



ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)  
GRADO EN INGENIERÍA ELECTROMECÁNICA

MEMORIA PROYECTO FIN DE CARRERA

Exploring Galileo's Performance in Iceland

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Islandia – Madrid 2018





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## ACKNOWLEDGEMENT

To my family,  
my project director, Sæmundur E Þorsteinsson,  
and Manuel Andrés Castro

## **Estudiando la actuación de Galileo en Islandia**

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### **Resumen del proyecto**

Galileo es el sistema europeo de navegación por satélite, del que se espera que proporcione más servicios que su homólogo estadounidense, Global Positioning System (GPS), como servicios de emergencia y comerciales. El sistema está siendo desarrollado por la Agencia Espacial Europea (ESA, por sus siglas en inglés), la cual puso en órbita el primer satélite de Galileo en el año 2005. El sistema Galileo fue abierto al público en el año 2016, pero actualmente aún no está totalmente desplegado. Galileo estará constituido por un total de 30 satélites en el año 2020. De este sistema de navegación se espera una oferta de actuación mejorada respecto a otros sistemas de navegación ya existentes como el GPS, GLONASS o BeiDou.

El objetivo de este proyecto es conocer mejor el sistema para su uso en Islandia. Este país depende mucho de la navegación por satélite, especialmente en sectores como la pesca, la aviación o el propio uso público.

La metodología del proyecto empieza con el aprendizaje de los fundamentos y las bases de las tecnologías GNSS. Después de este acercamiento inicial a la navegación por satélite, se seleccionará el hardware necesario. El módulo de evaluación de GNSS se comprará a la marca U-Blox, que también distribuye el software de evaluación GNSS para explorar las capacidades del módulo comprado. Todo el hardware necesario para el proyecto ha sido provisto por la Universidad de Islandia. Con todo preparado, se encontrará la forma de grabar, tratar y comparar los datos provenientes de los diferentes GNSS. Y al mismo tiempo, se entregará una memoria del proyecto y una presentación al final del trabajo.

# **Exploring Galileo's performance in Iceland**

Author: Boned Fernández, Juan Miguel

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Collaborative Entities: Háskóli Íslands - University of Iceland, ICAI – Universidad Pontificia de Comillas.

## **Project Summary**

Galileo is the European GNSS (Global Navigation Satellite System) which is expected to provide more services than the American counterpart (GPS), like emergency or commercial services. The system is being developed by the European Space Agency (ESA) and it launched the first Galileo satellite in 2005. Galileo was opened for the public in 2016 and now the system is not totally unfolded but will be declared operational in 2020. Then, the Galileo constellation will consist of 30 satellites. This navigation system is expected to offer enhances performance compared to other GNSS like GPS, GLONASS or BeiDou.

The objective of this project is to gain experience from its usage in Iceland. This country is very dependent on satellite navigation, especially in sectors like general navigation of ships, fishing, aviation and general public use.

The methodology of the project started with learning the basis of GNSS technology. After this first approach to satellite navigation, the hardware was selected. An evaluation module for GNSS was provided by U-Blox. This company also delivers the proper software to explore the modules' capabilities. All hardware required for this project was provided by the University of Iceland. With everything ready, the way to record and compare data from several GNSSs was found. At the same time, a report was written and a final presentation will be done as well.



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## **Chapter I: Introduction**

### **Objective of the project**

The European Union opened a new Global Navigation Satellite System (GNSS) named Galileo, to the public on 15 December 2016. Currently there are many GNSSs being used around the world: The Russian GLONASS, Chinese BeiDou and the best-known American GPS. The Indian IRNSS and the Japanese QZSS are regional positioning systems designed primarily to enhance performance over India and Japan. This project aims at testing the European GNSS Galileo's performance in Iceland and compare its performance to the performance of GPS and GLONASS. Thus gain experience from its usage in this country. Furthermore, technology that aggregates satellites from different GNSSs constellations to measure position will be investigated.

### **Motivation/Justification of the project:**

This project is inspired by the fact that Iceland is very dependent on satellite navigation. It is possible to see this dependence in the navigation of ships, in the aviation and the general public use.

Fishing industry is one of the most outstanding commercial activities for Iceland. Therefore, the performance of a GNSS is very convenient for the fishing fleet. Trawlers should avoid obstacles that lie on the bottom of the ocean in order to not get stuck there with the trawl behind the ship. It is also very useful to save or record the most relevant spots and paths where fish is likely to be found. For both actions, accuracy is essential.

On the other hand, aviation sector could also enhance their performance when landing an aircraft. An ILS (Instrument Landing System) is based on a ground system, which gives an aircraft assistance when landing and taking off. This is a very expensive system that could be complemented by a satellite navigation system and even replaced if the satellite system if accuracy and reliability are enough.

Lastly, a project like this one could enhance the general public use performance of Galileo in a country depending heavily on satellite navigation like Iceland.

### **Methodology of the project:**

The methodology of the project is following:

In order to complete the project, a first approach to GNSS technology is required. For that reason, the first weeks were dedicated to learn the fundamentals of GNSS technology. The next step was to set up an evaluation module for GNSS using a U-Blox chip, and for that it is required to set up proper software as well to explore the capabilities of the module.

After having set up everything, the moment came to try to read and store GNSS data from the module and find ways to use the information to calculate the position. If possible, compare data coming from different GNSSs (GPS, GLONASS, BeiDou and Galileo).

Next target was to explore the possibilities to utilize more than one GNSS for calculating a single position.

During the development of the project, a report was written and a final presentation at the end of it. A Gantt chart for the project execution is shown in Figure 1.

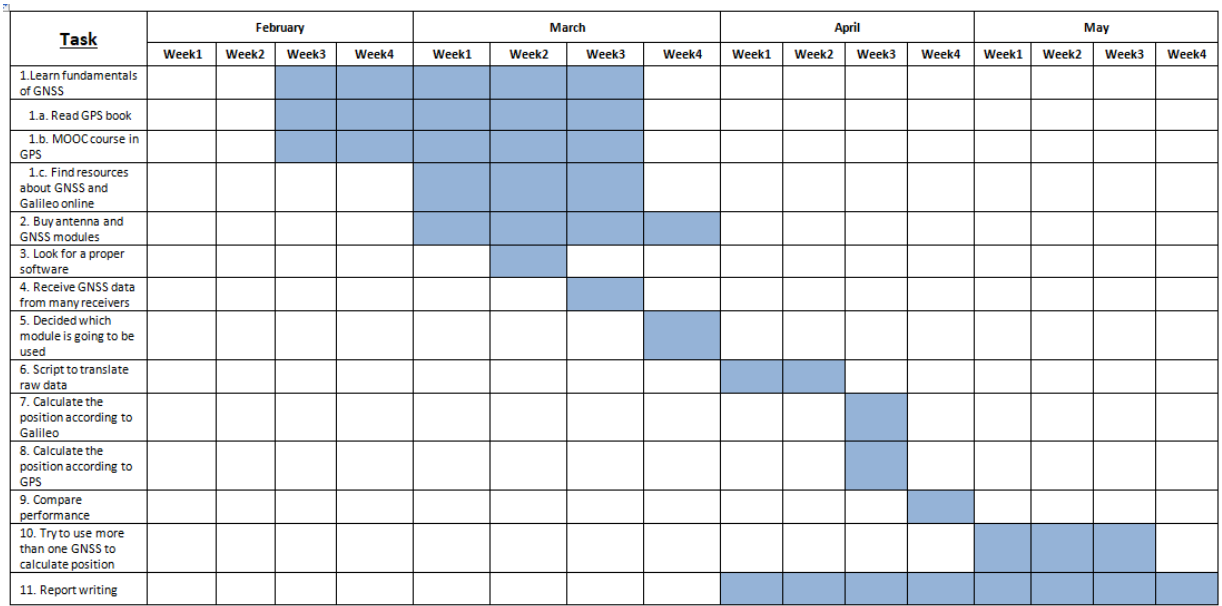


Figure 1: Gantt Chart

## Resources to be used

For the realization of this project there are some items that are expected to be completely necessary. First of all, a personal computer is required in order to install software that might be useful for this project and for all office IT tasks.

The GNSS modules initially chosen for the project are coming from the U-Blox brand. The following modules were ordered at the beginning:

1. UBLOX MAX-8Q GPS GNSS receiver board
2. UBLOX NEO-M8T TIME & RAW receiver board
3. Ublox SAM-M8Q GPS, GLONASS, Galileo, QZSS and SBAS receiver
4. NEO-M8N Triple Band receiver

Also a High performance active GPS antenna was ordered to be used with the modules.

Due to the fact that all modules are coming from the same brand, it was decided to set up software developed by U-Blox called u-Center to interface easily with the data coming from the modules.

After having set up everything, each module will be tested in order to decide which could make the best performance during the project development.

## Chapter II: State of the art

### A brief history of navigation

When people need to travel long distances it is essential to be able to represent them on a map. Nowadays this sounds easy but in the past, exact maps did not exist and exact positioning was very difficult. However, in the sixteenth and seventeenth centuries, and especially in the twentieth century, great progress was made in the field of geodesy and positioning technologies, allowing people to easily find their position anywhere on earth. Currently, after those years of researching and incremental steps, it is possible to get centimeters, even millimeters, of accuracy.

It is appropriate to describe the main fields that allow a navigation system to be useful. These fields are geodesy, timekeeping and astronomy. Geodesy is the study of the shape and size of the earth, Timekeeping tries to measure time accurately and astronomy allows to find reference frames for positioning.

Every one of these three fields posed a challenge by itself. At the very beginning, the Greeks knew the earth to be spherical, which is a good approximation. They created a reference frame with some degrees of freedom, using the equator plane and a chosen meridian of the earth. This spherical representation, with some changes is still used. The latitude, which describes north-south position from the equator, was easy to determine and measure using the Pole Star, but the longitude continued to be a challenge for its proper measurements for many centuries, Figure 2. Even some relevant characters like Columbus had to deal with this uncertainty during his navigation routes.

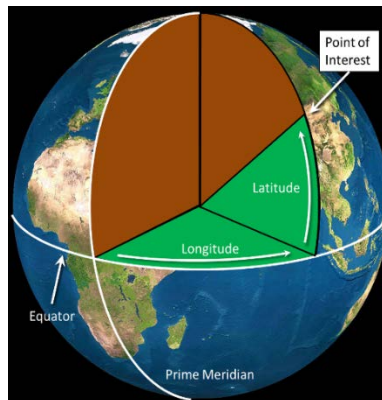


Figure 2: Knowing Polar star position, it is possible to calculate latitude easily. But longitude is a different story.

Longitude is very closely related with time. Due to the fact that the earth rotates  $360^\circ$  in 24 hours and therefore one hour means a longitude of  $15^\circ$ , it is possible to use the difference between two local time zones to know the longitude of these places. So now the challenge is to measure time as accurately as possible. In the 1500s mechanical clocks were built, but they had an error of a few minutes per day, which is not affordable for a navigation system. Two centuries later, John Harrison built in 1760 a

clock without pendulum with an error of a few seconds per month, which became a relevant event for navigation. [1]

As an alternative, other methods were developed for sailing. Based on the improvement of the telescope, Galileo Galilei (1564-1642) proposed to teach sailors to observe Jupiter's moons to find their longitude. But the idea never became practical at sea, although it was useful for finding the longitude on land. [1]

Another method studied during the seventeenth and eighteenth centuries was to use lunar orbits to determine location using the distance between the moon and certain stars. At that time, star position was unmapped and lunar motion was not fully understood. Leonhard Euler (1707-1783) described the moon's motion around the earth as a three body problem, including the Sun. Nevertheless, the method never came into effect because the chronometers were already ahead. [1]

At the end of the eighteenth century, the essential instruments for navigation were a sextant, an accurate clock (to write down the time of the measurements), an almanac (a summary of the position of certain celestial bodies) and a magnetic compass. The problem of navigation was temporarily solved until the arrival of iron ships which interfered with the compass measurements. [1]

In order to solve the problem above, the invention of the gyrocompass in the early twentieth century was a good alternative to the magnetic compass. Now, inertial navigation based on a gyroscope became a very interesting solution. A gyroscope is a spinning mass which is free to turn in any direction. The key point of this spinning mass is that it keeps pointing at one star even ignoring the earth's motion, so this ability led to inertial navigation systems (INS). An INS (Figure 3) consists of three accelerometers that sense the three rotations (yaw, pitch and roll) and keeps track of them, providing velocity components. The next iteration of the device is to include position coordinates, what was a very complex challenge during the twentieth century. [1]

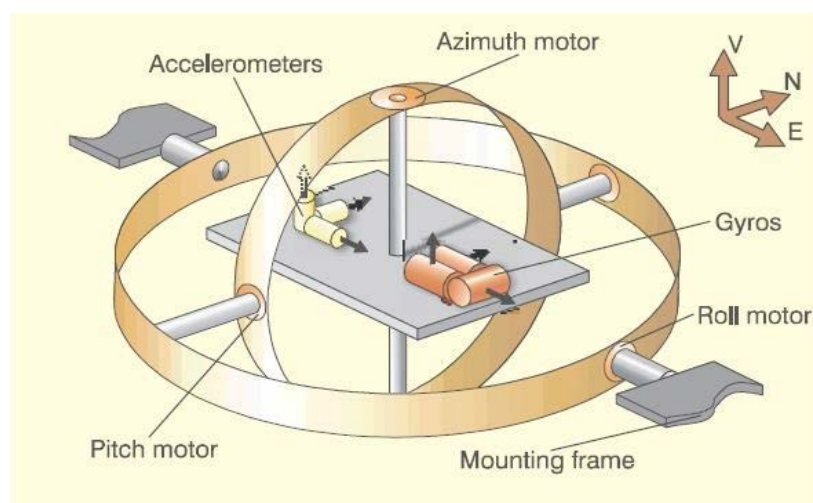


Figure 3: INS description

To update position coordinates, an external source was required and here is where GPS (Global Positioning System) takes a very relevant role. The cornerstone for GPS success was the microelectromechanical systems (MEMS) integrated in satellites which were developed during this century. [1]

Radio navigation systems were developed during the twentieth century. It is important to know that these types of systems exploit the principles of propagation of electromagnetic radio waves.

Users on land or over ocean are usually satisfied with two-dimensional position estimation, but aviators, e.g. need altitude in real time. Some examples could be trilateration, hyperbolic positioning or Doppler positioning.

