Software Systems in the entire world is the Global Positioning System also known as the GPS. This software, initially created by the US military in 1973 only became available to the general public in 1983 and since then it is used hundreds of millions of times a day in every single corner of the globe.

However precise the GPS can be, it can certainly suffer a fewer enhancements and that is one of the reasons why the European Commission together with the European Space Agency and the EUROCONTROL began in 2005 the operations of the so called European Geostationary Navigation Overlay Service, or EGNOS. This service, among other things has the capacity to enhance the information we get from the satellite systems, in particular, it was created to enhance the GPS information.

In fact, by adding an EGNOS receptor to a GPS one, using an SDR (Software-defined radio) in the process to implement it we can get locations with a better precision and we can additionally add an error factor and a confidence margin to the EGNOS data that can enhance and better the results obtained from the satellite.

A practical analysis done with three different locations, Lisbon, Troia and Madrid, using the developed EGNOS receptor on an existent open-source program, the SoftGNSS, shows that the results obtained with the GPS with the EGNOS receptor are always more precise, in other words, closer to the real location than the ones observed with a GPS only system. Besides this advantage, by using this approach it was also possible to get protection and alarmistic levels that cannot otherwise be obtained.

Keywords: Global Navigation Satellite Systems (GNSS), Software-defined radio (SDR), EGNOS (European Geostationary Navigation Overlay Service), GPS (Global Positioning System), HPL (Horizontal Protection Level), VPL (Vertical Protection Level), SoftGNSS

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Chapter 1

Introduction

1.1 Motivation

The first satellite navigation system, named Transit, was deployed in the 1960s by the US military. Unlike the modern systems, to calculate the receiver's position, it used the Doppler Effect: the satellites traveled on well-known paths and broadcast their signals on a well-known frequency.

The modern systems use different methods, calculating the receiver position by precisely timing the signals sent by satellites high above the Earth. For example, with three or more satellites, and after knowing their distance to the receiver, it is possible to find their position using the trilateration method.

Today there are two satellite navigation systems available worldwide: GPS (maintained by the USA) and GLONASS (maintained by Russia), the first being the most used. Other three systems are in development: COMPASS (China), Galileo (European Commission) and IRNSS (India).

A joint-venture between ESA (European Space Agency), the European Commission and EUROCONTROL, started the development of EGNOS (European Geostationary Navigation Overlay Service) with the objective of improving the performance and reliability of the GPS and hereafter the Galileo. The EGNOS ownership was then transfered to the European Comission with the official start of operations being set to October 1^{st} 2009.

One of the benefits of EGNOS is that by using an EGNOS-compatible GPS receiver we can get a location more accurate - to about one meter - than the one that would be calculated solely based on a GPS receiver - to about seven meters. Also, EGNOS broadcasts an integrity signal which gives GPS users the information they need to validate the signals received from the GNSS satellites. Last but not least, the EGNOS synchronisation with Universal Time Coordinated (UTC) allows users to have a precise and reliable time reference.

Summing up, EGNOS augments the GPS satellite navigation system and makes it suitable for safety critical applications such as flying aircraft or navigating ships through narrow channels.

Furthermore, the hardware of EGNOS and GPS receiver is the same, which makes it possible to use the GPS project for EGNOS and add a software-defined radio system to create a more flexible and less expensive location solution when compared with one that uses a hardware-based receiver.

A software-defined radio (SDR) is a radio communication system where components that have been typically implemented in hardware are instead implemented by software (in this case) on a personal computer.

One of the great advantages of using an SDR is that having an open-source program makes it easier to implement modifications without an associated cost. Besides, using an SDR system has the advantage of making further developments whenever necessary.

1.2 Goals and Tasks

The main goal of this work is to implement an EGNOS receiver on a SDR system. In order to achieve this objective, the open source program FreeGNSS will be used since it already has the GPS receiver implemented. In the end, both receivers, GPS and GPS with EGNOS corrections, should work on the same program, depending on user's choice.

The main requirements to achieve this goal are:

- Obtain the rectified location with better precision.
- Calculate HPL (Horizontal Protection Level).
- Calculate VPL (Vertical Protection Level).

The HPL and VPL are statistical bounds that enable to measure the risk of the current position and will be further explained in section 3.4.6.

To achieve these goals, the following tasks are proposed:

- Understand GPS and EGNOS way of work and differences between them. (Chapter 2)
- Analyze possible front-ends and choose the most suitable one. (Section 3.2)
- Match the signal obtained on the front-end with what the software is expecting. (Section 3.3)
- EGNOS signal acquisition. (Section 3.4.1)
- Decrypt EGNOS signal. (Section 3.4.2)
- Obtain EGNOS navigation message. (Section 3.4.3)
- Calculate corrected position. (Section 3.4.5)
- Calculate HPL and VPL. (Section 3.4.6)
- Test and analyze results. (Chapter 4)

1.3 Outline

In chapter 2, the GNSS fundamentals are explained focusing especially on GPS and EGNOS systems. Their behavior as well as the way their navigation message is presented are also covered. Galileo fundamentals will be explained in this chapter to compare with both GPS' and EGNOS'.

Chapter 3 refers to the work developed, beginning with the base program used and the hardware chosen for the work. All the steps of the implementation from acquiring the signal to calculating the receiver's position will be explained in detail. Finally, chapter 4 will enclose the results obtained during the experiments followed by the conclusions and future work suggestions in chapter 5.

Chapter 2

GNSS Fundamentals

2.1 Introduction

Global Navigation Satellite Systems (GNSS) is the standard generic term for satellite navigation systems or sat nav. The GNSS allows electronic receivers to determine their location (longitude, latitude and height) with a precision of a few meters and determine the precise time using time signals transmitted along a line-of-sight by radio on satellites. The most used GNSS is Global Navigation System (GPS) but there are other systems available and in development.

In order to implement any part of a GNSS receiver, it is necessary to understand and know the characteristics of the signals emitted by the satellites.

In this chapter an overview of the GPS, Galileo and EGNOS position systems and the most relevant properties of the various signals and data are presented. Due to the scope of this thesis and the limitations in space only a brief explanation of characteristics of the signals handled by such systems will be presented.

2.2 Satellite Navigation

Satellite navigation systems are comprised of three functional segments: the space segment, corresponding to the operating satellites constellation; the control segment, corresponding to the ground stations involved in the monitoring of the system; and the user segment, represented by the receivers for civilian and military use.

The basis of all GNSS systems is that a user determines its position by performing measurements with respect to at least four GNSS satellites at the same time. With four measurements it is possible to resolve four unknowns: his position (X, Y, and Z or Latitude, Longitude, and Height) and the clock error of his GNSS receiver.

The measurements that are made by GNSS receivers are not distance measurements but the amount of time it took the signal to travel from the satellite to the receiver, i.e., the travel time. However, to measure this travel time, the receiver has to know the exact time the signal left the satellite as well as the time the signal arrived at the receiver. In order for the receiver to know the exact time of transmission of the signal, every signal gets a time-tag when sent. Then, the measured travel time is multiplied by the signal travel speed to get the actual distance between the satellite and the receiver.

Knowing the distance between the satellites and the user is not enough to calculate the receiver's location. In order to do so the satellites' current position is also necessary. All this information, which encompasses satellite position, clock biases and more, is contained in what is referred to as the satellite broadcast ephemerides.

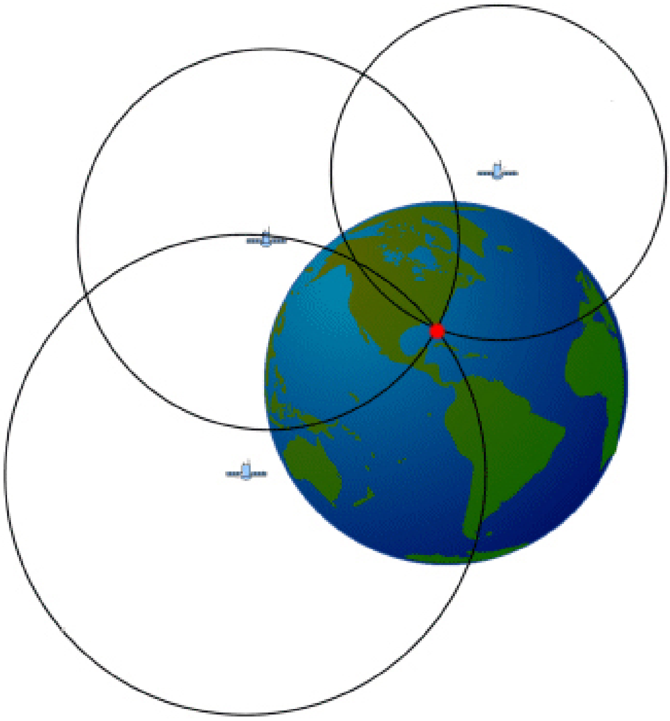

Figure 2.1: Positioning using trilateration method

To conclude and calculate the receiver's position the trilateration (Figure 2.1) method must be applied.

2.3 GPS

The Global Positioning System (GPS) is a continuously available space-based satellite navigation system providing highly accurate position, velocity and time (PVT). It is maintained by the United States government and is freely accessible to anyone with a GPS receiver, who has a line of sight to three satellites.

2.3.1 Structure

The GPS consists of three segments: the Space Segment (SS) composed by satellites; the Control Segment (CS) composed by a series of earth stations – a master control station, an alternative master control station, four dedicated ground antennas and six dedicated monitor stations and the User Segment (US) composed by the military, civil, commercial and scientific user receivers.

Figure 2.2: Orbit of three satellites in 12 hours

The satellites, which are part of the SS, orbit the earth with a speed of 3.9 km per second and have a circulation time of 12 h sidereal time, corresponding to 11 h 58 min earth time (Figure 2.2). This means that the same satellite reaches a certain position about 4 minutes earlier each day. The height of the orbits is about 20000 km. The satellites are arranged on 6 planes, each of them containing at least 4 slots where satellites can be arranged equidistantly.

2.3.2 Signal

The GPS' signals are transmitted in two different radio frequencies, Link 1 usually referred as L1 and Link 2 as L2, in the Ultra High Frequency (UHF) band that comprises the frequencies between 500 MHz and 3 GHz. These frequencies are called Carriers. Both frequencies are derived from a common frequency, $f_0 = 10.23$ MHz:

$$f_{L1} = 154 * f_0 = 1575.42 MHz \tag{2.1}$$

$$f_{L2} = 120 * f_0 = 1227.60 MHz \tag{2.2}$$

Three parts are needed to create a GPS signal: Carrier Wave, Navigation Data and Spreading Sequence (Figure 2.3).

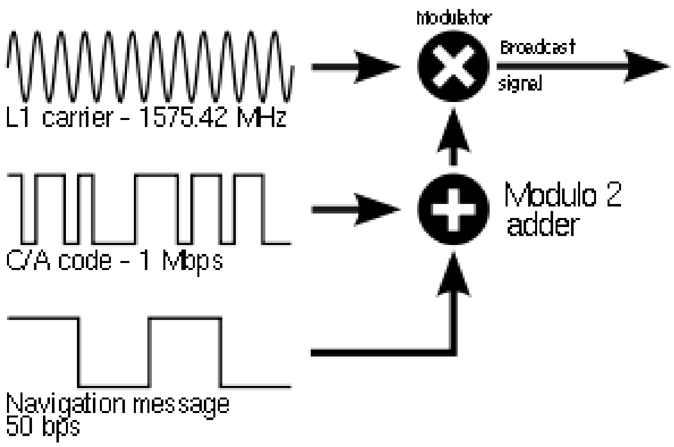

Figure 2.3: L1 signal structure and modulation

Carrier Wave: the carrier wave of frequency f_{L1} and f_{L2}

Navigation Data: this data contains information about the satellite orbit and it is uploaded to all satellites from the GPS Ground Control Segment stations.

Spreading Sequence: each satellite signal has two Spreading Sequences, also called codes. The first one is the coarse acquisition code (C/A), and the other one is the encrypted precision code (P(Y)). The C/A code is a sequence of 1023 chips (a chip corresponds to 1 bit but does not hold information). The code is repeated each millisecond (ms) giving a chipping rate of 1.023MHz. The code P(Y) is a longer code with a chip rate of 10.23MHz. It repeats itself each week. The C/A code is only modulated on the L1 frequency and the P(Y) code is modulated in the L1 and L2 frequencies.

Since all signals from satellites are modulated into the same L1 carrier frequency, an identifier is needed to separate the signals after demodulation. This is accomplished by assigning a unique pseudorandom code to each one. These sequences belong to a unique set of sequences known as Gold Sequences, named after Robert Gold the first person describing them. They are also referred to as pseudo-random noise sequences, or simply PRN sequences, because of their characteristics.

Gold sequences are unique, but belong to a family of pseudorandom sequences. Although they are deterministic sequences, they appear random hence the name. Each C/A code is generated using a tapped linear feedback shift register (LFSR). It generates a maximal-length sequence of $N = 2^n - 1$ elements, where n is the number of registers.

A Gold code is the sum of two maximum-length sequences. The GPS C/A code uses n = 10, which leads to a length of 1023 chips. With a chip rate of 1.023 MHz the C/A code duration is 1 ms.

Thirty seven codes can be generated although two of them (34 and 37) are identical. The first thirty-two are used for satellites and the remaining ones are reserved for other uses, including ground transmitters.

Gold codes were chosen as spreading codes thanks to two particular properties:

Nearly Orthogonal codes - All C/A codes are nearly uncorrelated with each other.

Nearly no cross-correlation except for zero lag - All C/A codes present low correlation values with themselves, except for zero lag. This is the fundamental property used to find out if two codes are perfectly aligned.

2.3.3 Accuracy

Accuracy which is the proximity of measurement results to the true value is a key point of a GPS system. The US Department of Defense provides accuracy specifications for the GPS system and those are the following:

- Accuracy less than 17 meters (95%), available for 99% of the time or more for horizontal service.
- Accuracy less than 37 meters (95%), available for 99% of the time or more for vertical service.

- Accuracy less than 40 ns (95%) for temporal service.

