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TFC TITLE: Prototype of a GBAS ground station. Implementation of the differential corrections according to CAT I MOPS ED-114

TITULATION: Telecommunications degree, Specialization in Telecommunications Systems. Aeronautics degree, Specialization in Air Navigation.

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Resum

La precisió que GNSS i GBAS són capaces de donar és la clau per a millorar el trànsit aeri on apareixen els colls d'ampolla: a les àrees terminals dels principals aeroports. La seva implementació representaria reducció de costos i manteniment en comparació als sistemes actuals de control i guiatge, que romandrien com a sistemes de backup.

Aquest projecte, se centra en el processat de la informació que proporcionen els satèl·lits en els seus missatges (navegació i observacions) de forma que es produeixi una sortida que permeti millorar els procediments d'aproximació, navegació i aterratge.

Aquesta millora es dona per mitjà d'un coneixement del posicionament de les aeronaus més precís. Això, comporta diferents tasques com el prototipat d'algoritmes amb Matlab (test de monitoratge d'integritat) amb efemèrides incorrectes i altres errors per validar la resposta del sistema. Es realitzaran comprovacions i tests amb dades reals per analitzar el seu comportament i el impacte que tenen errors coneguts per aconseguir un sistema robust i adaptable.

El següent pas serà la codificació i generació del missatge GBAS (tipus 1) per a l'estació GBAS. Aquesta estació estarà formada per fins a 4 receptors de referència situats en les rodalies de l'aeroport. El missatge generat ha de satisfer amb els requeriment CAT I i proveir dades per a les operacions de aproximació i aterratge.

El projecte es troba ubicat a la base un projecte major anomenat CATGOS, que està sent desenvolupat per Indra, i té com a objectiu la implementació i certificació d'una estació GBAS en un entorn aeroportuari en un termini de 4 anys.

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Overview

The accuracy that GNSS and GBAS can provide is the key to improve air traffic where bottlenecks appear: terminal areas surrounding main airports. Its implementation would represent lower budgets in cost and maintenance in comparison to current guidance systems that would remain as backup.

This project focuses on processing raw satellite data and producing a standard output to increase air traffic navigation, approach and landing capacities in terminal areas. This involves tasks such as algorithm prototyping in Matlab and -integrity monitoring testing- with bad ephemeris data to check the output response. The impact of known errors will be analyzed to obtain a robust and scalable system.

The next step will be the GBAS message codification and generation (Type 1) for a GBAS station. This station will be made up of four reference receivers located in the proximity of airport's Runways to accomplish CAT (I) requirements and provide the best measurements in approach and landing maneuvers.

The project is located in the base of an ambitious bigger scheme (CATGOS) under development by Indra, which aims to implement and certificate a GBAS station for an airport environment in a four-year prospect.

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INTRODUCTION: GNSS and GBAS

Aviation has always been reluctant to import straightaway the knowledge that has been developed in science. The reason for this has been the complexity to adapt scientific advances in such a standardized and homogeneous industry involving such a heterogeneous scenario and actors.

Technological evolution has allowed improvements in many areas, particularly in those related to Navigation. Beacons, navigation systems and aids have enhanced better precision, continuity, integrity and availability requirements as well as a reduction in the workload of controllers or route optimizations.

However, facts such as the economic globalization, the airport saturation and the constant growth in passengers and flights, have been compelling to trigger changes and upgrade present systems.

Navigation is a major issue in the transformations that are expected to happen. In a 10-year horizon, on-board and land positioning systems are meant to work with satellite data in terminal areas. In order to allow predictions come true, several dates have been set in the next years to upgrade and renew the systems and techniques which are used today.

This project purpose is settled along this line. The project's goal is, based on the specifications in the MOPS ED-114, to develop an application to check the performance enhancement provided by a GBAS station in front of the one offered by a simple GPS receiver.

The project consists of three chapters. First chapter contains an introduction to the theoretical bases of GPS and GBAS; it is intended to provide the essential background to understand the project. Second chapter is focused on the organization followed in the development of the application; on one side, there is an application description of the function blocks; on the other side, there is a description of the main functions that are carried out with the user interface developed. Lastly, the third chapter shows the validation process followed to verify the results extracted from the whole procedure; these validations have been developed in two phases: using Pegasus® (Eurocontrol positioning software) in the GPS positioning and using an extra reference receiver to balance the accuracy of the pseudorange corrections provided by the GBAS station.

The scope of this work is limited due the difficulty that comprises to understand the organization of the application, evaluating the results, and checking many important parameters in aeronautics such as continuity, availability and integrity.

The major complexities and limitations will appear when arriving to the validation process. This happens because this technology is still being developed and tested. However, different sets of verifications have been accomplished under different circumstances (time, date, receivers…) to confirm the soundness of the results.

Summing up, this document describes the process followed to develop a prototype of a GBAS ground station according to CAT I MOPS ED-114, including technical definitions of the fundamentals of GPS and GBAS, a description of the function organization, a user interface, and the validations and conclusions that I have drawn throughout its development.

CHAPTER 1: GNSS and GBAS

The sustainability of the air transportation dwells in the capacity to adapt itself to the growth rates that is believed that it will experience.

The answer to this challenge is to improve all the aspects to afford higher capacities of transportation. This means, bigger airplanes, more infrastructures and better systems and practices.

If we speak of the systems and practices to be achieved, they lead us to one significant step: the use of the GNSS to guide and control airplanes.

But what is the GNSS? How does it work and how this technology is capable of improving air navigation? What is the expected scenario when this process comes down to reality?

The word **GNSS** means *Global Navigation Satellite System* and it refers to the systems that are able to determine the position (longitude, latitude and altitude) of a receiver with global coverage in all conditions.

There are two operative GNSS: GPS (officially NAVSTAR-GPS) developed by the American Department of Defence (DoD) and GLONASS developed by the former Soviet Union, although Galileo is currently being built jointly by the European Union and the European Space Agency.

Nowadays, the only fully operational GNSS is the GPS. It is the only reliable system, but the restoration of GLONASS and the Galileo launching can assure the use of this technology as a reliable source.

1.1 GPS general description

The main use of GPS is determining the position of a receiver and it's aimed to be used as a navigation aid in air navigation. Nonetheless, the use of GPS in aeronautics has not been deployed yet in Europe.

GPS was the first GNSS to be built and since this system become free available for civilian use in 1983 it has become the main system to provide positioning worldwide.

1.1.1 System detail

The current GPS is formed by three major segments:

– Space segment (SS): It was originally designed for 24 sv, organized in six planes with four satellites each. The orbital planes are centered on the Earth.

The six planes have a 55º tilt relative to Earth's equator and are separated 60º from each other. The orbits are placed at an altitude of approximately 20,200 Km. and are almost circular. The system is arranged so that at least four satellites are always within line of sight from anywhere in the world except the polar regions.

Nowadays there are 31 actively broadcasting satellites in the GPS constellation. These additional sv are used to provide better measurements by providing additional information.

– Control Segment (CS): The position of every sv is monitored by one of the five monitoring stations (MS) owned by the US Air Force and placed in Hawaii, Colorado Springs, Ascension Island, Diego Garcia and Kwajalein.

  This information is sent to the Master Control Station (MCS) which is responsible of using the information updates to synchronize the atomic clocks on board the sv and adjust the ephemeris of each satellite and other biases. With this information, the MCS generates the navigation messages.

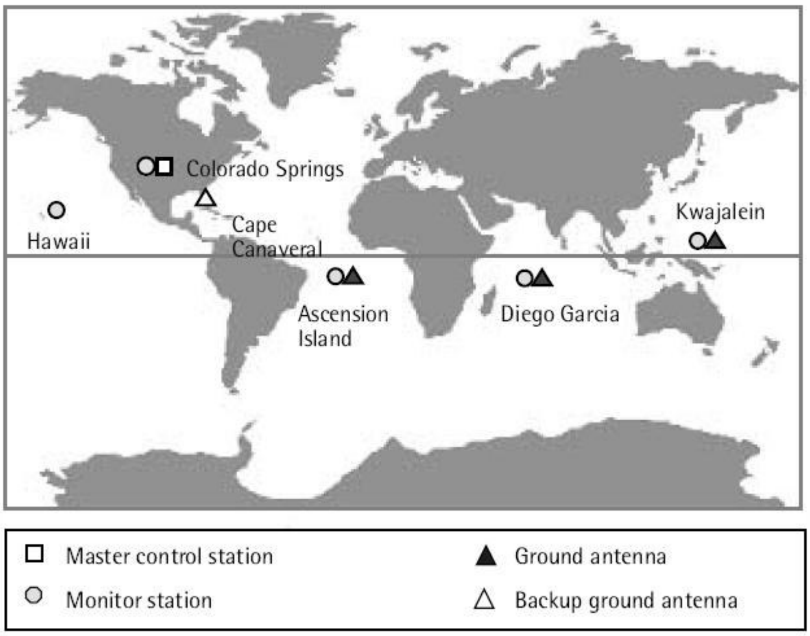


Fig.1. GPS control segment [IGPS]

– User Segment (US): Any user's GPS receiver forms part of this segment. Its main function is receiving the signals and resolving the equations to find an accurate position. Some receivers may include an input for differential corrections.

1.1.2 Signals

All the satellites of the GPS constellation continuously broadcast a Navigation Message. This message contains basic information of the satellite: its clock, its orbit and other parameters.

The **Navigation message** is sent in frames modulated at 50 bps. Each message is made up by 25 frames (30 sec). Each frame consists of 4 subframes in which the parameters are organized.

The transmission of this information is done in two frequencies in the L band. These frequencies have a ratio of $\frac{120}{154}$. They are derived from the fundamental frequency $(f_0 = 10{,}23MHz)$ at which atomic clocks resonate with a 10^{-13} stability.

The resulting frequencies are

$$L1 = 154 \times 10{,}23MHz = 1575.42MHz$$
$$L2 = 120 \times 10{,}23MHz = 1227.60MHz$$

The reason for which two frequencies are used is to allow the user cancel the error derived from ionosphere which constitutes the most complicated correction to be performed to provide an accurate positioning. Nonetheless, the aeronautic standards forbid the use of the frequency cancellation.

Different signals modulate the carrier frequencies.

- Coarse / Acquisition (C/A): This code modulated the L1 carrier phase using a 1MHz Pseudo Random Noise (Code). The sequence is repeated in a one-second interval. This code is the basis for the SPS.
- Precise (P): This code modulates in both the L1 and the L2. It is also a PRN code at a 10MHz frequency. This code is encrypted into the Y-Code when Anti/Spoofing is turned on.
- Navigation Message: As it has been previously introduced, this signal is made up with data related to the satellite and other parameters.

On one hand, the first carrier (L1) is a mix of the Navigation Message, coarse-acquisition (C/A) code and encrypted precision P(Y) code. On the other hand, the second carrier (L2) is a mix of the Navigation Message and the encrypted precision code.

The next image gives an idea of how signals are distributed, with its corresponding codification.

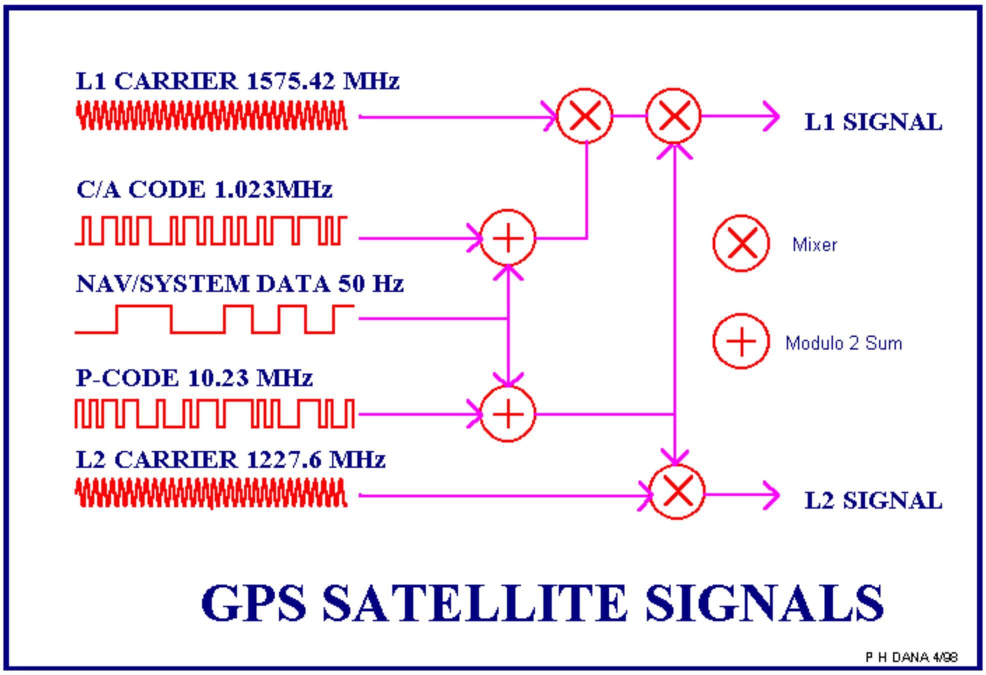


Fig.2. GPS satellite signals [web1]

1.1.3 Reference systems

In engineering, it is generally intended to represent processes with mathematic models of events that actually happen in the real world. This is not simple, because real processes do not occur following exact models or behaviors as mathematics predict. For this, it is necessary to adapt them with models that can best resemble to the reality.

It is highly necessary to determine the reference systems taken to adequate the inputs and obtaining the outputs in a way that inputs and results could be understood and explained.

When it comes down to this subject, it is necessary to specify a **space reference system**, to be aware of the position relative to a known coordinate point (origin), and the **time reference system** because time coordination between transmitter and receiver is paramount to solve positioning equations with accuracy.

Additionally, it is necessary to consider facts related to the Earth. It has not a regular geometry and it is necessary to find the best approximation model; there exist several constant motions that need as well to be considered. For this matter, it is necessary to take an **Earth reference model**.

1.1.3.1 Earth's reference model

The Earth's shape is not perfect. It has a particular geometry that does not fit with any geometrical body. The geometrical figure which can represent it more properly is the ellipsoid.

After several improvements in the way Earth is represented, in 1984 the DoD developed the ***WGS-84*** (World Geodetic System), which is a particular reference ellipsoid that adjusts well the Earth shape. This is the currently reference model used in GPS.

While position in a Cartesian coordinates was represented by (x,y,z) coordinates, the parameters that define position in this kind of body are (λ,Φ,h) and stand for latitude, longitude and height.

1.1.3.2 Space reference system

The GPS takes us into a complex scenario where we find a transmitter, the sv, and a receiver, the GPS receiver. Between them there exists a unidirectional data exchange that goes from the sv towards the GPS receiver.

The complexity dwells in the fact that the transmitter is moving in orbits at the same time that the receiver is located near the Earth's surface. The receiver is under the Earth's forces in contrast with the sv which is moving freely in space.

The first step to decide the reference system is to set an origin or center from which all measures will be referred to. This issue leads us to decide if this point has to be fixed or if it has to move along with the natural Earth's movements.

– The **Conventional Inertial System (CIS)** or **Earth Centered Inertial (ECI)**:

Its origin is set in the Earth's mass center. X, Y and Z axis are fixed with the particular position that the Earth and several points had the J2000.0 epoch (12h. UTC of the 1st Jan 2000).

To be rigorous, this is not a pure inertial system because the Earth is exposed to various other effects such as nutation and precession. However, it is good enough to be used with this purpose.

The major point is that axes directions are fixed with the particular configuration of a specific epoch and they stay untouched in this way.

– The **Conventional Terrestrial System (CTS)** or **Earth centered Earth Fixed (ECEF)**:

Its origin is also set in the Earth's mass center. The Z axis has the Earth's rotation axis defined by the CIO (Conventional International Origin), the X axis is obtained by the intersection of the Z axis and the Greenwich meridian and the Y axis is orthogonal to the X and Z axis.

The most important feature regarding this system is that axes are set along with the Earth motions, so they are perfectly adapted to the Earth position comprising all affectations that it could suffer.

1.1.3.3 Time reference system

As it can be deduced from the way it works GPS, it is required to establish a precise time system which help to minimize errors in the equations involving time calculations.

There have been a few time reference systems in the search of a more realistic one. Facts like the development of better clocks or the consideration of irregularities such as the continuous Earth rotation or other periodic variations have been possible to identify and determine.

These concepts led to modifications that were gradually included in the reference time. Eventually, the UTC (Universal Time Coordinated), which is the mean atomic time that encloses all this matters, was found.

A specific time was invented for its use in GPS, it was called ***GPST*** (GPS time). Its origin epoch was set at 00:00h UTC the night that goes from 5th to the 6th of January of 1980 and it is calculated the same way that the UTC.

1.1.4 Principles of GPS

After the previous sections, where elements that made up the system, the signals that are transmitted and the reference models used have been explained, it is time to move on to the fundamentals that allow the position calculation of the receiver.

In a few words, the GPS consists of knowing the distance between some satellites and the receiver to know the position of the receiver; we will call this distance *pseudorange*.

A group of sv are sending continuously messages to the Earth. These messages contain an accurate time of its emission due to the atomic clocks in the sv.

The receiver interprets the data in this message and knows the time at which message has been received. This information allows the receiver to determine the position of each sv in its view and obtaining the distance between the sv and itself.

The distance calculated between the receiver and a certain sv create an uncertainty, because the position of the receiver has 3 dimensions, but this can be unraveled. As we have three dimensions to specify, the employment of three sv will guide to an intersection of three spheres where the receiver is expected to be located. However, the intersection of three spheres will cause two possible solutions. So, one more sv is needed to get rid of one of the possible solutions and provide integrity to the measure.

At least four satellites are needed to provide a reliable measure. If a higher number of sv are visible and are transmitting healthy data, the information is used redundantly to support the results.

1.1.4.1 *Corrections*

If we go back to the basic idea of the GPS, – finding the pseudorange– we cope with a few elements that can have an effect of the final measure. Some corrections are needed to be done to prevent the system from a wrong result.

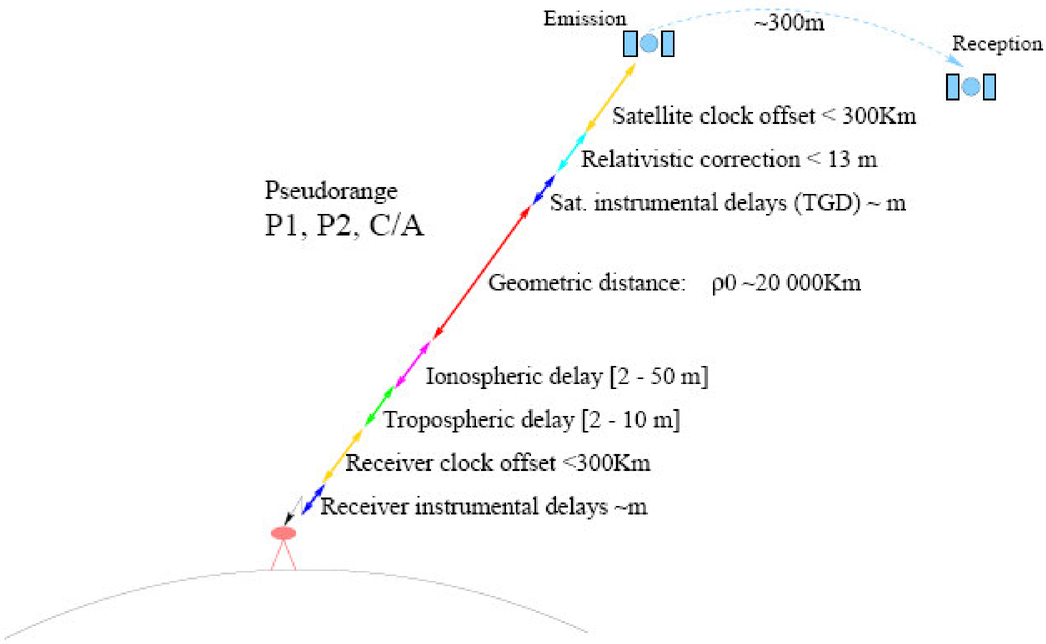


Fig.3. Pseudorange components

The main sources of error come from the computed **time** between the message emission and reception and the **layers** that the signal has to go through to arrive to the receiver.

Regarding the time, errors are found because of the clocks offsets and the clocks' lack of synchronization. There is another time delay called total group delay that it is transmitted in the navigation message and it is caused by the instruments. The second issue is due to functioning in different gravitational contexts cause a relativistic delay

Regarding the layers, it is known that the troposphere and the ionosphere introduce delays. Tropospheric error can be cancelled with different models based on the proportion of wet and dry component. Ionospheric error can be cancelled with a two-frequency receiver. Unfortunately, aeronautic standards don't allow the use of two frequencies, so this error has to be modeled using a model such as the **Klobuchar model.**

1.1.4.2 Positioning procedure

Space and Time are the two basic elements to deal with to find the receiver position. They are strictly connected through the expression $P = c \cdot \Delta t$.