Trilateration (Figure 4) is based on the radio waves propagation speed, because knowing the speed and the time of arrival of the signals coming from spread transmitters, it is possible to estimate the position of the receiver. If a radio navigation system is based on this idea, it is called TOA (*time-of-arrival*) and an example of it is the GPS system. [1]

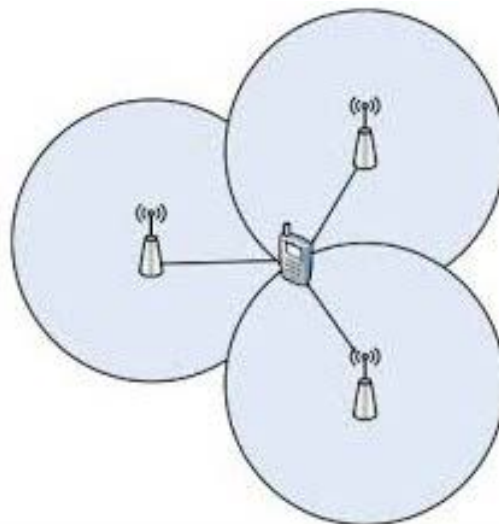


Figure 4: Trilateration positioning [11]

On the other hand, another example of radio navigation system is the Hyperbolic positioning (Figure 5). These types of systems are based on the measurement of the difference in the times of arrival of signals: *time-difference-of-arrivals* (TDOA). For a 2-D positioning representation, at least three stations at known locations are required.

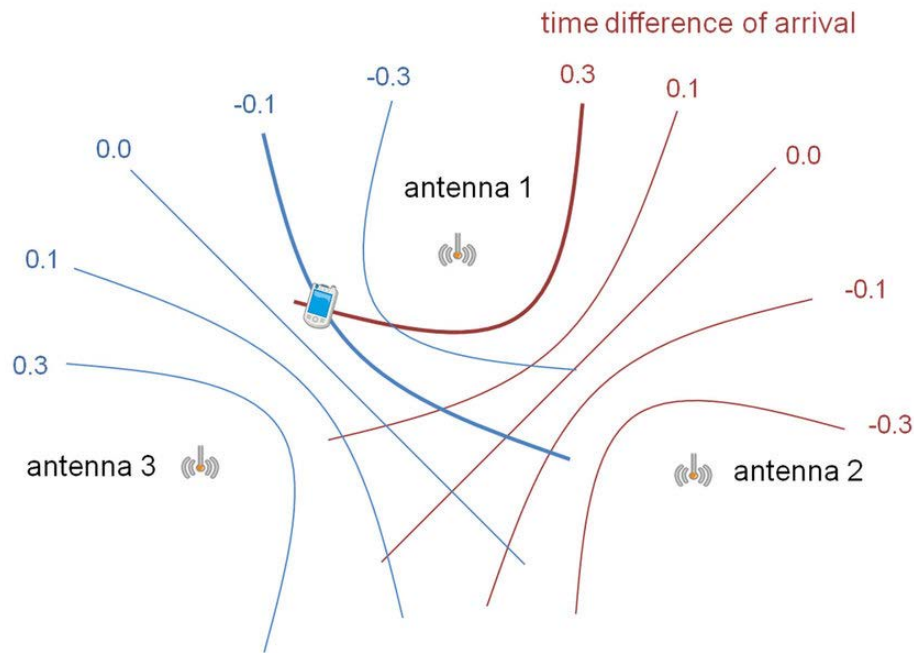


Figure 5: Hyperbolic positioning [12]

Finally, the last example is Doppler positioning. As the name says, this system is based on the Doppler effect. Due to World War II, an incredible evolution started in radio navigation. In the latter part of the 20th century, two new radio systems took center stage: LORAN and Omega. Both of them are TDOA systems. Loran (Long Range Radio Aid to Navigation) was designed as high-power hyperbolic system primarily for ships. On the other hand, Omega was the first worldwide, continuously available radio navigation system that was operational from 1970s to 1997. [1]

All improvements and developments described above opened the way for satellite age. The first landmark was the launch of *Sputnik I* by the Soviet Union in 1957. And the Cold War was the frame from where the space race reached a huge evolution in satellite technology.

GPS is one of the first of a new generation of navigation systems based on multiple satellites and due to its success many Global Navigation Satellites Systems (GNSS) were developed through the years.

### Current Navigation technologies

Nowadays, GPS is not the only GNSS currently working in the world, there are many of them which share a frequency band of the spectrum where atmospheric opacity is minimum, as seen in Figure 6. [9]

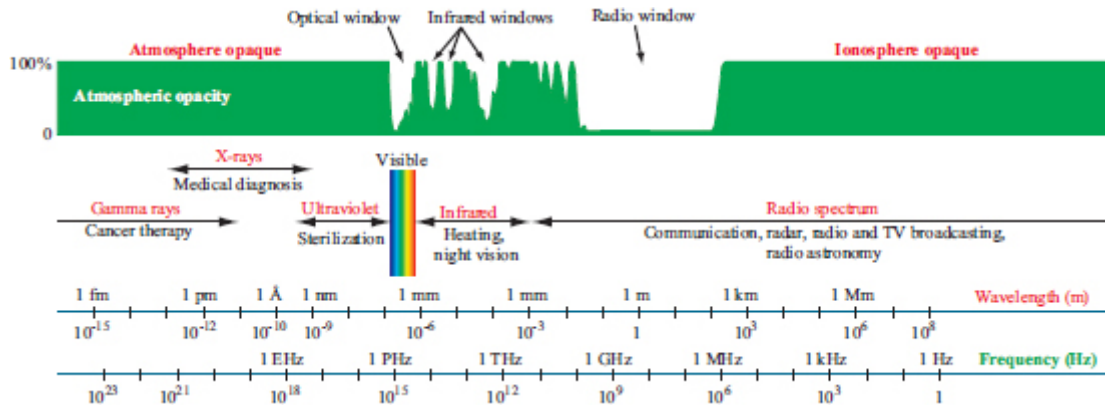


Figure 6: Atmospheric opacity according to the wavelength [9]

This band is between 1.2 GHz and 1.6 GHz belonging to the L band which is the lowest part of the microwave spectrum. All GNSS are located in this frequency band. The GNSS frequencies are shown in Figure 6 distributed between 1.2 GHz and 1.6 GHz approximately.

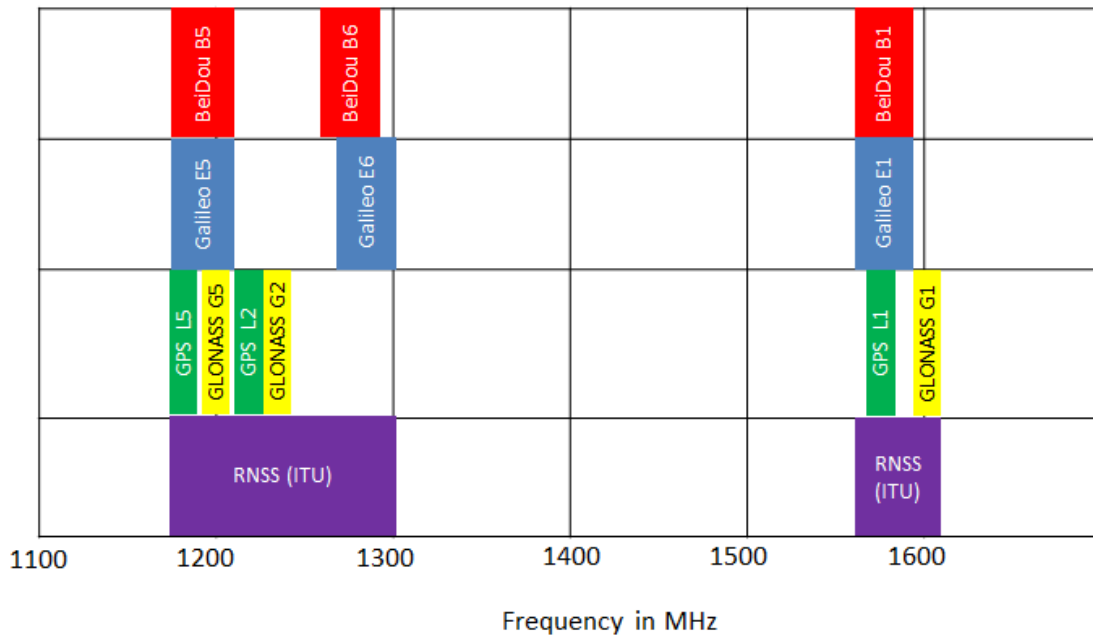


Figure 7: GNSSs frequency structure

As shown in Figure 7, every GNSS has a frequency band available for its use. GPS, e.g. has L1 (1575.42 MHz), L2 (1227.60 MHz) and L5 (1176.45 MHz). L1 and L2 are currently used for civil and military purposes, and L5 is used just for the military. On the other hand, Galileo is centered in three available bands: E1 (1575.42 MHz) for open service, E5 (1191.795 MHz) and E6 (1278.75 MHz). Moreover, some additional services share the frequency bands used by Galileo and GPS. GLONASS, Radio-Navigation Satellite Service (RNSS) and Aeronautical Radio Navigation Service (ARNS).



A GNSS system has several error sources. The main error sources for GPS are shown in Table 1. [8]

Table 1: Error budget for GPS system when the receiver has not assisted GPS to improve the performance

Error Source	Random	Bias	Total
Ephemeris	0.1	1.0	1.0
Clock	0.4	1.0	1.2
<b>Ionosphere</b>	<b>0.4</b>	<b>4.0</b>	<b>4.0</b>
Troposphere	0.5	0.5	0.7
<b>Multipath</b>	<b>0.3</b>	<b>1.0</b>	<b>1.4</b>
Receiver Noise	0.2	0.5	0.5
Raw pseudorange	0.75	4.4	4.6
Smoothed pseudorange	0.25	4.4	4.4
Horizontal			
Vertical			
<b>Ionosphere &amp; multipath are wild cards!</b>			

The ionospheric errors depend on solar activity and are an important source of error. Multipath and reflection of the satellite signals coming from the environment are another important error source. A good model of the ionosphere behavior and a proper design of the antennas can reduce these sources of error.

The geometry is also relevant in order to enhance the accuracy of the system. The more spread the satellites are in the sky the better is the positioning, their lines of position intersect at an angle close to  $90^\circ$ . When the satellites are close to each other, the lines of position intersect at a small angle producing a high Dilution of Precision (DOP). The DOP results from the available geometry and is a multiplication factor for error (see Figure 8). [10]

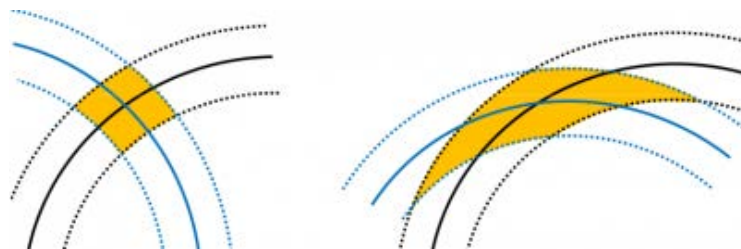


Figure 8: DOP effect in positioning: 2-D illustration of the variation of the uncertainty region with the geometry. [10]

Everything written before about reliability of a GNSS is related with the errors coming from the system itself and the environment. But nowadays there is another source of error produced by humans that use so called jammers. A jammer is a device employed to hide people's position over an area. This is dangerous because it also renders GNSS services useless to everyone nearby who could need them. However, there are also some techniques available, specifically for military purposes to overcome this problem.

In the following a description of the GNSS GPS, Galileo, GLONASS, BeiDou, IRNSS and QZSS is given.

- **GPS description**

The space segment of GPS has between 24 and 32 satellites; the constellation is shown in Figure 9. The minimum number of satellites that allows having at least 4 visible satellites working is 24. There are up to 8 spare satellites that can replace satellites that become defunct. The spare satellites are however also used to provide additional measurements that enhance the GPS performance. [2]



Figure 9: GPS satellite constellation [13]

GPS offers two types of services:

1. Standard Positioning System (SPS): This service is open to all and is available throughout the world. It is based on the use of L1 and C/A code (coarse acquisition). The skew on a horizontal plane in the SPS is less than 10 m, with a view to the sky undisturbed.
2. Precise Positioning System (PPS): This service is intended for military use. It is based on the use of the P (Y) code and the Y code is not generally known. The PPS service has a much smaller error and more protection against human-to-human interference than the SPS service.

- **Galileo Description**

The European Space Agency (ESA) is currently working on the installation of the GNSS system Galileo. The system is expected to be fully operational in 2020 and it will have of 24 satellites plus 6 extra satellites, i.e. a total of 30 satellites.

The system was opened to the public for testing in December 2016 and it is designed to provide more accuracy than GPS.

Galileo will offer more services than GPS.

1. Open service will be open to all world citizens free of charge, shown in
- 2.
3. Table 2.

Table 2: Service performances for Galileo Open Service [15]

	<b>Galileo Open Service (positioning &amp; timing)</b>	
	<b>Single Frequency (SF)</b>	<b>Dual Frequency (DF)</b>
<b>Coverage</b>	Global	
<b>Accuracy (95%)</b>	Horizontal: 15 m	Horizontal: 4m
	Vertical: 35 m	Vertical: 8m
<b>Availability</b>	99.8 %	
<b>Timing Accuracy wrt UTC/TAI</b>	N/A	30 ns
<b>Ionospheric Correction</b>	Based on SF Model	Based on DF Measurements
<b>Integrity</b>	No	

***Service Performances for Galileo Open Service***

Single frequency service uses band L1, E5a, E5b or E5a and E5b together, while dual frequency service uses L1 and E5a for the best ionospheric error cancellation.

4. Commercial service. Users pay for the service in order to get a guaranteed service quality, e.g. availability.
5. Search and rescue (SAR) service. Here is a lot of support for searching for people in need. The satellites target the location of the emergency center on UHF, which allows a 98% probability of finding the emergency sign 100 meters within 10 minutes. Additionally, you can send messages through Galileo satellites to emergency services. This improves the rescue service and reduces the likelihood of false emergency services.