The actual accuracy users are able to attain depends also on factors outside the GPS architecture, including atmospheric effects, sky blockage, and receiver quality. Neverthless, real-world data from the FAA shows that their high-quality GPS SPS receivers provide better than 3 meters horizontal accuracy (Figure 2.4).

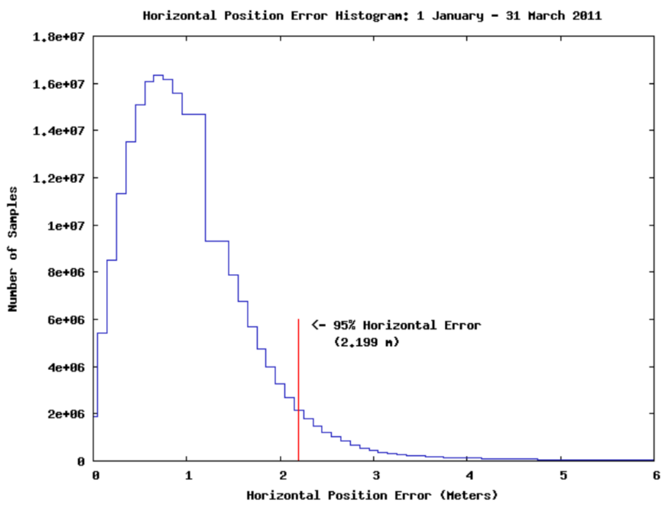

Figure 2.4: Horizontal Accuracy from FAA data collected in early 2011

2.3.4 Navigation Message

The navigation data transmitted by the GNSS system provides the user with the information necessary to compute the precise locations of each visible satellite and time of transmission for each navigation signal. Every satellite receives from the ground antennas the navigation data which is sent back to the users through the navigation message. The Navigation Message provides all the necessary information to allow the user to perform the positioning service.

The navigation message is transmitted in the L1 frequency with a bit rate of 50bps. It is a 1500-bit-long frame separated in 5 subframes of 300 bits. Each subframe contains 10 words of 30bits. Subframes 1, 2, 3 are repeated in each frame and 4 and 5 have 25 versions (with the same structure, but different data) which are referred to as page 1 to 25 (Figure 2.5). With the bit rate of rate of 50bps, the transmission of a subframe lasts 6s, one frame lasts 30s, and one entire navigation message lasts 12.5 minutes.

All subframes begin with two special words, the telemetry (TLM) and the handover word (HOW). The telemetry is the first word of each subframe and contains an 8 bit preamble (used for frame synchronization) followed by 16 reserved bits and parity. The handover word contains a 17 bit truncated version of the time of week (TOW), two flags supplying information to the user of anti-spoofing and a subframe ID to indicate which of the 5 subframes is the current.

Besides the TLM and the HOW, each subframe contains eight words of data.

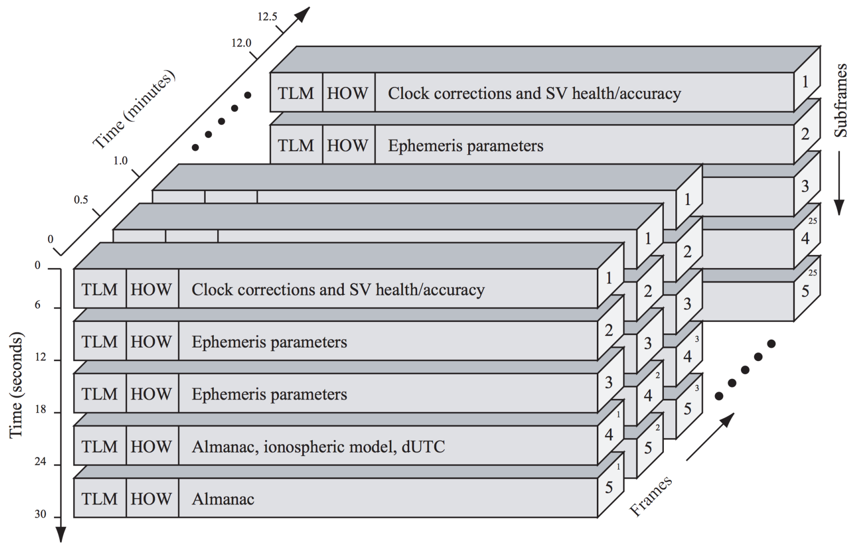

Figure 2.5: GPS Navigation Data Structure

The first subframe contains all the clock information; needed to compute at what time the navigation message is transmitted from the satellite. It also contains health data indicating whether or not the data should be trusted.

The second and third frames contain the satellite ephemeris data, which is the information about the satellite orbit and is necessary to compute its position.

The fourth and fifth subframes contain satellite almanac data. Each satellite transmits almanac data of all satellites but only transmit ephemeris data for itself. The remainder is for various data like UTC parameters, health indicators and ionospheric parameters. This data can be received from any GPS satellite and is considered valid for up to 180 days.

2.4 Galileo

Galileo is the European global navigation satellite system providing a highly accurate, guaranteed and global position service under civil control (as opposed to GPS which is under military control). The Galileo system offers several services, some free of charge and others for commercial use. L1 OS signal is the open service one.

2.4.1 Structure

The fully deployment Galileo system consists of:

- A constellation of 30 satellites in Medium-Earth Orbit (MEO), equivalent to an altitude of 23,222 km with each satellite containing a navigation payload and a search and rescue transponder;
- A global network of Galileo Sensor Stations (GSS) providing coverage for clock synchronization and orbit measurements;

- Two Control Centers and two Launch Early Operations (LEOP) Centers;
- A network of Mission Uplink stations;
- Several Telemetry, Tracking and Control (TT&C) stations.

Additionally, the Galileo's infrastructure is organized in three major segments: the Space Segment, the Ground Segment and the User Segment.

The main functions of the Space Segment are to generate and transmit code and carrier phase signals with a specific Galileo signal structure, and to store and retransmit the navigation message sent by the Control Segment. These transmissions are controlled by atomic clocks on board of the satellites.

The Ground Segment is the responsible for the proper operation of the GNSS system by controlling and maintaining the status and configuration of the satellite constellation, predicting ephemeris and satellite clock evolution, keeping the corresponding GNSS time scale (through atomic clocks) and updating the navigation messages for all the satellites.

Finally, the User Segment is composed by Galileo receivers. Its main function is to receive Galileo signals, determine pseudoranges (and other observables), and solve the navigation equations in order to obtain their coordinates and provide a very accurate time and position.

2.4.2 Signal

Likewise GPS, all GALILEO satellites use the same frequency bands and make use of code division multiple access (CDMA). The signal is transmitted using Right-Hand Circular Polarization (RHCP), the same as GPS.

The signal is transmitted on the frequency $f_{L1} = 1575.42$ MHz and it is composed of three channels, called A, B and C. L1-A is identical to L1 public regulated service (PRS), which is a restricted access signal, since it's ranging codes and navigation data are encrypted. The data signal is the L1-B (B channel of L1) and the data-free signal is L1C (C channel of L1). A data-free signal can be also called a pilot signal. The L1C signal is used only for ranging measurements and is not modulated by navigation data.

The L1 OS signal has a 4092 code length with a 1.023 MHz chip rate giving a repetition of 4ms. On the pilot channel a secondary code with length of 25 chips extends the repetition interval to 100ms.

In order to overcome the difficulty of separating wanted from unwanted signals, very long codes are used. However, to avoid delaying acquisition process, the codes have what is called escape-routes, also known as tiered code. This means that these codes are built in layers so that when there is a strong signal is possible to acquire on a simple layer. The full-length code is used only when necessary.

2.4.3 Services and Accuracy

The Galileo system will have five main services:

- Open access navigation - This service provides simple timing, and positioning accuracy down to 1 meter and will be available free of charge for everybody's usage with an appropriate mass-market equipment.

- Commercial navigation (encrypted) - Provides high precision to the centimeter.
- Safety of life navigation – Open service for applications where guaranteed precision is essential comprising integrity messages for error warning.
- Public regulated navigation (encrypted) - Aimed for government agencies, this service is continuous available even if other services are disabled in time of crisis.
- Search and rescue - Picks up distress beacon locations and is also designed to send feedback, for example, confirming that help is on its way.

The L1 OS signal, used in open access navigation, is expected to guarantee a horizontal accuracy better than 15 m, 35 m for vertical accuracy, 50 cm/s for velocity and a timing accuracy better than 100 ns.

If a dual frequency receiver is used, the results are improved by a factor of 4, making horizontal accuracy up to 4 m and vertical up to 8 m.

The Galileo's system is still not being used which means that only with public usage better results will be achieved. Right now, new satellites are being deployed and the start of services offering for the public is planned for 2016. But only by 2020 the full constellation (30 satellites - 24 operational and 6 active spares) is expected to be concluded.

2.4.4 Navigation Message

Similar to the GPS's, Galileo's message is composed by a frame, containing subframes that are themselves composed by pages. The page is a basic structure for the navigation message and contains: synchronization word (SW); data field; cyclic redundancy check (CRC) bits for error detection and tail bits for the forward error correction (FEC) encoder. In Galileo's system CRC and data encoding are used to provide a better signal and better data integrity. The synchronization word, for L1 OS, is a fixed 10-bit sequence. (Figure 2.6)

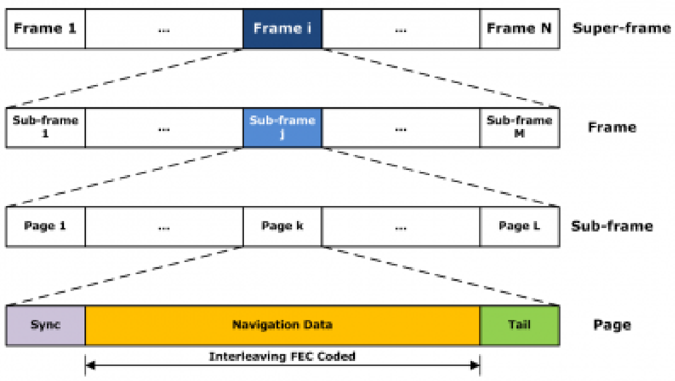

Figure 2.6: GALILEO Navigation Data Structure

Additionaly, Galileo uses the Viterbi convolutional coding scheme characterized by the following values: coding rate = $\frac{1}{2}$, constraint length 7, generator polynomials $G1 = 171$ (octal), $G2 = 133$ (octal) and encoding sequence G1 and then G2.

The navigation message contains all parameters necessary to compute the position of a Galileo satellite, clock correction parameters, parameters for conversion of Galileo System Time (GST) to UTC and GPS Time (GPST), and service parameters including an almanac.

Parameter	No. of Bits	Scale Factor	Unit
μ_0	32	2^{-31}	semicircle
Δn	16	2^{-43}	semicircle/s
e	32	2^{-33}	dimensionless
$\sqrt{a}$	32	2^{-19}	$m^1/2$
Ω_0	32	2^{-31}	semicircle
i_0	32	2^{-31}	semicircle
ω	32	2^{-31}	semicircle
$\dot{\Omega}$	24	2^{-43}	semicircle/s
$\dot{i}$	14	2^{-43}	semicircle/s
C_{uc}	16	2^{-29}	radian
C_{us}	16	2^{-29}	radian
C_{rs}	16	2^{-6}	m
C_{rc}	16	2^{-6}	m
C_{ic}	16	2^{-29}	radian
C_{is}	16	2^{-29}	radian
t_{oe}	14	60	s
$IODnav$	9	-	-

Table 2.1: Galileo ephemeris parameters

In order to guarantee a better accuracy, Galileo ephemeris contains 17 parameters as defined in Table 2.1, valid for four hours. Every three hours a new ephemeris is uploaded, hence an overlap of one hour occurs.

2.5 EGNOS

In operation since the summer of 2005, EGNOS (European Geostationary Navigation Overlay Service) was designed to complement the American GPS system. Alone, it cannot provide any positioning information, only augmenting the GPS signal.

The ease of use and round-the-clock availability at any point on the globe of GPS, combined with its unrivalled intrinsic performance, have led many users to want to use GPS for specific applications for which it was not initially designed.

Among such applications are those for which a high degree of integrity is required, as aircraft landing, command and control systems for trains, or those for which accuracy to within a meter or below is necessary, as geodesy, ship docking, among others.

To answer such user demand, there was the need to implement systems to complement the GPS which could compensate for certain inadequacies that the system might have or even improve its performance while at the same time continuing to benefit from the technological and operational advancement already offered by the GPS itself. EGNOS was the joint-venture between the European Commission, the European Space Agency (ESA) and the Eurocontrol created to answer these demands.

Called, the European Geostationary Overlay Service (EGNOS) complements the American GPS system, which is made up of a number of navigation payloads aboard satellites in geostationary orbit, a ground-based network comprising a series of positioning stations and several control centers, all of which are interconnected.

EGNOS, while dependent on the GPS, is able to offer services today that are similar to those that in the future will be offered by Galileo. The three main services include improving the GPS' positioning accuracy, providing the user with information on the GPS reliability by sending "integrity messages", giving confidence thresholds and alarms in the event of anomalies and emitting a signal synchronized with the Universal Time Coordinated (UTC). Although it is possible, pseudorange measurements from geostationary satellites are not activated.

2.5.1 Structure

The EGNOS system consists of three geostationary satellites and a network of ground stations.

The three geostationary satellites are at an altitude of 36,000 km - one positioned east of the Atlantic and the other two above Africa – in the equatorial plane. Unlike the GPS' and the GLONASS' satellites, the EGNO's don't generate signals, they have a transponder that does nothing more than relay the signal processed on the ground and send it into space.

The ground stations (more than forty) are linked together to create an EGNOS network, which consists of:

- 34 RIMS (Ranging and Integrity Monitoring Stations): receive signals from the US GPS satellites;
- 4 MCC (Mission Control Centers): data processing and differential corrections counting;
- 6 NLES (Navigation Land Earth Stations): accuracy and reliability data is send to three geostationary satellite transponders to allow end-users' devices to receive them.

In order to function correctly, EGNOS service provision requires the following steps (Figure 2.7):

First Step: Collection of measurements and data from the GPS satellites.

Second Step: Calculation of differential corrections, estimation of residual errors and generation of EGNOS messages.