There also exist the a few terms (stated in previous section) that must be considered and used to correct de non-desired effects and the deviations caused by the mathematic model that is being used.

$$P1_i^j = \rho_i^j + c(dt_i - dt^j) + rel_i^j + T_i^j + \alpha_1 I_i^j + K1_i^j + M_{P_{1,i}}^j + \varepsilon_{P_{1,i}}^j$$

In the general expression of the pseudorange we found:

ρ_i^j = geometric distance between transmitter and receiver at the moment of reception

dt_i = Offset receiver clock

dt^j = Offset satellite clock

rel_i^j = Relativistic correction

T_i^j = Tropospheric delay

$\alpha_1 I_i^j$ = Ionospheric delay

$M_{P_i}^j$ = Multipath

K_i^j = Instrumental delays

$\varepsilon_{P_i}^j = noise$

In addition, while the transmission between transmitter and receiver is being carried out, both change its position. This aspect has also to be reflected on the calculation of the distance, in a way that pseudorange is calculated in the same epoch of time for both elements.

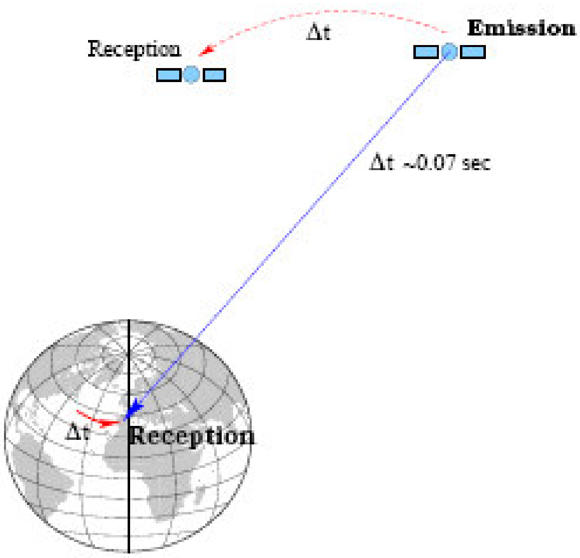


Fig.4. Emission and Reception coordinates

1.1.4.3 Augmentation systems

Augmentation systems were conceived in order to allow a better performance of the GPS in concrete areas or regions. However, some suppositions done in the models taken as reference haven't been corrected yet (e.g. using the WGS-84 cause notable height differences in many parts of the globe).

To correct these difficulties, obtaining a more accurate system response and also to relieve load of work from the user segment, there are systems which use additional information that provides local enhancement.

There can be three types:

- SBAS (Satellite Based Augmentation System): This system uses a network of geostationary satellites as a complementary data source.

- ABAS (Aircraft Based Augmentation System): This system uses additional information from aircraft sensors.

- GBAS (Ground Based Augmentation Systems): This system employs ground based equipments that behave like ground satellites offering differential correction that enhances the final positioning.

GBAS is the augmentation system that will be used as reference for developing the application resulting out of this work. For this, when arriving at this point, it is needed to deepen in this subject.

1.2 GBAS general description

GBAS is the abbreviation of Ground Based Augmentation System. This method allows improving navigation system's attributes such as accuracy, reliability and availability through the use of terrestrial radio messages, transmitting in the VHF and UHF bands [WIK].

GBAS is to be applied to improve current aids to perform precision approach, landing and any kind of maneuvers in Terminal Area. This system would allow precision approach for CAT I, II and III and it would eventually be able to guide aircrafts autoland. Nonetheless, up to now it is only approved to be used in vertical guide approach APV-I and APV-II (less restrictive than CAT I).

Many companies have launched projects regarding this matter, where it is intended to show the capabilities of this system to provide more accurate information for precision landing. However, it is still a long path to go, just because standardization is a very tough process when it comes to the aeronautic issues.

There are two reference documents that are drawn on the subject which have been used in this work to develop a Matlab® application. These documents are basically the MOPS and the LAAS (see bibliography).

1.2.1 Why GBAS rather than of other aids?

There are thee standard non-visual aids to precision approach and landing gathered in Annex 10 ICAO, which is referred to Radio Navigation Aids:

- Instrumental Landing System (ILS)
- Microwave Landing System (MLS)
- Global Navigation Satellite System (GNSS)

GBAS infrastructure is aimed to be to the chosen one needed in future precision navigation aids. We can understand the reasons in a closer comparison:

If we **compare GBAS to ILS**, we can draw some conclusions which explain the advantages regarding the use of GBAS. We found that:

Efficiency

- ✓ Fewer infrastructures. ILS system requires equipment in every header of every Runway.
- ✓ Frequency assignation is simpler. The same frequency range allows a bigger number of operations due to the fact that TDMA is applied.
- ✓ Power consumption is lowered an average of 10%.

Adaptability

- ✓ Due to the use of VHF range of frequencies, signal is less sensitive to multipath. This **eliminates the interferences** and it also permits fewer restrictions in new buildings in and around the airport facility or carry out precision and landing approach in airports which do not have a suitable geography to install ILS.
- ✓ Same response in all-weather circumstances in front of ILS.

Coverage and integrity

- ✓ *The ILS localizer signal outside the coverage areas can lead to false capture and reverse sense indications.*[ICAO] This phenomenon is commonly known as false capture and it occurs when any aircraft capture signal outside the glide path coverage sectors (more than 10 degrees far from the G/S path). This problem does not exist with GBAS.
- ✓ *The validity of the Localizer capture is recommended to be confirmed by cross-checking with other sources of navigation information.*[ICAO] GBAS standards are designed to match integrity requirements without needing to check with other sources or systems.

Costs

- ✓ Setting up and maintenance costs are notably lower.

Ecological

- ✓ Noise is reduced between 30% and 40%.

If we made the same **comparison with MLS,** we would find many more resembles than with ILS. For example, an excellent performance in all weather conditions, the wide spread of channels or the low multipath interference. Anyway, certain and important aspects are still worse than the features that GBAS is capable of, like precision vertical guidance approach (CAT I) or integrity and availability parameters.

For this reason, most MLS systems have been turned off or not implemented in many countries (The FAA suspended the MLS program in 1994), awaiting the widespread use of GNSS navigation aids to be used. ILS is the system that is extensively used today.

We can clearly see that adopting GBAS involves numerous benefits for the same purpose in front of the use of ILS and MLS.

1.2.2 Why GBAS in terminal area?

GNSS is expected to support all phases of flight and aerodrome surface operations. However, present SARPs provide for en-route, terminal and approach landing operations down to Category I precision approach.

Among the flight phases stated before, terminal and approach landing operations requirements are clearly stricter. Air traffic is more congested and this context provides the worst case situation to be considered in order to state general specifications and limitations for other phases of flight.

Considering the higher requirements to satisfy in the terminal area, a sharper performance of the GNSS is needed and GBAS' purpose is to respond to this situation.

The GBAS system yields **local corrections** of the pseudorange distances from satellites to the aircrafts as well as gives to the system accuracy, continuity, availability, integrity parameters and other data relative to the system.

A GBAS station has to smooth and supervise GPS data in the particular surrounding area around its placement. Performance is dramatically improved, but this shortens the reach where corrections are valid: this is called **differential GPS**. Additionally, the message sent from GBAS station includes information about the different approaches to each of the Runway Headers specified in the Final Approach Segment (FAS).

The route phase of flight does not need a performance as precise as those involved in the terminal area, and the GNSS standards can adjust to it. Furthermore, GBAS would not be able to provide correction for all phases of flight. Its results are only valid in a certain radius around its placement because of the variation of ionosphere and troposphere.

1.2.3 Tests and initiatives

Honeywell is doing tests in more than 20 airports in the world with this technology, where several stations are set in the framework of the FAA certification of this system.

Thales is also working on this issue. They are developing a GBAS station and they expect to execute tests in three European airports.

The **FAA** is supervising in the Memphis airport how different tests are done in a non-federal certification of a GBAS station. Tests are taken by a joint combination of companies: FedEx, Honeywell, Boeing and Rockwell-Collins among others.

In **Germany**, the "Deutsche Flugsicherung GMBH (DFS)" has installed a SLS-4000 GBAS station in Bremen where is doing evaluation tests with Tuifly airplanes and expects to publish conclusions in late 2008.

In **Australia**, the "Precision Landing System SLS-4000" GBAS CAT I Stations are in a certification process. This system has been installed in Sidney airport and Qantas airline has installed the corresponding onboard systems. The certification process is to finish in 2008.

1.2.4 Principles of GBAS

In a few words, the GBAS is based on a station that gathers information from some GPS receivers and transmits a set of values that permit to enhance the GNSS positioning. The GBAS station is typically made up with four reference receivers and a base which process the information and broadcasts the message. The system is based on finding the pseudorange correction needed to provide a more accurate positioning of the final receiver.

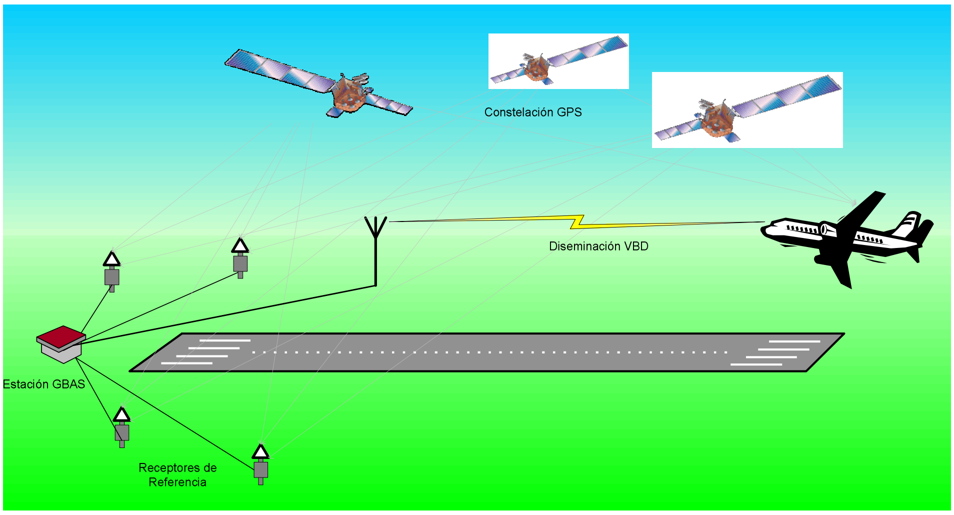


Fig.5. GBAS system

1.2.4.1 Pseudorange correction (PRC_{CSC})

In a preliminary part, the data drawn by each receiver is processed independently. Each reference receiver calculates the Pseudorange correction needed to cancel all the errors that are produced in GNSS positioning.

The following equation is used to find the Pseudorange correction:

$$PRC_{CSC} = R - P_{CSC} - (\ c \times \Delta t_{SV-GPS}\ )$$

Where:

PRC_{CSC} is the Pseudorange correction

P_{CSC} is the smoothed Pseudorange

R is the geometric range

ΔT_{SV-GPS} is the correction due to clock errors

c is the speed of light in vacuum ($2.99792458 \cdot 10^8$ m/s)

The corrections shall be based on the carrier smoothed code Pseudorange measurements for each satellite. These measurements don't have the satellite broadcast troposphere and ionosphere corrections applied, but they have been corrected by satellite clocks. [MOPS]

1.2.4.2 Geometric Range (R)

The geometric Range (or calculated Range) is the geometric distance between the GPS ranging source antenna phase center location and the corresponding reference receiver antenna phase center location. [MOPS]

For this matter, the position of the GPS ranging source (X_k,Y_k,Z_k) ECEF coordinates is computed. Then, corrections that will be explained in the following paragraphs are applied in order to find the Pseudorange correction.

The determination of the ECEF coordinates of the satellite comes out of these equations:

$$\text{The computed mean motion is: } n_0 = \sqrt{\frac{\mu}{A^3}}$$

$$\text{The time from the ephemeris reference epoch is } t_k = t_{SV} - t_{OE}$$

Where:

$\sqrt{A}$ is a value of the semi-major axis in broadcast in subframe 2

μ is the Earth universal Gravitational parameter ($3.986005 \cdot 10^{14} m^3 / s^2$)

t_{SV} is the GPS system time at time of transmission

t_k is the actual total time difference, corrected for the beginning or end of the week crossovers, between the time t and the epoch time t_{oe}

t_{oe} is the Reference time of ephemeris in subframe 2

$$\text{The corrected mean motion is: } n = n_O + \Delta n$$

$$\text{The mean anomaly is: } M_k = M_o + n t_k$$

$$\text{The eccentric anomaly (solved iteratively) is: } Mk = Ek - e \sin Ek$$

The true anomaly is:

$$Vk = \tan^{-1}\left\{\frac{\sin vk}{\cos vk}\right\} = \tan^{-1}\left\{\frac{\sqrt{1-e^2}\,\sin Ek/(1-e\cos Ek)}{(\cos Ek - e)/(1-e\cos Ek)}\right\}$$

$$\text{The argument of latitude is: } \Phi_k = v_k + \omega$$

Where:

Δn is the mean motion difference in subframe 2

M_o is the GPS Mean Anomaly in subframe 2

e is the GPS ephemeris eccentricity in subframe 2

ω is the argument of the perigee is subframe 3

The second harmonic perturbations corrections are adjusted with the following equations:

The argument of latitude correction is: $\delta u_k = c_{us}\sin 2\Phi_k + c_{uc}\cos 2\Phi_k$
The orbit radius correction is: $\delta r_k = c_{rc}\cos 2\Phi_k + c_{rs}\sin 2\Phi_k$
The correction of the angle of inclination is: $\delta i_k = c_{ic}\cos 2\Phi_k + c_{is}\sin 2\Phi_k$
The corrected argument of latitude is: $u_k = \Phi_k + \delta u_k$
The corrected orbit radius is: $r_k = A/(1 - e\cos E_k) + \delta r_k$
The corrected angle of inclination is: $i_k = i_o + \delta i_k + (IDOT)t_k$

Where:

c_{uc} is the GPS ephemeris amplitude of the cosine harmonic corrections to the argument of latitude
c_{us} is the GPS ephemeris amplitude of the sine harmonic corrections to the argument of latitude
c_{rc} is the GPS ephemeris amplitude of the cosine harmonic corrections to the orbit radius
c_{rs} is the GPS ephemeris amplitude of the sine harmonic corrections to the orbit radius
c_{ic} is the GPS ephemeris amplitude of the cosine harmonic corrections to the angle of inclination
c_{is} is the GPS ephemeris amplitude of the sine harmonic corrections to the angle of inclination

The positions in the orbital plane are:

$$X_k' = r_k + \cos u_k$$
$$Y_k' = r_k + \sin u_k$$

The corrected longitude of the ascending node is: $\Omega_k = \Omega_o + (\dot{\Omega} - \dot{\Omega}_e)t_k - \dot{\Omega}_e toe$

The satellite ECEF coordinates at time tk are calculated by positions in the orbital plane are:

$$Xk = X_k' \cos\Omega_k - Y_k' \cos i_k \sin\Omega_k$$
$$Yk = X_k' \cos\Omega_k - Y_k' \cos i_k \cos\Omega_k$$
$$Zk = Y_k' \sin i_k$$

Where:

Ω_o is the GPS ephemeris longitude of the ascending node of the orbit plane at weekly epoch, in subframe 2
$\dot{\Omega}$ is the GPS ephemeris rate of right ascencion, broadcast in subframe 3
$\dot{\Omega}_e$ is the Earth's rotation rate ($7.2921151467 \cdot 10^{-5}\ rad/\sec$)
ω is the argument of the perigee is subframe 3

Finally, we obtain the satellite ECEF coordinates at time t_k: $SV_{tk} = \begin{bmatrix} X_k \\ Y_k \\ Z_k \end{bmatrix}_{ECEF}$

Once we have found the satellite coordinates, we can compute the geometric distance between the satellite and the receiver antenna.

$$R = P_{ant} - SV_{tk}, \text{ with } P_{ant} = \begin{bmatrix} X_{ant} \\ Y_{ant} \\ Z_{ant} \end{bmatrix}_{ECEF}$$

$$|R| = \left|\sqrt{R_x + R_y + R_z}\right| = \left|\sqrt{(X_{ant} - X_k) + (Y_{ant} - Y_k) + (Z_{ant} - Z_k)}\right|$$

1.2.4.3 Smoothed Pseudorange (P_{CSC})

The pseudorange measurement for each receiver needs to be smoothed in order to eliminate peaks and provide a softer signal.

$$P_{CSC_n} = \alpha P + (1-\alpha)\left(P_{CSC_{n-1}} + \frac{\lambda}{2\pi}(\phi_n - \phi_{n-1}) \right)$$

Where:

P_{CSC_n} is the smoothed pseudorange

$P_{CSC_{n-1}}$ is the previous smoothed pseudorange

λ is the L1 wavelength

Φ_n is the carrier phase

Φ_{n-1} is the previous carrier phase

α is the filtering weighting function equal to the interval divided by 100s $\left(\frac{\mathrm{T}}{\mathrm{S}}\right)$

Some considerations must be observed in order to provide a valid measurement:

- The filter sample interval (T), shall not exceed 2 seconds more than once during every 60-second interval.
- After a gap of pseudorange and carrier phase measurements of more than 2 seconds, the filter shall be reinitialized.

1.2.4.4 Satellite clock error correction ($c \cdot \Delta t_{SV\text{-}GPS}$)

The errors due to clocks involve both the satellite clocks on-board the sv as well as the receiver clock, installed in the GPS receiver. So, it is necessary to compute the time that has taken to make the communication between both. A detailed expression of this calculation:

$$\boxed{\Delta t_{SV\text{-}GPS} = \Delta t_{SV} - \Delta t_{GPS}}$$

The time corrections that are considered in the MOPS for GBAS systems are:

- the satellite clock error $a_{f0} + a_{f1}(t - t_{oc}) + a_{f2}(t - t_{oc})^2$
- the relativistic correction term $\Delta t_r = Fe\sqrt{A}\sin E_k$
- the differential satellite group delay T_{GD}
- the clock error between epochs Δt_{GPS}

The complete expression used:

$$\Delta t_{sv} = a_{f0} + a_{f1}(t - t_{oc}) + a_{f2}(t - t_{oc})^2 + \Delta t_r - T_{GD}$$

Where:

Δt_{SV} is the satellite code phase time offset

a_{f0}, a_{f1} and a_{f2} are the polynomial coefficients given in subframe one

t_{oc} is the clock data reference time, contained in subframe one

t is the GPS time

e is the GPS ephemeris eccentricity contained in subframe one

$\sqrt{A}$ is a value of the semi - major axis in broadcast in subframe 2

F is a constant whose value is $-4.442807633 \cdot 10^{-10}\ sec/m^{1/2}$

T_{GD}, the total group delay is in broadcast in subframe 2

The value of Δt_{GPS}, that is the reference receiver clock error between epochs, can be found in the observation Rinex file produced by the receiver. If the observation time values differ from the interval, the value of Δt_{GPS} will be the difference from both.

For example:
The fig.6 corresponds to an observation file from a station and dates from 01/01/08. The observations seen are at 3:30:00 and 3:30:01. The interval is 1s.

The GPS receiver does not have any delay. Therefore:

$$\Delta t_{GPS} = 3:30:1.0000000 - 3:30:0.0000000 - 1 = 0$$

3:30:00 observation

```
 08  1  1  3 30  0.0000000  0 10G12G 9G22G30G 5G28G18G17G26G15
-15995382.93748 -13157456.25747  22091403.4634   22091399.3544
  -4986665.45648 -29668143.77848  20236671.8084   20236667.4224
  -6775859.07247  -5345189.71544  23929467.1774   23929458.6514
   -518974.73446                   25195732.8774
  -9391492.90847  -7282311.64945  23232540.3404   23232535.9434
   4637046.98046   1837053.70143  24990652.1924   24990646.8784
   -152125.58647 -22506341.61346  22574226.7514   22574221.7504
-10862595.63548 -11456947.93446  22798997.4464   22798993.2884
  -3350049.05448 -17365582.14047  21564928.8724   21564925.5374
-11663621.70548 -21874906.83748  20825833.7534   20825829.5684
```

3:30:01 observation

```
 08  1  1  3 30  1.0000000  0 10G12G 9G22G30G 5G28G18G17G26G15
-15998063.60648 -13159545.08847  22090893.4724   22090889.0854
  -4987887.73248 -29669096.19948  20236439.1474   20236434.8324
  -6777151.60147  -5346196.89044  23929220.7004   23929213.0184
   -522652.67846                   25195034.1924
  -9394876.52547  -7284948.23645  23231896.1974   23231892.1394
   4640243.11746   1839544.20943  24991260.4024   24991254.9964
   -151321.15347 -22505714.78246  22574379.7754   22574374.8284
-10862092.13148 -11456555.58746  22799093.5184   22799089.2514
  -3347268.31448 -17363415.33147  21565458.0884   21565454.5894
-11661773.10148 -21873466.36348  20826185.6904   20826181.0284
```

Fig.6. Rinex observation file

Fig.7 corresponds to another observation file from a station which dates from 30/01/02. The observations seen are at 0:09:00 and 0:09:30.0010000. The interval is 30s.