6. Security of life. This service is provided at a surcharge. It is designed to increase the safety of people and goods and to provide service insurance, etc. under. International Civil Aviation Organization (ICAO) and International Maritime Organization (IMO) requirements.
7. Public regulated services. This service is intended exclusively for government agencies. The service is encrypted with special protection against anti-jamming. The service is conceived for security services, parties that run important infrastructure and for military use. [5]

- **GLONASS description**

Globalnaya Navigatsionnaya Sputnikovaya Sistema (GLONASS) was completed in 1995, but in 2001 it was almost neglected due to the bad economic situation of Russia. But in 2007 the system was rebuilt and now it consists of a cluster with 24 satellites spread in three different orbits. Likewise, GPS, GLONASS offers the same 2 services (SPS and PPS) with a comparable accuracy. [4]

- **BeiDou description**

This service has been available since 2000 in China and neighboring countries, but in 2006 the Chinese government decided to expand their services all over the world. They will finish the BeiDou satellite system by 2020. [6]

Beidou's services are divided into two: local services and all-terrain services. Both of them include two modes:

1. Public service: comparable to GPS and offering accuracy within 10 meter.
2. Authorized service: It will probably be paid and more reliable.

- **IRNSS (Indian Regional Navigational Satellite System) or NAVIC description**

IRNSS will be a GNSS developed and built by the Indian government. It is planned to have 7 satellites (Figure 10), three of them are on geostationary orbits (GEO), and it is planned to cover an area of about 1500 kilometers around India.

There will be two services: Special Positioning System (SPS) and Precision Service (PS). Both of them will be carried on L5 band (1176.45 MHz) and S band (2492.08 Mhz).

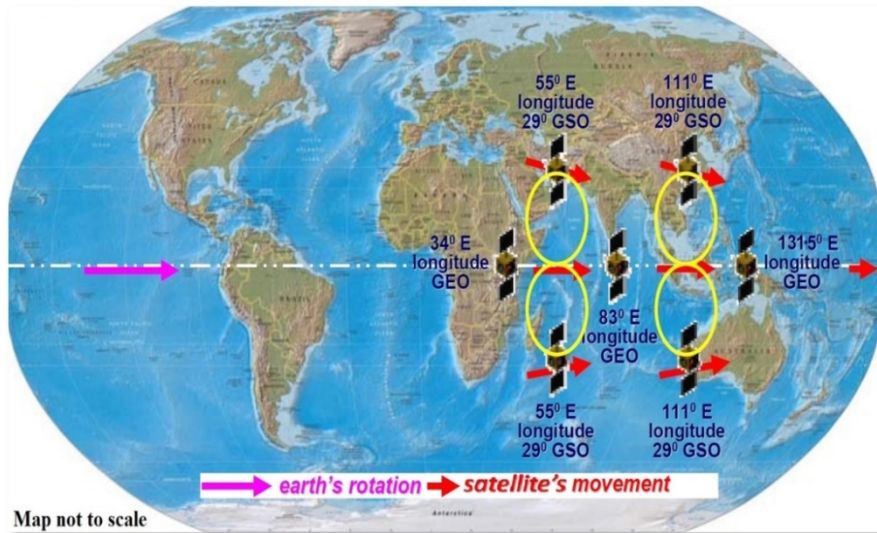


Figure 10: IRNSS satellite constellation [14]

- **QZSS (Quasi-Zenith Satellite System) description**

The QZSS is a regional satellite system developed by the Japanese government. The QZSS service area covers the East Asia and Oceania regions and its platform is multi-constellation GNSS. The space segment consists of three satellites placed in periodic a Highly Elliptical Orbit (HEO) and a fourth in a geo-stationary orbit, and all of them will pass over the same ground track. QZSS is designed so that at least one satellite out of three satellites exists near zenith over Japan. This ground track helps to reduce the reflections of the satellite signals produced by buildings or vertical surfaces that induce errors in the measurements. [3]



Figure 11: QZSS satellites ground track [3]

## Chapter III: Description

### Hardware used

The hardware required for this project is basically a computer, a GNSS evaluation module and an antenna. The requirements for the Personal Computer (PC) are the possibility to install the evaluation software provided for free by U-Blox support webpage.

The GNSS evaluation module thought at the beginning for this project was either MAX-M8Q or NEO-M8T. Both modules are from the company U-Blox. This company started in 1997 and develops devices related with wireless communication, like modules built for GNSS communication. The company also offers support like product resources and evaluation software.

The MAX-M8Q module was chosen because it can receive information from up to 3 GNSSs concurrently. It means that every single combination of constellations (GPS, GLONASS, Galileo and BeiDou) can be tracked, which is very convenient for this project. GPS, GLONASS and BeiDou are enabled for default, but Galileo is not. It can be enabled by sending a configuration message to the module.

In Figure 12, the block diagram of MAX-M8 is shown. It is possible to see that it just has two possible interfaces available: UART and I2C.

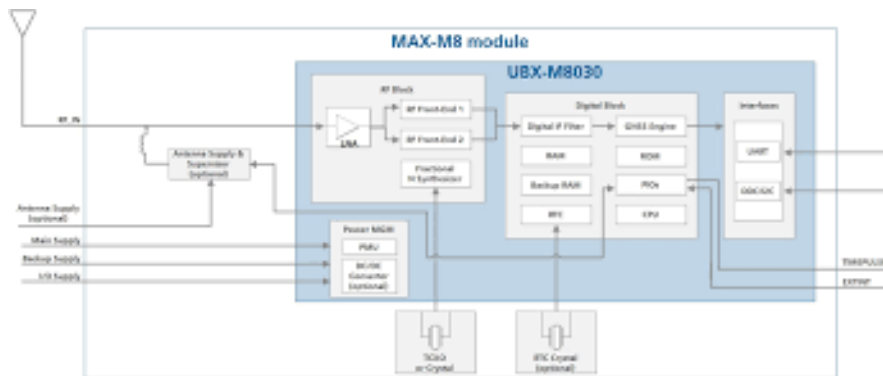


Figure 12: MAX-M8 Block Diagram

The easiest way to communicate the module with the computer is the USB interface, which is not available in this module. Therefore, two options were possible at this point, either look for a UART-USB bridge or use another module for the GNSS evaluation.

The first option was explored and the findings were that the UART-USB bridge STEVAL-PCC018V1 (Figure 13) is easy to set up and cheap.



Figure 13: STEVAL-PCC018V1 USB-UART bridge

But even though it was a pretty good solution, the shipment was expected to take too much time, so this option was discarded.

The second option was, to use a different module: NEO-M8T (Figure 14). This module was chosen for the same reasons as MAX-M8Q modules. It can track many GNSS systems concurrently, because of the dual RF front-end architecture (it is possible to see it in the block diagram in Figure 15). Due to the fact that Galileo, QZSS and SBAS share the same frequency band as GPS, they can always be tracked together with GPS. But overall, the main reason is, as shown in Figure 15, NEO-M8T has a USB interface available in the module board.



Figure 14: NEO-M8T GNSS module

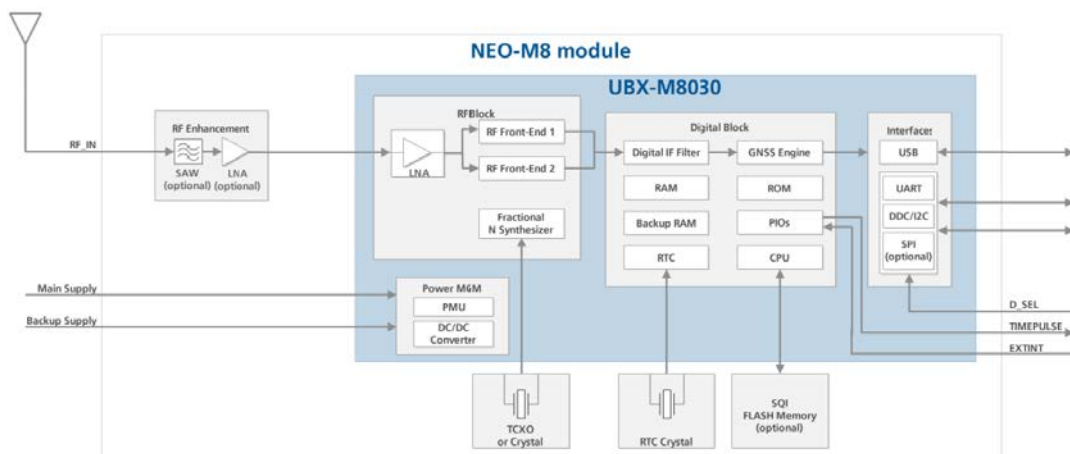


Figure 15: NEO-M8T Block diagram



The last part of the hardware equipment is the antenna. The antenna chosen for this task is *Tallysman Accutenna® TW2410/TW2412 Magnetic Mount GPS/GLONASS Antenna* (Figure 16).



Figure 16: Antenna for reception of GNSS signals

This antenna is a good option for working with Galileo because its technology covers GPS L1 and GLONASS L1 frequency bands, which as seen in Figure 7, Galileo's E1 frequency band also works within this threshold. One of the main benefits of this antenna is the design to reject multipath signals, which as explained in the GPS error budget (Table 1) it is a wild card when talking about sources of errors.

## Data

All GNSS broadcast their data under the NMEA (National Marine Electronics Association) protocol. It can be NMEA 0180, NMEA 0182, NMEA 0183 or NMEA 2000. Nowadays the most used standard is NMEA 0183.

NMEA standard is a serial communication standard which organizes the information using ASCII encoding when transmitting data. There are many types of NMEA messages, but all of them have the same structure. For this project, there are two important sentences namely GLL and GSA.

Here is an example of GLL NMEA sentence:

```
$GAGLL,4024.66520,N,00347.80755,W,220309.00,A,A*6A
```

\$GAGLL is the first field. The two first letters (GA) indicates that this is Galileo's sentence. GP is for GPS, GL is for GLONASS and GN denotes the rest of GNSS or a sentences coming for more than one GNSS at the same time (GPS+Galileo, for example). In this field, GLL says that this message includes position information. In Figure 17 it is possible to see all fields included in GLL sentence.



```

.      1      2 3      4 5      6 7
      |      | |      | |      | |
$--GLL,1111.11,a,yyyyy.yy,a,hmmss.ss,A*hh
1) Latitude
2) N or S (North or South)
3) Longitude
4) E or W (East or West)
5) Time (UTC)
6) Status A - Data Valid, V - Data Invalid
7) Checksum

```

Figure 17: GLL sentence structure [16]

In the example above, the field 4024.66520 is the latitude. The first two digits are the latitude in degrees (40), and the rest of the number is the minutes in latitude with decimals (24.66520'). Next field indicates the direction of the latitude from the equator, either North or South, North in this case. The field number three indicates the longitude measurement. Again it follows the same format as the latitude field, but the first 0 denotes a negative number, so in this case the measurement is -3 degrees and 47.80755 minutes of longitude to the West, from the Greenwich meridian. Then, this measurement belongs to Madrid, Spain. Field number 5 indicates the Universal Time Coordinated when the measurement was done, and fields six and seven are just control information.

A sentence measured by Galileo in Reykjavík would be something like:  
**\$GAGLL,6408.33715,N,02157.31740,W,122521.00,A,A\*64**

The GSA sentence will now be explained. This sentence helps to evaluate the different Dilution of Precision (DOP): Position (PDOP), Horizontal (HDOP) and Vertical (VDOP). The differences between them are explained in Chapter IV.

```

.      1 2 3      14 15 16 17 18
      | | |      | | | | |
$--GSA,a,a,x,x,x,x,x,x,x,x,x,x,x,x,x,x,x,x,x,x,x,x,x,x,x,x,x*x*hh
1) Selection mode
2) Mode
3) ID of 1st satellite used for fix
4) ID of 2nd satellite used for fix
...
14) ID of 12th satellite used for fix
15) PDOP in meters
16) HDOP in meters
17) VDOP in meters
18) Checksum

```

Figure 18: GSA sentence structure [16]

Here is an example: \$GPRMC,A,3.72,S,80.86,W,0.00,0.00,0.00,1.24,1.79,2.0F

In this case, the GSA sentence is coming from GLONASS. The relevant information for the project is given in fields 15, 16 and 17, which are PDOP, HDOP and VDOP respectively. If there are blanks in the example, it means that there were no satellites available to complete the sentence, which is not necessarily bad.

### Implementation: Hardware and Software

The software used in this project is “*u-center\_v18.05.02*”. This evaluation software is developed by U-Blox as a support for their devices and is very helpful while working with GNSS because of the broad options available for GNSS study. The most helpful option is (the possibility) to select which GNSS (or combination of them) is going to be recorded. This option/action saves a lot of time because, otherwise it would take very long to filter the relevant sentences for the subsequent comparison.

There is also one option that makes this software perfect for this project: it offers the possibility to display a deviation map (and some other interesting displays), which is very convenient for the discussion of the results. The deviation map is a chart where the information coming from GLL sentences is plotted in a graph with East-West and North-South coordinates.

This software was released as a support for the devices sold by the company and is totally free, along with the drivers if required. In this case, the driver *u-blox GNSS VCP Device Driver for Windows, v3.10* was installed in the PC used for this project.

To configure the module for receiving GNSS data, some instructions have to be sent through the USB port. Basically, the main instructions used in this project were UBX-CFG-GNSS and UBX-CFG-CFG. In Figure 19 and Figure 20 the configuration assistants inside the u-center software are shown. The first one allows to enable which GNSS are going to be tracked or recorded by the module.

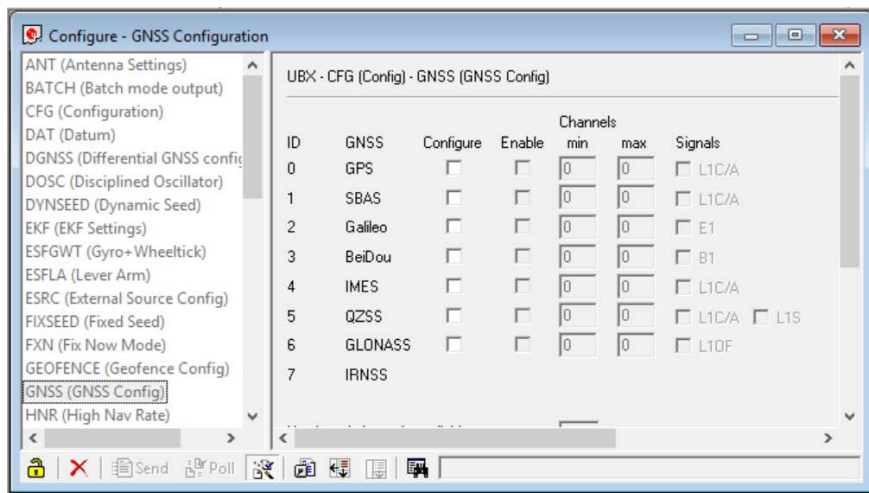


Figure 19: GNSS Configuration assistant

And the second one allows to save the configuration set before recording .