Third Step: Transmission of EGNOS messages to users via the geostationary satellites.

A data integrity verification process is conducted in parallel with these steps.

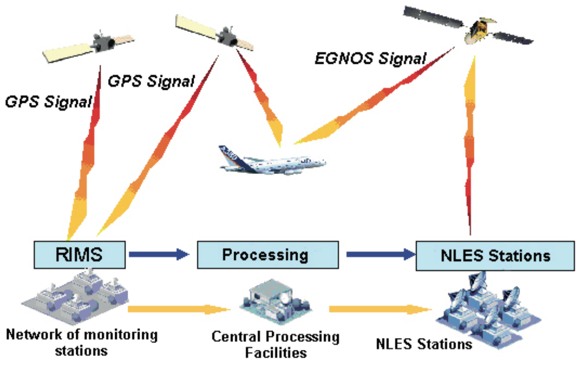

Figure 2.7: EGNOS Infrastructure

2.5.2 Signal

GPS and EGNOS systems use the same frequency and modulation. A single carrier frequency of 1575.42 MHz (GPS L1) and message symbols at a rate of 500 symbols per second (sps) will be added modulo-2 to a 1023-bit PN code, which will then be bi-phased shift-keyed (BPSK) modulated onto the carrier at a rate of 1.023 Mchips per second.

The geostationary EGNOS satellites use three different PRN codes for acquisition (codes 120, 124 and 126) and the navigation message is encoded like GALILEO's - Viterbi convolutional coding scheme characterized by the following values: coding rate = $\frac{1}{2}$, constraint length 7, generator polynomials $G1 = 171$ (octal), $G2 = 133$ (octal) and encoding sequence G1 and then G2. (Figure 2.8)

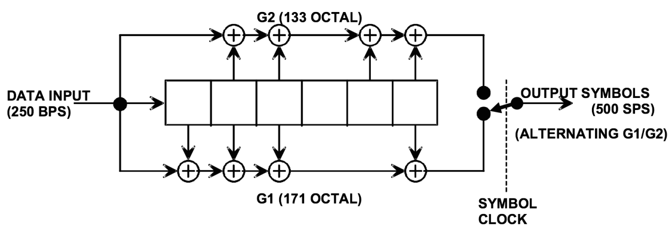

Figure 2.8: Viterbi convolutional coding scheme

2.5.3 Accuracy and Integrity

One of the main advantages of EGNOS is its improved accuracy when compared to a position solely calculated using a GPS. By broadcasting differential corrections to the GPS' orbits, GPS' clocks and the ionospheric corrections, the EGNOS is able to better the GPS' location information with an horizontal accuracy of 1 to 3 meters and a vertical accuracy 2 to 4 meters.

Additional improvements brought by EGNOS to the various GPS error components can be found on table 2.2.

Another important EGNOS differentiator is the integrity it delivers, which is enabled by the four parameters that characterize it, which are: thealarm limit, protection level, integrity risk and Time To Alarm (TTA). Further information on the integrity performance levels can be found on table 2.3.

Error Type	GPS	EGNOS
Orbit and clock synchronisation	1 m	0,5 m
Tropospheric error	0,25 m	0,25 m
Ionospheric error	2 m	0,3 m
Receiver noise	0,5 m	0,5 m
Multipath	0,2 m	0,2 m
UERE (quadratic sum of errors - 1 σ)	2,31 m	0,83 m
HDOP (function of geometry of visible satellites)	1,1	1,1
Horizontal positioning accuracy error (1 σ) = UERE x HDOP	2,54 m	0,92 m
Horizontal positioning accuracy error (2 σ, 95 %)	5,08 m	1,84 m

Table 2.2: Summary of GPS-EGNOS errors: typical orders of magnitude

Parameter	Performance Level
Integrity risk	$2 * 10^7$ per 150 seconds
Time To Alarm	6 s
Vertical Alarm Limit	50 m
Horizontal Alarm Limit	40 m

Table 2.3: EGNOS integrity performance levels

The EGNOS uses a system time known as ENT (EGNOS Network Time), linked to the UTC (Coordinated Universal Time). All the differential corrections broadcast by EGNOS are referenced according to the ENTand the accuracy obtained when comparing to the UTC is less than 50 nanoseconds.

2.5.4 Navigation Message

The EGNOS system transmits its messages at a rate of 250 bits per second and the size of every message transmitted is 250 bits, which enables one message to be transmitted per second.

Several message types can be transmitted by the system. In table 2.4 are the ones transmitted nowadays.

Four parts compose the messages. The first is 8 bit long and is part of the 24 bit long preamble (01010011 10011010 11000110) that spreads over three successive messages. It is used, like GPS and GALILEO, for message synchronization. The second – 6 bit long – is the message type (0 to 63). The next part, containing 212 bits, corresponds to the useful data contained in the message – which are specific to the message type. The last part has 24 bits for parity, which ensure that the data were not corrupted during transmission (no bit error). (Figure 2.9)

For each message type transmitted, there is thus validity period and a maximum refresh period, which must be taken into account by the system in the transmitted signal. In the table 2.5, these are detailed for each message type.

Type	Contents
0	GEO Information Useless (SBAS test mode)
1	PRN Mask
2-5	Fast corrections
6	Integrity Information
7	Fast corrections degradation factor
9	GEO ranging functions parameters
10	Degradation parameters
12	SBAS Network Time/UTC offset parameters
17	GEO satellites almanacs
18	Ionospheric grid point masks
24	Mixed fast corrections/long term satellite error corrections
25	Long term satellite error corrections
26	Ionospheric delay corrections
27	SBAS service message
63	Null message
Others	Reserved

Table 2.4: List of EGNOS messages

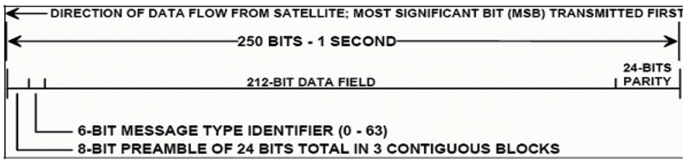

Figure 2.9: EGNOS Messages type structure

Types	Data contained	Refresh period(s)	Validity period	
			En Route, Terminal, NPA	Precision Approach
0	Don't use for safety applications	6	N/A	N/A
1	PRN mask	120 ^{note2}	600	600
2 to 6, 24	UDREI	6	18	12
2 to 5, 24	Fast Corrections	Variable ^{note1}	Variable ^{note1}	Variable ^{note1}
24, 25	Long Term Corrections	120	360	240
9	GEO Navigation Data	120	360	240
7	Fast Correction Degradation	120	360	240
10	Degradation Parameters	120	360	240
18	Ionospheric Grid Mask	300 ^{note2}	1200	1200
26	Ionospheric Corrections	300	600	600
12	UTC Timing Data	300	86400	86400
17	Almanac Data	300	None	None
27	Service Level	300 (if used)	86400	86400
28	Clock. Ephemeris Covariance Matrix	120	360	240

Note 1: The value depends on the degradation factor for the fast corrections.

Note 2: When the masks are modified, message type 1 or 18 must be repeated several times before the new mask can be used. This ensures that all users have received the new mask before it is applied.

Table 2.5: EGNOS messages refresh and validity periods

Chapter 3

An EGNOS SDR Receiver

A Software Defined Radio (SDR) system can be defined as being a radio communication system where components that typically would be implemented on a specific hardware like ASIC (Application Specific Integrated Circuits) are instead implemented directly on a software, either running on a personal computer or other embedded computing device. The idea of an SDR is to position the analog-to-digital converter (ADC) as close to the antenna as possible, so that the entire data processing would be done on software.

The advantage of signal processing through software is the flexibility and the adaptability to new operating scenarios. The challenge associated, on the other hand is the required processing power, particularly for wide-band spread spectrum systems such as the GPS. Typically, a general purpose microchip cannot achieve the same throughput than a chip that is specifically design only for that particular task.

Figure 3.1 exemplifies the trade off between SDR flexibility and ASIC Processing Throughput is exemplified.

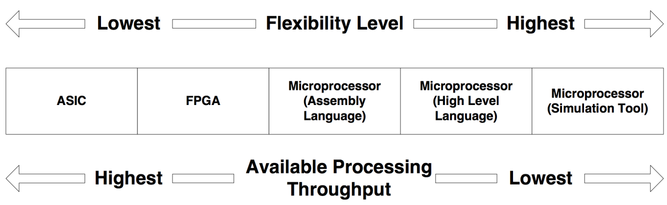

Figure 3.1: Trade off between SDR flexibility and ASIC Processing Throughput

Because of the similarity between the GPS' and the EGNOS' signals, it is possible to implement EGNOS capabilities to a SDR GPS Receiver System. In this project, an open-source program (Explained in section 3.1) will be used to implement EGNOS functionalities, using a front-end (Explained in section 3.2) that saves a signal compatible with the software.

3.1 SoftGNSS 3.0

The open-source program used on this thesis to implement the EGNOS functionalities was the Soft-GNSS version 3.0. This was a program developed by Danish GPS Center/Aalborg University as a GNSS SDR Receiver. The code was than improved by GNSS Laboratory/University of Colorado.

The reasons behind the choice of this software are linked with the following factors:

Open-Source Being an open-source software, it is possible to add functionalities and adapt what is already done to new features.

GPS Receiver It is a GPS receiver with all its functionalities.

Input Parameters It is prepared to receive different inputs (changing the settings) making it more flexible.

Popular It is used for a lot of projects, making the learning curve lower and making it easier to find help.

Figure 3.2 represents an actual data flow and the MATLAB functions used by the software receiver.

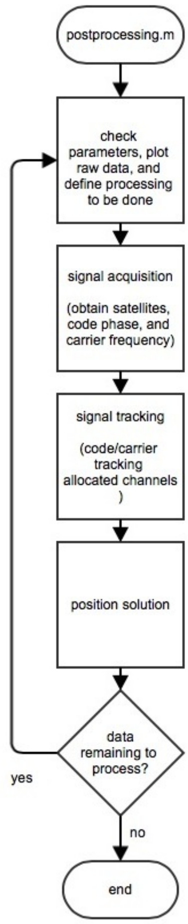

Figure 3.2: GNSS software receiver flow diagram

3.2 Hardware

The first option for the front-end was the GN3S Sampler v2 (Figure 3.3). This Sampler has been co-developed by the University of Colorado Aerospace Department and SiGe Semiconductor. This front-end is 100% compatible with the software, making it a perfect choice but the estimated time of arrival (4 months after ordering) wasn't viable.

Figure 3.3: GN3S Sampler v2

The second option was the ***ACORDE's ACGNS-L1 E1-FE-V1*** (Figure 3.4). ACORDE's ACGNS L1-E1 FE USB consists of a GNSS front-end (FE) with an USB interface optimized for real-time Software Defined Radio applications and signal recording.

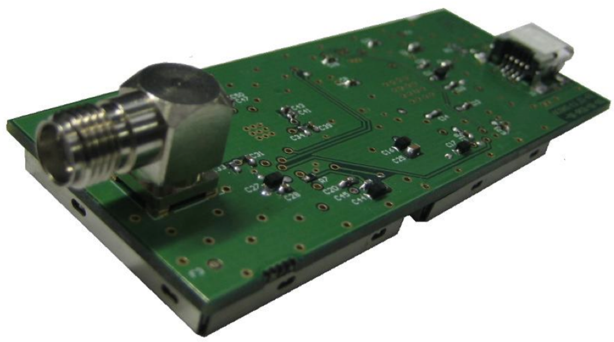

Figure 3.4: ACORDE's ACGNS-L1 E1-FE-V1

The universal GPS receiver MAX2769 is the core of the ACGNS L1-E1 FE USB front-end. A dedicated MCU acts as a bridge between the MAX2769 and a computer by means of a USB interface, which allows the configuration of the MAX2769 and access the data samples using a custom protocol over USB.

At USB message level, the ACGNS L1-E1 FE USB front-end supports one control endpoint and one data endpoint. The control endpoint allows sending configuration messages to the MAX2769, whereas the data endpoint is used to perform the data acquisition.

In order to manage the ACGNS L1-E1 FE USB front-end, ACORDE offers an application that implements the custom USB protocol already mentioned which includes the following software:

- Library for low-level GNSS front-end management (Linux):

  "libgnssfe.a" (static library)

  "libgnssfe.h" (header for the library)

- Server application (Linux):

  "appgnssfe" (binary)

  "config.dat" (ASCII default configuration file)

- Example client applications

  "client_appgnssfe" (Linux example binary)

  "client_appgnssfe.cpp" (Linux example source code)

  "client_appgnssfe.m" (Matlab example)

However, the signal saved using this front-end and its software is not compatible with SoftGNSS which requires a couple of changes either in SoftGNSS or on the saved signal. In section 3.3 these changes will be explained.

The antenna used was the **u-blox ANN-MS-0-005** (Figure 3.5) that has the following features:

- Built-in low noise amplifier with 27 dB gain and 1.8 dB noise figure.
- Five meters coaxial cable
- Magnetic base
- Industrial temperature range: –40 to +85°C

Figure 3.5: u-blox ANN-MS-0-005

3.3 Signal Converter

The scope of this project was to implement EGNOS functionalities and not add support to more front-ends. Changing SoftGNSS implies changes in settings and an additional task on the main process in order to detect the type of signal and convert it. Making these changes to the program to incorporate two front-ends (the one made to SoftGNSS and the one used on this project) is unnecessary and out of scope.

For this reason, the choice was to create a script to be run before the main program. This script, made for the used front-end and also for others with similar properties, converts the saved signal to a new signal recognized by SoftGNSS.