We find that there exists a delay:

$$\Delta t_{GPS} = 0:09:30.0010000 - 0:09:0.0000000 - 30 = 0.001s$$

0:09:00 observation

```
02  1 30   0  9  0.0000000  0  7 07 27 13 04 20 01 24
  24295800.110      661644.262 5    7709914.04245  24295810.5674
  22987783.106    -9488853.842 6   -7220354.36346  22987789.2484
  20488550.730   -20027580.103 8  -15392032.73447  20488553.5794
  20907182.737   -17521994.456 7   -8374846.15247  20907187.3444
  23223209.282    -2982550.537 6   -2167518.19446  23223214.6394
  21658827.985   -11926914.303 8   -9137953.52947  21658833.0724
  23239704.366    -8978157.985 6   -6815399.03846  23239709.3014
```

0:09:30.001 observation

```
02  1 30   0  9 30.0010000  0  7 07 27 13 04 20 01 24
  24313629.500      755337.436 5    7782921.42645  24313638.3854
  22973600.083    -9563385.763 6   -7278431.11846  22973605.9684
  20491610.819   -20011499.635 8  -15379502.48247  20491613.6794
  20905660.695   -17529993.739 7   -8381079.36047  20905665.1144
  23239398.226    -2897474.676 6   -2101225.35646  23239403.4304
  21672912.292   -11852900.800 8   -9080280.66447  21672917.3564
  23225407.756    -9053286.612 6   -6873940.81446  23225412.6214
```

Fig.7. Rinex observation file with receiver delay

1.2.4.5 Smoothed clock adjust Pseudorange correction (PRC_{SCA})

After that, the Pseudorange correction goes through a smoothing and clock adjust process whose purpose is to eliminate the delay time generated in the reference receiver processing of data.

$$PRC_{sca}(i,j) \equiv PRC_{csc}(i,j) - \sum_{i \in s_c} k_i \times PRC_{csc}(i,j).$$

Where:

PRC_{CSC} is the smoothed Pseudorange correction

i is the sv index

j is the reference receiver index

k_i is the weighting factor for the satellite height with $\sum_{i=1}^{Nc} k_i = 1$

N_c is the number of elements in set Sc

Sc is the set of valid ranging sources tracked by all reference receivers

Some considerations must be observed in order to provide a valid measurement:

- N_c shall be at least 4.
- It is needed to provide a relationship between weight and height to outline the values of k_i . An elevation-weight chart is needed to specify this correlation. As default, the following elevation-weight proportion will be used, unless a weight chart is given:

```
"Elevation";"Weight"
0;2
10;5
20;10
40;15
60;20
90;30
```

Fig.8. Default elevation-weight char [PEG]

To obtain a smooth output and arriving to a mathematical relationship for the intermediate values, the elevation-weight chart values have been linearized.

Elevation	Weight
0	2
10	5
20	10
40	15
60	20
90	30

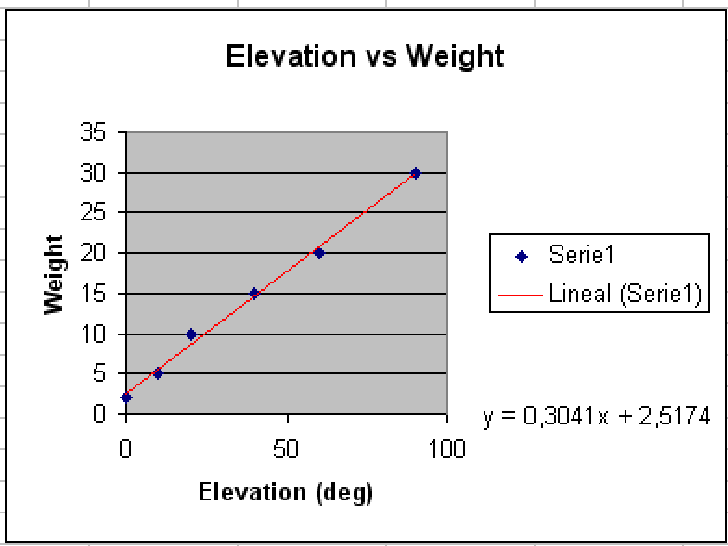


Fig.9. elevation-weight chart linearization

The same process would be carried out if a new weight chart were provided. This table will be used as default unless other information was provided.

1.2.4.6 *Broadcast Pseudorange correction (PRC_{TX})*

Eventually, the Pseudorange corrections obtained from the reference receivers (PRC_{sca1}, PRC_{sca2}, PRC_{sca3} and PRC_{sca4}) are employed to get a single correction of the Pseudorange. GBAS reference receivers are presupposed to have very similar processing time and all receivers should see the same satellites within the same time. Thus, they should have the same valid ephemeris and subsequently they all should have very similar receiver delays.

$$PRC_{TX}(i) \equiv \frac{1}{M(i)} \sum_{\substack{j=1 \\ j \in S_i}}^{M(j)} PRC_{sca}(i,j)$$

Where:

PRC_{SCA} is the smoothed and clock adjusted Pseudorange correction

i is the sv index

j is the reference receiver index

k_i is the weighting factor for the satellite height with $\sum_{i=1}^{Nc} k_i = 1$

M is the number of GPS reference receivers which made up the GBAS station

Si is the set of reference receivers with a valid measurement for satellite i

M shall be at least 2; there must be two or more reference receivers with valid measurement to get a PRC_{TX} valid measurement.

Bad data from PR_{sca1}, PR_{sca2}, PR_{sca3} and PR_{sca4} can damage the final ***PRC_{TX}*** result. Consequently, different **monitors** ought to be implemented to identify and ignore values which are not appropriate for the broadcast pseudorange correction.

The implementation of these monitors is a tough and long process that requires tests that must adapt them to the many situations that can be found or expected. In addition, the process to establish and justify thresholds and limits to discriminate the valid and invalid data makes it more difficult. Due to the purpose and scope of this work, the design of these monitors will be carried out in another company project.

CHAPTER 2: Developing the application

When an application is going to be developed, the first thing to think about is the potential users of it, and in which way the product is going to improve their jobs, in other words, ensure that there is market for your product.

There is a vast range of processes and industries that can take advantage from the use of GPS and its augmentation systems, such as GBAS or SBAS. Among these, those involving the transportation of people in aeronautics or those requiring high precision are particularly suitable for this type of applications.

There is a vast range of processes and industries that can take advantage from the use of GPS and its augmentation systems, such as GBAS or SBAS. Among these, those involving the transportation of people in aeronautics or those requiring high precision are particularly suitable for this type of applications.

2.1 Application description

The process that goes from receiving some RINEX files from different stations until getting a more accurate position of a receiver is complicate and thorough.

Many tasks have been developed to make it possible. In order to understand the organization of these tasks, the jobs have been organized in sections. The main three parts that make up the whole scheme are based on the following:

- The **first one** involves all the tasks related to the pre-processing of the Rinex files such as the load of constants, reading the navigation and observation Rinex files, checking the validity of ephemeris or the presence of cycle slips.

  Each Rinex file is processed independently and it generates a specific set of structures to be used in the processing part.

- The **second one** is made up by the tasks in the first part of the processing.
  The first part of the processing is accomplished with the information retrieved by the pre-processing of the Rinex files. It is also handled independently.

  The most significant outputs generated in this part are the range, the smoothed pseudorange, the correction of the pseudorange, the position of each satellite (X_k, Y_k, Z_k) and its elevation.

- The **third one** is made up by the second part of the processing.
  The second part of the processing gathers the information processed by every single receiver in order to provide final measurements for the GBAS station in the area covered by the stations.

In this process, every correction of the pseudorange (Prc_{csc}) of each receiver and satellite gets a smoothed and time clock receiver adjustment. This operation results in Prc_{sca}. The considerations to obtain the Prc_{sca} are based on the elevation of all the satellites seen by a GPS receiver at current epoch.
Among the outputs, the most important value is the broadcast correction of the pseudorange (prcTx) which will be the value broadcast to allow the rover to get a more accurate positioning.

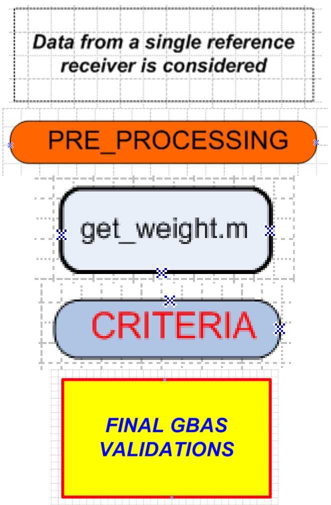
The complexity of the application has led to the necessity of implementing a diagram. In this diagram, a basic methodology has been followed to facilitate the comprehension of the process as a whole but also to grasp the purpose of each particular part. The main rules to have in mind are:

- The diagram goes from left to right and is **sequentially** executed. The sequences are separated from each other by different vertical lines (dash and dot) and a title is posted at the top of each section.

- Variables and relations (lines) which connect the different parts of the diagram are colored to remark the quality of each one as:

  - **INPUT**
  - **OUTPUT**
  - **LOCAL VARIABLE / RELATION**

- Each **diagram block** has a specific color code and a particular meaning:



Reference Block: Major information

Script Block: contains one or more functions

Function block: carries out a specific job

Additional block: unspecified tasks

Validation block: Results examination

Fig.10. Diagram blocks

The picture gives a schematic view of how functions are organized in blocks. It also informs which inputs are produced and which outputs are generated by each block *(see **"catgos.vsd"**).*

This image may be adequate to understand what is the aim and scope of the main blocks of the three parts of the project. However, it is not deep enough to know what processes lay beneath. For this, an explanation of these key blocks is done in the following paragraphs.

2.1.1 Pre-processing

This section consists of three main blocks. These blocks produce the necessary data outputs out of the Rinex files that allow the data processing.

The block responsible for reading the navigation Rinex file is called **get_eph.m.** It reads the ephemeris and stores it in a structure called *eph* to be used in successive functions.

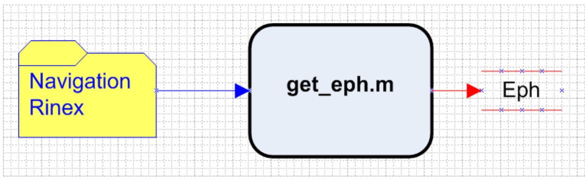


Fig.11. Get_eph block

The ephemeris output is a structure consisting of all the fields included in the broadcast navigation message that the satellite has transmitted. It is timely organized to ease the process of observation validation that is detailed in the following paragraphs.

Field	Value
sv	2
toc	2454557.58333333
af0	0.0001868237741292
af1	3.183231456205e-012
af2	0
iode	4
crs	16.90625
deltan	5.054853412077e-009
m0	-0.8936718537741
cuc	8.530914783478e-007
ecc	0.008839639020152
cus	6.122514605522e-006
roota	5153.700853348
toe	180000
cic	-1.825392246246e-007

Field	Value
omega0	0.8320289756094
cis	-1.210719347e-007
i0	0.9438961399201
crc	255.15625
omega	2.501095042545
omegadot	-8.319989418098e-009
idot	1.017899542459e-010
codes	1
weekno	1473
l2flag	0
svaaccur	2
svhealth	0
tgd	-1.722946763039e-008
iodc	4
tom	172818
fint	4

Fig.12. Ephemeris fields (example)

The ephemeris structure fields have been organized in the same order that they are specified in the navigation message.

The block responsible for reading the observation Rinex file that produces each GPS reference receiver is called **get_obs.m**. It reads and stores in matrix the most significant values of the header and the body such as C1, L1, interval, epochflag, etc.

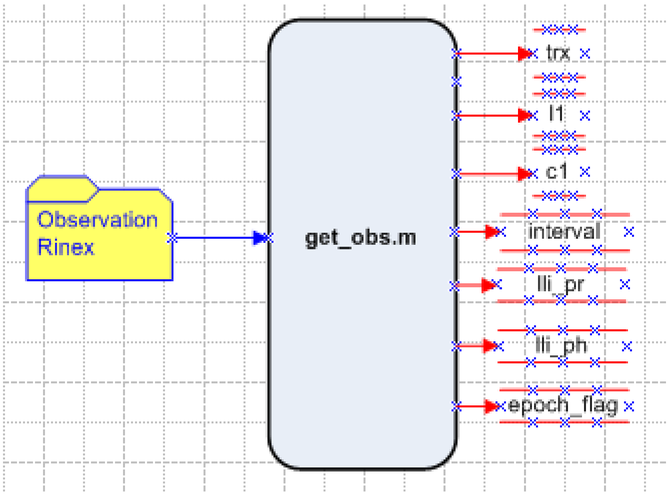


Fig.13. get_obs.m block

The third major block in this section is called **rx_mask.m**. This block's purpose is to determine the validity of the measurements that have been provided in the Rinex files. To do so, it uses outputs from the *get_eph* and *get_obs* blocks to check the observations considering the ephemeris. The *mask* output is a binary matrix which states which observations are considered valid and which not.

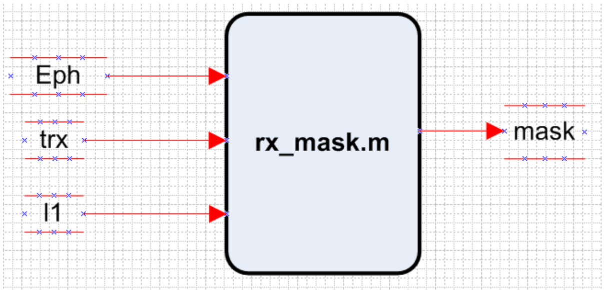


Fig.14. rx_mask.m block

2.1.2 Processing (Part one)

This stage is made up by a single function called **g_calc.m** whose inputs are the outputs that have been drawn in the pre-processing section. This function carries out all the tasks regarding an independent processing of the receiver.

It obtains the smoothed Pseudorange (P_{CSC}), the geometric range (r), the clock errors $(deltaTg)$ or the Pseudorange correction $(\Pr c)$ explained in the GBAS principles. Apart from that, other parameters have been drawn and extracted from the function to contrast it with other sources, such as the satellite position (X_k, Y_k, Z_k).

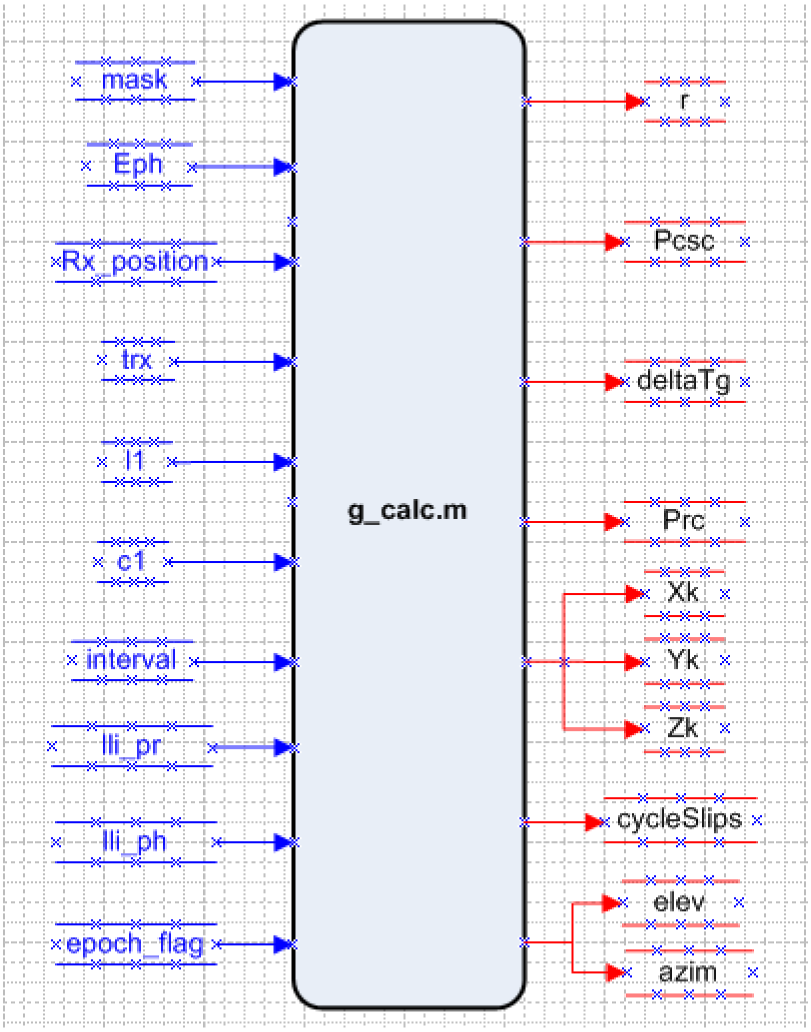


Fig.15. g_calc.m block

Several functions regarding the data processing are included in the *g_calc.m* block. The cycle slip detection has been one of the most challenging problems to specify and correct.

If we look to the Technical Note for Pegasus, we find the Cycle Slip detector design. From this document it can be drawn that:

- The cycle slip jump detection condition is based on the difference between the raw pseudorange value (C1) and the phase value (L1) for each epoch, satellite and receiver.
- A value of 15 m. is set as threshold to determine the presence of a Cycle Slip.
- The medium value of jumps is stored and subtracted from the C1 value before smoothing process in case a jump is detected for all satellites in view.

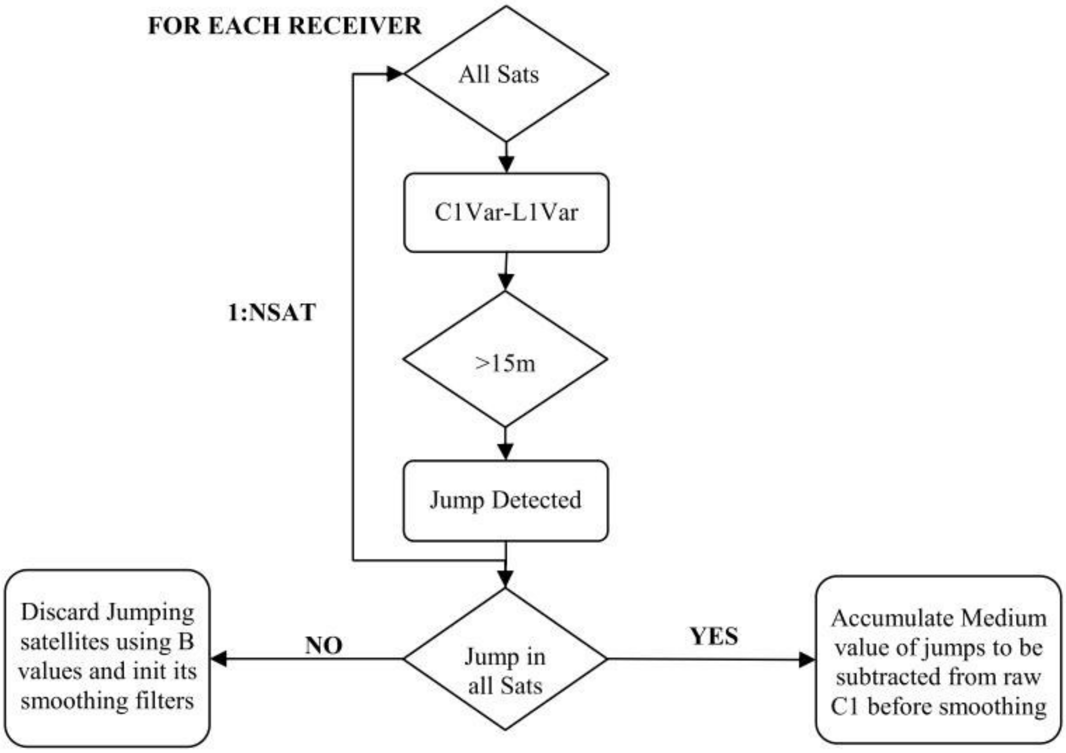


Fig.16. Cycle Slip Detector Scheme included in Pegasus Technical Note [PEG]

Differently from the Pegasus design, the cycle slip detector included in the designed application takes into account other patterns:

- The cycle slip jump detection condition is also based on the difference between the raw pseudorange value (C1) and the phase value (L1) for each epoch, satellite and receiver.
- The threshold value set to determine the presence of a Cycle Slip is varying. This value corresponds to the jump mean value of a slide window which takes the previous 100 samples (if there is data) to the current epoch.
- When a Cycle Slip is detected: the epoch is considered invalid (NaN). The jump mean value and the slide window is reset.