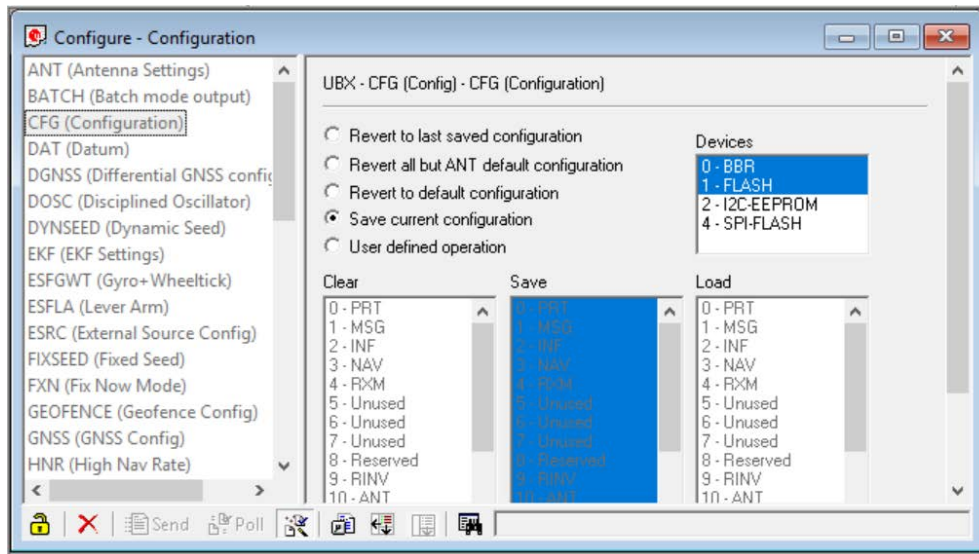


Figure 20: Configuration assistant

## Gathering Data

Gathering data is important. A milestone in this project was to find the way to record information from the satellites and how to organize it in order to find relevant results. The first step on gathering data is to set up all devices and software required, as explained before, for recording satellites activity. Every recording is about 24 hours approximately, which is consider to be a big enough sample for a later study of it.

It is interesting to see how different GNSS work for the same purpose, to measure the location of a spot on the earth surface. A comparison between different GNSS result could be interesting to evaluate Galileo's performance. For this reason, the gathering data system had to work several days in a row recording all relevant GNSSs (Galileo, GPS, GLONASS, BeiDou) and their combinations.

The main problem here is that the files were huge to be process entirely in Matlab, at least with the PC available. Every single file has a lot of non-useful sentences for the project, and their process just led to stall the computer several times.

Therefore, before to be able to plot and show the relevant information coming from the satellites, it was necessary to filter or select the sentences that give the information related with position and Dilution of Precision (GSA and GLL sentences). For this task, notepad++ ended up being a very useful software for filtering the sentences from these huge files recorded. With notepad++, a manageable text file with relevant data is achieved and it can be imported later into an Excel document where the information from the satellites can be organized. This organization is mainly based on two different types of excel files: GLL file for 2DRMS calculation and GSA file for DOP calculation.

2DRMS (2 times Distance Root Mean Square) and DOP (Dilution of Precision) are two representative rates when calculating the location of a position and its quality.

Finally, the last step of the procedure is to import these GSA Excel files to Matlab (using the `importdata` instruction) and plot the scatter diagrams to show how DOP changes during the time recorded.

## Chapter IV: Analysis of the results

### Longitude explanation

The main problem of a receiver located in a high latitude is the sky view. A receiver located in Reykjavík, Iceland is more likely to see available satellites in a lower height over the horizon, which can carry some problem of precision or accuracy due to the fact that satellites might be less spread out in the sky than a receiver in a lower latitude, like Madrid, Spain.

This is basically the idea which makes understandable why, in order to test Galileo's performance in Iceland, two different latitudes will be compared: Reykjavík (64 degrees) and Madrid (40 degrees). This comparison aims to evaluate if the latitude, where the receiver is located, affects the precision and the accuracy of Galileo.

In order to calculate properly the units' transformation, it is important to explain that 1 longitude degree is not the same in Madrid and Reykjavík.

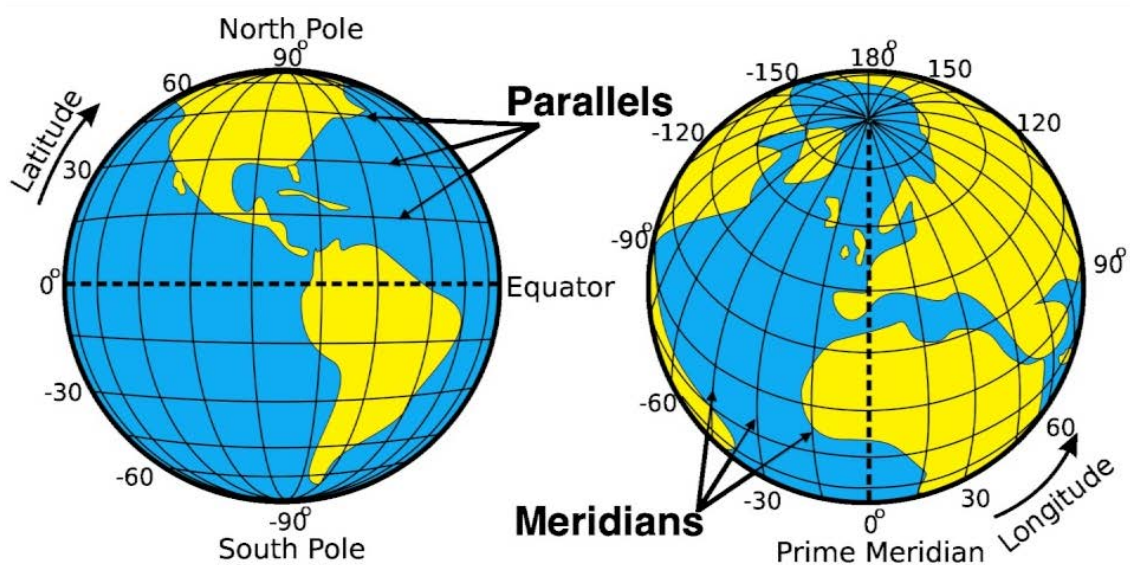


Figure 21: Latitude and longitude visualization [18]

As it is possible to see in Figure 21 all meridians are always the same size, so  $1^\circ$  latitude never changes, it is always constant. But is not the same story for parallels, which change size, shrinking when moving away from the equator. So when the closer is the parallel to the poles, the shorter is the distance in meters on the Earth's surface. It means that  $1^\circ$  longitude has not the same value in meters in Madrid than in Reykjavík. This is important when calculating the DRMS, because it is in meters.

To calculate this transformation, it is necessary to turn to the definition of nautical mile. One nautical mile is defined as one minute of a meridian (Figure 22) and this distance is 1852 meters approximately [20].

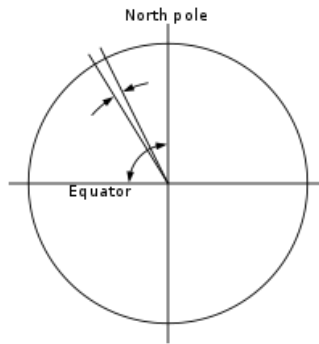


Figure 22: Nautic mile definition

Therefore, to find the value of  $1^\circ$  latitude, and  $1''$  latitude is necessary to multiply and divide 1852 by 60, respectively. So  $1^\circ$  latitude is about 111.12 km, and  $1''$  latitude ( $1'/60$ ) is about 30.87 meters.

As seen in Figure 21 and Figure 22, one degree in longitude depends on latitude. And this dependence is multiplying  $1^\circ$  in latitude by the cosine of the latitude studied

In Reykjavík the latitude is about  $64^\circ$ , therefore  $1^\circ$  longitude is about 48.71 km ( $111.12 \text{ km} \times \cos(64^\circ)$ ) and  $1''$  is 13.53 meters approximately. But in Madrid, longitude changes. Madrid is located about  $40^\circ$  from the equator, so  $1^\circ$  longitude is about 85.1 km and  $1''$  is 23.36 meters approximately.

The Table 3, summarize these calculations:

Table 3: Degrees to meters equivalences

	Reykjavik	Madrid
$1^\circ$ latitude	111.12 km	111.12 km
$1''$ latitude	30.87 meters	30.87 meters
$1^\circ$ longitude	48.71 km	85.1 km
$1''$ longitude	13.53 meters	23.36 meters

## Relevant studied rates

In order to quantify the quality of Galileo's performance, it is relevant to calculate 2DRMS and DOP index.

Distance Root Mean Square (DRMS) represents the radius of a circle which includes 68% of measurements recorded in a specific amount of time (in this case, every recording is about 24 hours). This circle has its center in the coordinate origin of a chart where the receiver is supposed to be placed, and whose axis are latitude and longitude. In this chart the errors of the measurements in meters are plotted.

But the relevant rate is 2 times DRMS (2DRMS), whose radius includes 95% of the measurements done.

If 2DRMS is a large number, it means that the measurements of the location are very dispersed, therefore, there is a low accuracy of the system. On the other hand, a small 2DRMS indicates that the system is very accurate, because almost all measurements are in a very reduced space.

As said before, 2DRMS is defined as two times DRMS:  
 $2drms = 2 \cdot drms$

And this number is defined as

$$drms = \sqrt{(r_1^2 + r_2^2 \dots r_n^2) \cdot \frac{1}{n}}$$

Equation 1: DRMS definition [21]

Here  $\mathbf{r}$  is the distance from the origin (where the device is actually located), see Figure 23, to the measurement done by the system. Therefore, a perfect accuracy means every  $\mathbf{r}$  equals to 0 and DRMS would be null.

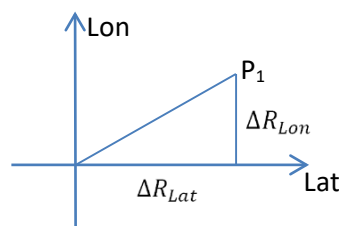


Figure 23: Error distance

$$P_1 = (Lat_1, Long_1)$$

Equation 2: Point measured coordinates

Those  $\mathbf{r}$  are calculated as the square root of the sum of  $\Delta$  Lat on the square and  $\Delta$  Long on the square of the measurement (Pythagoras theorem).

$$\Delta R^2 = \Delta R_{Lat}^2 + \Delta R_{Lon}^2$$

Equation 3: Delta R calculation

Delta is the subtraction between the latitude/longitude measured and the average latitude/longitude of all measurements (n) done in the recording.

$$(\overline{Lat}, \overline{Lon}) = Avg (Lats, Longs)$$

Equation 4: Origin calculation

$$\Delta P_1 = (Lat_1 - \overline{Lat}, Lon_1 - \overline{Lon})$$

Equation 5: Delta Point measured coordinates

Here, Avg means average, and suffix 1 means measurement 1.

It is possible to make this operation faster by understanding that DRMS is:

$$drms = \sqrt{(\sigma_x^2 + \sigma_y^2)}$$

Equation 6: Equivalent DRMS definition [22]

Where  $\sigma_x$  and  $\sigma_y$  are the standard deviations of all latitudes measured and all longitudes measured.

So the rate it will be calculated later is 2DRMS:

$$2drms = 2 \cdot \sqrt{(\sigma_x^2 + \sigma_y^2)}$$

Equation 7: Equivalent 2DRMS definition

As said before, files with these measurements are GLL files, and as a result of selecting the proper sentences and apply Equation 1, these calculations are summarized in Table 4.



Table 4: DRMS and 2DRMS table

	REYKJAVÍK		MADRID	
	DRMS	2DRMS	DRMS	2DRMS
<b>Galileo</b>	2.001445961	4.002891922	6.641816863	13.28363373
<b>GPS</b>	1.001679455	2.003358909	1.77000327	3.54000653
<b>GLONASS</b>	5.262937175	10.52587435	5.221500015	10.44300003
<b>Beidou-QZSS</b>	30.01018547	60.02037095	31.5434257	63.0868514
<b>Galileo-Beidou-QZSS</b>	3.087619698	6.175239395	6.068836122	12.13767224
<b>GLONASS-Galileo</b>	3.691524582	7.383049165	4.656879665	9.313759329
<b>GPS-Galileo</b>	0.933059546	1.866119091	1.305069019	2.610138037
<b>GPS-GLONASS</b>	1.018843853	2.037687706	2.428703252	4.857406505
<b>GPS-SBAS</b>	1.120356975	2.240713949	1.681769568	3.363539137
<b>Galileo-SBAS</b>	2.100962979	4.201925958	16.68820994	33.37641988
<b>GLONASS-SBAS</b>	5.63325838	11.26651676	6.169353368	12.33870674

The information gotten from GLL sentences (explained in chapter III), is not in the right units for calculating the standard deviation. The format is DDmm.mmmm, where the 2 first digits are sexagesimal degrees, and the rest are minutes and minute decimals.

In order to get all the measurements in the proper units, it is necessary to understand how the coordinates system works, so the error can be calculated in meters. This has already been calculated before in this document.

The second relevant rate is Dilution of Precision (DOP). This concept is used in navigation to define the effect of geometry on positioning as explained in Figure 8 (*“The geometry is also relevant in order to enhance the accuracy of the system. The more spread the satellites are in the sky the better is the positioning, their lines of position intersect at an angle close to 90°. When the satellites are close to each other, the lines of position intersect at a small angle producing a high Dilution of Precision (DOP). The DOP results from the available geometry and is a multiplication factor for error”*).