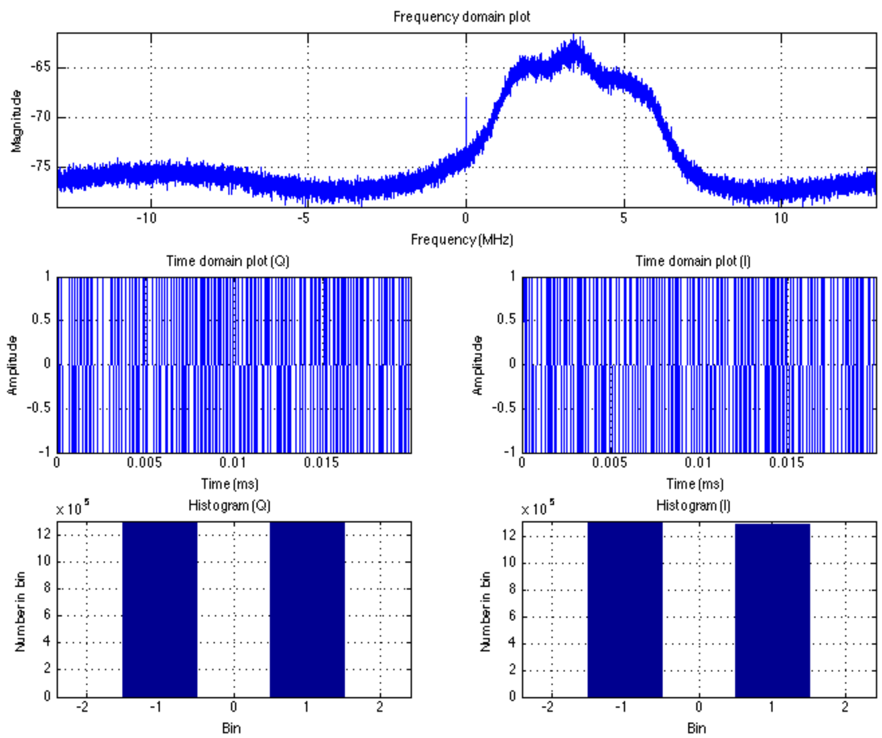

Figure 3.6: Probe Data of a converted signal

From the original signal, each bit is extracted from each byte resulting in a complex signal (I and Q) (Figure 3.6). The extracted bits are then saved (in complex form) in a new converted file ready to be read by the main program.

3.4 EGNOS Implementation

In order to implement the EGNOS functionalities in this GPS SDR Receiver, it is necessary to update the Acquisition, Tracking and Navigation Message decodification and implement the new calculations for corrected position and protection levels.

The main objective is to implement these new functionalities independently, so that it might be possible to use only the GPS Receiver if wanted. A new parameter will be added to the settings in order to choose between GPS and GPS/EGNOS Receiver.

3.4.1 Signal Aquisition

The purpose of the acquisition phase is to identify all satellites visible to the user. Two properties are determined when the acquisition of a visible satellite is done:

Frequency The frequency of the signal suffers the Doppler effect, differing from its nominal value. This is caused by the relative motion of the satellite and user velocity, approaching values as high as 10kHz (for a stationary receiver on Earth, the Doppler frequency shift will never exceed 5kHz).

Code Phase The code phase denotes the point in the current data block where the C/A code begins.

The received signal s is a combination of signals from all n visible satellites, as explained in equation 3.1.

$$s(t) = s^1(t) + s^2(t) + ... + s^n(t) \tag{3.1}$$

For satellite k, the incoming signal s is multiplied by the local generated C/A code of that satellite. On this process, the signals from other satellites are nearly removed with the cross correlation between the C/A code generated and the ones from the remaining satellites. In order for this to occur, the desired C/A code from the satellite and the generated one must be properly aligned in time (correct code phase).

After this the signal must be mixed with a locally generated carrier wave to remove the carrier wave of the received signal. The two frequencies must be close but, as mentioned earlier, the frequency from the satellite signal can change up to $\pm$10kHz from the nominal frequency, so it is sufficient to search the frequency in steps of 500 Hz, resulting in 41 different tests for fast-moving receivers and 21 for static receivers.

In the end, all the signal components are squared and summed providing a numerical value.

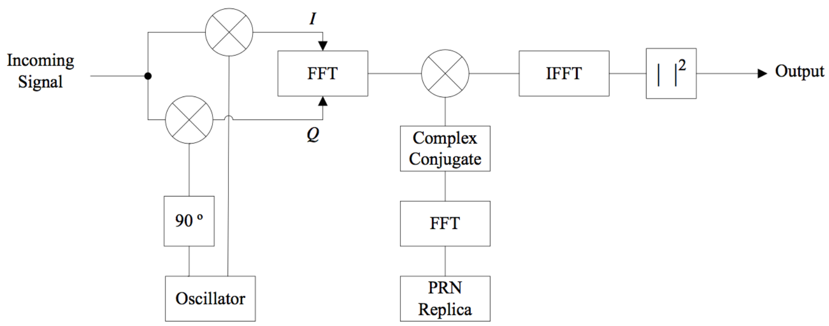

Figure 3.7: Block diagram of the parallel code phase search algorithm

There are three standard methods of acquisition, all based on search procedures, with different complexities and repetitions:

- Serial search
- Parallel frequency space search
- Parallel code phase search

Analyzing the results in Table 3.1 the method chosen was the third one: the Parallel code phase search. Figure 3.7 presents the block diagram of this method.

Algorithm	Repetitions	Complexity
Serial search	41,943	Low
Parallel frequency space search	1023	Medium
Parallel code phase search	21	High

Table 3.1: Repetitions and complexities of the three acquisition algorithms

The only difference between signals generated by the GPS and the EGNOS satellites are the PRN used. So, to also acquire EGNOS satellites, the only necessary change on the code is to test three new PRNs - in this case 120, 124 and 126. All the remaining steps are the same.

3.4.2 Tracking

The purpose of the acquisition phase is to provide rough estimates of the frequency and code phase parameters. The purpose of tracking is to refine these values, keep track, and demodulate the navigation data. A basic demodulation scheme is shown in Figure 3.8.

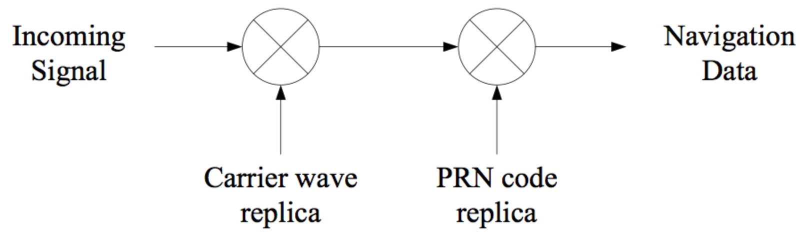

Figure 3.8: Basic demodulation scheme

In order to start the tracking phase, the incoming signal is multiplied by a replica of the carrier with the same Doppler frequency. This is done to wipe off the carrier wave from the signal and is usually called the carrier loop, often using Phase Lock Loops (PLLs). Then, the result is multipled by a code replica with the same delay as the incoming signal. This loop is referred to as the code loop, often referenced as Delay Lock Loop (DLL).

Due to these two operations, the tracking module has to generate two replicas, one for the carrier and one for the code, to perfectly track and demodulate the signal from one satellite. The resulting output is the navigation data.

The carrier loop, the PLL, consists of two parts. The first part is the loop discriminator that is used to find the phase error on the locally generated carrier signal. The output of this discriminator is the phase error (or a function of the phase error) and is then filtered by the second block, the loop filter. The filtered output is used as a feedback to the numerically controlled oscillator (NCO), which then adjusts the frequency used to generate the next carrier signal. By using this approach the local carrier wave is able to be an almost precise replica of the input signal carrier signal.

The problem of using an ordinary PLL is that it is sensitive to 180° phase shifts. Due to GPS signal bit transitions, the PLL used in this case has to be insensitive to those phase shifts.

To solve this issue, GPS tracking blocks employ a PLL named Costas loop (Figure 3.9). Since Costas loops rely on tangent to output the phase error, they are insensitive to the 180° phase shifts.

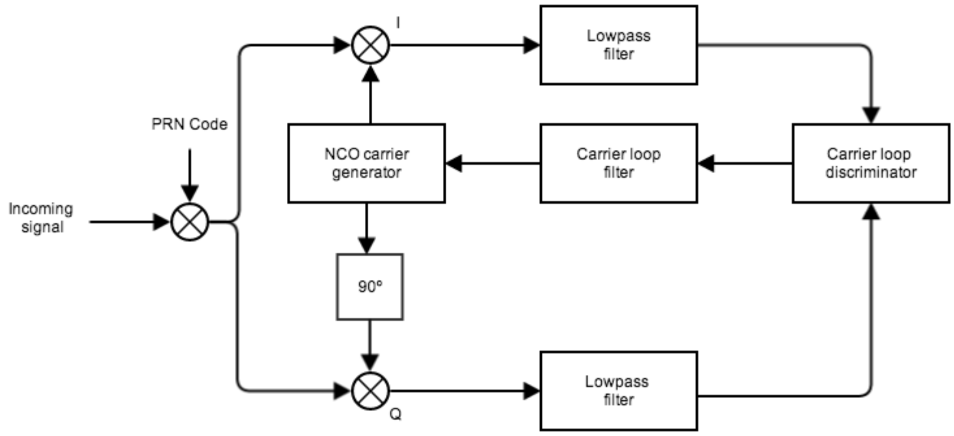

Figure 3.9: Costas loop used to track the carrier wave.

The goal of the code tracking loop is to keep track of a precise value of the code phase for a specific signal. Having a rough estimate of the code phase using acquisition, it is up to this tracking loop to refine and keep track of that value.

The code tracking loop used is DLL also called an early-late tracking loop. The primary idea is to correlate the incoming signal with three local code replicas as shown in Figure 3.10.

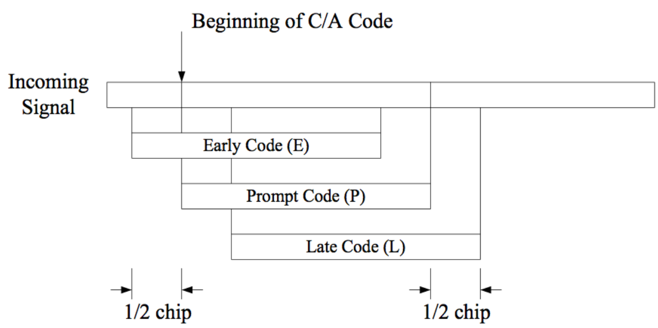

Figure 3.10: Input signal and early, prompt and late code delays.

After carrier removal by the PLL, the signal is correlated against three replicas: an early code, a prompt code and a late code, usually spaced by 1/2 chip of each other. The output of these correlations is a numerical value indicating how much the specific code replica correlates with the code contained within the input signal. Figure 3.11 shows the basic block diagram.

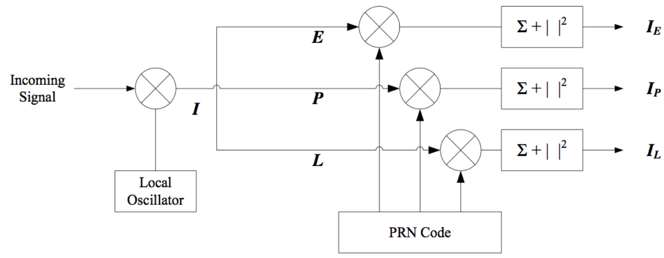

Figure 3.11: Basic block diagram of an early-late tracking loop.

The three correlation outputs are then compared to see which one provides the higher correlation. Three different possible outcomes are represented in Figure 3.12.

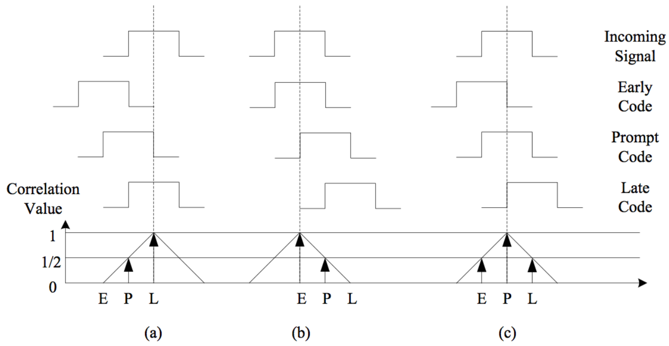

Figure 3.12: Code Tracking: a)Late code is higher; b) Early code is higher; c) prompt code is higher.

If a prompt code has the higher correlation, the signal is nearly aligned and the aim is to try and get the early and late correlation values as equal as possible.

Since GPS and EGNOS signals have the same properties, the above explained process is valid for both. Having GPS code already implemented, there are no changes needed to support EGNOS signals.

3.4.3 Navigation Message Obtention

After tracking the incoming signal, the output is the Navigation Message. But unlike GPS', EGNOS' Navigation Message data is convolutional encoded with a Forward Error Correction (FEC) code. In order to decode the navigation message, it is necessary to use a Viterbi decoder as mentioned in section 2.5.2. The approach to decode the EGNOS messages will be explained in the next section (3.4.4).

The next step, already having the decoded Navigation Message, is to find the preambles to determine the location of the beginning of a message. The preamble is composed by three 8-bit words (01010011 10011010 11000110) that spreads over three successive messages. Because of the Costas loop's ability to track the signal with a 180° phase shift, the preamble can occur in an inverted version (10101100 01100101 00111001). Finding this sequence with a temporal distance of 1 second between each one of the three words is enough to authenticate the preamble.

Each message is saved in a buffer containing both the message data and the time it was received. Only one message is saved in the buffer, being replaced when a new one is received. The exceptions are message types 24, 25 and 26 which keep the last 25, 15 and 25 messages received, respectively.

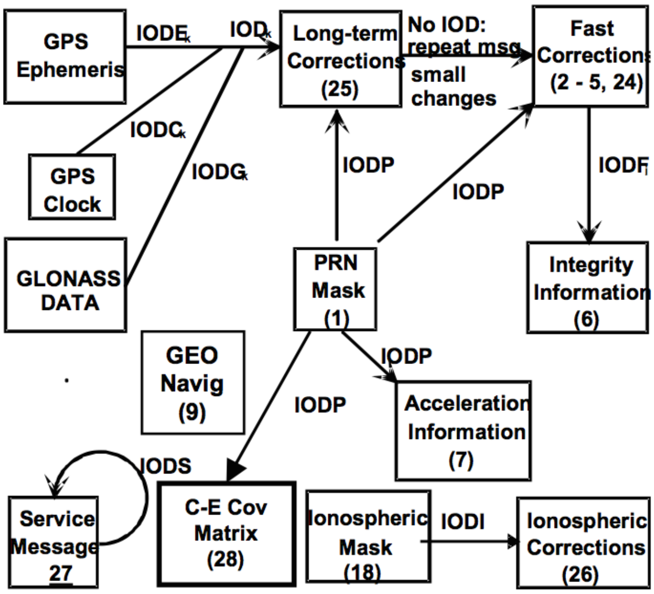

Figure 3.13: Interrelationships of messages.