A cycle slip detection example is detailed below. In it, it can be appreciated that:

- There is a great jump in the phase value (l1) from epoch 6884 to epoch 6885. The cycles slip matrix (cyc) detects that jump and sets its value to one in this epoch.
- When the **cycle slip detector is not active**, the smoothed Pseudorange detection supplied is mistaken because the smoothed Pseudorange uses previous phase value (see page 27). This error is not corrected until epoch 6909, when the lack of phase forces a smoothing filter reset.
- When the **cycle slip detector is active**, each C1-L1 variation is analyzed. When the jump surpasses the mean value of the window, this epoch is discarded and smoothing filter is reset.

	c1	l1	cyc	smoothed_prc (inact. CycleSlip)	smoothed_prc (act. CycleSlip)
6880	2.4148e+07	-5.3377e+06	NaN	-20.3599	-20.4304
6881	2.4148e+07	-5.3346e+06	NaN	-20.3118	-20.3816
6882	2.4149e+07	-5.3315e+06	NaN	-20.3208	-20.3899
6883	2.4150e+07	-5.3284e+06	NaN	-20.3198	-20.3882
6884	2.4150e+07	-5.3253e+06	NaN	-20.2894	-20.3571
6885	2.4151e+07	-2.7378e+07	1	4.1551e+06	NaN
6886	2.4151e+07	-2.7375e+07	NaN	4.1136e+06	-17.1237
6887	2.4152e+07	-2.7372e+07	NaN	4.0724e+06	-17.1054
6888	2.4153e+07	-2.7369e+07	NaN	4.0317e+06	-17.1123
6889	2.4153e+07	-2.7366e+07	NaN	3.9914e+06	-17.1404
6890	2.4154e+07	-2.7363e+07	NaN	3.9515e+06	-17.1918
6891	2.4154e+07	-2.7360e+07	NaN	3.9119e+06	-17.2065
6892	2.4155e+07	-2.7356e+07	NaN	3.8728e+06	-17.2841
6893	2.4156e+07	-2.7353e+07	NaN	3.8341e+06	-17.2934
6894	2.4156e+07	-2.7350e+07	NaN	3.7958e+06	-17.3244
6895	2.4157e+07	-2.7347e+07	NaN	3.7578e+06	-17.3409
6896	2.4157e+07	-2.7344e+07	NaN	3.7202e+06	-17.3598
6897	2.4158e+07	-2.7341e+07	NaN	3.6830e+06	-17.3861
6898	2.4159e+07	-2.7338e+07	NaN	3.6462e+06	-17.3747
6899	2.4159e+07	-2.7335e+07	NaN	3.6097e+06	-17.4751
6900	2.4160e+07	-2.7332e+07	NaN	3.5736e+06	-17.4237
6901	2.4160e+07	-2.7329e+07	NaN	3.5379e+06	-17.4578
6902	2.4161e+07	-2.7326e+07	NaN	3.5025e+06	-17.4941
6903	2.4161e+07	-2.7322e+07	NaN	3.4675e+06	-17.5319
6904	2.4162e+07	-2.7319e+07	NaN	3.4328e+06	-17.5316
6905	2.4163e+07	-2.7316e+07	NaN	3.3985e+06	-17.5265
6906	2.4163e+07	NaN	NaN	NaN	NaN
6907	2.4164e+07	NaN	NaN	NaN	NaN
6908	2.4164e+07	NaN	NaN	NaN	NaN
6909	2.4165e+07	-2.7304e+07	NaN	-20.6702	-20.6702
6910	2.4166e+07	-2.7301e+07	NaN	-19.5874	-19.5874
6911	2.4166e+07	-2.7298e+07	NaN	-19.6063	-19.6063
6912	2.4167e+07	-2.7295e+07	NaN	-19.6257	-19.6257
6913	2.4167e+07	-2.7291e+07	NaN	-19.6293	-19.6293

Fig.17. PRC modification depending on the Cycle Slip detector status

2.1.3 Processing (Part two)

At this point, it is necessary to take on the values obtained from the single processing of the different GPS receivers to arrive to a single set of values that will eventually be broadcast.

This procedure implies the implementation of tasks regarding a single processing with all the data from the reference receivers. However, in this section the calculation of the *Smoothed clock adjust Pseudorange correction* (PRC_{SCA}) of each receiver has also been included.

The reason for this is that the display of the loops in this part of the process was optimal to diminish time consumption that this process would take if it was included in the first part of the processing.

If we go back to expressions stated in the GBAS principles, we found two related expressions with additional parameters:

$$PRC_{sca}(i,j) \equiv PRC_{csc}(i,j) - \sum_{i \in s_c} k_i \times PRC_{csc}(i,j). \quad PRC_{TX}(i) \equiv \frac{1}{M(i)} \sum_{\substack{j=1 \\ j \in S_i}}^{M(j)} PRC_{sca}(i,j)$$

Next three functions are aimed to get the parameters needed to carry out the previous equations.

In first place, there are two pairs of parameters fundamental to understand the correlation of the receivers and the satellites. These are obtained with function **get_sets_svrx.m.**

Its purpose is to specify a few data variables containing in each epoch different values: how many and which sources are seen by a particular satellite and how many and which valid satellites are seen by all sources.

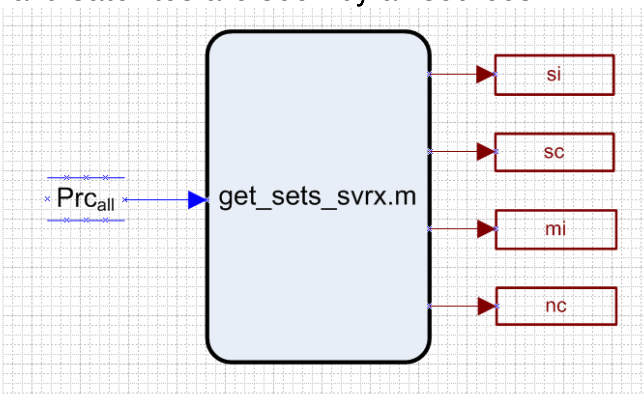


Fig.18. get_sets_svrx.m block

Sc is the set of valid ranging sources tracked by all reference receivers

N_c is the number of elements in set Sc

Si is the set of reference receivers with a valid measurement for satellite i

Mi is the number of elements in set Si

In second place, we have the k_i .The weighting factor complies $\sum_{i=1}^{Nc} k_i = 1$.

This parameter depends on the satellite elevation, but the procedure for assigning it is flexible. The MOPS does not specify any particular criteria for the relationship between elevation and weight. Nevertheless, Pegasus indicates the use of *weight charts* to relate both variables. Hence, there exist broad interpretations in setting up this relation in the **get_weight.m** function.

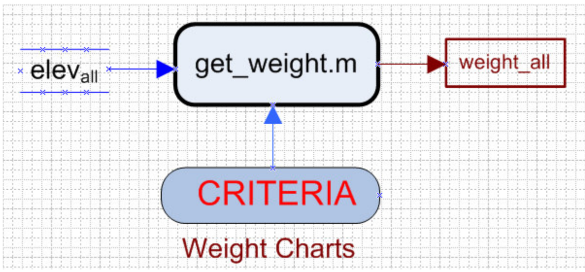


Fig.19. get_weight.m block

Once each satellite elevation has been considered, it is time to weigh its contribution in the epochs of each receiver. In other words, it is necessary to analyze every single epoch for each receiver. This process is carried out by the **weighting_function.m**, which follows these steps:

- Find the sum of weights of all sv seen by all reference receivers (in Sc).
- Select for each sv, the corresponding weight_all parameter.
- Normalize its value to 1, relative to the sum of the weight calculated before.

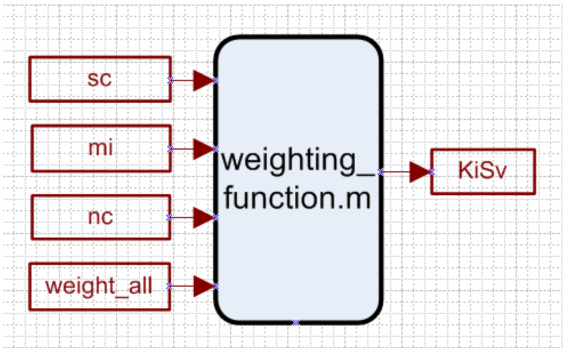


Fig.20. weighting_function.m block

This method leads to the $KiSv$ value which is essential to obtain the PRC_{SCA} and eventually the PRC_{TX} values.

The last stage of the processing part is the **bcast_corrections.** In this module occurs all the calculations to generate the output values that will be broadcast in the GBAS message.

These tasks involve:

- Using the $KiSv$ with its corresponding PRC value to obtain the PRC_{SCA} for every receiver.
- Obtain PRC_{TX} as an equal distribution (depending on M_i) of all the PRC_{SCA} values
- Finding the *range rate correction* (rrc), which indicates the rate of change of the pseudorange correction and is based on the difference between the current and the immediately prior averaged corrections of PRC_{TX}.
- Finding the *Broadcast values* (*B-values)* which are obtained by the expression:

$$B_{PR}(i,j) = PRC(i) - \frac{1}{M(i)-1} \sum_{\substack{k \in S_i \\ k \neq j}} PRC_{SCA}(i,k)$$

Where:

- *i* is the sv index
- *j* is the reference receiver

$B_{PR}(i,j)$, the Bvalue for i^{th} sv and j^{th} reference receiver, is the difference between the broadcast Pseudorange correction for the i^{th} satellite, $PRC_{TX}(i)$, and the mean correction (after clock receiver adjust) done by all the receivers excluding the j^{th} reference receiver.

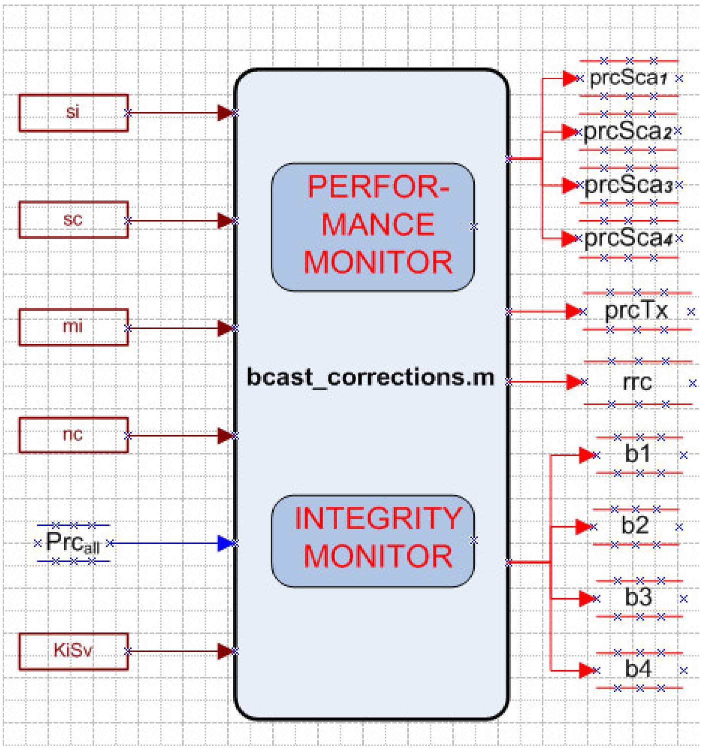


Fig.21. bcast_corrections.m block

This unit also contains two monitors which help to turn down invalid measurements or those which differ considerably with the average value. The procedure to distinguish between what is valid and what is still in process of improvement, but in a first approximation:

- The **performance monitor** is designed to reject the corrections done by individual reference receiver for sv which are not seen by the rest of receivers.
- The **integrity monitor** is designed to not to take into account values of any receiver which are different from the current average value of the rest of receivers a certain percentage.

After all the data has been processed, outputs need to be organized in the GBAS message type 1 structure and broadcast. This is accomplished by the **message_generator.m** function.

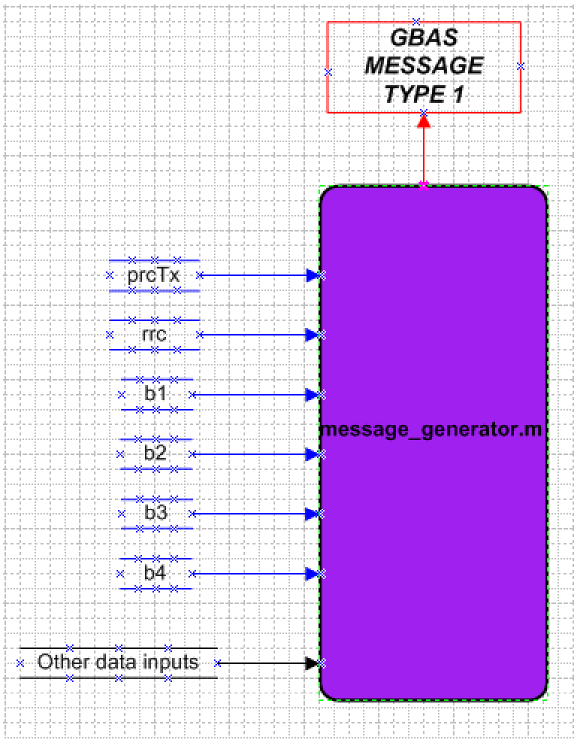


Fig.22. message_generator.m block

The implemented message (Type 1) consists of a header with stable values, followed by *N* measurement blocks that refer to the values found in the consecutive epochs. The values in header and the blocks are organized in bits depending on their length and their expected range of values (see fig. 15). The description of each component in the message is found in MOPS (pg. 66-69).

Data Content	Bits Used	Range of Values	Resolution
Modified Z-count	14	0 to 1199.9 sec	0.1 sec
Additional Message Flag	2	0 to 3	1
Number of Measurements (N)	5	0 to 18	1
Measurement Type	3	0 to 7	1
Ephemeris Decorrelation Parameter (p)	8	0 to 1.275 x 10^{-3} m/m	5 x 10^{-6} m/m
Ephemeris CRC	16		
Source availability duration	8	0 to 2540s	10s
For N Measurement Blocks:			
Ranging Source ID	8	1 to 255	1
Issue of Data (IOD)	8	0 to 255	1
Pseudo-range Correction (PRC)	16	±327.67 m	0.01 m
Range Rate Correction (RRC)	16	± 32.767 m/s	0.001 m/s
σ_{pr_gnd} (unsigned)	8	0 to 5.08 m	0.02 m
B_1	8	±6.35 m	0.05 m
B_2	8	±6.35 m	0.05 m
B_3	8	±6.35 m	0.05 m
B_4	8	±6.35 m	0.05 m

Fig.23. GBAS message type 1 content

2.2 *Application user interface*

The execution of the Matlab application is based on functions and scripts and it is launched in the command line. It is necessary to modify inputs and particular values in order to select the situation required to be processed.

Searching the appropriate files to make modifications or verifying partial results after different sections are complex actions. For this reason, a user interface has been designed to make simpler the execution and the verification of results.

In this section of the work, the developed application will be explained. In order to adapt and allocate its utilization to a concise part of the project, the application is arranged in three segments: *Rinex load,* where the Rinex files are loaded, *Data processing,* where the processing of the information is carried out and *Plots* where results can be analysed through the display of charts.

The distribution of elements in the application is designed for ease of use. In all three screens of the application, the input parameters will be placed at the right side of the screen and the outputs will be displayed automatically at the right side. Furthermore, messages and time information will appear at the bottom to notify the application current status.

2.2.1 Rinex load

When the application is launched, it appears the initial screen which corresponds to the first section (*Rinex Load*). In it, it is possible to initialize the Rinex files regarding the navigation files and the observation files regarding the rover and the Reference Receiver stations which make up the GBAS station.

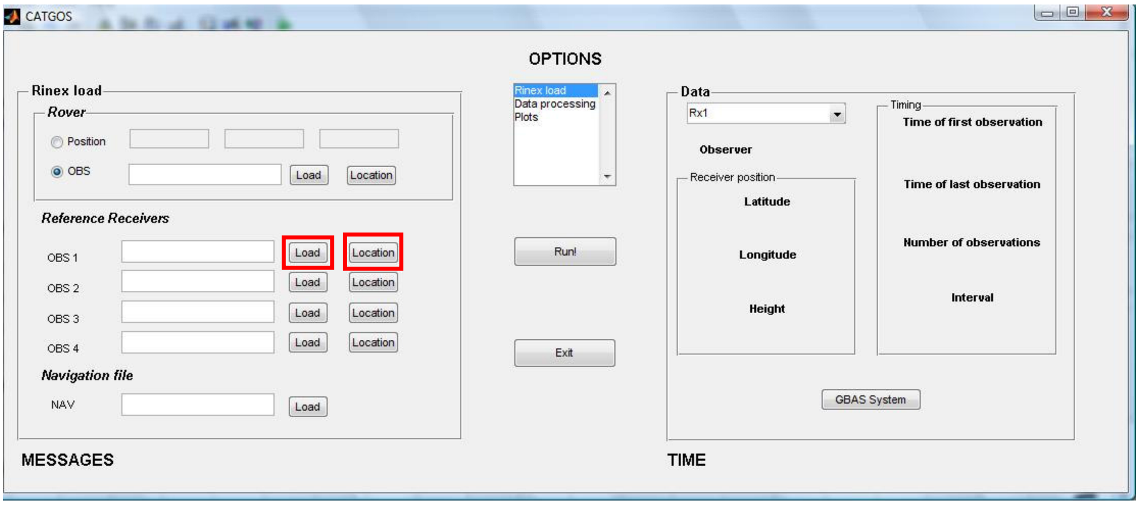


Fig.24. Application initial screen

If we click on the 'Load' button a windows dialog pops up to select the file to be used. It is also possible to place the Earth's position of every file that has been loaded with the 'Location' button. After pushing this button, a web browser is launched with the maps.google application with the selected position found in the Rinex file.

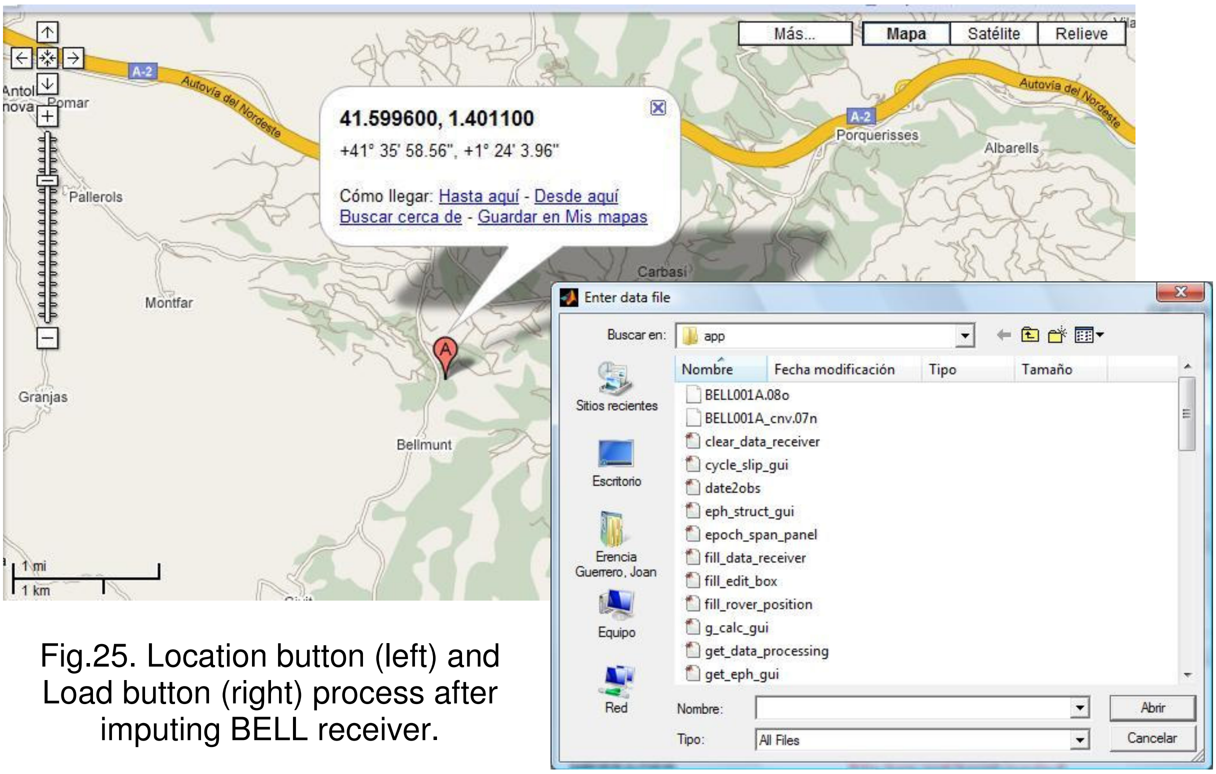


Fig.25. Location button (left) and Load button (right) process after imputing BELL receiver.

Every time a file is loaded, the application is updated with the new data to inform the user the application status and the main information.