Q is an estimate of the matrix of noise’s covariance in the unknowns due to the noise in the measured quantities [17]:

$$Q = \begin{bmatrix} q_x^2 & q_{xy} & q_{xz} & q_{xt} \\ q_{xy} & q_y^2 & q_{yz} & q_{yt} \\ q_{xz} & q_{yz} & q_z^2 & q_{zt} \\ q_{xt} & q_{yt} & q_{zt} & q_t^2 \end{bmatrix}$$

Equation 8: Q matrix

From this matrix it is possible to find PDOP (Position Dilution of Precision), TDOP (Time Dilution of Precision) and GDOP (Geometric Dilution of Precision).

GDOP states how errors in the measurement will affect the final state estimation and it depends on PDOP and TDOP:

$$GDOP = \sqrt{PDOP^2 + TDOP^2}$$

Equation 9: GDOP definition

And using the diagonal from the Q matrix:

$$PDOP = \sqrt{q_x^2 + q_y^2 + q_z^2}$$

Equation 10: PDOP definition

$$TDOP = \sqrt{q_t^2}$$

Equation 11: TDOP definition

At the same time, PDOP can be related with HDOP (Horizontal Dilution of Precision) and VDOP (Vertical Dilution of Precision), which are more intuitive for understanding the quality of the measurements. HDOP and VDOP are defined as follow:

$$HDOP = \sqrt{q_x^2 + q_y^2}$$

Equation 12: HDOP definition

$$VDOP = \sqrt{q_z^2}$$

Equation 13: VDOP definition

In the study coming next, PDOP, HDOP and VDOP will be presented in order to show the DOP. Looking at the diagrams it is possible to see how PDOP is more or less the superposition of HDOP and VDOP diagrams.

To clarify, Table 5 shows some ranges to understand if the values read from the DOP charts are expressing a high or a low quality.

Table 5: DOP quality table [17]

<b>DOP Value</b>	<b>Rating</b>	<b>Description</b>
<1	Ideal	Highest possible confidence level to be used for applications demanding the highest possible precision at all times
1-2	Excellent	At this confidence level, positional measurements are considered accurate enough to meet all but the most sensitive applications.
2-5	Good	Represents a level that marks the minimum appropriate for making accurate decisions. Positional measurements could be used to make reliable in-route navigation suggestions to the user.
5-10	Moderate	Positional measurements could be used for calculations, but the fix quality could still be improved. A more open view of the sky is recommended.
10-20	Fair	Represents a low confidence level. Positional measurements should be discarded or used only to indicate a very rough estimate of the current location.
>20	Poor	At this level, measurements are inaccurate by as much as 300 meters with a 6-meter accurate device (50 DOP × 6 meters) and should be discarded.

### Galileo's performance

Reykjavík and Madrid are the places where the results will be compared.

- Performance in Reykjavík

Figure 24 and Figure 25 are the deviation maps recorded from Galileo GLL files in Reykjavík over approximately 24 hours. The positioning coordinates are 64° 8' 20.2725'' latitude and 21° 57' 19'' longitude.

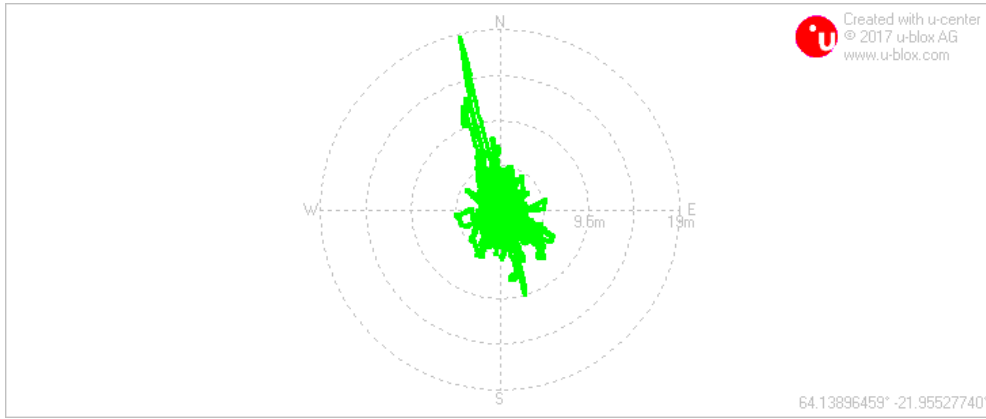


Figure 24: Deviation map by Galileo in Reykjavík

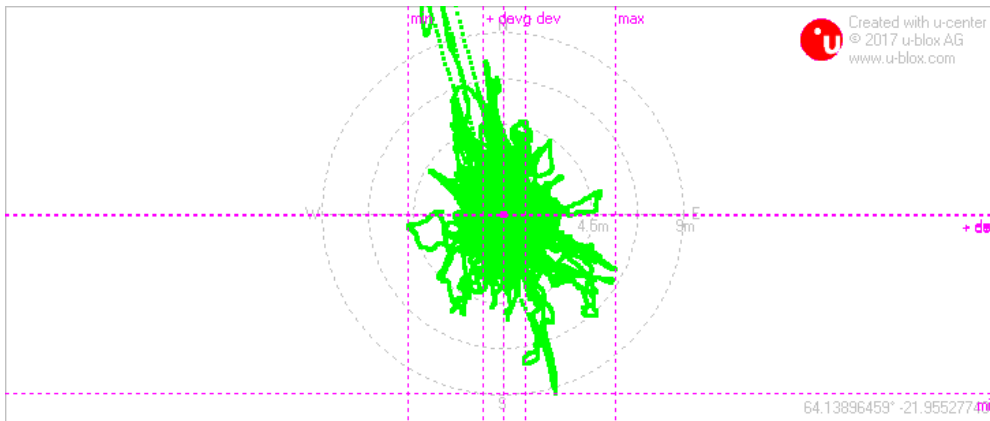


Figure 25: Zoom of Deviation map by Galileo in Reykjavík

It is possible to see in Figure 24 that the maximum error is about 19 meters, and deviation in both directions is quite small, which is consistent with the small 2DRMS (just 4 meters) shown in the Table 6.

Table 6: DRMS and 2DRMS Galileo Reykjavík

DRMS	2DRMS
2.001445961	4.002891922

The errors are mostly oriented in a specific direction. This is something that happens when satellites are aligned in the perpendicular direction, i.e. the PDOP becomes high. This phenomenon is shown in Figures 25, 26 and 27.

After 15:35 hours recording this was the deviation map (Figure 26) :

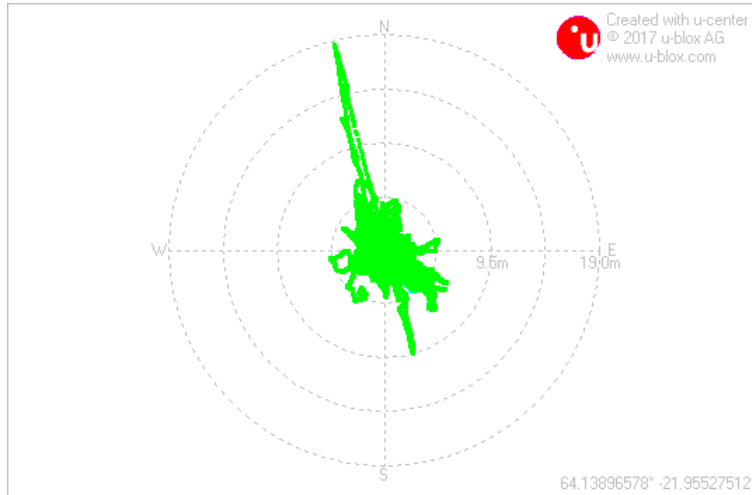


Figure 26: Deviation map after 15:35 hours recording

In Figure 27 the satellite alignment in the sky is shown.

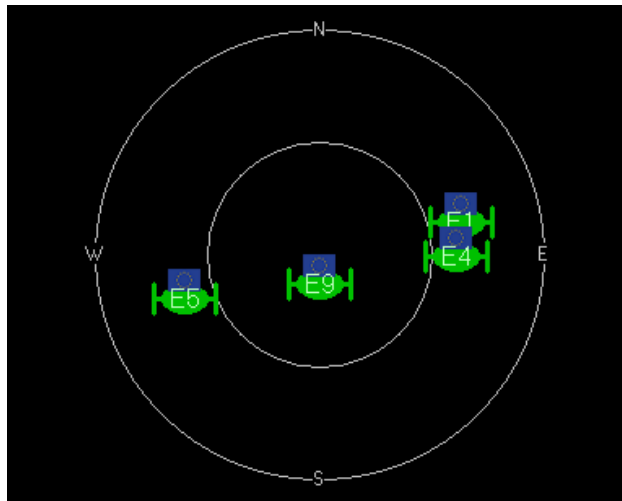


Figure 27: Sky view at 4 am

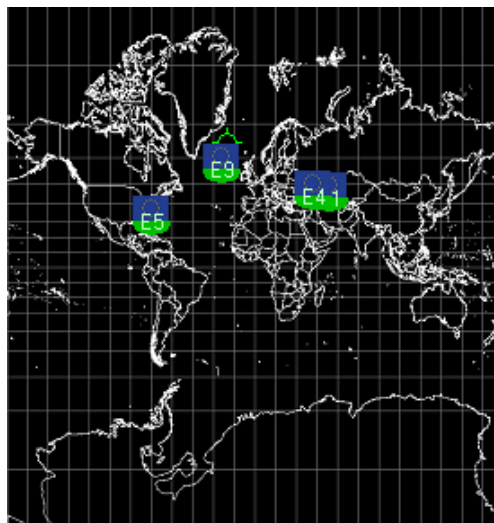


Figure 28: projection of the satellites on the ground

At this moment, there are just four Galileo satellites for calculating the position of the receiver. And due to the fact that they are moving, it is expected that the optimal geometry for positioning could be lost during a period of time. This fact should appear somehow in the Galileo GSA files, where DOP is recorded during this time. Next figures show the scatter diagram of PDOP (Figure 29), HDOP (Figure 30) and VDOP (Figure 31). As it is possible to observe, after 15 hours recording, there is a peak in every DOP chart, and as explained before, DOP will affect the measurements as a multiplication factor.

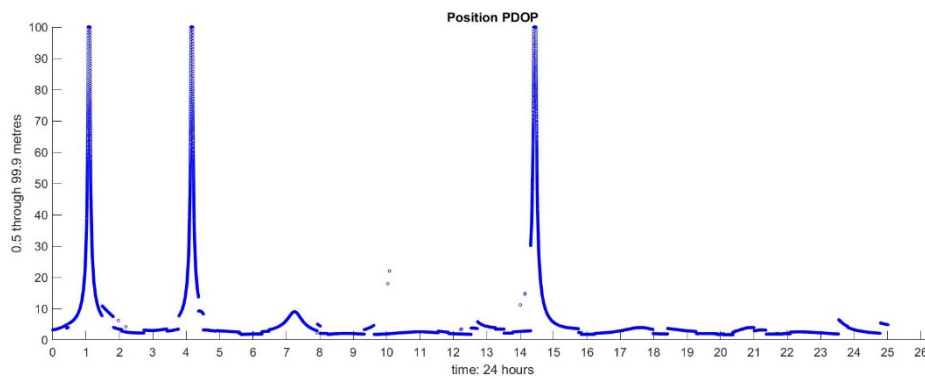


Figure 29: PDOP Galileo in Reykjavík

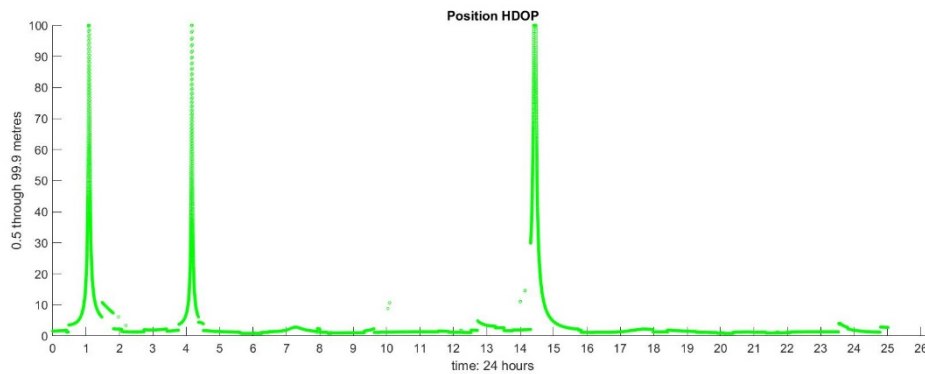


Figure 30: HDOP Galileo in Reykjavík

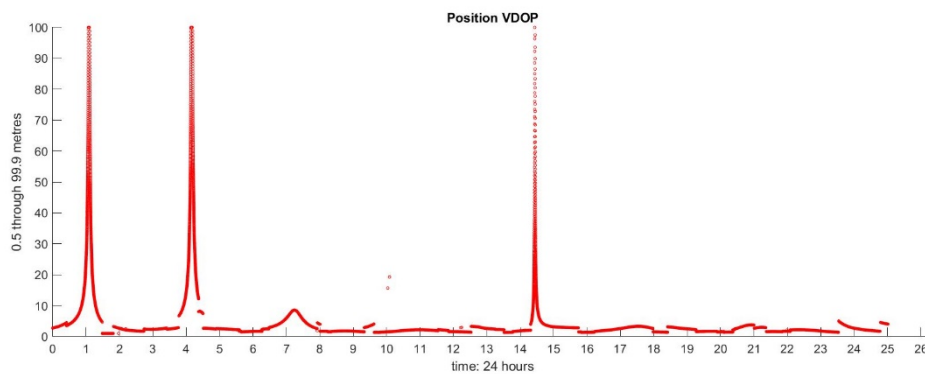


Figure 31: VDOP Galileo in Reykjavík

After all, this peak on the error is a problem related with the satellites location, because the optimum geometry was not available for positioning due to the fact that all satellites available were aligned. So this problem would be solved finding more satellites available at that time. This type of event happens because Galileo's constellation is not complete yet, it is expected to be complete in 2020.

In order to test if more satellites will reduce the error related with DOP, more satellites should come into play and the easiest way is to compare Galileo's DOP during 24 hours with another GNSS performance. The most interesting GNSS to compare with is GPS or GLONASS and test the performance either using one of them or combined with Galileo.