The messages and relationships between message types are briefly explained in Figure 3.13 and on the list that follows.

Do Not Use for Safety Applications Message Type 0 The first message type, Message Type 0, will be used primarily during system testing. The receipt of a Message Type 0 will result in the cessation of the use of any ranging data and all message types 1-7, 9-10, 18, 24-28 obtained from that SBAS signal (PRN code). Other message types may be retained, such as message type 17, for potential performance enhancements. In addition, that SBAS signal (PRN code) will be deselected for at least one minute.

PRN Mask Assignments Message Type 1 The PRN Mask is given in Message Type 1. It consists of 210 ordered slots, each of which indicates if data is provided for the corresponding satellite as defined in Table 3.2.

PRN Slot	Assignment
1 to 37	GPS/GPS Reserved PRN
38 to 61	GLONASS Slot Number plus 37
62 to 119	Future GNSS
120 to 138	GEO/SBAS PRN
	Future GNSS/GEO/SBAS/Pseudolites

Table 3.2: PRN Mask Assignments.

Note that the satellites for which corrections are provided must be ordered from 1 to a maximum of 51, in order to decode Message Types 2 - 5, 6, 7, 24, 25 and 28. Data in Message Types

2-5, 6, 7 and the fast corrections part of Message Type 24 are provided sequentially. Long term corrections in Message Types 24 and 25 and clock- ephemeris covariance matrix data in Message Type 28 may or may not be provided sequentially, since the PRN Mask number is specified for each correction. The mask will be followed by a 2-bit issue of data PRN (IODP) to indicate the mask's applicability to the corrections and accuracies contained in messages to which the mask applies.

Fast Corrections Message Types 2 - 5 The fast corrections messages format is illustrated in Figure 3.14. Message Type 2 contains the data sets for the first 13 satellites designated in the PRN mask. Message Type 3 contains the data sets for satellites 14 - 26 designated in the PRN mask, etc., through Message Type 5, which contains the data sets for satellites 40 through 51 designated in the PRN mask.

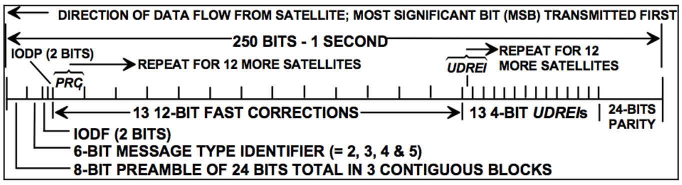

Figure 3.14: Types 2 - 5 Fast Corrections Messages Format.

Integrity Information Message Type 6 The integrity information message is shown in Figure 3.15. Each message includes an IODF$_j$ for each fast corrections Message Type (2 - 5). Since all satellites in the PRN mask are mapped to Message Types 2-5, it is not necessary to explicitly include an IODF for Message Type 24 in Message Type 6. The information transmitted in Message Type 6 should be applied to the applicable satellites in Message Type 24. Message Type 6 allows the fast corrections of Message Type 2-5 and 24 to be updated infrequently, commensurate with the dynamics of the satellite clock errors.

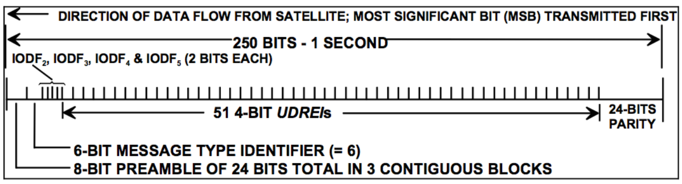

Figure 3.15: Types 6 Integrity Message Format.

Fast Correction Degradation Factor Message Type 7 The σ^2_{UDRE} broadcast in Types 2 - 6 and 24 applies at a time prior to or at the time of applicability of the associated corrections. The Type 7 message specifies the applicable IODP, system latency time (tlat) and the fast correction degradation factor indicator (aii) for computing the degradation of fast and long term corrections. The Type 7 message format is shown in Figure 3.16

Degradation Factors Message Type 10 The degradation factors are several and will be described in Table 3.3.

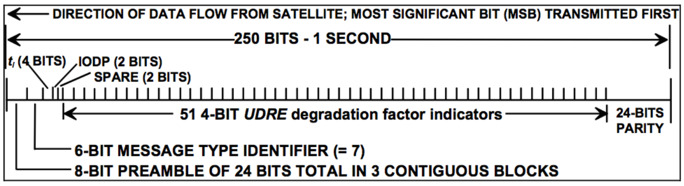

Figure 3.16: Type 7 Fast Correction Degradation Factor Message Format.

Parameter	No. of Bits	Scale Factor (LBS)	Effective Range	Units
B_{rrc}	10	0.002	0 to 2.046	m
C_{ltc_lsb}	10	0.002	0 to 2.046	m
C_{ltc_v1}	10	0.00005	0 to 0.05115	m/s
I_{ltc_v1}	9	1	0 to 511	s
C_{ltc_v0}	10	0.002	0 to 2.046	m
I_{ltc_v0}	9	1	0 to 511	s
C_{geo_lsb}	10	0.0005	0 to 0.5115	m
C_{geo_v}	10	0.00005	0 to 0.05115	m/s
I_{geo}	9	1	0 to 511	s
C_{er}	6	0.5	0 to 31.5	m
C_{iono_step}	10	0.001	0 to 1.023	m
I_{iono}	9	1	0 to 511	s
$C_{ionoramp}$	10	0.000005	0 to 0.005115	m/s
RSS_{UDRE}	1	-	0 to 1	unitless
RSS_{iono}	1	-	0 to 1	unitless
$C_{covariance}$	7	0.1	0 to 12.7	unitless
Spare	81	-	-	-

Table 3.3: Type 10 Degradation Factors.

Long Term Satellite Error Corrections Message Type 25 Message Type 25 will be broadcasted to provide error estimates for slow varying satellite ephemeris and clock errors with respect to WGS-84 ECEF coordinates. These corrections are estimated with respect to the GNSS broadcast clock and ephemeris parameters. The long-term corrections are not applied for SBAS satellites operated by that service provider. Instead, the Type 9 GEO Navigation Message will be updated as required to prevent slow varying GEO satellite errors.

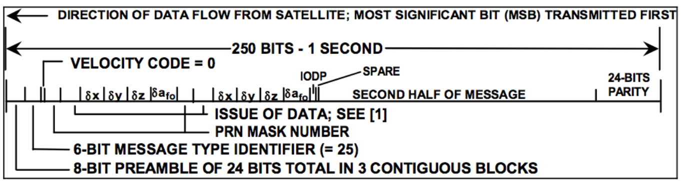

Figure 3.17: Type 25 Long Term Satellite Error Corrections Velocity Code = 0.

Figure 3.17 presents the first half of the Type 25 message representing the corrections for the long term satellite position and clock offset errors of two satellites when only those corrections are needed for the required accuracy. Figure 3.18 presents also the first half of the Type 25 message but, this time, representing corrections for the long term satellite position, velocity, clock offset and drift errors of one satellite when velocity and drift corrections are also needed.

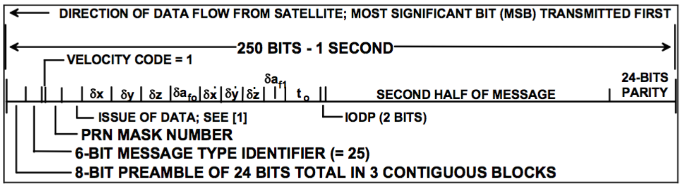

Figure 3.18: Type 25 Long Term Satellite Error Corrections Velocity Code = 1.

Mixed Fast Corrections/Long Term Satellite Error Corrections Messages Type 24 Figure 3.19 presents the Type 24 Mixed Fast Correction/Long Term Satellite Error Corrections Message.

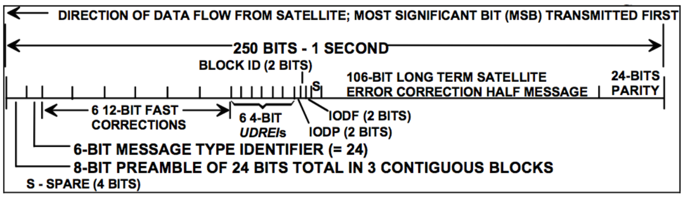

Figure 3.19: Type 24 Mixed Fast Correction/Long Term Satellite Error Corrections Message Format.

Ionospheric Grid Point Masks Message Type 18 The ionospheric delay corrections are broadcasted as vertical delay estimates at specified ionospheric grid points (IGPs), applicable to a signal on L1. In order to facilitate flexibility in the location of these IGPs, a fixed definition of densely spaced IGP locations is used, resulting in a large number of possible IGPs. The predefined IGPs are contained in 11 bands (numbered 0 to 10). Bands 0-8 are vertical bands on a Mercator projection map, and bands 9-10 are horizontal bands on a Mercator projection map.

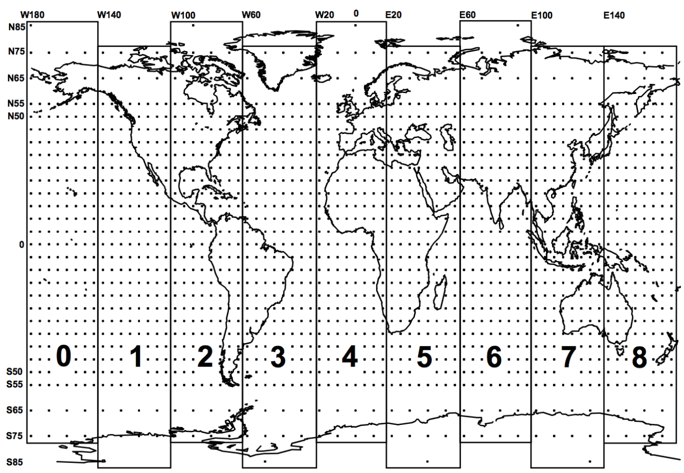

Figure 3.20: Predefined Global IGP Grid (Bands 9 And 10 Are Not Shown).

Since it would be impossible to broadcast IGP delays for all possible locations, a mask is broadcasted to define the IGP locations providing the most efficient model of the ionosphere at the time.

The total IGP grid represents too many IGPs for broadcasting in a single message. Thus, the grid is divided into 11 Bands (numbered 0 to 10), and each message indicates the Band associated with 201 possible IGPs (bands are designated with rectangular areas with bold numbers in Figure 3.20). Each one of the bands 0-8 cover 40° of longitude; bands 9- 10 cover 25° of latitude and 360° of longitude. When bands 9 and/or 10 are sent, the IGP mask values are set to 0 in bands 0-8 for all IGPs north of 55°N and south of 55°S. Message Type 18 provides a mask for any one of the 11 bands indicated by the band number.

The format of Message Type 18 is illustrated in Figure 3.21.

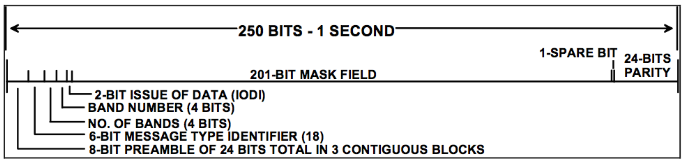

Figure 3.21: Type 18 IGP Mask Message Format.

Ionospheric Delay Corrections Messages Type 26 The Type 26 Ionospheric Delay Corrections Message provides the users with vertical delays (relative to an L1 signal) and their accuracy (σ^2_{GIVE}'s) at geographically defined IGPs identified by band number and IGP number. Each message contains a band number and a block ID that indicates the location of the IGPs in the respective band mask. Messages Type 26 format can be seen on Figure 3.22.

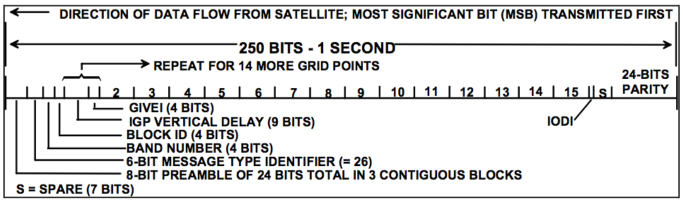

Figure 3.22: Type 26 Ionospheric Delay Corrections Message Format.

GEO Navigation Message Type 9 Type 9 GEO Navigation Message (message format in Figure 3.23) contains the position, velocity and acceleration of the geostationary satellite, in ECEF Coordinates, and its apparent clock time and frequency offsets. Also included is the time of applicability (t_0) and an accuracy exponent (URA) representing the health of the GEO ranging signal. a_{Gf0} and a_{Gf1} will be an estimate of the time offset and drift with respect to SBAS Network Time. Their combined effect will be added to the estimate time when the satellite's transmited the message itself.

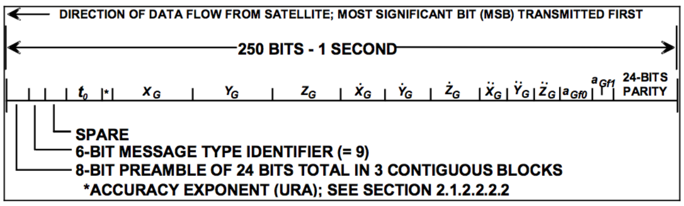

Figure 3.23: Type 9 GEO Navigation Message Format.

GEO Almanacs Message Type 17 Almanacs for GEOs will be broadcast periodically to alert the user of their existence, location, the general service provided and health and status. Almanacs for three satellites will be broadcast in the GEOs Almanacs Message Type 17 illustrated in Figure 3.24. These messages are repeated to include all GEOs. Unused almanacs have a PRN number of 0 and should be ignored.