Fig.26. Messages and time information

As long as the files are introduced, information about the receivers can be displayed (at any time) at the right side of the application (***Data***) to get the gist of the situation. This displays permits to know the receiver position and data related with the observations.

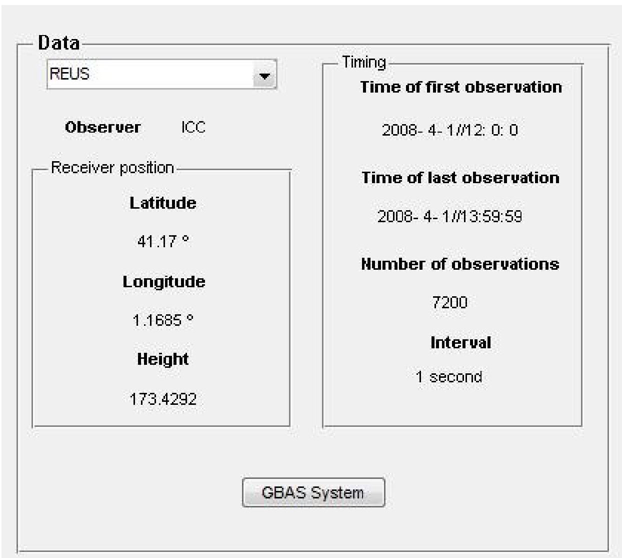


Fig.27. Data display of the selected input (REUS)

In this panel, there is button called ‘GBAS System’ which generates a *.kml* file with the information that has been introduced previously. When all four reference receivers and the rover have been loaded, this button launches google.earth application and places the position of the receivers (with its corresponding number) and the rover (with a plane icon).

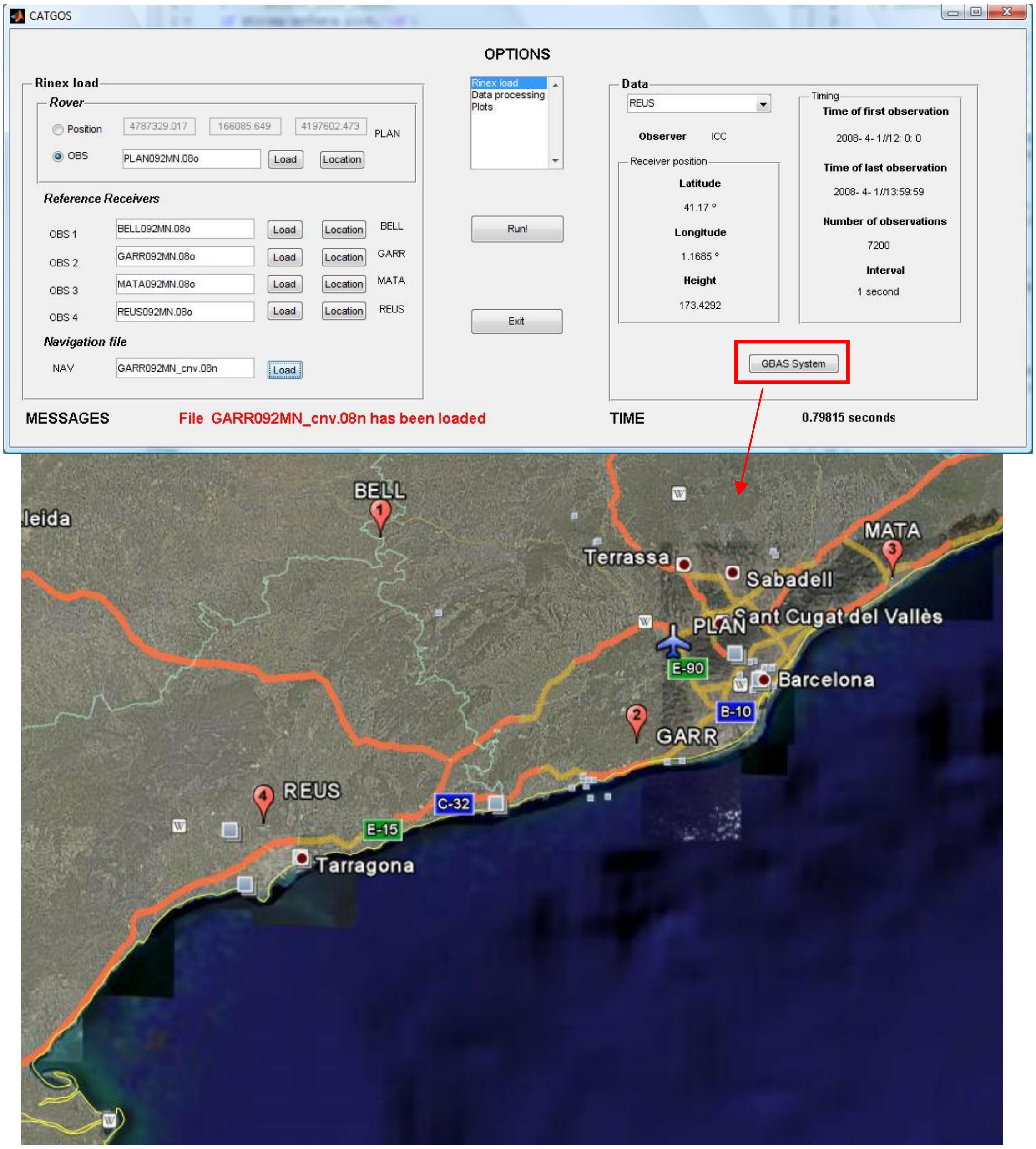


Fig.28. GBAS System display in Google Earth

2.2.2 Data processing

After the Rinex load, it is time to accomplish the data processing. We can move on this part of the application selecting the ‘*Data processing*’ option in the central menu of the application.

A new panel comes into view at the left side of the application. In it, different options can be selected in order to indicate the processing characteristics that the user desires. These options begin in first place with the selection of an independent receiver or the GBAS station; it is possible to select either the period in time or the period in epochs to be processed; the elevation threshold can also be modified as well as other parameters.

Regarding the data span considered to be processed, it is possible to specify an initial and end time or doing it considering a First and Last Epoch. A checkbox allows selecting automatically the whole data interval, updating the previous values either of time or epochs.

Next image gives an example of the period selection of data:

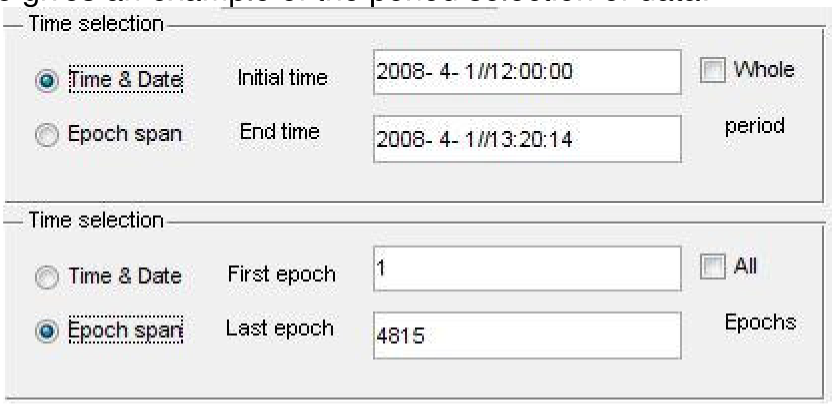


Fig.29. Time selection automatic conversion

The elevation of the satellites in view is constantly calculated in the data processing. The threshold value at which this data is considered acceptable or not acceptable can be set by the user too.

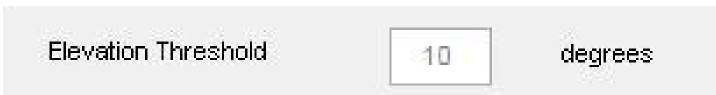


Fig.30. Threshold value selection (10 deg by default)

When the GBAS Station is selected as the Receiver, additional options appear in the screen. These options are related with the manner that data from reference receivers is expected to be used.

The first option is related with the weight distribution of the measures of the reference receivers. A default elevation-weight file is used, but another file can be used after specifying its location with the load button.

Another option is the activation of the performance and integrity monitors. The selection of any of each will involve the selection of the other one because its design.

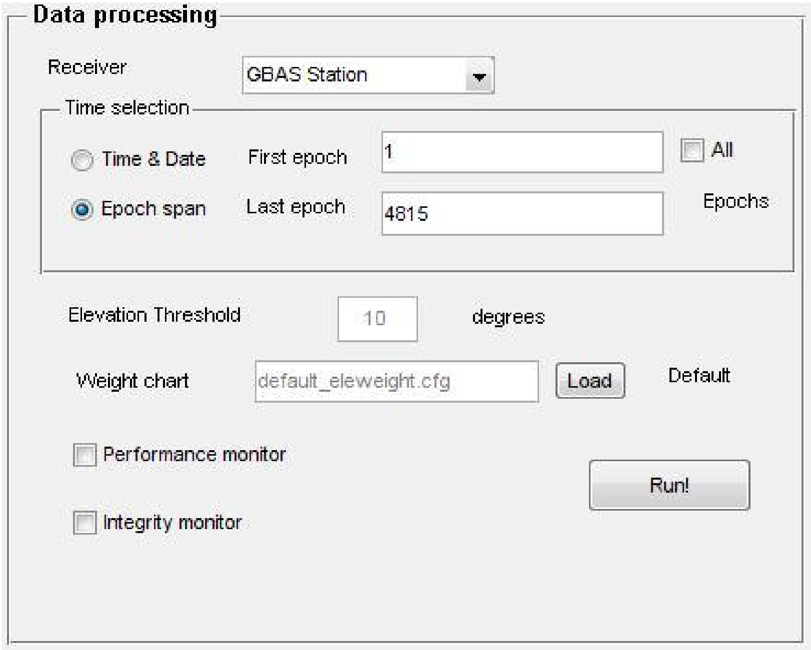


Fig.31. GBAS Station receiver options

After the data has been processed, a new message status will appear notifying the finalization of the process.

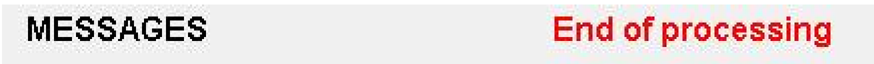


Fig.32. End of processing message

Moreover, it will be still available the option of displaying main information of the Rinex files loaded at the right side of the application.

2.2.3 Plots

Last screen is intended to present charts and graphs. In it, the left panel of the screen allows the user to decide what variables want to display. The right panel shows the result selected.

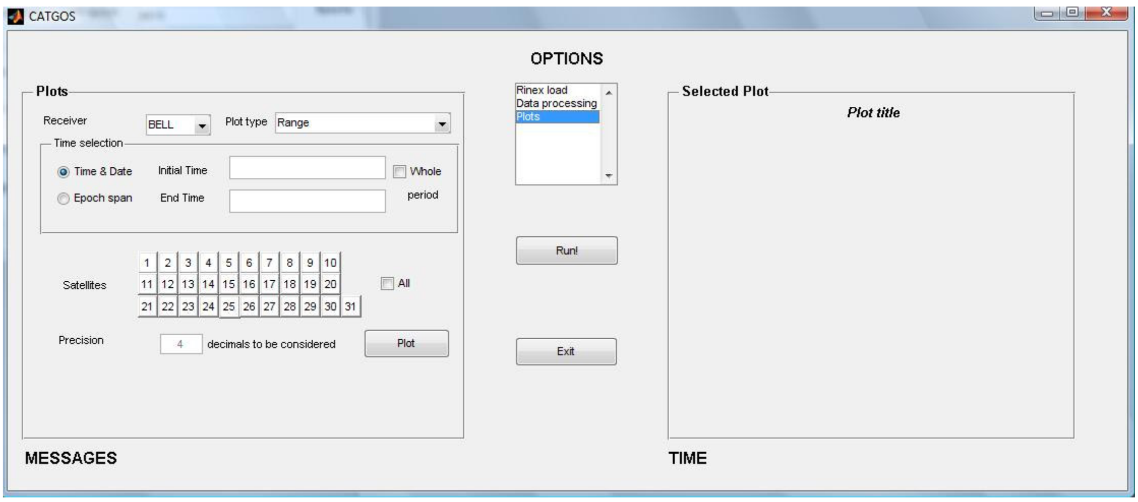


Fig.33. Plots menu initial screen

The plot panel allows several options: selecting the receiver data; the magnitude to be plot; the period in which this will be displayed; the satellites to consider in the display, etc. However, it is very important to underline that these options are only suitable and applicable when they refer to a set of data that had been previously processed in the data processing screen.

The magnitudes susceptible to be displayed depend on the receiver selected. If we refer **to a particular reference receiver**, we can find these magnitudes in the plot type option:

– Range – Pr (raw) – Pr (smoothed)	– Time correction – PR Correction (raw) – PR Correction (smoothed)	– X Sat Position – Y Sat Position – X Sat Position

Nevertheless, when referring to **the GBAS Station as a whole**, we can find these magnitudes in the plot type option:

– Prc_{SCA1} – Prc_{SCA2} – Prc_{SCA3} – Prc_{SCA4}	– Prc_{TX} – $Prc_{SCA\ rover}$

The possible values that appear as '*Plot type*' change depending on the receiver selected because the purpose is to provide the usual variables the user is expecting to analyse the behaviour whichever the situation is.

The surplus options endorsing the output visualization include:

- A **period selection panel** (the same explained in the data processing)
- A **satellite set of buttons**, which allows the user remove the contribution displayed for a particular satellite. When the plot is displayed, satellites plotted are highlighted.

Fig.34. Satellite set of buttons

- A **precision element,** that is aimed to round the value results until a particular number of decimals.

- A **rover difference checkbox**, which is aimed to provide the difference of the value that has been selected to plot in front of the same value obtained in the rover station.

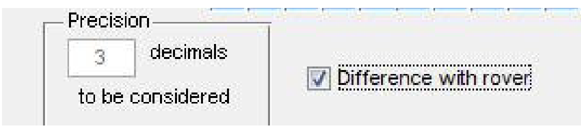


Fig.35. Precision element and rover difference checkbox

– A **formula display field**, which is updated automatically with the expression referenced with the MOPS of the variable set in the '*Plot type*' field.

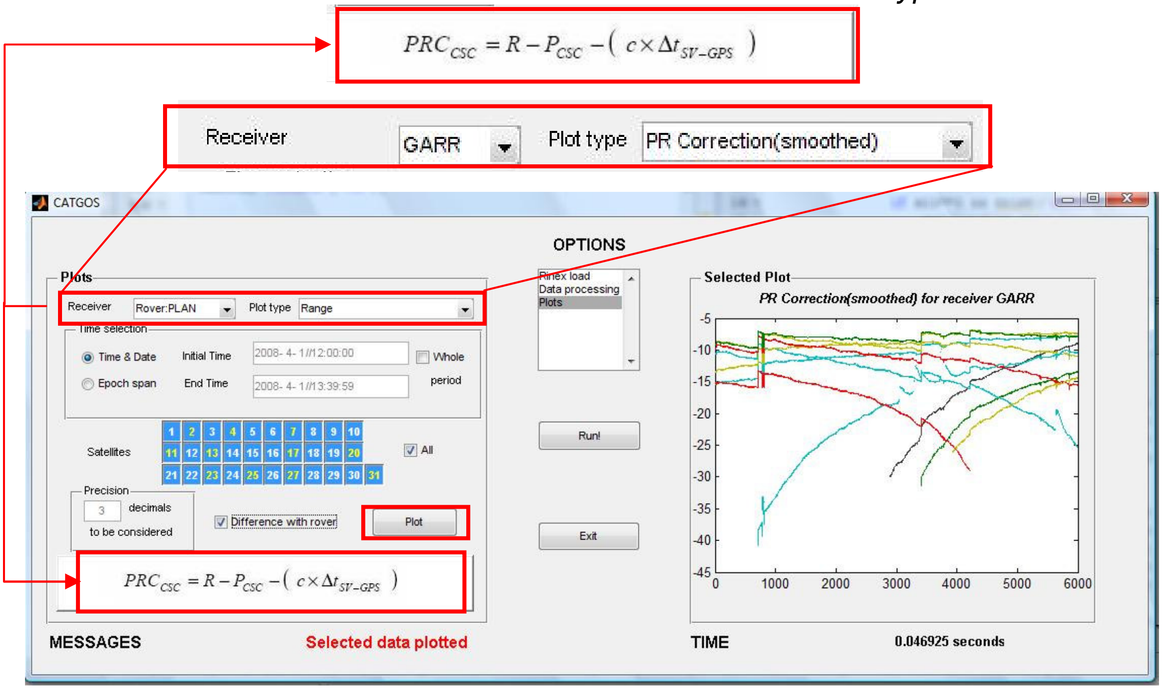


Fig.36. Displayed formula after plot launch

The '*Plot*' button re-launches the application to show in the '*Selected Plot'* panel the graph. When the process is finished, it also appears a status message and the time elapsed in the operation.

CHAPTER 3: Results

Before analyzing the results, let's review the process which has led to this point. First of all, the theoretical fundamentals have been set. Secondly, it has been described the application: structure, layout, functionality, etc. in order to know how to run the user's chosen data.

At this point, it is necessary to specify a detailed scenario and set different situations. Afterwards, some tests will be performed to validate the obtained results and evaluate its authenticity.

The GBAS station used in the application is comprised by 4 GPS reference receivers, whose position depend on the loaded rinex files. Different receivers (see Annex 2) have been utilized, but the configuration more largely used has been the following one.

This configuration will be used to validate the results exposed in this work:

Fig.37. GBAS station

The distance between the reference receivers is farther than what it would be appropriate. However, these were the closest receivers from which data could be more easily retrieved. This inconvenience will be indicated in the interpretation of the results.

In order to understand the assignment of the results validations, it is advisable to review the diagram figure which has been formerly explained and detailed (section 2 of the work).

On one hand, the first set of validations is obtained with the results considering the GPS stations independently. Its purpose is to validate independent GPS positioning for a rover using a known receiver to find more accurate features (DGPS). It is possible to carry out this test with all four receivers (one at a time) which made up the GBAS station.

These results can be compared one-to-one with the results returned by PEGASUS when using the same Rinex file selection.

On the other hand, the second sets of validations are done with the results after data has been processed by all four GPS reference receivers, just before the broadcasting.

These validations retrieve the information that would result from analyzing the rover as a GBAS station. The validation of these results is a more complex process, which will be deeply explained in the following paragraphs.

3.1 Validating processing receivers independently

This point corresponds with the ***Initial gbas validation – Pegasus Validations*** block. The first part to validate a GBAS station is the GPS positioning of a known fixed receiver (one of the Reference Receivers of the GBAS station).

To do so, the same Rinex files have been used as input values in both Pegasus and the application developed. It is expected to find similar outputs related to the positioning (range, smoothed Pseudorange, clock error corrections, Satellite position (Xk,Yk,Zk)).

Different receivers in separate time spans have been used to confirm that an independent and autonomous procedure is carried out.

The tests taken have been taken on the following dates and periods:

- On **01/Jan/2008** from 00:00h until 04:00h and from 11:00h until 13:00h.
- On **01/Feb/2008** from 16:00h until 18:00h.
- On **02/Mar/2008** from 05:00h until 07:00h.
- On **01/Apr/2008** from 12:00h until 14:00h.
- On **15/May/2008** from 20:00h until 22:00h.

These tests have been done with at least all the ICC stations (BELL, GARR, PLAN, REUS, MATA), and data from other stations has been used in some of the dates stated before (UPC3, UPC4, LEICA_G, LEICA_W).

The following graphs show the differences found between the results obtained with Pegasus and my application are due to 01/01/08 from 00:00h until 04:00h (14400 epochs) for the ICC's BELL station.

- Regarding the **range** and **time correction (including all time errors)**, we found that the difference has a 10^{-5} magnitude or better.

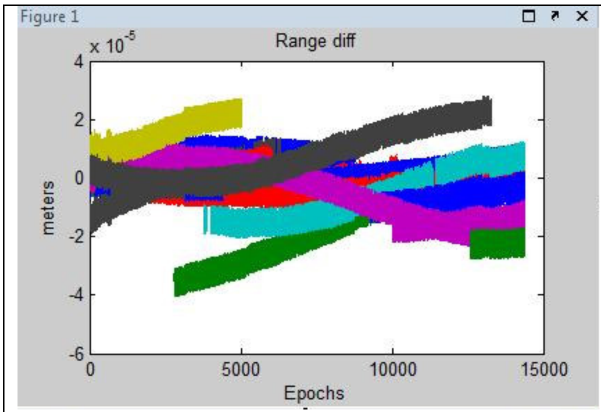


Fig.38. Range difference (sec. 1.2.4.2)

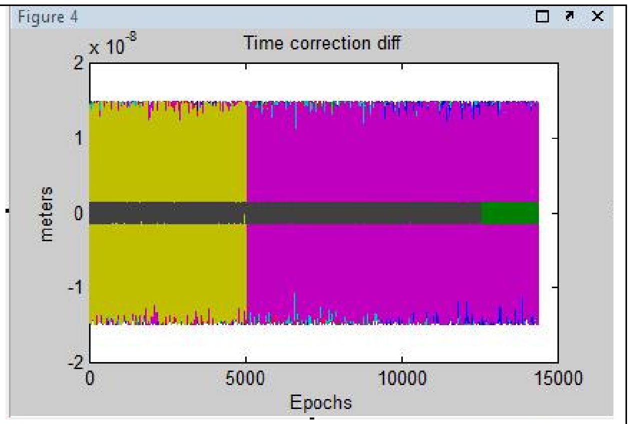


Fig.39. Time correction diff. (sec. 1.2.4.4)

– Concerning the **satellite position (x,y,z)** and the **corrected pseudorange (PRC)** which follows the expression stated in the 1.2.4.1 of this work, we found a difference of a 10^{-4} order of magnitude.