- Performance in Madrid

Figure 32 and Figure 33 show the deviation map of Galileo after one-day recording. It is possible to see that here, the maximum error is around 68 meters.

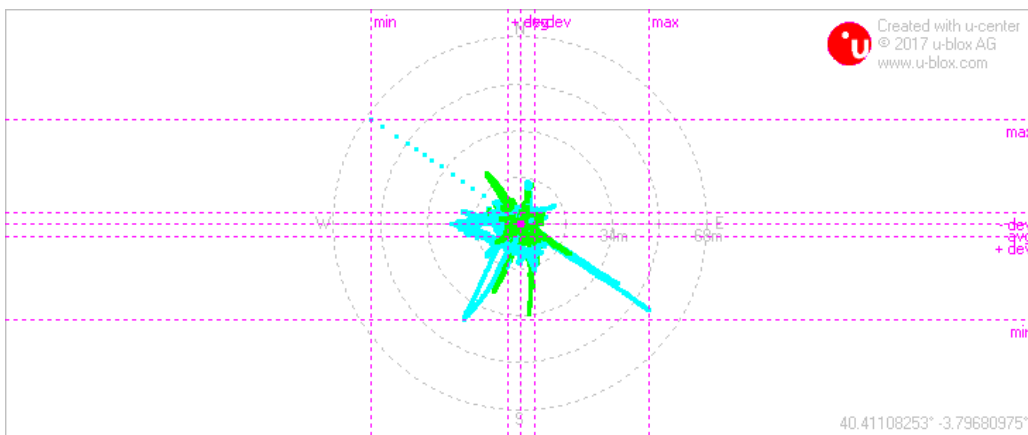


Figure 32: Deviation map of Galileo in Madrid

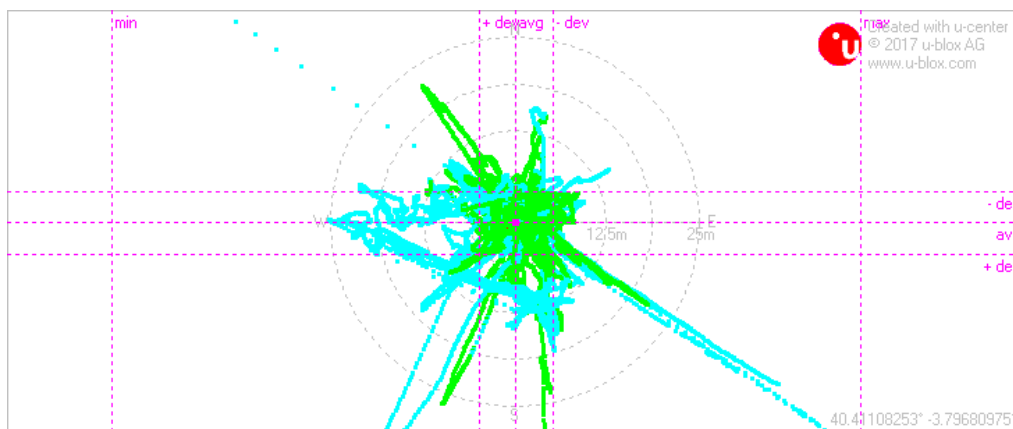


Figure 33: Zoom of deviation map of Galileo in Madrid

Table 7: DRMS and 2DRMS of Galileo Madrid

DRMS	2DRMS
6.641816863	13.28363373

In this case, such a huge peak of error has consequences in the 2DRMS. The 2DRMS indicates that 95% of the measurements are in a circle with a 13.28 meters' radius. Again, it is possible to see the error in a very concrete direction, which is the perpendicular to the satellites alignment in the sky.

In Figure 34 the moment is shown when the peak is reached and the satellites alignment (Figure 35) at this moment: Time recorded: 19:13 hours.

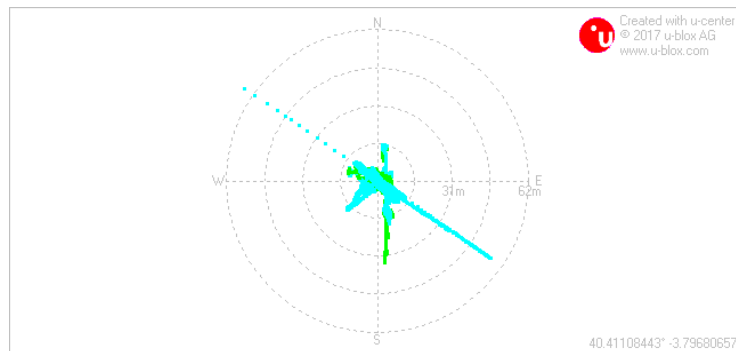


Figure 34: Moment where the error peak is reached in Madrid by Galileo

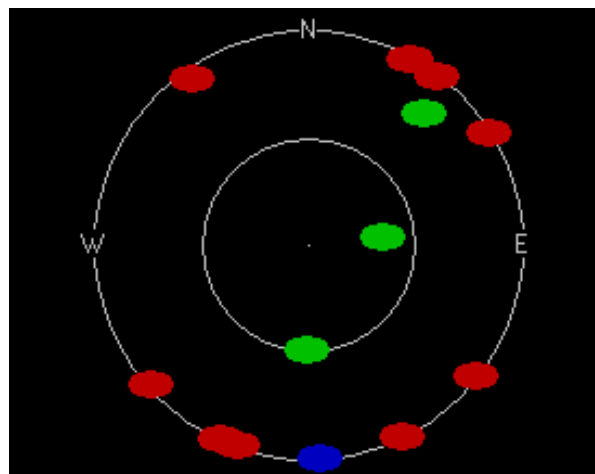


Figure 35: Sky view at that moment.



In the Figure 34 and Figure 35 the instant is shown where the maximum error (around 68 meters) is reached in the deviation map. It is after 19:13 recording when the event happens and the direction of the error is perpendicular to the satellites alignment.

In Figure 34, there are just 3 satellites available (green color) aligned in the sky, so the error is very big while the satellites are in these positions. After some time, new satellites become available and the geometry changes allowing a better position estimation.

These colored dots represent the satellites and their state. Green means satellite available used in navigation (without aiding data or assisted information), blue means satellite signal available but not for use in navigation and red means satellite signal not available. [23]

The fact that this alignment is possible makes the system less reliable. It can be solved with more Galileo satellites or using satellites from another cluster, like GPS or GLONASS. As said in last section, talking about the performance Reykjavík, Galileo's constellation is not totally unfolded, so these kind of error are expected.

To avoid this error an extra GNSS could be used. This case will be discussed later when Galileo and GPS are used at the same time to calculate the same position.

In Figure 36 and Figure 37 it is possible to see how the PDOP and HDOP reach the maximum value, which means a high error multiplication factor because of the deficient geometry of the satellites at 19 hours.

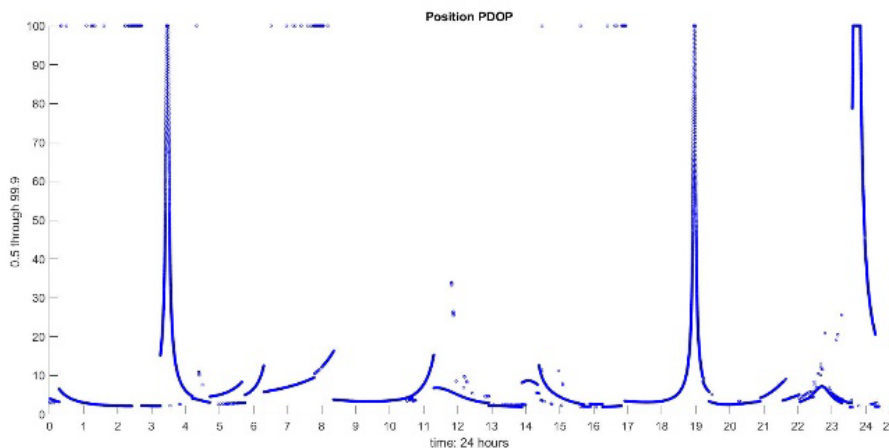


Figure 36: PDOP Galileo in Madrid

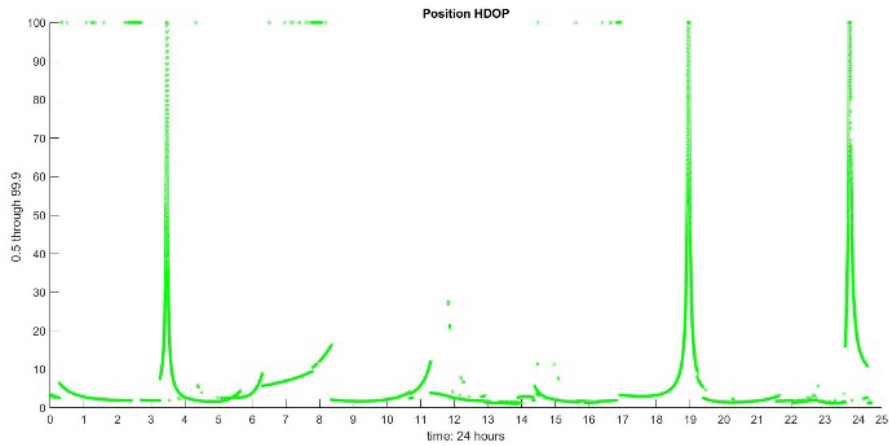


Figure 37: HDOP Galileo in Madrid

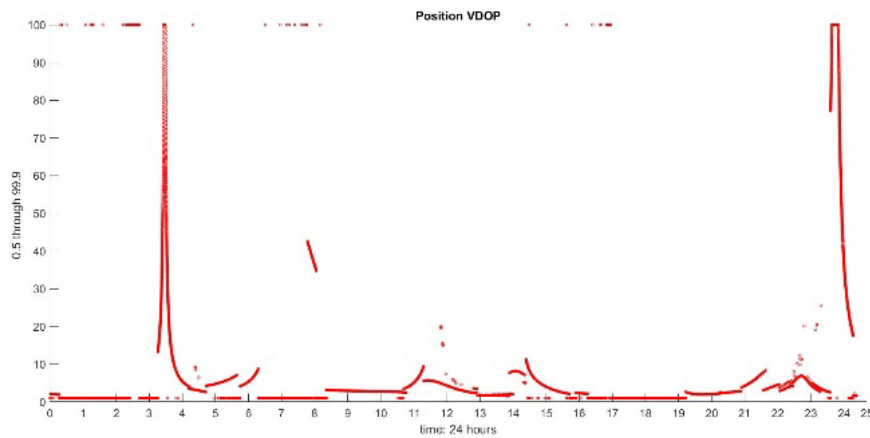


Figure 38: VDOP Galileo in Madrid

## GPS' performance

- Performance in Reykjavík

To check if the presence of more satellites could enhance the performance, Galileo's results are going to be compared with GPS in this section.

In the Figure 39 the deviation map shows how the error is always lower than 3.5 meter during the whole time it was recorded (24:02:09 hours).

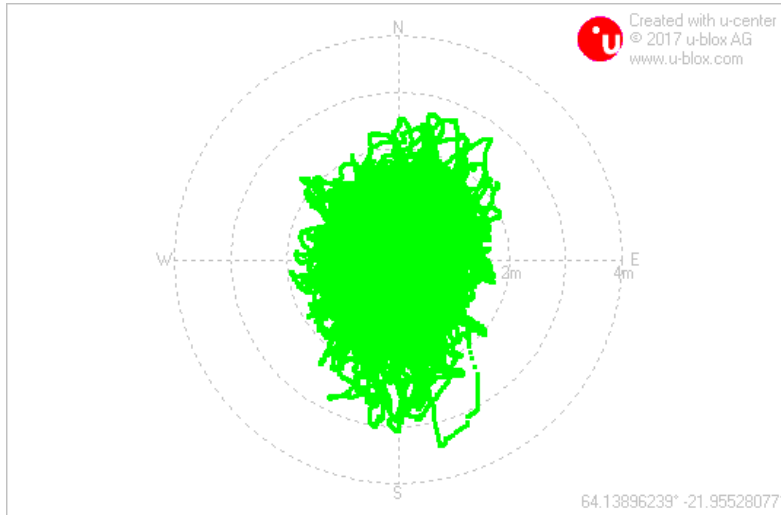


Figure 39: GPS deviation map in Reykjavík

Table 8: DRMS and 2DRMS GPS Reykjavík

DRMS	2DRMS
1.001679455	2.003358909

According to 2DRMS calculation in Table 8, the accuracy of the GPS is actually very good, because 95% of measurements are inside a circle with 2 meters radius. This is half of the radius calculated for Galileo in Reykjavík, as shown in Table 4 and Table 6.

At the end of the record the sky view is shown in Figure 40. As it is possible to see, there are 9 available satellites for positioning, which allows the optimum geometry for the device location.

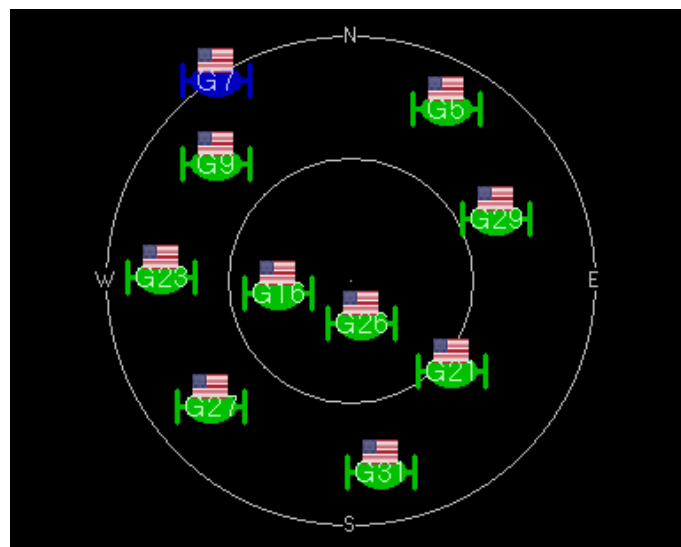


Figure 40: Sky view in Reykjavík by GPS

The high presence of available GPS satellites makes the DOP lower than for the Galileo navigation system. In the following images the DOP value is always lower than 4, which is a very good rate and assure a low error (remember scatter DOP diagrams from GNSS Galileo, where DOP reached the maximum, 99.9, several times).