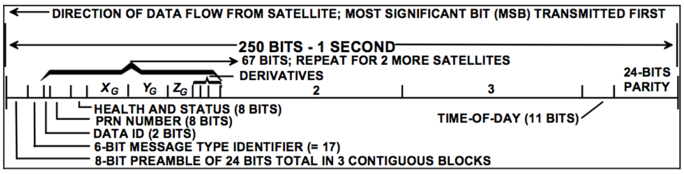

Figure 3.24: Type 17 GEO Almanacs Message Format.

SBAS Service Message Type 27 Type 27 messages may be transmitted to increase the σ_{UDRE} values in selected areas. The format of Message Type 27 is given on Figure 3.25. Type 27 message parameters apply only to the service provider transmitting the message.

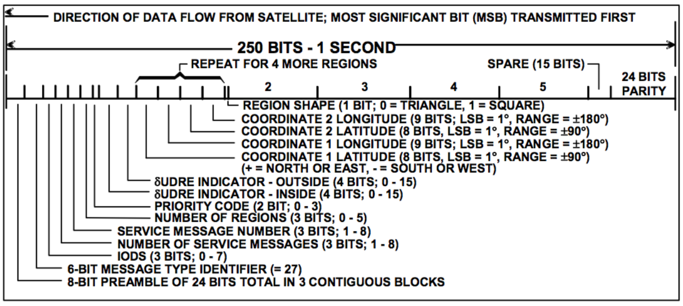

Figure 3.25: Service Message Type 27.

The Number of Service Messages parameter in each Type 27 message indicates the total number of unique Type 27 messages for the current Issue of Data, Service (IODS). Each unique message for that IODS includes a sequential Service Message Number. The IODS is incremented in all messages, each time that any parameter in any Type 27 message is changed.

Null Message Type 63 and Internal Test Message 62 The Null Message Type 63 is used as a filler message if no other message is available for broadcast for the one-second time slot. The Internal Test Message Type 62 is used for internal testing purposes only.

SBAS Network Time/UTC/GLONASS Time Offset Parameters Message Type 12 Message Type 12 consists of the 8-bit preamble, a 6-bit message type identifier (= 12) followed by 104 information bits for the UTC parameters, then followed by 3 bits to indicate the UTC time standard from which the offset is determined. The next 20 bits are the Time of Week (TOW) in seconds of the beginning of the message, followed by a 10 bit GPS Week number (WN). The final 75 bits are spare bits.

Clock-Ephemeris Covariance Matrix Message Type 28 Message Type 28 provides the relative covariance matrix for clock and ephemeris errors. This is an expansion of the information contained in the σ_{UDRE} since it specifies the correction confidence as a function of user location. Message Type 28 provides increased availability inside the service volume and increased integrity outside.

The covariance matrix is a function of satellite location, reference station observational geometry, and reference station measurement confidence. Consequently it is a slowly changing function of time. Each covariance matrix only needs to be updated on the same order as the long-term corrections. Each message is capable of containing relative covariance matrices for two satellites. This maintains the real-time six-second updates of integrity and scales the matrix to keep it within a reasonable dynamic range.

3.4.4 Viterbi Decoder

The Viterbi algorithm is a dynamic programming algorithm for finding the most likely sequence of hidden states – called the Viterbi path – that results in a sequence of observed events as seen on Figure 3.26. The algorithm has found universal application in decoding the convolutional codes used in both CDMA and GSM digital cellular, dial-up modems, satellite, deep-space communications, and 802.11 wireless LANs.

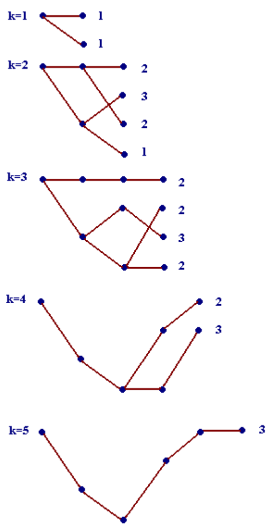

Figure 3.26: Viterbi path - Steps k to find the path

The algorithm keeps a backward pointer (ϕ) for each state ($t > 1$), and stores a probability (δ) with each state. The probability δ is the probability of having reached the state following the path indicated by the back pointers.

When the algorithm reaches the states at time, $t = T$, the δ's for the final states are the probabilities of following the optimal (most probable) route to that state. Thus selecting the largest, and using the implied route, provides the best answer to the problem.

EGNOS navigation message is encoded using a Viterbi convolutional coding scheme, which is characterized by the following values: coding rate = $\frac{1}{2}$, constraint length 7, generator polynomials $G1 = 171$ (octal), $G2 = 133$ (octal) and encoding sequence G1 and then G2. (Figure 3.27) Only by using a Viterbi decoder, can we get any data grom the EGNOS navigation message.

For this work, a viterbi decoder was needed since the hardware (ACORDE's ACGNS-L1 E1-FE-V1) together with the software (SoftGNSS v3 - running in MatLab) used represent a complete solution

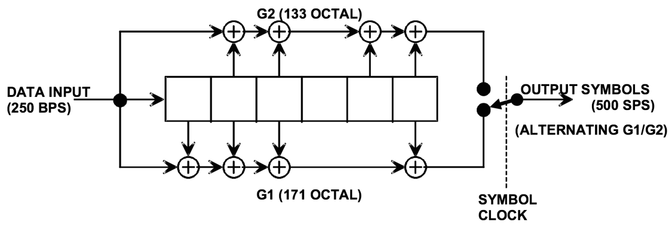

Figure 3.27: Viterbi convolutional coding scheme

for a GPS Receiver but cannot decode the EGNOS navigation message. The first approach was with a viterbi decoder from Matlab present in the Communications System Toolbox which would allow a seamless integration with SoftGNSS v3. Unfortunately the use of this decoder came to no results (a complete explanation about this issue can be found on section 5.1). A work-around was needed in order to proceed with the flow and to ultimately reach the goal of calculating a corrected location.

The work-around used needs an external tool that has to be run at the same time at which the signal is recorded by the front-end. Both signal captures must be synchronized in order to be grouped by the program. The external tool is the **ESA SISNeT User Application**, that allows to record the live uncoded navigation messages from the three satellites using only an internet connection.

To run the program (Figure 3.28) a login is need and it can be requested from ESA. After loging in, the user is able to see a live stream of the navigation messages sent by the satellites, select which messages to show, see post-processing information like EGNOS Message Type, GPS Week and GPS Time and, finally, logging all this information on a text file.

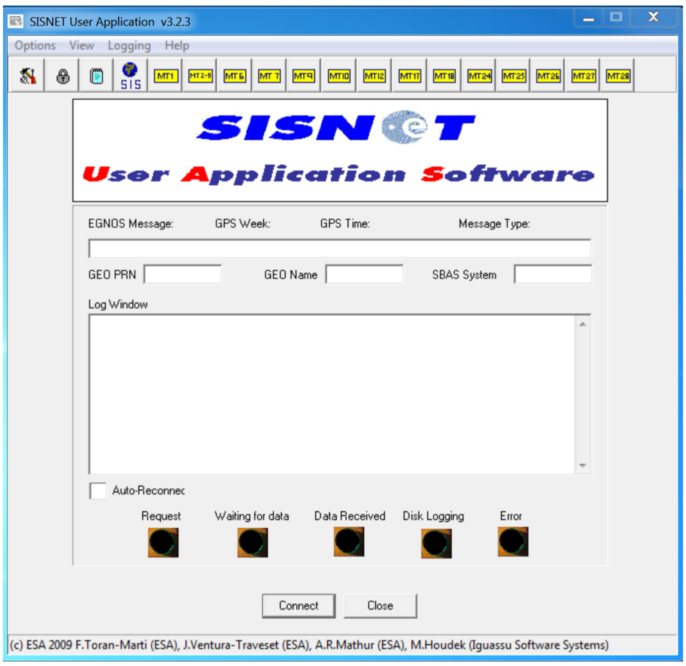

Figure 3.28: ESA SISNeT User Application GUI

This logging file was then read by the program and the information on it was afterwords used as a substitute for the information got from the satellite. This way, and since the logging file has the information required, all the remaining process kept the same.

3.4.5 Position Calculation

To apply EGNOS corrections on the GPS signal, a position needs to be found to know which parameters should be applied. For each measurement done, EGNOS corrections are calculated. The parameters calculated are fast and long term corrections, corrected satellites positions and ionospheric and tropospheric delays.

Bit N°	1	2	3	4	5	6	7	...
PRN Mask	0	0	1	0	1	0	1	
PRN Code N°			GPS PRN 3		GPS PRN 5		GPS PRN 7	

Figure 3.29: Example of PRN Mask.

Both long and fast term corrections are applied to the GPS satellites. Message type 1 defines which satellites will have pseudoranges corrected (example on Figure 3.29). After having this information, if message types 10, 24 and 25 are available in the buffer, Long Term corrections are calculated for each satellite. The same is done for Fast Term corrections if message types 2-5, 6, 7, 10 and 24 are available.

Long term corrections are broadcasted by EGNOS to correct long-term variations in the ephemeris errors (orbit parameters: δ_x, δ_y and δ_z) and clock errors (δ_{af0}) of the GPS satellites. They are also used to calculate Fast Term corrections.

Fast corrections are broadcasted by EGNOS to correct rapid variations in the ephemeris errors and clock errors of the GPS satellites and are used to calculate protection levels, explained in section 3.4.6.

To estimate the ionospheric error for each receiver/satellite line of sight, the Ionospheric Pierce Points (IPPs) must be identified.

Each IPP is defined as being the intersection between the atmospheric layer located at an altitude of 350 km and the line originating at the receiver position and which is directed at the GPS satellite in question. (Figure 3.30)

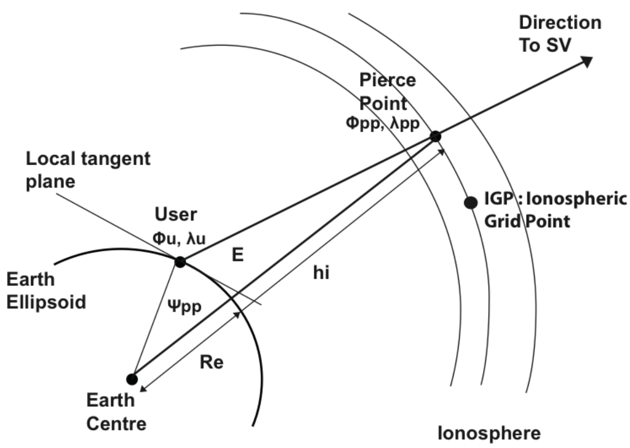

Figure 3.30: Principle of the Ionospheric Pierce Point (IPP).

EGNOS transmits ionospheric corrections enabling the ionospheric error to be estimated for each

IPP. These ionospheric corrections are broadcasted for each one of the points on a virtual grid situated at an altitude of 350 km. These points are called Ionospheric Grid Points (IGPs) as explained in section 3.4.3.

The receiver knows the position of these particular points and the estimated delay for each of them and is thus able to estimate the ionospheric delay for each IPP and therefore each pseudorange. In order to do that, an interpolation must be performed between the values provided for the IGPs close to each IPP. The receiver takes into account an obliquity factor (angle at which the ionosphere is traversed).

The reason why the calculation depends on receiver's location is the Tropospheric refraction, which is a local phenomenon. The delay is calculated using a static model with user location as input.

The tropospheric delay correction [TC_i] for satellite i takes the form:

$$TC_i = -(d_{hyd} + d_{wet}) * m(El_i) \tag{3.2}$$

where [d_{hyd} , d_{wet} (m)] are the estimated range delays for a satellite at 90° elevation angle, caused by atmospheric gases in hydrostatic equilibrium and by water vapor respectively, and [$m(El_i)$ (dimensionless)] is a mapping function to scale the delays to the actual satellite elevation angle [El_i].

[d_{hyd} , d_{wet}] are calculated from the receiver's height and estimates of five meteorological parameters: pressure [P (mbar)], temperature [T (K)], water vapor pressure [e (mbar)], temperature lapse rate [β (K/m)] and water vapor "lapse rate" [λ (dimensionless)].

3.4.6 Protection Levels Calculation

As mentioned on chapter 1.2, protection levels are bounds that statistically allow us to measure a certain position error. They do so with a confidence level derived from the integrity risk requirement. The Horizontal Protection Level (HPL) is the radius of a circle in the horizontal plane, with its center being at the true position, which describes the region assured to contain the indicated horizontal position. The Vertical Protection Level (VPL) is the half length of a segment on the vertical axis with its center also being at the true position, which describes the region assured to contain the indicated vertical position.

As described in section 3.4.5, protection levels are calculated for each measurement. The following parameters, transmitted by EGNOS, are needed to establish the protection levels:

- UDRE (User Differential Ranging Error), which characterizes the estimated residual errors in the orbit/clock corrections for each satellite.
- GIVE (Grid Ionospheric Vertical Error), which describes the potential error level in the ionospheric corrections.

To obtain UDRE and GIVE, the following EGNOS messages must be retrieved:

- Message type 1 to obtain the PRN mask
- Message types 2-5, 6, 24 for orbit and ephemeris errors (UDRE)
- Message types 18 and 26 for ionospheric error (GIVE).

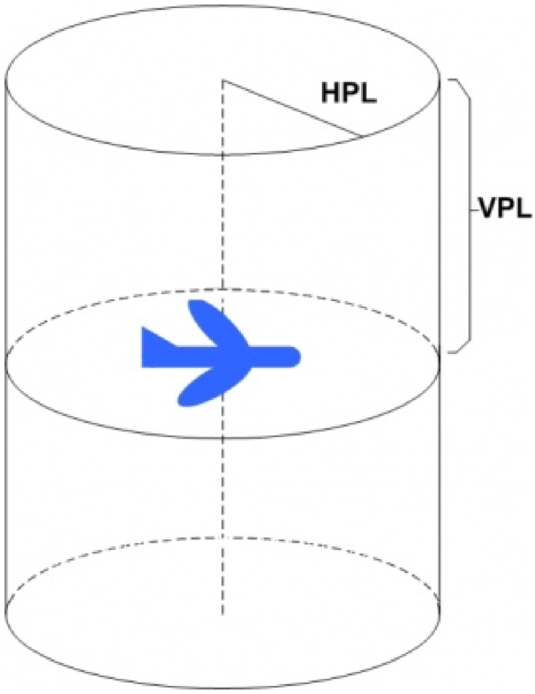

Figure 3.31: Horizontal and Vertical Protection Levels on a plane.