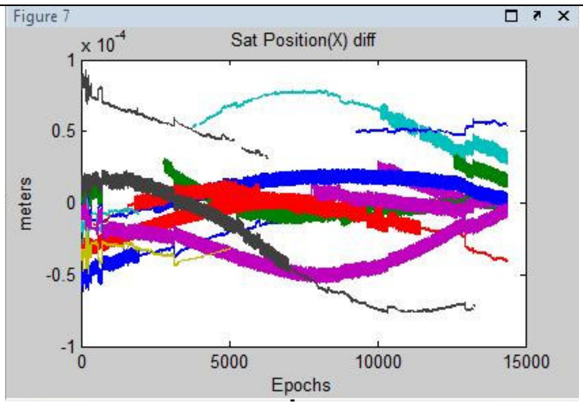


Fig.40. X coordinate of the satellite position difference

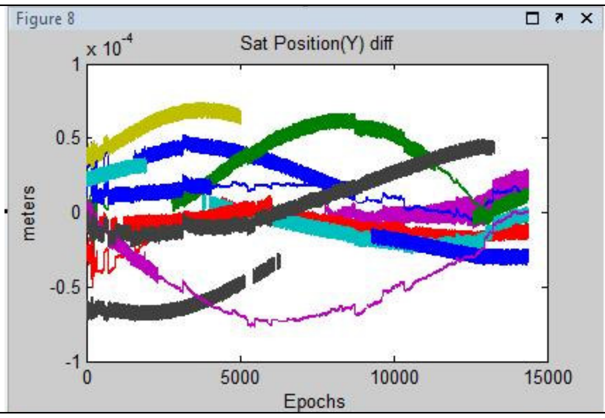


Fig.41. Y coordinate of the satellite position difference

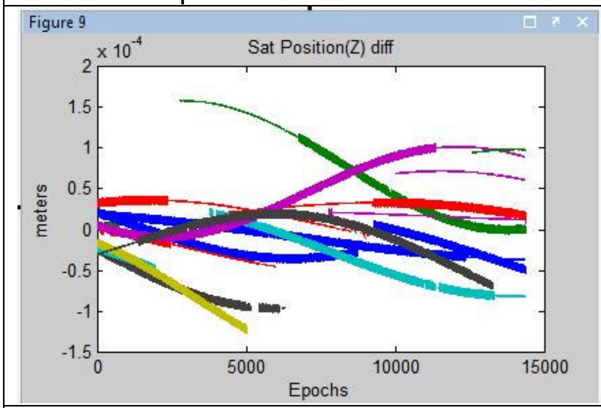


Fig.42. Z coordinate of the satellite position difference

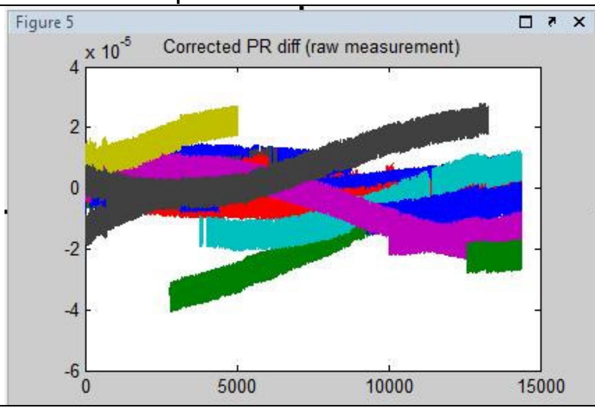


Fig.43. Corrected Pseudorange difference (section 1.2.1.4) using C1 instead of P_{CSC}

– Finally, if we compare the **corrected pseudorange (PRC)** using the P_{CSC}, which follows the expression stated in the 1.2.4.1 of this work, we found differences with the result obtained with Pegasus.

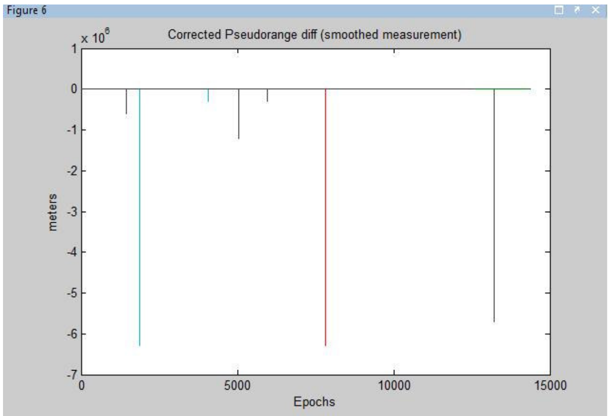


Fig.44. Corrected Pseudorange difference (section 1.2.4.1)

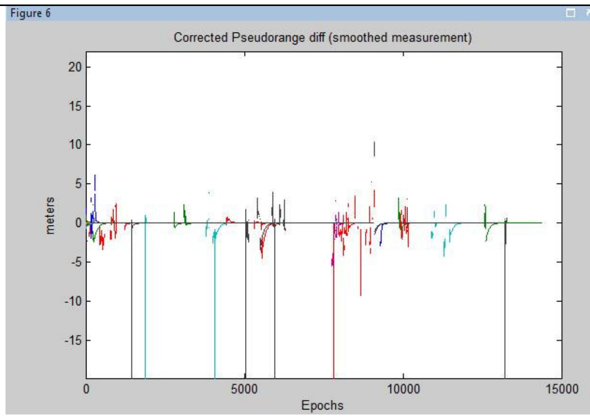


Fig.45. Corrected Pseudorange difference (enlarged)

In the whole period analyzed, two types of variations can be observed: **sharp differences** in punctual epochs and satellites; **slight differences** (less than 10 m) in the entire time span for all the sv of the constellation.

The reason dwelling in these variations is found in the way that the Smoothing filter is designed. The expression stated in the MOPS says that:

$$P_{CSC_n} = \alpha P + (1-\alpha)\left(P_{CSC_{n-1}} + \frac{\lambda}{2\pi}(\phi_n - \phi_{n-1}) \right)$$

If we analyse the inputs and outputs of a period where C1 and L1 are missing we will be able to specify the basis of this disparity. In this case, the epochs 1874–1884 for the satellite 25:

	c11 <14400x31 double> 25	l11 <14400x31 double> 25	peg_prc <14400x31 double> 25	prc <14400x31 double> 25
1871	2.5349e+07	8.9580e+06	-20.2380	-20.2380
1872	2.5349e+07	8.9610e+06	-20.2967	-20.2967
1873	2.5350e+07	8.9641e+06	-20.2801	-20.2801
1874	2.5350e+07	8.9671e+06	-20.3142	-20.3141
1875	2.5351e+07	8.9701e+06	-20.3344	-20.3344
1876	NaN	NaN	558.1573	NaN
1877	NaN	NaN	1.1366e+03	NaN
1878	NaN	NaN	1.7151e+03	NaN
1879	NaN	NaN	2.2936e+03	NaN
1880	2.5354e+07	-2.4098e+07	6.2956e+06	NaN
1881	2.5354e+07	-2.4095e+07	NaN	-20.2771
1882	2.5355e+07	-2.4092e+07	6.2956e+06	-18.8788
1883	2.5356e+07	-2.4089e+07	-20.8766	-19.8837
1884	2.5356e+07	-2.4086e+07	-20.8678	-20.3077
1885	2.5357e+07	-2.4083e+07	-20.8729	-20.2980
1886	2.5357e+07	-2.4080e+07	-20.9051	-20.3582
1887	2.5358e+07	-2.4077e+07	-20.9592	-20.5041

Fig.46. C1, L1, PRC found by Pegasus and PRC found by the developed app.

In the epoch span that goes from 1876 until 1879, C1(P) and L1(ϕ_n), are missing. Pegasus provides P_{csc} values for the following epochs after 1876 until C1 and L1 values are restored despite the lack of values. However, this lack of information is considered in the developed application providing an uncertainty as output (NaN).

Thus, we can state that the **sharp differences** found between both filters are due the dissimilar filter design when the inputs are missing.

The **slight differences** found along all the analysed period are caused by a different initialization of the filter. When data from a new satellite is retrieved or after C1 and L1 data has missed for an epoch span, Pegasus needs 3 epochs to reset the P_{csc} output. This can be observed in the figure shown before.

In epoch 1880, C1 and L1 data is restored. Therefore, it is expected to found output values in the next epoch. Pegasus resets the filter in next epoch (1881) and it uses epochs 1882 and 1883 to reinitialize the output. This procedure produces slight differences that are progressively reduced as processing leaves behind the reset epoch.

3.2 Validating GBAS results processing receivers altogether

Once the GPS positioning for the reference receivers compound the GBAS station have been validated, it is time to assemble the set of outputs of all the receivers into a single one.

To validate the final results in this test, a reference receiver located within the GBAS coverage area has been used as a rover. Subsequently, the theoretically unknown position of the rover is now acknowledged. The use of a well-known position will allow to determine the precision of the output obtained.

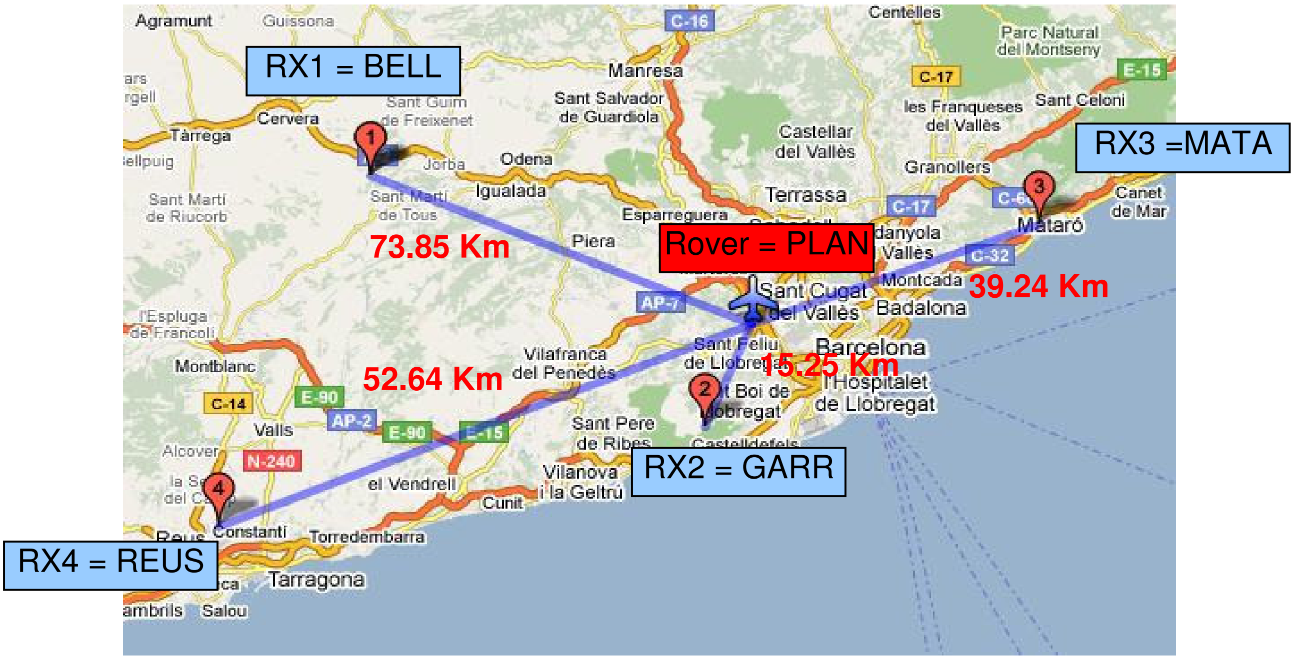


Fig.47.GBAS System. Reference receivers (blue) and rover (red).

3.2.1 *Theoretical base*

In order to understand the assignment of the results validations, it is advisable to review the diagram figure which has been formerly explained and detailed (section 2 of the work). This point corresponds with the ***Final GBAS Validations*** block.

The modus operandi used to verify the system's outputs is explained below. The mathematic expressions are colored to give additional information:

- (blue) Expression is referred to the GBAS reference receivers
- (yellow) Expression is referred to the rover
- (red) Expression is referred to the GBAS station

Just after the first part of the processing was carried out, we obtained one PRC for every reference receiver:

$$PRC_{CSC\,1} = \rho_1 - P_{CSC\,1} - (c \cdot deltaT_{SV-GPS})_1 \quad [1]$$
$$PRC_{CSC\,2} = \rho_2 - P_{CSC\,2} - (c \cdot deltaT_{SV-GPS})_2 \quad [2]$$
$$PRC_{CSC\,3} = \rho_3 - P_{CSC\,3} - (c \cdot deltaT_{SV-GPS})_3 \quad [3]$$
$$PRC_{CSC\,4} = \rho_4 - P_{CSC\,4} - (c \cdot deltaT_{SV-GPS})_4 \quad [4]$$

If we knew the rover position (the rover position is unknown), we could say that:

$$PRC_{rover} = \rho_{rover} - P_{CSC\,rover} - (c \cdot deltaT_{SV-GPS})_{rover} \quad [5]$$

However, the rover position is known just because a reference receiver has been employed as rover. Therefore, we can arrange expression [5] as:

$$\rho_{rover} - P_{CSC\,rover} - (c \cdot deltaT_{SV-GPS})_{rover} - PRC_{rover} = 0$$

Gathering similar terms:

$$\rho_{rover} - (P_{CSC\,rover} + PRC_{rover}) - (c \cdot deltaT_{SV-GPS})_{rover} = 0$$

- The first term is the geometric range of the rover
- The second term corresponds with the rover PR and its correction
- The third term is due to satellite clock delays

This expression varies depending on the rover capabilities. That is, if the rover was equipped with the smooth filter, it would be able to use $P_{CSC\,rover}$. Nevertheless, its lack will represent the use of the raw measurement of the Pseudorange (C1) instead.

$$\rho_{rover} - (C1_{rover} + PRC\csc_{rover}) - (c \cdot deltaT_{SV-GPS})_{rover} \approx 0 \quad [6a]$$
$$\rho_{rover} - (P_{CSC\,rover} + PRC\csc_{rover}) - (c \cdot deltaT_{SV-GPS})_{rover} \approx 0 \quad [6b]$$

The main idea of the GBAS system is to obtain the best Pseudorange correction (PRC) in order to wipe the several errors that appear in the process. In other words, the GBAS purpose is aimed to find the PRC which best adjusts the Pseudorange measure to make the second term as similar to ρ_{rover} as possible.

The next step to validate the response of the system will be using PRC_1, PRC_2, PRC_3 and PRC_4 values and swap them instead the PRC_{rover} value.

$$\left|\rho_{rover} - \left(C1_{rover} + PRC\,\mathrm{csc}_1\right) - \left(c \cdot deltaT_{SV-GPS}\right)_{rover}\right| = \left|\Delta P_1\right| \approx 0 \quad [7a]$$

$$\left|\rho_{rover} - \left(C1_{rover} + PRC\,\mathrm{csc}_2\right) - \left(c \cdot deltaT_{SV-GPS}\right)_{rover}\right| = \left|\Delta P_2\right| \approx 0 \quad [8a]$$

$$\left|\rho_{rover} - \left(C1_{rover} + PRC\,\mathrm{csc}_3\right) - \left(c \cdot deltaT_{SV-GPS}\right)_{rover}\right| = \left|\Delta P_3\right| \approx 0 \quad [9a]$$

$$\left|\rho_{rover} - \left(C1_{rover} + PRC\,\mathrm{csc}_4\right) - \left(c \cdot deltaT_{SV-GPS}\right)_{rover}\right| = \left|\Delta P_4\right| \approx 0 \quad [10a]$$

Or the next expressions, if the smoothing is applied:

$$\left|\rho_{rover} - \left(P_{CSC\,rover} + PRC\,\mathrm{csc}_1\right) - \left(c \cdot deltaT_{SV-GPS}\right)_{rover}\right| = \left|\Delta P_1\right| \approx 0 \quad [7b]$$

$$\left|\rho_{rover} - \left(P_{CSC\,rover} + PRC\,\mathrm{csc}_2\right) - \left(c \cdot deltaT_{SV-GPS}\right)_{rover}\right| = \left|\Delta P_2\right| \approx 0 \quad [8b]$$

$$\left|\rho_{rover} - \left(P_{CSC\,rover} + PRC\,\mathrm{csc}_3\right) - \left(c \cdot deltaT_{SV-GPS}\right)_{rover}\right| = \left|\Delta P_3\right| \approx 0 \quad [9b]$$

$$\left|\rho_{rover} - \left(P_{CSC\,rover} + PRC\,\mathrm{csc}_4\right) - \left(c \cdot deltaT_{SV-GPS}\right)_{rover}\right| = \left|\Delta P_4\right| \approx 0 \quad [10b]$$

$|\Delta P_1|$, $|\Delta P_2|$, $|\Delta P_3|$ and $|\Delta P_4|$ shall be similar to 0. The closest to 0 ΔP_x values are, the better. Anyway, it must be said that the use of smoothed Pseudorange will provide better results, as it has been demonstrated before.

Next step is considering the clock delays in the reference receivers. This consideration requires finding the PRC_{sca} defined in section 1.2.4.5 and the PRC_{TX} defined in section 1.2.4.6:

$$PRC_{sca}(i,j) \equiv PRC_{csc}(i,j) - \sum_{i \in S_c} k_i \times PRC_{csc}(i,j).$$

$$PRC_{TX}(i) \equiv \frac{1}{M(i)} \sum_{\substack{j=1 \\ j \in S_i}}^{M(j)} PRC_{sca}(i,j)$$

In the PRC_{sca} calculation, the $\sum_{i \in S_c} k_i \times PRC_{csc}(i,j)$ term gathers a delay that is common for all the measurements. This term's purpose is to adjust the reference receiver's clock by considering the elevation of the satellites seen through a weight matrix.

The PRC_{sca} is carried out for every satellite and epoch seen by every receiver independently. It indicates that the clock from every receiver has been adjusted autonomously.

The value obtained in the PRC_{sca} is not a value which can be exchanged for the PRC_{csc} value. This value is not intended for replacing PRC_{csc} in the expression [5]. Nonetheless, this value is aimed to provide a Pseudorange correction which does take into account the receiver clock delay of every reference receiver. Finally these values are used to broadcast a mean correction (PRC_{TX}) which will be enclosed in the GBAS message.

3.2.2 *Obtained result*

To figure out how the theoretical base matches to reality, several figures and examples are displayed next. In order to ease their interpretation, formulas which have been numbered in the previous section will be referenced.

The following tests have been carried out with different dates and times, the same way that it is specified in section 3.1. Graphs show the differences found between the results obtained using the rover solution and using the reference receivers that compound the GBAS station.

Data in graphs used is due 01/04/08 from 12:00h until 13:40h (6000 epochs) for the ICC's stations of BELL, GARR, MATA, REUS and PLAN as rover station.

- The first set of graphs show the [6a], [6b] expressions for the specified date and time span.