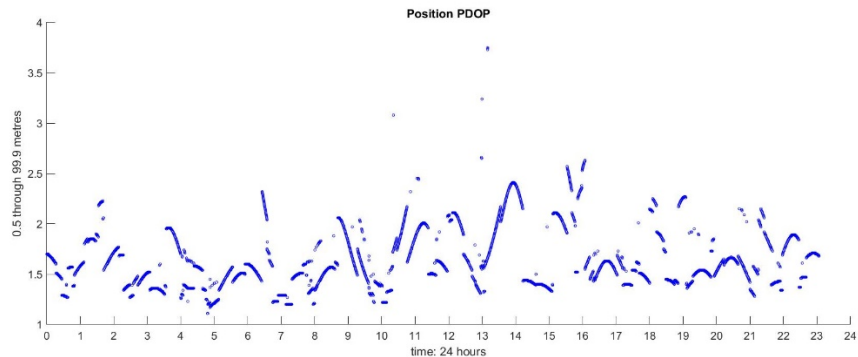


Figure 41: PDOP GPS in Reykjavík

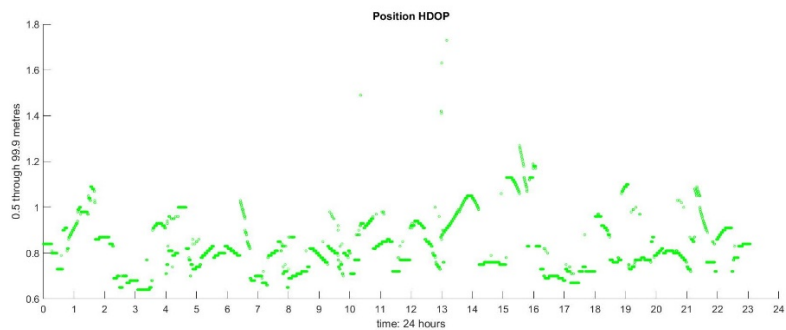


Figure 42: HDOP GPS in Reykjavík

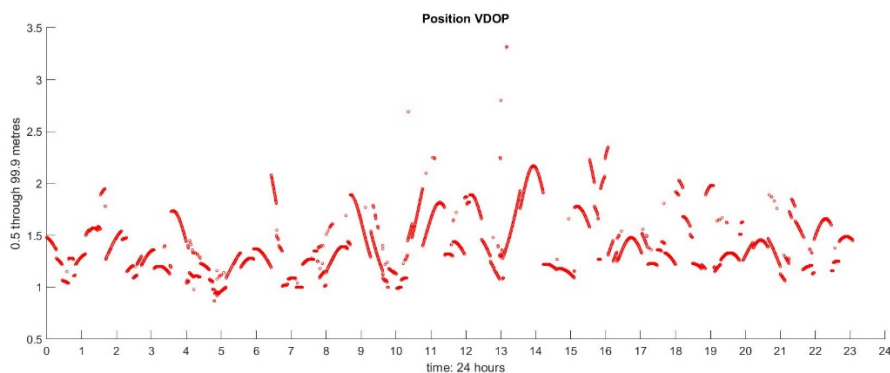


Figure 43: VDOP GPS in Reykjavík

- Performance in Madrid

GPS performance in Madrid is also pretty good, since the maximum error is always lower than 6.5 meter, as shown in Figure 44, after 25 hours and 21 minutes

recording. This good performance is also possible because the high number of satellites available for positioning sky Figure 45.

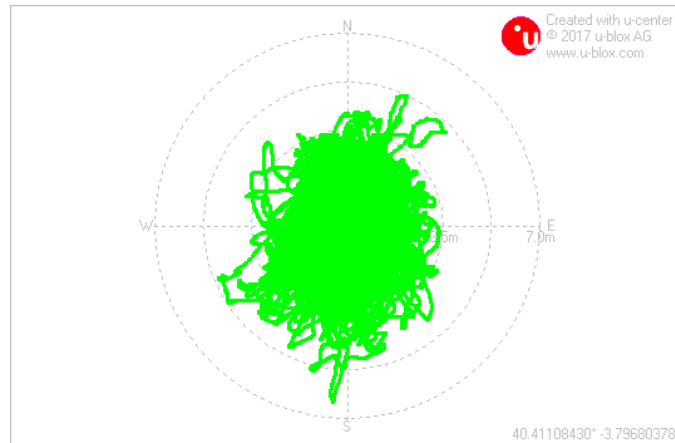


Figure 44: GPS deviation map in Madrid

Table 9: DRMS and 2DRMS GPS Madrid

DRMS	2DRMS
1.77000327	3.54000653

In this case, 2DRMS is 3.54 meters (Table 9). This number is 1.5 meters larger than GPS performance in Reykjavík, but is still very good. Comparing performances in Madrid, GPS is much better than Galileo, where 2DRMS of Galileo is 13.28 meters (See Table 7).

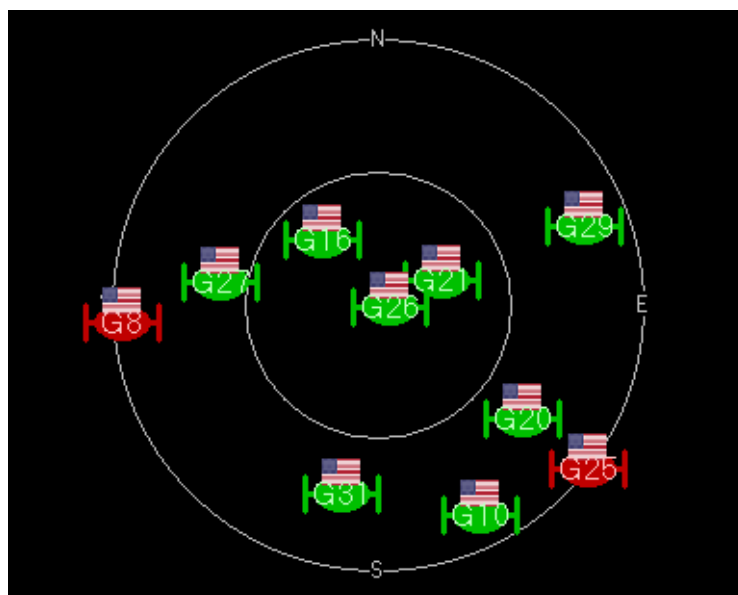


Figure 45: GPS sky view in Madrid

The high number of satellites also reduce the DOP multiplication factor as shown in Figure 46, Figure 47 and Figure 48, where the maximum PDOP is never higher than 6, which means between good and moderate quality according to Table 5: DOP quality table [17].

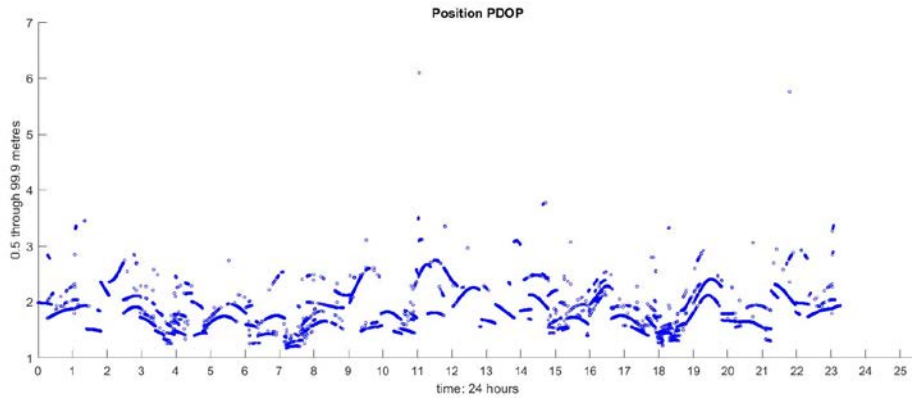


Figure 46: PDOP GPS in Madrid

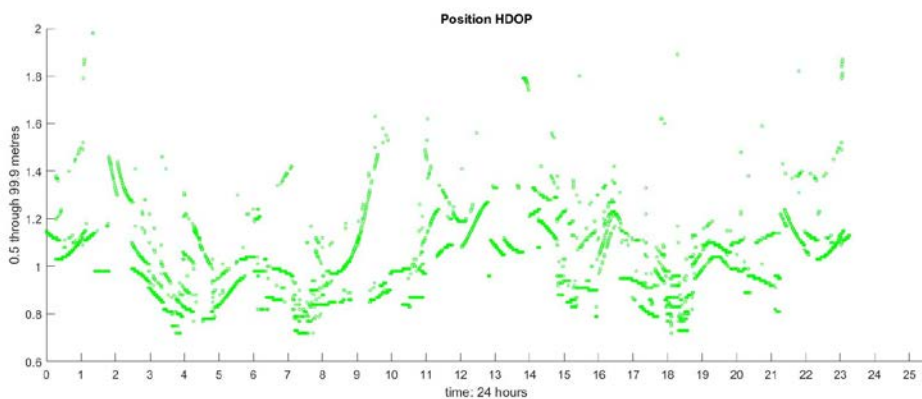


Figure 47: HDOP GPS in Madrid

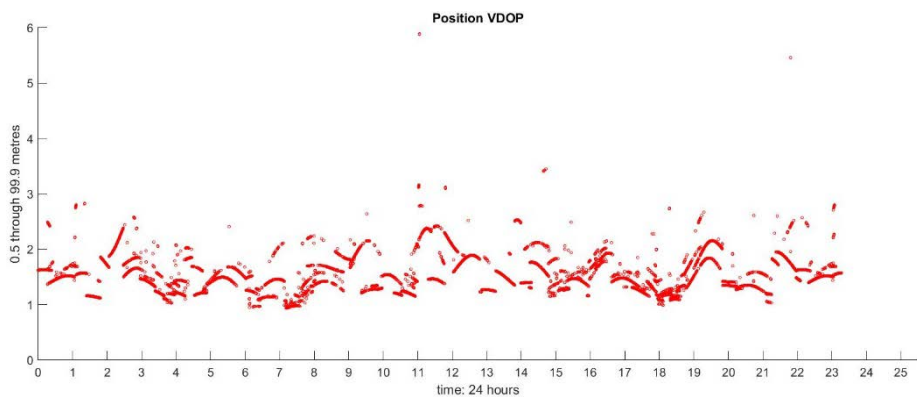


Figure 48: VDOP GPS in Madrid

## Galileo and GPS altogether performance

In this section, results coming from Galileo and GPS in conjunction will be discussed to show that it is possible to enhance Galileo's performance (and even GPS performance too) using another extra cluster from a GNSS already seen before: GPS.

- Performance in Reykjavík

Figure 49 shows now the deviation map in Reykjavík by Galileo and GPS working together. The error is never higher than 3 meter approximately, which is the best result achieved until the moment.

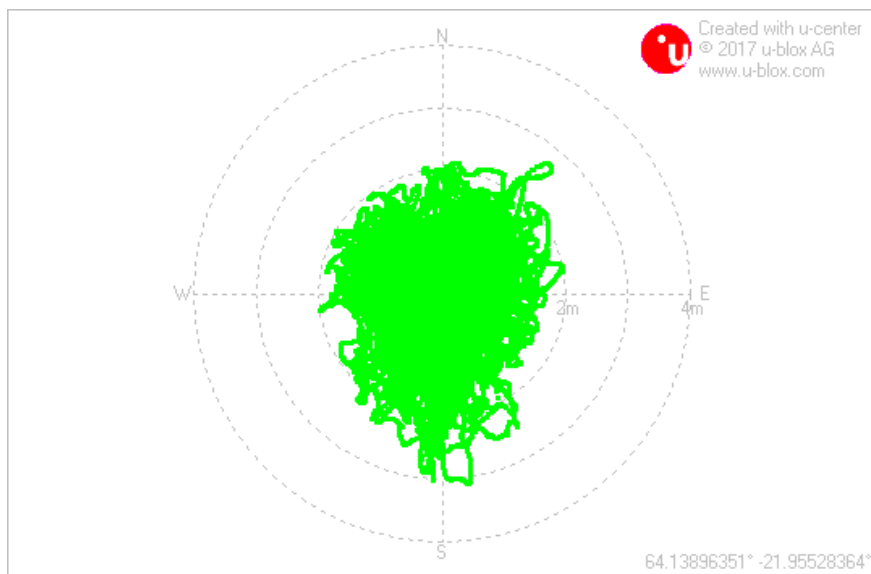


Figure 49: Galileo+GPS altogether deviation map in Reykjavík

As seen in GPS section, there are no errors oriented in very specific directions, the error is more or less uniform around the origin. This is because there is never an alignment of satellites during the recording (24:13 hours) due to the fact that there are lot of satellites available in each moment. As it is possible to see in Figure 50, 16 satellites are being used to find the best geometry for positioning in that moment.

Table 10: DRMS and 2DRMS Galileo + GPS Reykjavík

DRMS	2DRMS
0.933059546	1.866119091

For this reasons, it is not just a coincidence that the 2DRMS is even better than cases before. The 95% of measurements are inside a circle with a radius smaller than 2 meters, just 1.87 meters, which means a very good accuracy of the system. The best accuracy found among the results shown in the initial table (Table 5: DOP quality table [17]).

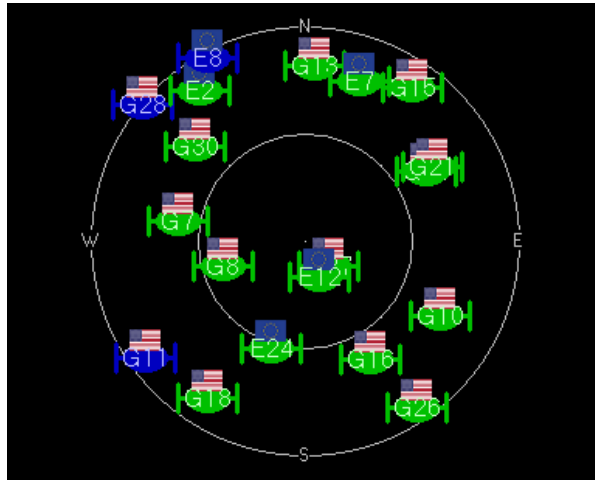


Figure 50: Sky view in Reykjavik using Galileo + GPS

Due to the fact that it is possible to find a better geometry for positioning, DOP charts are expected to show low values. And the images showing PDOP, HDOP and VDOP never reach a value higher than 2.3.