With all the information needed on the receiver, the protection levels are then calculated using the MOPS (Minimum Operational Performance Standard) DO229 standard, established and controlled by the US Radio Technical Commission for Aeronautics (RTCA).

According to this standard, HPL and VPL (Figure 3.31) are calculated using this equations:

$$HPL_{SBAS} = \begin{cases} K_{H,NPA} \cdot d_{major} \text{ for en route through LNAV} \\ K_{H,PA} \cdot d_{major} \text{ for LNAV/VNAV,LP,LPV approach} \end{cases} \tag{3.3}$$

$$VPL_{SBAS} = K_v d_u \tag{3.4}$$

where:

$$d_{major} = \sqrt{\frac{d_{east}^2 + d_{north}^2}{2} + \sqrt{\frac{d_{east}^2 - d_{north}^2}{2} + d_{EN}^2}} \tag{3.5}$$

d_{major} corresponds to the error uncertainty along the semimajor axis of the error ellipse.
$d_{east}^2 =$ variance of model distribution that overbounds the true error distribution in the east axis.
$d_{north}^2 =$ variance of model distribution that overbounds the true error distribution in the north axis.
$d_{EN} =$ covariance model distribution distribution in the east and north axis.
$d_U^2 =$ variance of model distribution that overbounds the true error distribution in the vertical axis.

The value of K_H for computing HPL is:

$K_{H,NPA} = 6.18$ for en route through LNAV

$K_{H,PA} = 6.0$ for LNAV/VNAV, LP, LPV

The value of K_V for computing VPL is:

$K_V = 5.33$

In the end, as mentioned before, for each measurement there will be a correspodent HPL and VPL.

Chapter 4

Tests and Results

To validate the implementation explained on chapter 3, three experiments were made (all of them static measurements on known locations): Lisbon (4.1), Troia (4.2) and Madrid (4.3).

For all of them, the real location is known using satellite images to compare with the results. The output of the experiments will be GPS and GPS+EGNOS calculated locations and Protection Levels (in GPS+EGNOS output).

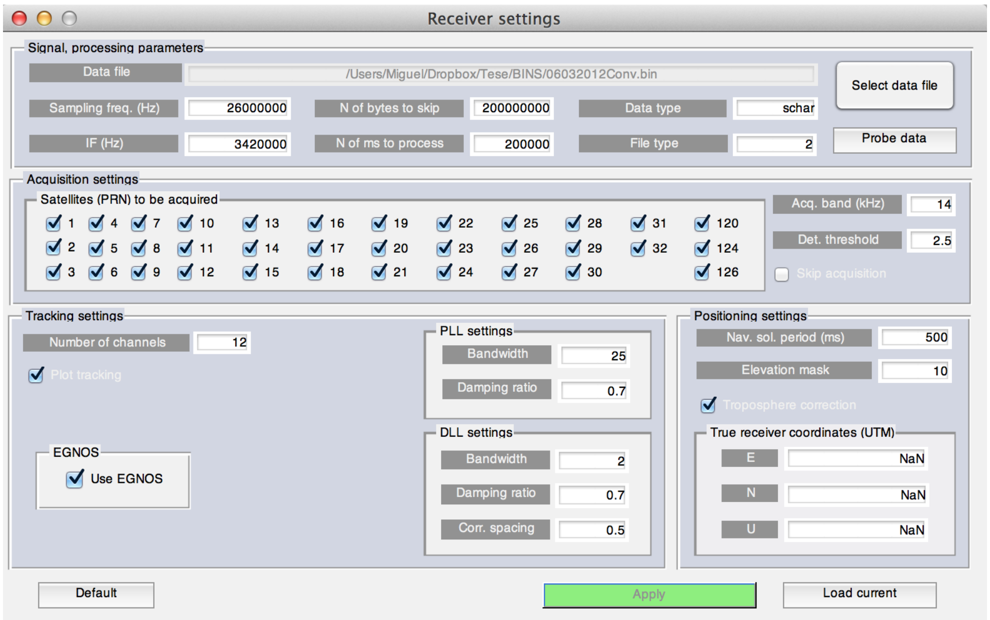

Figure 4.1: Settings used to process the saved signal.

The settings used (Figure 4.1) are the ones indicated by the front-end manufacture: Intermediate Frequency is 3.42MHz, 26MHz is the sampling frequency and the data type is schar.

Moving measurements were considered but not used for two different reasons:

- The open-source program used to implement the EGNOS receiver - *SoftGNSS 3.0* - was not ready for that type of results, leading to inconsistent values, given that the program cannot handle records of long periods of time, losing the position of the receiver. This can be explained because *SoftGNSS 3.0* does not check for new satellites and does not confirm that the previously found satellites are still in line of sight which ends up with the program beginning to process non-data. Not being able to process long periods of time makes the program unusable to process moving measurements.

- Moving measurements are not ideal to check accuracy because although the path calculated is the right one, each position in a specific time may be wrong. That is why static measurements are enough to check the validity and advantages of the implementation.

Following this line of thought, three results on distinct places and time will be shown below, leading to the conclusions in chapter 5.

4.1 Location One - Lisbon

The first location chosen has coordinates 38.746435, -9.164540, as demonstrated in Figure 4.2 and the signal was recorded on March, 6th 2014.

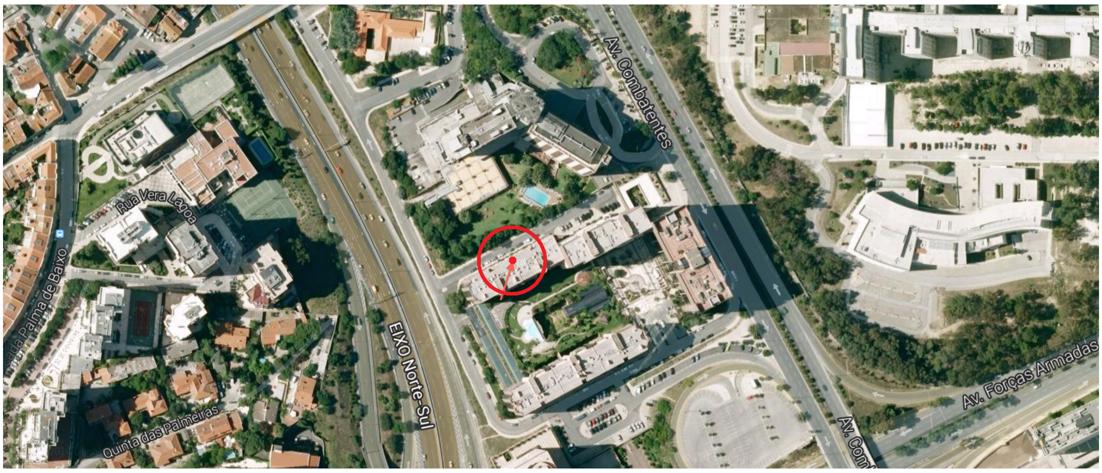

Figure 4.2: Known position of the first location. Sete Rios in Lisboa

The GPS satellites found in this record were with PRN 2, 5, 7, 8, 9, 10, 13 and 26 and EGNOS Inmarsat 3-F2 (PRN 120) as seen in Figure 4.3.

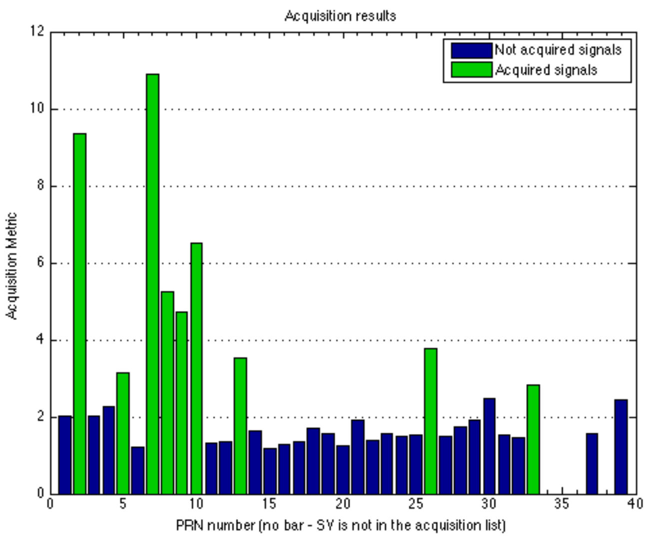

Figure 4.3: Aquisition - Lisbon record.

In Figure 4.4, the result from the tracking of two of the nine channels is plotted. The I and Q component of the baseband signal are plotted and the quality of the tracking is revealed by the concentration groups formed that need to be symmetric. On the right is the Navigation data extracted - where we can see the clear transition of bits - but for the GPS satellite is the final message and for EGNOS is the encoded message. Bellow, the plot for the Early, Prompt and Late code correlation value is showed. It is intended to always have the Prompt value higher than the Early and Late, and that is the case as we can be seen.

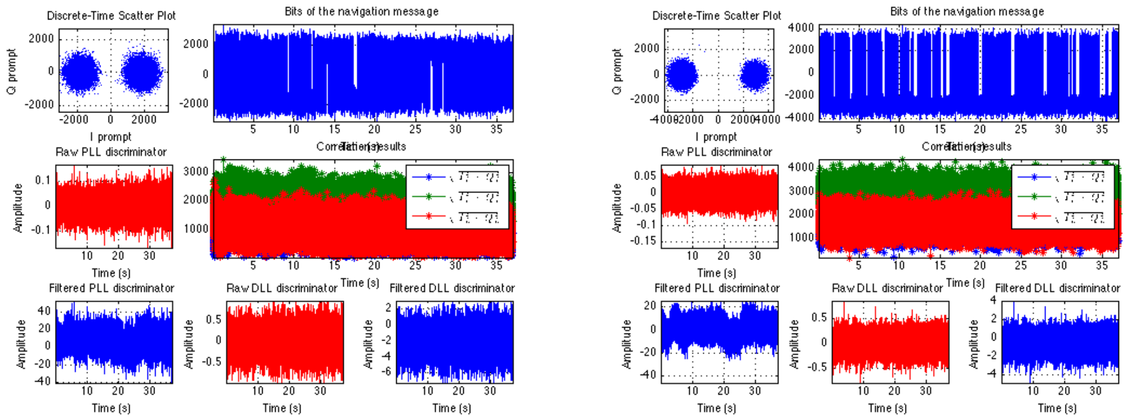

Figure 4.4: Tracking result for satellite PRN5 and PRN120 for acquisition 1

The plot of the raw PLL discriminator and raw DLL discriminator are show in red. They represent the error in the NCOs, and their filtered values are represented by the plots in blue.

The results of the navigation solution are presented on Figures 4.5 and 4.6 - the first using only GPS and the second with EGNOS. The navigation solution shows the coordinates variations, which, like the name says, represents the variation, in the Universal Transverse Mercator (UTM) coordinate system, of the easting, northing and up coordinate. In this case, lower variation means better tracking.

A two dimensions plot indicates the calculated positions for the processed signal, with a variation of about 10 meters. The result position is the red cross, which is the mean position.

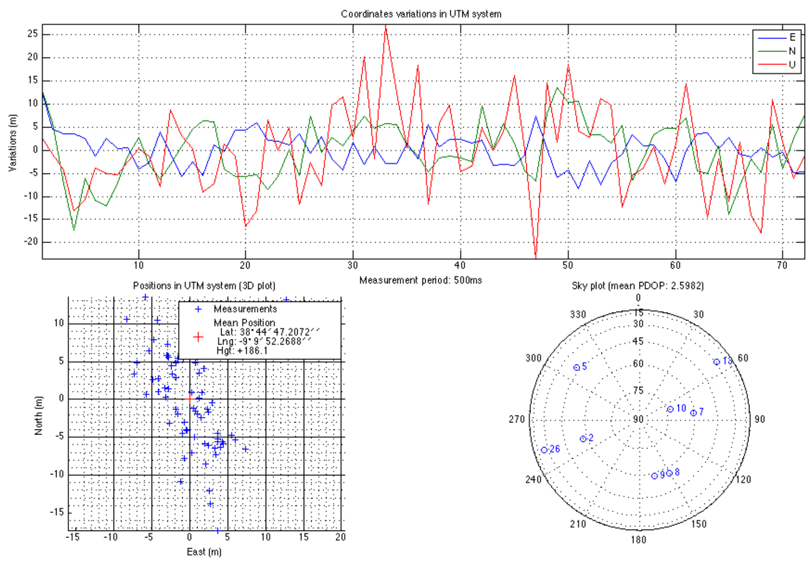

Figure 4.5: Navigation Solution for aquisition 1 - GPS Only

The final plot in the right shows the relative position of the acquired satellites in the sky. A value of Positional Dilution of Precision (PDOP) of 2.5982 was obtained which measures the distribution of the acquired satellites in the sky. The precision of the navigation solutions can be degraded by a non-even distribution of the satellites. A smaller PDOP value indicates a better distribution, and the value in this acquisition is good.

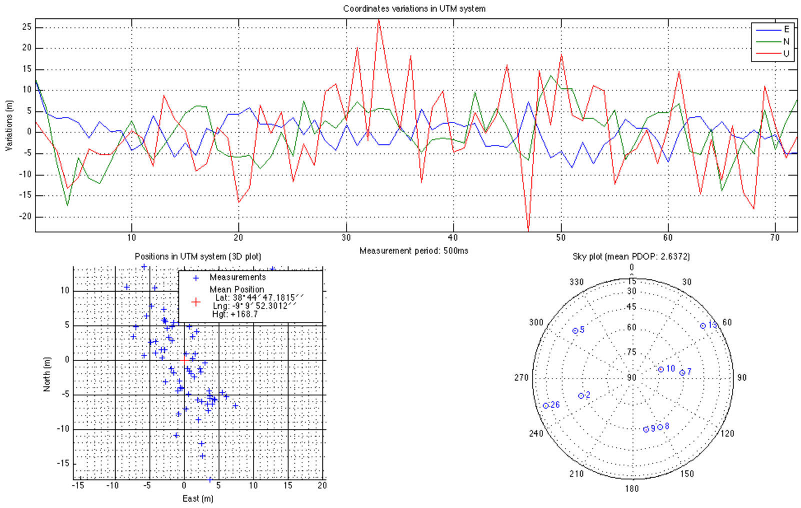

Figure 4.6: Navigation Solution for aquisition 1 - GPS with EGNOS

Using the EGNOS information (from EGNOS Inmarsat 3-F2) the results become better: the position calculated is closer to the real one and HPL and VPL also become available.