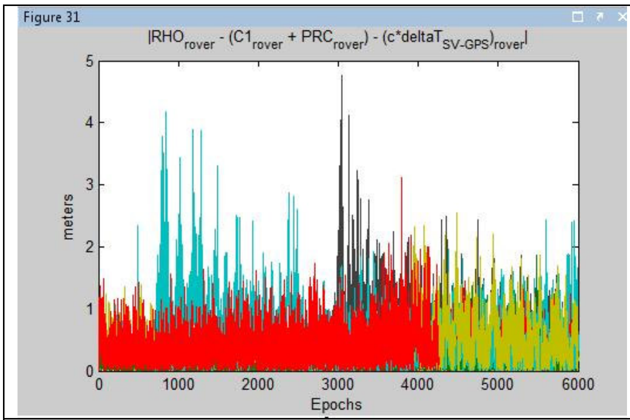


Fig.48. [6a] expression

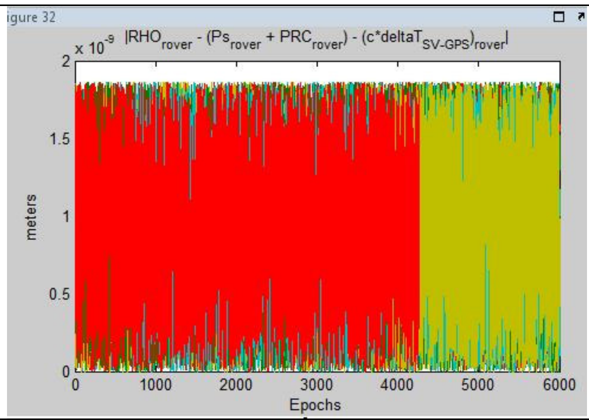


Fig.49. [6b] expression

They validate that the application of the rover Pseudorange correction makes the expression close to zero. In figure 48 it is remarkable the noise and the variations that affect the result when using the raw PseudoRange(C1). In figure 49, the result is very close to zero (10^{-9}) for two reasons: The smoothed Pseudorange (P_{csc}) is used; The PRC supplied is given by the receiver placed in the rover position.

- The second set of graphs show the [7a], [8a], [9a] and [10a] expressions for the specified date and time span.

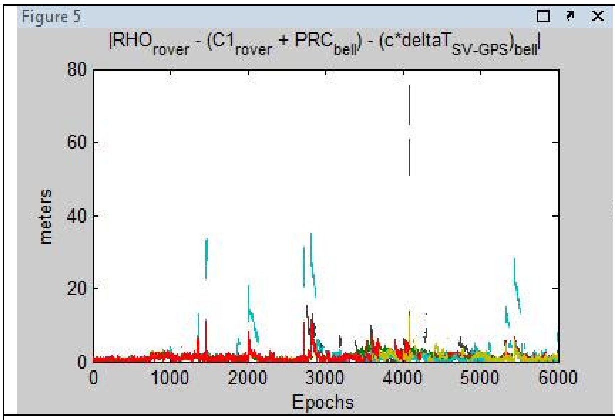


Fig.50. [7a] expression - BELL

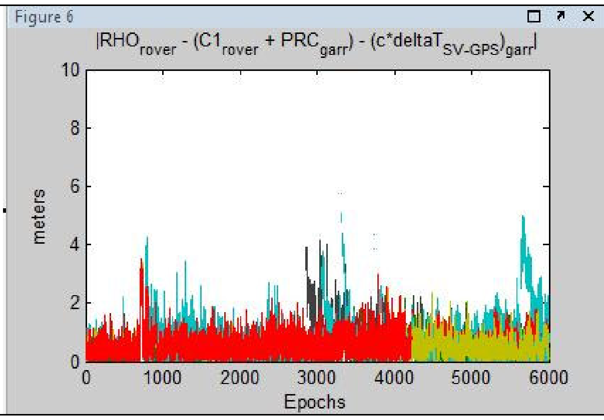


Fig.51. [8a] expression - GARR

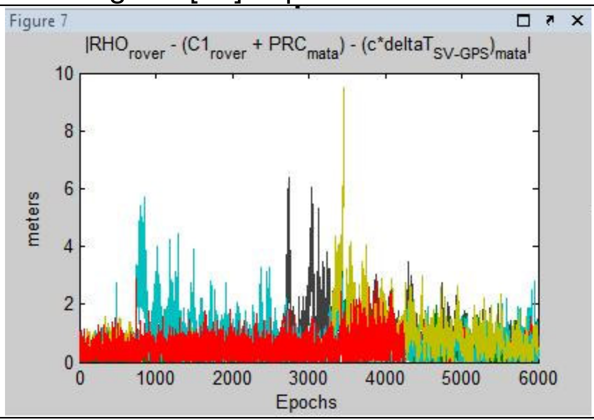


Fig.52. [9a] expression - MATA

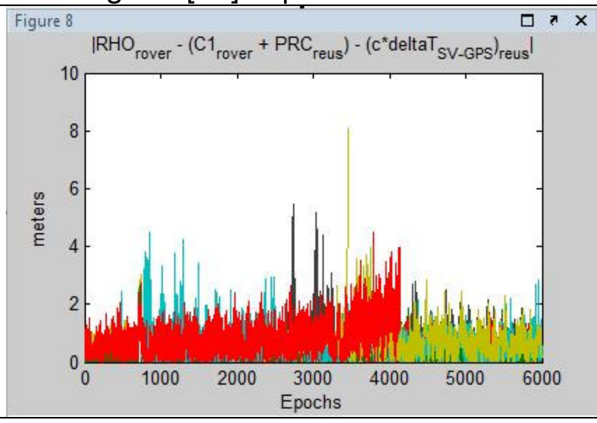


Fig.53. [10a] expression - REUS

Bell receiver provides PRC values that are clearly different in some epochs. This is caused because some of the satellites seen by this receiver are not seen by the rover. In the other three receivers, the $|\Delta P_{rx}|$ value is lower, despite the existing significant noise.

- The third set of graphs for the [7b], [8b], [9b] and [10b] expressions in the specified date and time span show the enhancement when the smoothing filtering is enabled.

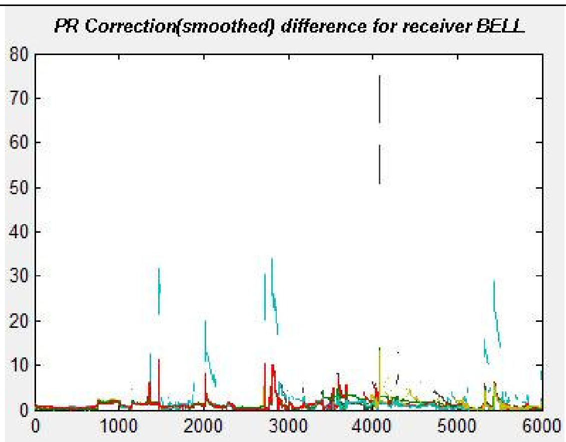


Fig.54. [7b] expression - BELL

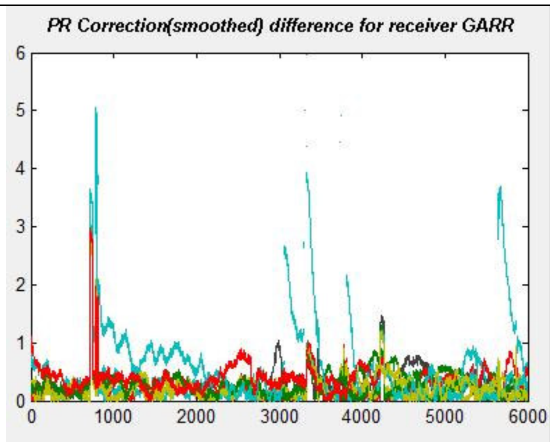


Fig.55. [8b] expression - GARR

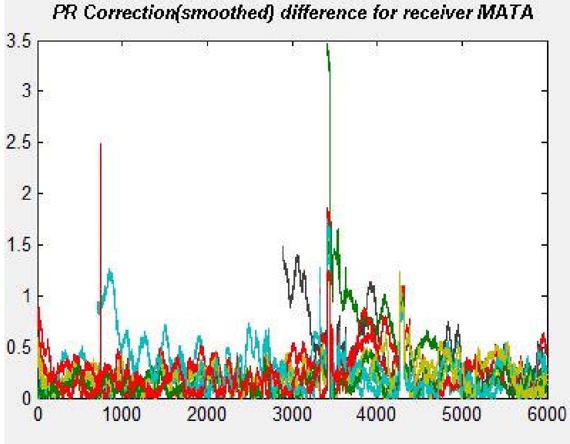
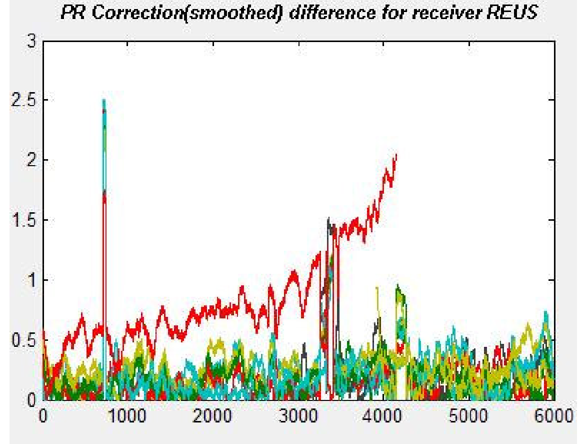
	

Fig.56. [9b] expression - MATA	Fig.57. [10b] expression - REUS

It is remarkable that the BELL receiver has **abrupt differences** in the value of the calculated PRC, particularly for satellites number 11 and 25 (light blue) and number 7 (black). The reason for these differences is the same that was given in the previous paragraph. The **signal noise** has been dramatically reduced because of the use of a smoothed Pseudorange (P_{csc}). Its effect reduces the signal unsteadiness shown in figures 50 to 53.

- Next step is to apply the receiver clock adjust for each receiver, which corresponds the $\sum_{i \in S_c} k_i \times PRC_{\mathrm{csc}}(i,j)$, or equivalently to PRC_{csc} - PRC_{sca}.

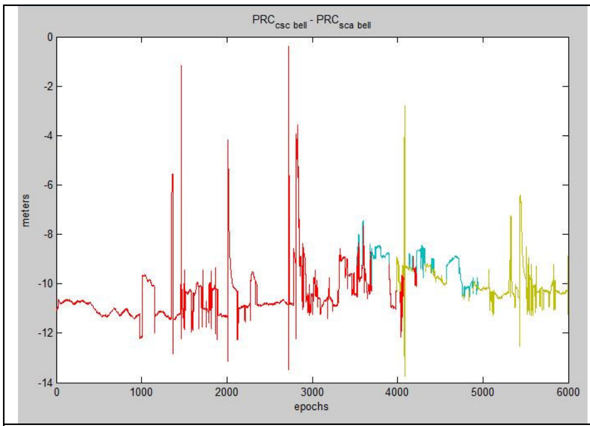
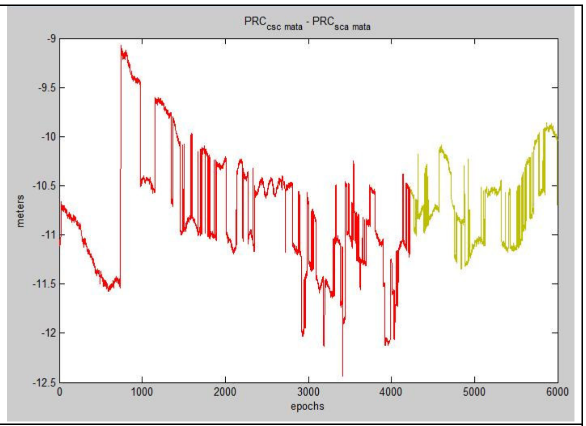
	

Fig.58. $PRC_{csc\ BELL}$ - $PRC_{sca\ BELL}$	Fig.59. $PRC_{csc\ GARR}$ -$PRC_{sca\ GARR}$

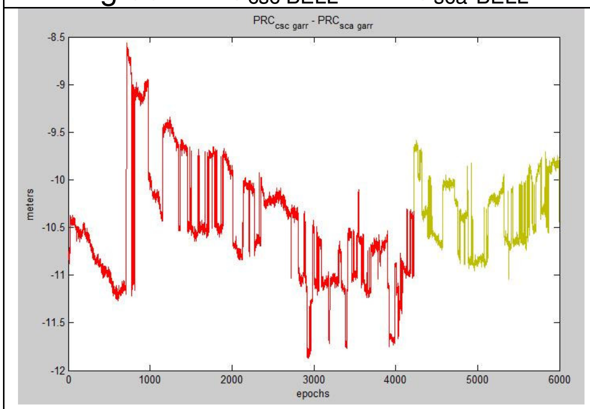
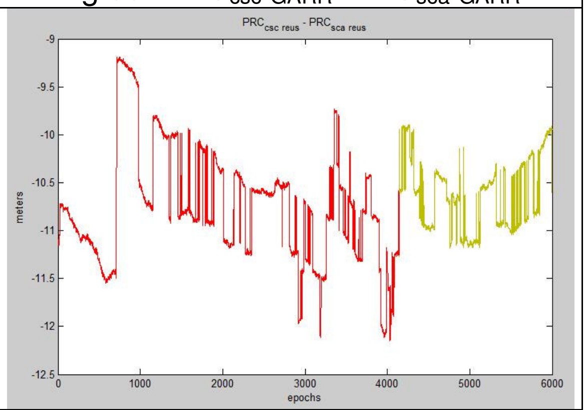

	

Fig.60. $PRC_{csc\ MATA}$-$PRC_{sca\ MATA}$	Fig.61. $PRC_{csc\ REUS}$ -$PRC_{sca\ REUS}$

The next example provides a detailed analysis of the process in epoch 1500.

Rx: BELL

	Sv_4	Sv_{11}	Sv_{13}	Sv_{17}	Sv_{20}	Sv_{23}	Sv_{25}	Sv_{31}
PRC_{csc}	-11.248	-10.742	-9.348	-9.002	-8.173	-7.749	-25.059	-14.710
PRC_{sca}	-1.095	-0.590	0.805	1.150	1.980	2.403	-14.906	-4.558
| Diff |*	10.15	10.15	10.15	10.15	10.15	10.15	10.15	10.15

Rx: GARR

	Sv_4	Sv_{11}	Sv_{13}	Sv_{17}	Sv_{20}	Sv_{23}	Sv_{25}	Sv_{31}
PRC_{csc}	-11.650	-10.961	-9.511	-9.391	-8.539	-7.986	-26.776	-15.194
PRC_{sca}	-1.129	-0.440	1.011	1.130	1.983	2.535	-16.254	-4.672
| Diff |[1]	10.52	10.52	10.52	10.52	10.52	10.52	10.52	10.52

Rx: MATA

	Sv_4	Sv_{11}	Sv_{13}	Sv_{17}	Sv_{20}	Sv_{23}	Sv_{25}	Sv_{31}
PRC_{csc}	-12.085	-11.350	-9.980	-10.040	-8.781	8.360	-28.102	-15.215
PRC_{sca}	-1.133	-0.398	0.972	0.912	2.171	2.593	-17.150	-4.262
| Diff |[1]	10.95	10.95	10.95	10.95	10.95	10.95	10.95	10.95

Rx: REUS

	Sv_4	Sv_{11}	Sv_{13}	Sv_{17}	Sv_{20}	Sv_{23}	Sv_{25}	Sv_{31}
PRC_{csc}	-11.929	-11.205	-9.732	-9.603	-8.777	-8.264	27.589	-15.986
PRC_{sca}	-1.101	-0.378	1.096	1.224	2.051	2.564	-16.672	-5.158
| Diff |[1]	10.83	10.83	10.83	10.83	10.83	10.83	10.83	10.83

Rx: Rover

	Sv_4	Sv_{11}	Sv_{13}	Sv_{17}	Sv_{20}	Sv_{23}	Sv_{25}	Sv_{31}
PRC_{csc}	-11.990	-11.100	-9.693	-9.705	-8.627	-8.265	-27.422	-15.434
PRC_{sca}	-1.228	-0.338	1.069	1.057	2.135	2.497	-16.660	-4.672
| Diff |[1]	10.76	10.76	10.76	10.76	10.76	10.76	10.76	10.76

This example is also suitable to introduce the next broadcast pseudorange correction (PRC_{TX}), which combines the PRC_{sca} values of the 4 reference receivers:

GBAS STATION

	Sv_4	Sv_{11}	Sv_{13}	Sv_{17}	Sv_{20}	Sv_{23}	Sv_{25}	Sv_{31}
$\|PRC_{TX}\|$	-1.114	-0.451	0.971	1.104	2.046	2.524	-16.722	-4.663

These results along with graphs 58 to 61 draw some conclusions:

The first important thing that can be observed in each graph is that **all the satellites follow a sole line**. That is to say they produce the same clock correction in the receiver in a particular epoch (BELL=10.15, GARR=10.52, MATA=10.95, REUS=10.83). This was expected to be this way.

[1] Diff is the difference | PRC_{csc} - PRC_{sca} | in meters, due the reference receiver clock adjust.

Second thing is that the **sharp variations** observed are caused by the inclusion or the exclusion of satellite(s) in sight of the receiver. These variations cause a lower or higher processing time in the receiver and therefore, the correction (in distance) of the receiver clock vary.

All receivers should have a similar **clock delay** (in meters) because they are the same model, same type of observer and they process the same navigation message (10.15≈10.52≈10.95≈10.83). Additionally, as they are relatively close to one another they ought to see the same satellites. However, PRC_{csc} data provided to Bell receiver for some satellites is particularly distant from the values obtained with other receivers (see peaks in figures 50 and 54).

If we compare the different PRC_{sca} of the different receivers with the $PRC_{sca\ rover}$:

	Sv_4	Sv_{11}	Sv_{13}	Sv_{17}	Sv_{20}	Sv_{23}	Sv_{25}	Sv_{31}	**Mean**
$Diff_{bell}$	0.133	-0.252	-0.264	0.093	-0.155	-0.094	1.754	0.114	0.357
$Diff_{garr}$	0.099	-0.102	-0.058	0.073	-0.152	0.038	0.406	0.001	0.226
$Diff_{mata}$	0.095	-0.060	-0.097	-0.145	0.036	0.096	-0.490	0.410	0.179
$Diff_{reus}$	0.127	-0.040	0.027	0.167	-0.084	0.067	-0.012	-0.486	0.126

With:

$Diff_{bell} = PRC_{sca\ bell} - PRC_{sca\ rover}$ (in meters)
$Diff_{garr} = PRC_{sca\ garr} - PRC_{sca\ rover}$ (in meters)
$Diff_{mata} = PRC_{sca\ mata} - PRC_{sca\ rover}$ (in meters)
$Diff_{reus} = PRC_{sca\ reus} - PRC_{sca\ rover}$ (in meters)

The same process with the GBAS station will produce:

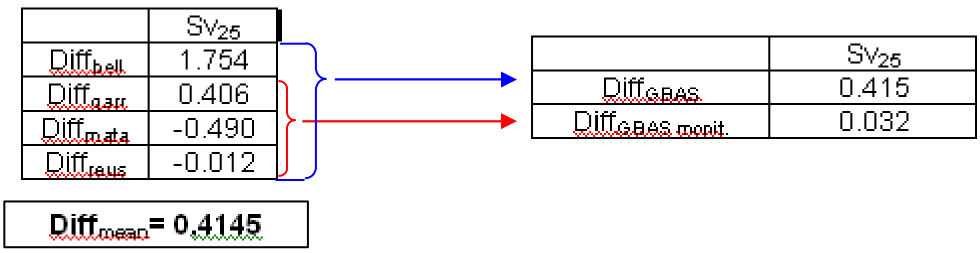
	Sv_4	Sv_{11}	Sv_{13}	Sv_{17}	Sv_{20}	Sv_{23}	Sv_{25}	Sv_{31}	**Mean**
$Diff_{GBAS}$	0.114	-0.113	-0.098	0.047	-0.089	0.027	0.415	0.009	0.114
$Diff_{GBAS\ monit.}$	0.114	-0.113	-0.098	0.047	-0.089	0.027	0.032	0.009	0.070

With:

$Diff_{GBAS} = PRC_{TX} - PRC_{sca\ rover}$ (in meters)
$Diff_{GBAS\ monit.} = PRC_{TX} - PRC_{sca\ rover}$ (with monitors, in meters)

After the clock of every reference receiver is adjusted, the PRC_{TX} value bonds better to the $PRC_{sca\ rover}$ than any particular receiver. What occurs in this epoch is extensible to the rest of the period analyzed.

Pseudorange correction value from satellite 25 for the BELL receiver is very far from the mean value ($PRC_{sca\ bell}$=1.754). However, when the monitors are active, this value is not taken into account in the PRC_{TX} calculation.



It can be appreciated that BELL receiver is providing a wrong PRC_{sca}. When the monitors designed are active, value is not taken to calculate the PRC_{TX} output, because it surpasses the mean value more than a specified threshold percentage.

	Sv_{25}	Relative to $\mathbf{Diff_{mean}}$
$Diff_{bell}$	1.754	323%
$Diff_{garr}$	0.406	97.9%
$Diff_{mata}$	-0.490	118,2%
$Diff_{reus}$	-0.012	2,9%
$\mathbf{Diff_{mean}}$	**0,4145**	---

In spite of the enhancement that can be observed with the activation of monitors (Mean difference is lowered), its design has been done without any standard procedure. Moreover, the selected thresholds to discriminate have been approximated after testing. For this reason, the activation of monitors is not recommended until a better developing is performed or a standard method is applied.

– At this point, it is possible to compare PRC_{sca} that the rover would supply with the PRC_{sca} provided by every reference receiver.