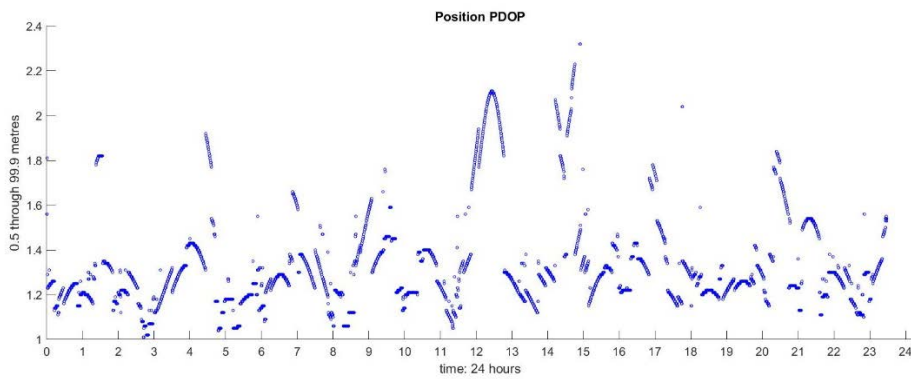


Figure 51: PDOP Galileo+GPS in Reykjavik

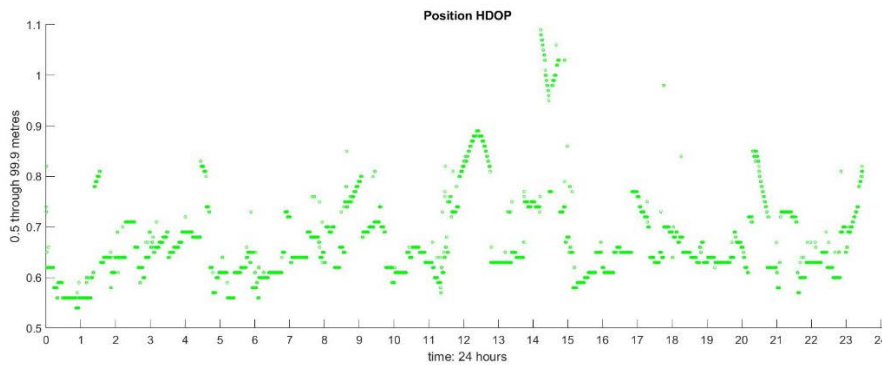


Figure 52: HDOP Galileo+GPS in Reykjavik



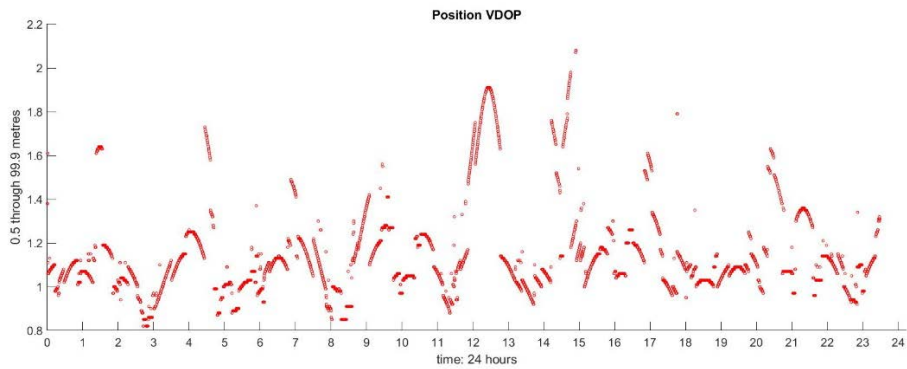


Figure 53: VDOP Galileo+GPS in Reykjavík

- Performance in Madrid

The deviation map of GPS and Galileo working together in Madrid positioning (Figure 54) display that this performance is notable good. The error is never higher than 4 meters, just one meter more than its performance in Reykjavík and better than both GPS and Galileo working alone in Madrid.

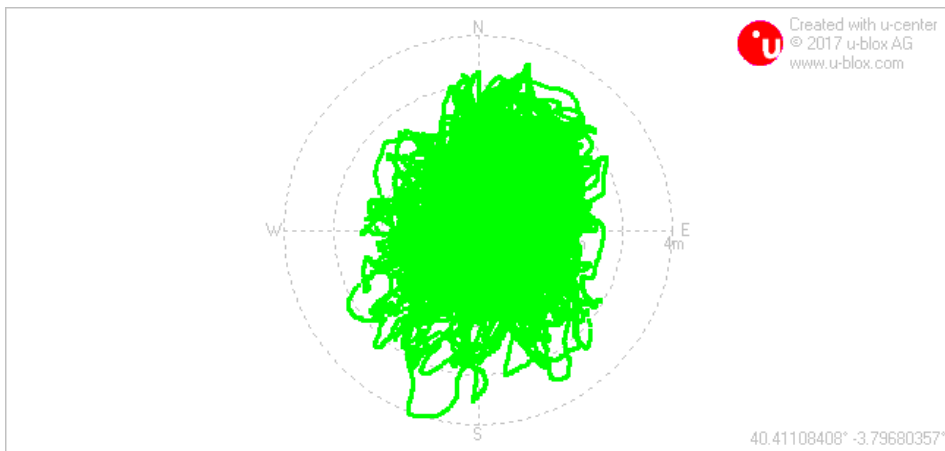


Figure 54: Galileo+GPS altogether deviation map in Madrid

Table 11: DRMS and 2DRMS Galileo + GPS Madrid

DRMS	2DRMS
1.305069019	2.610138037

This fact is also perceptible in 2DRMS, because it less than 3 meters, lower than the performance of Galileo and GPS in Madrid. Even though it is bigger than Galileo+Gps in Reykjavík, the performance is still one of the best ones, so the reason why the error is

bigger is probably because a higher value of the multiplication factor DOP in Madrid than Reykjavík.

After 24 hours recording, this was the sky view at that moment (Figure 55), with 11 satellites available.

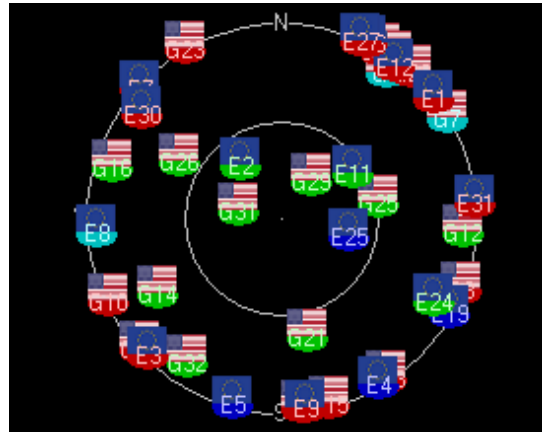


Figure 55: Sky view of Madrid by GPS and Galileo

As expected, the values of every type of DOP are very low (never higher than 2.8 approximately), but still a little higher than DOP rates in Reykjavík (always lower than 2.3). This means an increase of the error seen before.

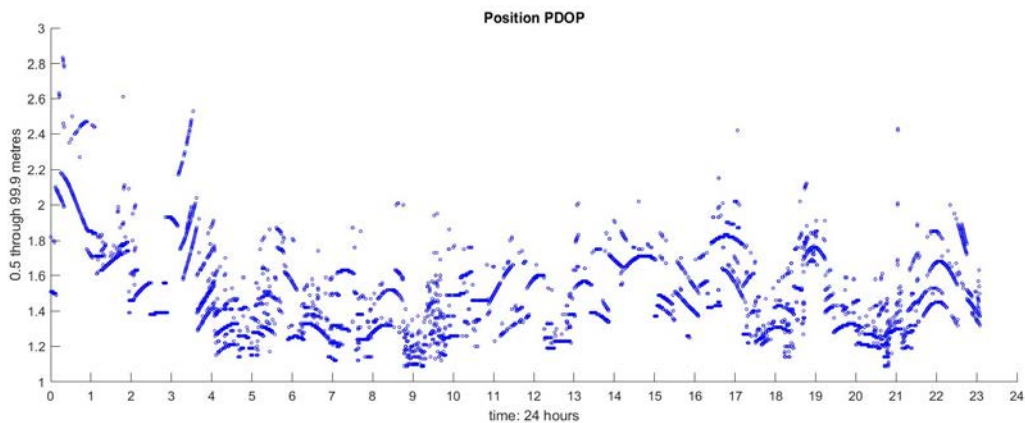


Figure 56: PDOP Galileo+GPS in Madrid

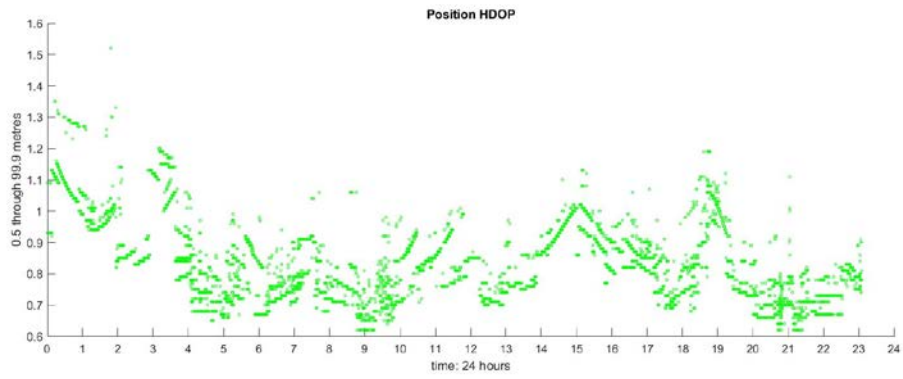


Figure 57: HDOP Galileo+GPS in Madrid

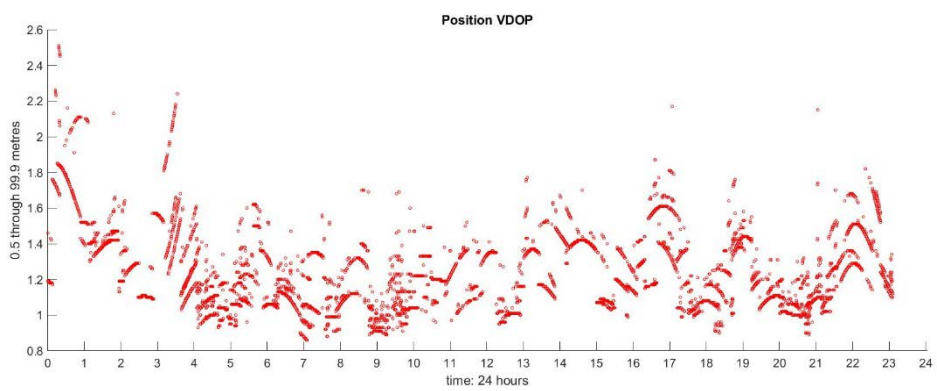


Figure 58: VDOP Galileo+GPS in Madrid

## Chapter V: Conclusions

### Conclusions about methodology

The methodology followed in this project was an important issue. The main problem upon facing the project was the author's scarcity of knowledge in this area, so it was required starting by increasing the knowledge doing a MOOC which explained the essential knowledge of GNSS navigation (See Figure 1: Gantt Chart). With no doubt whatsoever, the GPS MOOC broadcast by Stanford University and the book *Global Positioning System* by Pratap Misra and Per Enge were a very good initial resources to complete the project.

With a more grounded and solid knowledge the technical procedure for recording Galileo's data could start. It took a long time to finally be able to have the GNSS module communicate with the computer, and the main problem was that the NEO-M8T module arrived late from the time it was ordered. It was necessary to spend some time understanding the software and to make a research about NMEA protocol in order to find the relevant sentences for the project. After having recorded all relevant data from the sentences, a new problem showed up, the recording was huge for the software thought initially, as explained in Chapter III. But coping with this types of issues was, at least, expected, therefore it is appropriate to say that the methodology was excellent.

### Conclusions about results

After studying all 2DRMS, DOP diagrams, and deviation maps, there is no sign that proves that Galileo has a better performance in lower latitudes. Not only Galileo, but also all GNSS studied (Galileo, GPS, GLONASS...and their combinations) show there is not a strong correlation between the quality of the performance and the latitude of the receiver.

Galileo is working way much better in Iceland than in Spain. This is surprising, because the initial expectation was to find a lower DRMS in Spain due to the fact that it is in a 40 grades latitude and is more likely to see the satellites more spread out in the sky.

Galileo, GPS and their altogether combination has been studied deeply, but looking at Table 12 (an extract of the main table is repeated below) from the beginning of chapter IV, it is not possible to assure that a high latitude has a negative influence in the performance of any GNSS studied, as expected at the beginning of the project.

Table 12: Extract of Table 5

	REYKJAVÍK		MADRID	
	DRMS	2DRMS	DRMS	2DRMS
<b>Galileo</b>	2.001445961	4.002891922	6.641816863	13.28363373
<b>GPS</b>	1.001679455	2.003358909	1.77000327	3.54000653
<b>GLONASS-Galileo</b>	3.691524582	7.383049165	4.656879665	9.313759329
<b>GPS-Galileo</b>	0.933059546	1.866119091	1.305069019	2.610138037

### Recommendation for future projects

This project took place in 2018, when Galileo is not totally unfolded yet, which is a relevant aspect to keep in mind, as seen in the results. So it would be interesting to repeat a similar study after 2020, when the system will be completed and compare it with this one.

At the same time, it would be interesting to study the performance using Assisted GNSS. The performances studied in this project were unassisted, which means there is no information coming from Galileo's or GPS' augmentation systems. The information is coming straight from the satellites available at the moment. So it would be interesting to study the Assited instructions from *u-center* software. The usage of Assited Galileo would improve the precision and accuracy of the performance, and that is why it would be interesting to compare it with this results shown before, in Chapter IV. Furthermore, it would be interesting to study why the performances of the GNSS are better in Reykjavik than in Madrid, despite a more favorable DOP in Madrid.

## Chapter VI: References

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[1] Pratap Misra, Per Enge, “Global Positioning System. Signals, measurements and performance”, Second Edition, Ganga-Jamuna Press, Lincoln Massachusetts, 2012. ISBN:978-0-97095442-8

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MAX:

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Software:

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Driver:

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