For this record, the HPL was **13,2 meters** and the VPL was **17,4 meters**, which is considered safe by the FAA. More than a number, this gives a confidence radius of the real location. This confidence is very important either for static measureaments to find a spot but also for moving objects when entering narrow spaces with no visibility (aero-nautic objects, for example).

In table 4.1 the results are compared between them and with the real position and in Figure 4.7 the same information is detailed on a map.

	Latitude	$Lat\ \delta$	**Longitude**	$Lon\ \delta$	**Altitude**	$Alt\ \delta$
Real Position	38.746435	-	-9.164540	-	155.5	-
GPS Result	38.746446	0.000011	-9.164519	0.000021	186.1	30.6
GPS with EGNOS Result	38.746439	0.000004	-9.164528	0.000012	168.7	13,2

Table 4.1: Results comparison for aquisition 1 - Lisbon

As can be seen on table 4.1 and figure 4.7 the results (latitude, longitude and altitude) are more precise, i.e. are nearer to the real ones, when using the GPS with EGNOS than the ones got from GPS solely. Also, using EGNOS, additional information like protection levels can be calculated something that is not possible if only the GPS is used.

Figure 4.7: Position Results of Aquisition 1 - Real Position (Green) vs GPS Position (Blue) vs EGNOS Position (Red).

4.2 Location Two - Troia

The second location chosen has the coordinates 38.4545647 -8.8524426 (demonstrated in Figure 4.8) and the signal was recorded on August, 18th 2014.

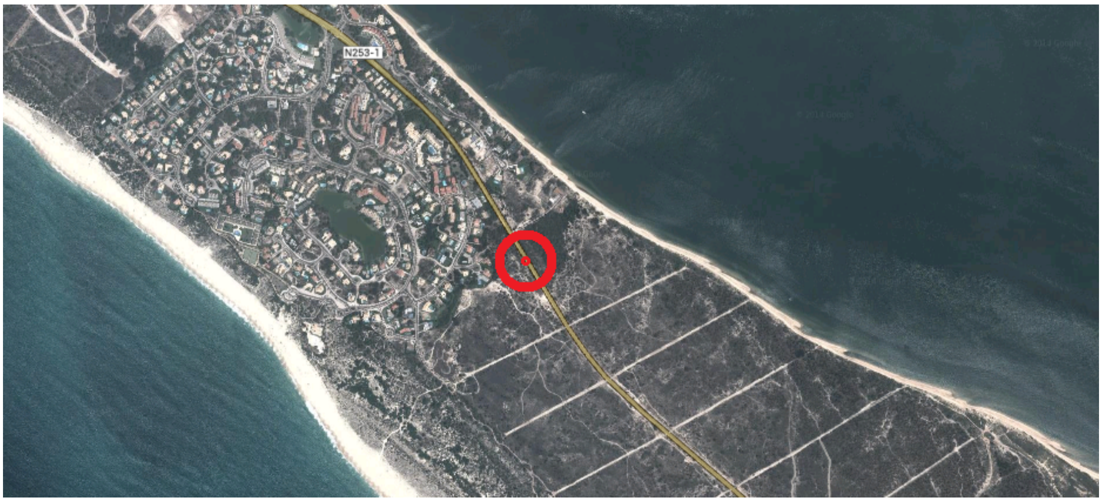

Figure 4.8: Known position of the second location. Troia in Setubal

On table 4.2 the results are shown. The HPL and VPL for this record were **11,5 meters** and **12,1 meters**, respectively.

	Latitude	*Lat* δ	**Longitude**	*Lon* δ	**Altitude**	*Alt* δ
Real Position	38.454396	-	-8.853282	-	0.1	-
GPS Result	38.454414	0.0000018	-8.852309	0.0000027	20.2	20.1
GPS with EGNOS Result	38.454410	0.0000014	-8.852302	0.0000020	9.3	9.2

Table 4.2: Results comparison for aquisition 2 - Troia

Figure 4.9: Position Results of Aquisition 2 - Real Position (Green) vs GPS Position (Blue) vs EGNOS Position (Red).

As seen on the Lisbon test, also on this second location EGNOS results were more precise than GPS ones.

4.3 Location Three - Madrid

The third location chosen has the coordinates 40.430008 -3.686944 demonstrated in Figure 4.10 and the signal was recorded on September, 13th 2014.

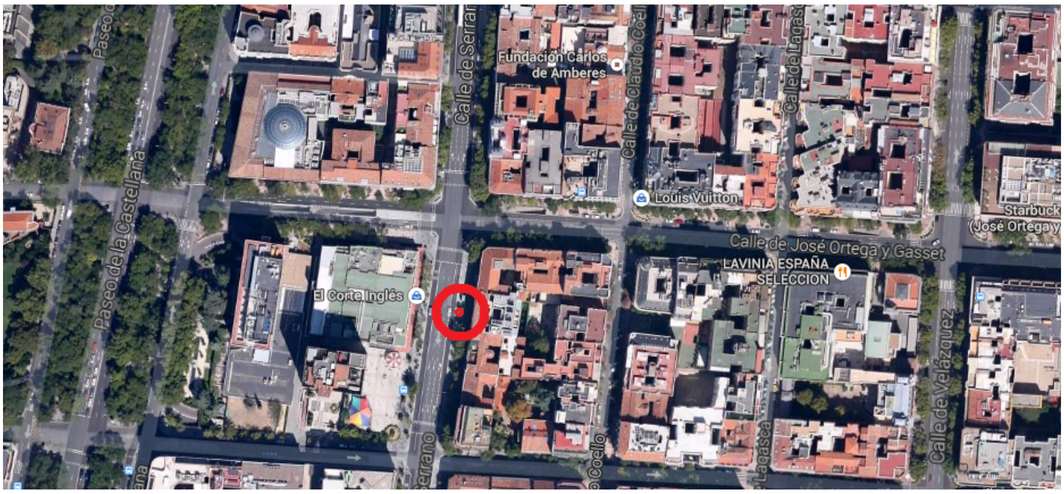

Figure 4.10: Known position of the third location. Salamanca in Madrid

On table 4.3 we can see the results. The HPL and VPL for this record were **6,8 meters** and **9,0 meters**, respectively. Again and like the previous two records, EGNOS results were better.

	Latitude	*Lat δ*	**Longitude**	*Lon δ*	**Altitude**	*Alt δ*
Real Position	40.430008	-	-3.686944	-	667.3	-
GPS Result	40.429999	0.0000009	-3.686929	0.0000015	729.9	62.6
GPS with EGNOS Result	40.430003	0.0000005	-3.686931	0.0000013	699.2	31.9

Table 4.3: Results comparison for aquisition 3 - Madrid

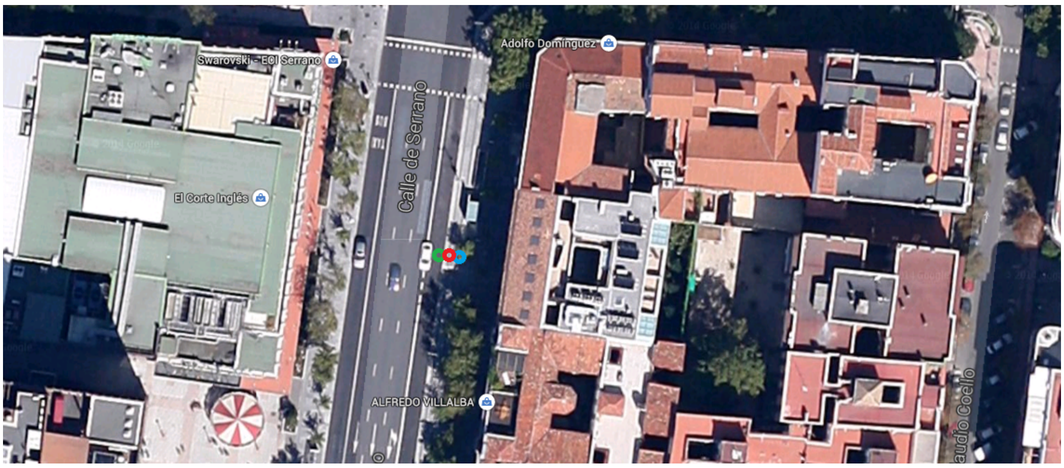

Figure 4.11: Position Results of Aquisition 3 - Real Position (Green) vs GPS Position (Blue) vs EGNOS Position (Red).

On this third location, once again, and confirming the previous two results, the results obtained using EGNOS were more precise than the ones got from the GPS.

4.4 Navigation Message Decoding

During the tests it was concluded that it was not possible to decode the navigation message using the Viterbi decoder. So, a series of tests were performed in order to detect what in the process was not working. At this point, four hypothesis were created:

Hypothesis 1 The problem was on the Viterbi decoder used

Hypothesis 2 The problem was on the Frontend used

Hypothesis 3 The problem was the antenna

Hypothesis 4 The problem happens when the signal is being received

With the objective of identifying which one of the three hypothesis was correct, the tests described bellow were undertaken:

Hypothesis 1

1. A random message was chosen
2. The random message was coded using an EGNOS Viterbi convolutional coding scheme and noise was added to it
3. Using various parameters combinations on the Viterbi decoder, the message was decoded

   Result - The original message was obtained with an accuracy higher than 99%

   Note - The same test was performed using an EGNOS known message, and the results obtained were exactly the same.

Hypothesis 2

1. A message was recorded using two different frontends, in the same place at the same time
2. The recording data obtained by each frontend was compared between the two of them

   Result - The coded navigation message obtained was the same from each one of the two different frontends used

Hypothesis 3

1. With the same frontend, the recording was made using three different antennas
2. The process of aquisition, tracking and decoding navigation message was done for each of the three records

   Result - For each one of the three different messages, it was still not possible to find the preambles after using the decoder

   Note - Given that there was only one frontend, it was impossible to perform the test with the same data.

Hypothesis 4

Unfortunately and given the tools at the hand, it was not possible to test this hypothesis in order to have a conclusion. Were they possible to make, the tests to be performed to analyse this hypothesis were:

1. The coded navigation message is recorded using the frontend and at the same time the same navigation message, this time decoded, is being recorded by a second source

2. The message from the second source is coded with the EGNOS Viterbi convolutional coding scheme

3. The two coded messages are compared in order to see if they match

   Note - The ESA SISNeT User Application provides us with the live messages that are being obtained, however there is no way to synchronised the messages obtained from this application and the ones saved using the Frontend

To conclude, the tests performed and described above, prove that neither the Decoder nor the Frontend or the Antennas were at faulty and the problems that I have come upon during this study are not related with neither one of the three.

Chapter 5

Conclusions

As this study comes to an end, it is now time to take some conclusions. The most noticeable one, and the one that was in fact the starting point of this entire study is that by using a GPS with the EGNOS receptor the location data acquired is without a doubt more accurate, in otherwords, closer to the real location coordinates, than when a solo GPS system is used. The results were 43 to 64 percent more accurate.

In order to take this conclusion, three locations were set and their data location was acquired using both a GPS and a GPS with an EGNOS receptor. In all three cases, the coordinates' variation was smaller whenever the EGNOS receptor was added to the GPS. To achieve the goal of this work, which was to develop the EGNOS receiver software, it was necessary to adapt and develop a software program to perform the acquisition, tracking and navigation message decoding from the three existing EGNOS satellites. Afterwards, the results had to be combined with a valid GPS signal to obtain the receiver location and protection levels. To acquire this data it was used an ACORDE's ACGNS-L1 E1-F1-V1, which is a GNSS FE with an USB interface optimized for real-time Software Defined Radio applications and signal recording.

The elaboration of a SDR EGNOS receiver was almost a success, proving the concept and obtaining very good results. The down side was the unsuccessful implementation of the decoder, forcing the use of other tools to complete the process. The decoder used, obtained very good results with other data and samples, only failing with the ones from the chosen FE. This lead us to conclude that the problem was in the signal acquisition, since other antennas were also used with the same FE, having similar results: working with GPS however unable to decode EGNOS Navigation Message.

In the end, and although the faced difficulties, the conclusion, as said above, is clear: the EGNOS receiver when implemented on a GPS system is able to get us more precise information on location, with an added error factor and a confidence margin to the EGNOS data that can enhance and better the results obtained from the satellite.

Unfortunately, future studies on this matter are unlikely to take place, given that at the moment, all the EGNOS interest is exchange over the modern system GALILEO, which will bring more advantages than EGNOS would.

5.1 Limitations

As stated before (in section 3.4.4), it was not possible to decode the EGNOS navigation message, given that the preambles were not found on the decoded message, which makes it impossible to calculate a correct location using the decoder and frontend chosen for this project. Further attention on this issue was given on section 4.4.

Various attempts to contact ESA were made, in order to get more information about the decoder used, however none of them successful.

One point should be taken into account and that is that the message decoder used on this project, the Viterbi decoder, is one present in the Matlab Telecommunications Toolbox list of available programs.

5.2 Future Work

As for future work, implementing a working Viterbi decoder is a priority for the program to become independent, given that at the moment it is necessary to use SisNET to get EGNOS messages. The decoder is the only missing piece, since the program is already prepared to receive the coded message and process the decoded one.

Developing a new version that works in real time is also a valid future research direction. It will solve problems of memory (saving the signal needs a lot of memory space) and also reduce the amount of time between saving the signal and getting the output.

Additionally, it was detected that in situations when the satellites are in positions that make their signals weak EGNOS functionalities cannot be used which is a starting point for a future research.

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