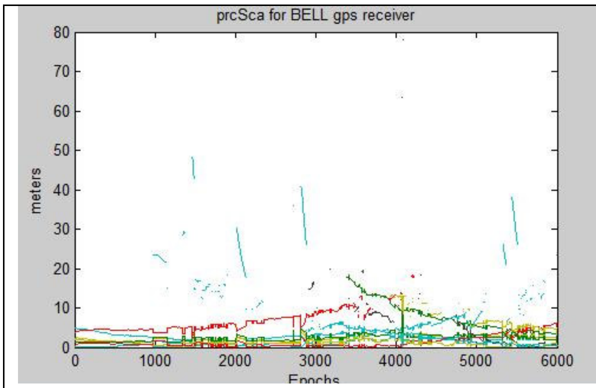


Fig.62. PRC_{sca} BELL

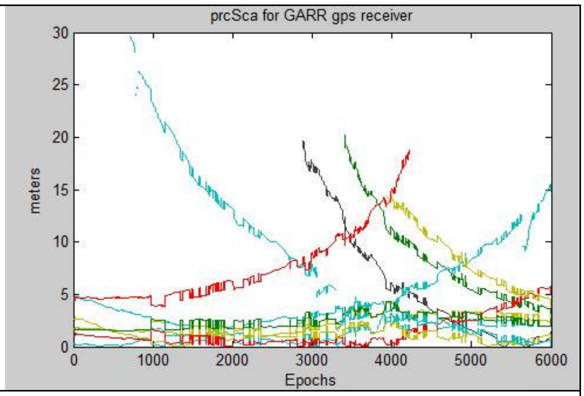


Fig.63. PRC_{sca} GARR

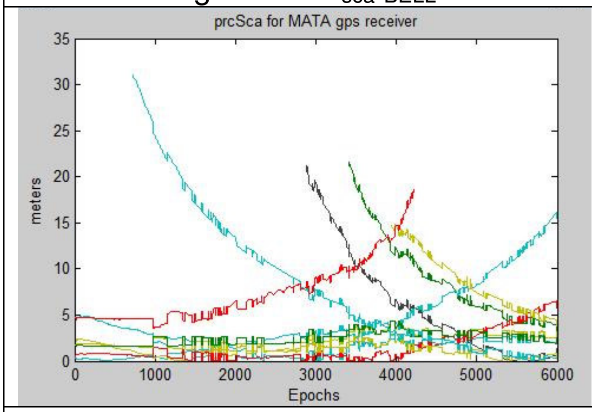


Fig.64. PRC_{sca} MATA

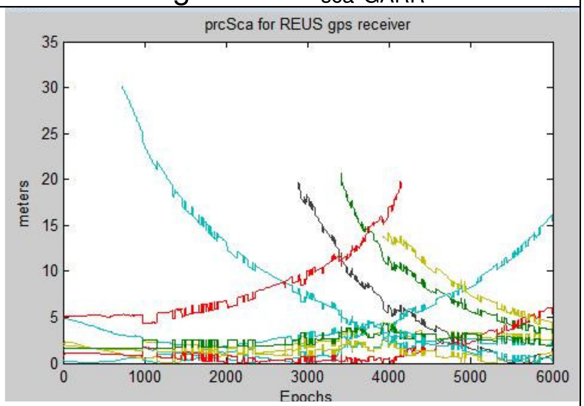


Fig.65. PRC_{sca} REUS

The same process using the data from the reference receiver placed at the rover position generates the PRC_{sca} rover.

The Pseudorange correction value is reduced considerably once the reference receiver clock has been adjusted. It can be appreciated that satellites need a higher Pseudorange correction as long as they reach lower elevations.

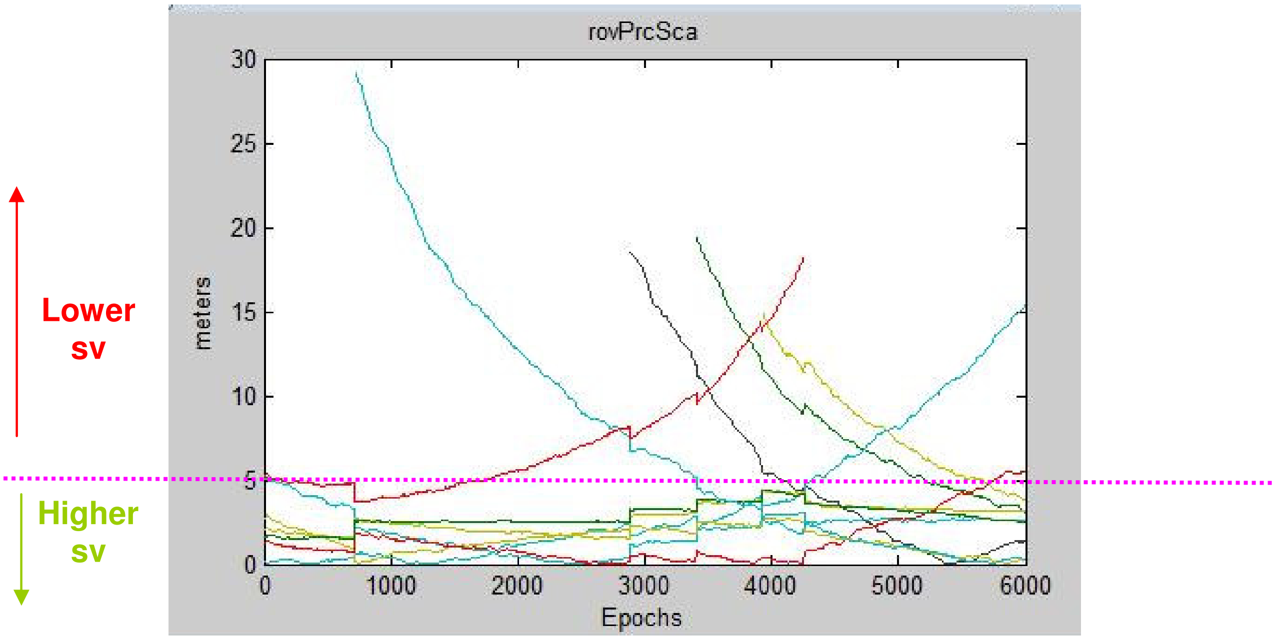


Fig.66. $PRC_{sca\ rover}$

At this point, we can compare the broadcast Pseudorange correction done by the GBAS system (PRC_{TX}), with the one expected by the rover $PRC_{sca\quad rover}$.

The impact of incorrect measurements is substantial, due to all values from reference receivers are equally weighed (0.25). In this case, we can say that the BELL receiver is the major responsible for the peaks found figure 67. For this reason, the activation of monitors (performance and integrity) eliminate these peaks and produce a better response.

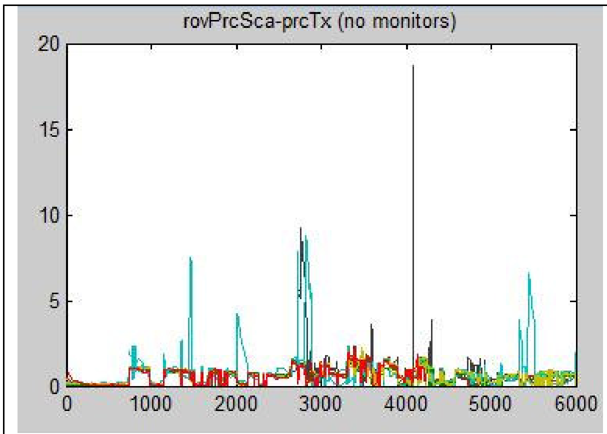


Fig.67. $PRCsca_{rover}$ - PRC_{TX}

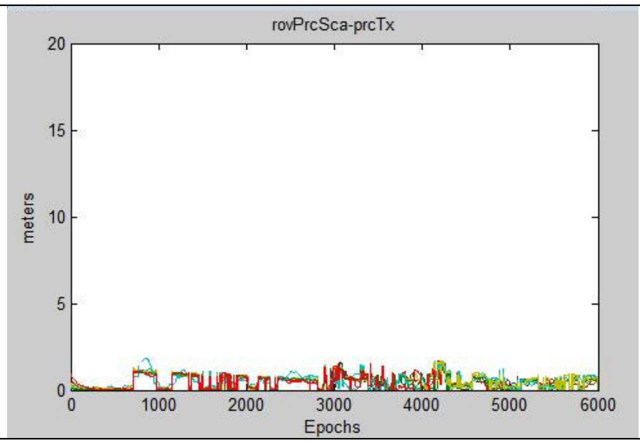


Fig.68. $PRCsca_{rover}$ - PRC_{TX} (w. monitors)

The result is clearly closer to zero and peaks are eliminated. It can be observed that the periods where receivers don't share the same satellites than the rover produce variations.

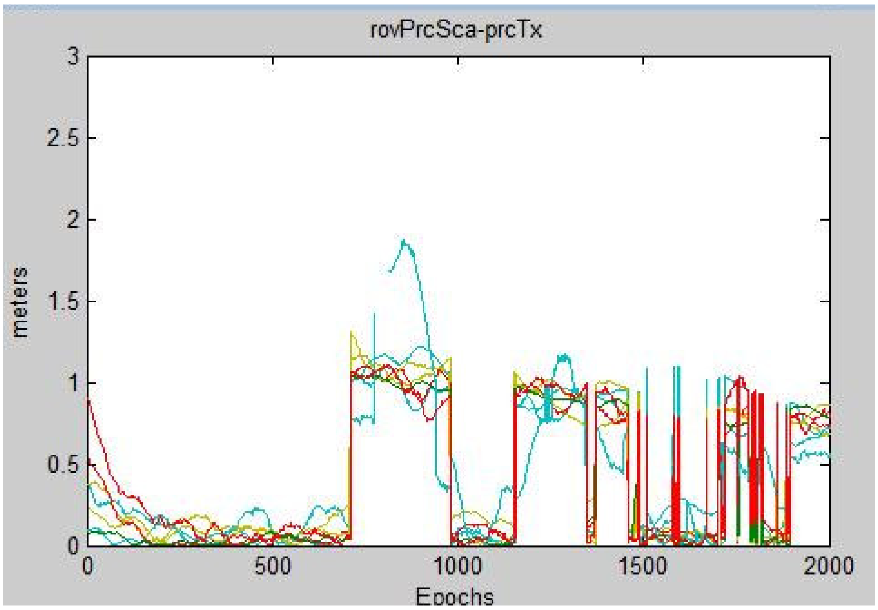


Fig.69. Detailed difference between $PRCsca_{rover}$ and PRC_{TX} (Active monitors)

However, periods where receivers and rover share same satellites, the PRC_{TX} is closer to $PRC_{sca\ rover}$ value. The divergence between PRC_{TX} and $PRC_{sca\ rover}$ in these periods is based on a mixture of facts: the big distance between the reference receivers that compound the GBAS station, the elevation threshold set, the elevation-weight matrix and others.

To summarize the main ideas we have been dealing with in this section:

- The $\mathbf{PRC_{csc}}$ values are referred to the Pseudorange correction needed without considering the reference receiver clock adjust.
- The $\mathbf{PRC_{sca}}$ values are referred to the Pseudorange correction needed considering reference clock adjust for the corresponding reference receiver.
- The **|Diff|=|** $\mathbf{PRC_{csc\ rx}}$ - $\mathbf{PRC_{sca\ rx}}$ **|** values are referred to the receiver clock adjust that is done due to the reference receiver clock delay. The correction applied is carried out for each receiver. For every receiver, all the satellites in sight share this difference and it varies every epoch.
- The $\mathbf{PRC_{TX}}$ values are referred to the mean Pseudorange correction broadcast considering the PRC_{sca} of all the reference receivers. The system adjustment depends on how these values resemble to the PRC that the rover would need.

CONCLUSIONS

The development of this project has allowed me to get important skills, such as:

- Broad software knowledge:
  - Managing projects with Microsoft Visio®.
  - Use of Hatanaka to parse and retrieve data from Rinex files.
  - Use of Pegasus® to process Rinex files and evaluate its outputs.
  - Program .kml files for Google Earth® and Google Maps®.
  - Expertise in the use of Matlab® environment (scripts, functions, GUI, objects, structures, time optimization).
- Organization and time management.
- Bring about in a sole application different options and managing different types of files using an interconnected and friendly environment.
- Deep GNSS comprehension:
  - Strengthen GPS fundamentals.
  - RINEX files: Types. Data transmitted. Organization in subframes.
  - Cycles Slips: Basis and Detection.
  - Reference systems: Earth's model, Time, Space.
  - GBAS theoretical base: time corrections, Pseudorange smoothing, Range calculation…

Regarding the results and their validation:

- Contrasting results of a single GPS receiver with Pegasus®:
  - It has been checked that the application of the MOPS ED-114 procedures provide the same response in the range(R), time correction(Trx), Pseudorange correction (with raw data, C1) and Satellite Positioning (X_k, Y_k, Z_k).
  - It has been concluded that the difference in the Smoothing Filtering of the Pseudorange is due the dissimilar filter design and filter initialization when data is missing for a certain span. These has reported differences in the smoothed Pseudorange (P_{csc}) and the corrected Pseudorange (with smoothed data, PRC_{csc})

- Contrasting results of the GBAS station with an extra receiver as rover:
  - The use of the smoothing filters generates a great enhancement in the Pseudorange correction value in terms of noise and reduction of peaks.
  - The Pseudorange corrections (the various Prc_{sca}) drawn are dissimilar and varying due the "relatively great" distance that exists between the reference receivers. This effect causes errors when one of the receivers employs data from a satellite which is not seen by the rest of receivers or the rover.
  - The Pseudorange value transmitted (Prc_{TX}) is a mean value of the Prc_{sca} of the different reference receivers and it depends on the elevation-weight proportion provided. These values adapts greatly to the expected value obtained by the rover station $Prc_{sca\ rover.}$

- The employment of designed monitors reduces peaks and diminishes the mean error.

There is still a long path to go in order to improve this application. Some hints about the enhancements to be applied would be:

- Translate the pseudorange correction needed into a coordinate positioning correction (X, Y, Z) and endorse a mean error relative to a known position.
- Improve the monitors designed by considering diverse situations (lack of data, contaminated data…). Observe the changes and implement a better and more robust code to adapt the performance in response to each circumstance.
- Test the application in a farther period span considering and evaluating parameters such as availability, continuity, integrity…

The project has adjusted to the purpose and limitations that have been set at the beginning. In my view, it has been worthy developing this application because it has offered me the opportunity to get the know-how about how a project should be carried out.

It also has been fulfilling the fact of expanding GNSS knowledge and contrasting the results achieved against other sources or using additional data.

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ANNEX 1 - ABBREVIATIONS

SV – Space vehicles (satellites)

WIK – Wikipedia

SARP – Standards and Recommended Practices

MOPS – Minimum Operational Performance Specifications

ICAO – International Civil Aviation Organization

GBAS – Ground Based Augmentation System

ANNEX 2 – GPS DATA SOURCES

Checking the validity of a process demands different situations to be considered. When this process involves different hardware devices to be analysed with specific software, this task becomes very important.

In our case, we have developed software to analyse different variables to be used for any GPS receiver. Although receivers must adjust to standards and specifications described in RINEX format, we need several measures from different GPS receivers in order to get reliable results that confirm that the underlying process is done properly.

Data from the following GPS receivers has been used:

Data from receivers of ICC (*Institut Català de Cartografia*, www.icc.cat)

BELL: Bellmunt de Segarra. Talavera (SPGIC: 271116002)
Coord LLA: 41.5996º 1.4011º 853.407 m
GARR: Massís del Garraf. Begues (SPGIC: 283130002)
Coord LLA: 41.2929º 1.4140º 634.81 m
PLAN: Les Planes. Pallejà. (SPGIC: 285124002)
Coord LLA: 41.4185º 1.9870º 319.954 m
REUS: IRTA Mas Bovè. Reus. (SPGIC: 265136002)
Coord LLA: 41.1700º 1.1685º 173.422 m
MATA: UPM. Mataró. Maresme. (SPGIC: 295119001)
Coord LLA: 41.5399º 2.4286º 123.548 m

To check the exact situation of this GPS stations, click here.

Data sustained by Dagoberto Salazar:

EBRE: Observatori de l'Ebre. Roquetes (Baix Ebre). (SPGIC: 249153002)
Coord LLA: 40.8208º 0.4923º 173.422 m

To check the exact situation of this GPS stations, click here.

Data from receivers in the SouthEast of England:

FARN: FARNBOROUGH GPS STATION
Coord LLA: 51.2779º -0.7727º 112.6458 m
TEDD: TEDDINGTON GPS STATION
Coord LLA: 51.423º -0.3435º 70.0288 m
AMER: AMERSHAM GBAS STATION
Coord LLA: 51.6772º -0.5594º 134.1314 m
STRA: STRATFORD GPS STATION
Coord LLA: 51.5446º 0.0095º 80.4494 m
WEIR: WEIR WOOD RESERVOIR GPS STATION
Coord LLA: 51.1010º 0.0076º 115.8776 m

To check the exact situation of this GPS stations, click here.

LEICA_E: East side of Sion's airport platform
Coord LLA: 46.2209318º 7.34235º 456.54761 m

LEICA_W: West side of Sion's airport platform
Coord LLA: 46.21594º 7.31100º 544.75210 m

LEICA_G: Sion's airport coordination centre office
Coord LLA: 46.22259º 7.33727º 541.72911 m

To check the exact situation of this GPS stations, click here.

Data sustained by gAGE (Group of Aeronautics and Geomatics).

UPC3: Politechnical University of Catalonia (U.P.C) GPS receiver at Castelldefels.
Coord LLA:41,27537º 1.98684º 76.47388 m

UPC4: Politechnical University of Catalonia (U.P.C) GPS receiver at Barcelona.
Coord LLA: 41.38866 2.11182º 167.04317 m

To check the exact situation of this GPS stations, click here.

ANNEX 3 – HATANAKA PROCESSING TUTORIAL

Data supplied by ICC and other sources has required a treatment to obtain GPS typical files with its typical file extension: (***.##o)*** for observation files and (***.##n)*** for navigation files.

The use of a file translator has been necessary. The program used is called Hatanaka and the process followed to obtain the Rinex files is detailed below:

1. Download the Observation File from the ftp server. (STAT###L.YY#)
2. Open with WINRAR this file and drag the file to the folder where **crx2rnx.exe** is located.
3. Type the file extension **.yyd** to the file.
4. Open a DOS console, get to the folder and enter the command: **crx2rnx.exe *STAT001L.08d***
5. A new file called STAT001L.08o will be created straightaway.

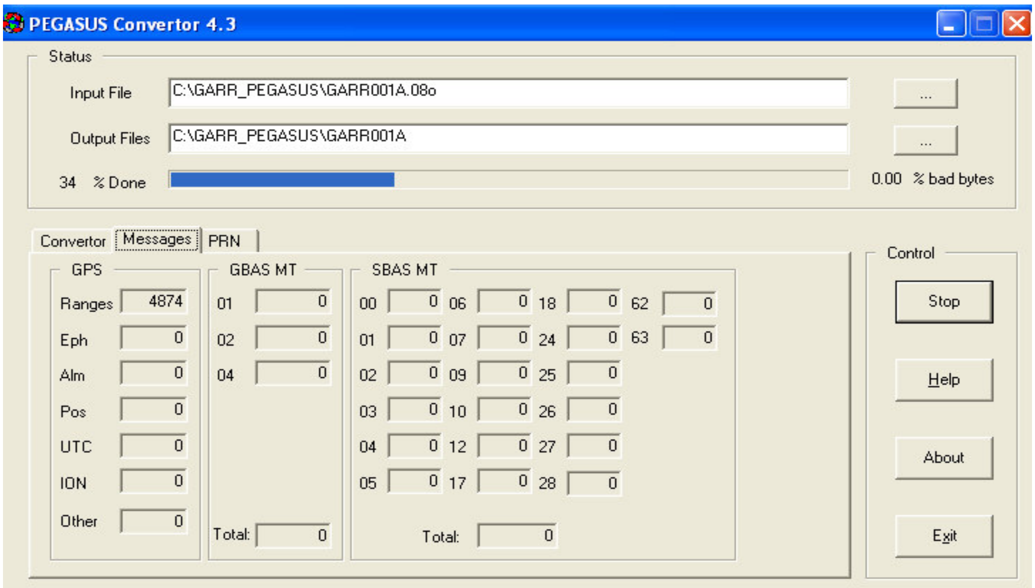
ANNEX 4 – PEGASUS TUTORIAL

This document pretends to be a step-by-step tutorial of usage of some of the Pegasus modules. Its results are intended to be used in front of those extracted from ours.

Convertor

This is the first module to be used. It generates an ASCII Format Output File which will allow the program make further calculations and solutions.

Input File must be specified, and Output File will be automatically generated. In the example shown below, we will be using the GARR Observation files.



In the folder where the input file is placed, output files shall be generated. All of them share the very initial name of the input file, but some have the tag ("_cnv"), which is given due to it comes from the convertor module.

Module information file – Contains relevant information of the processing. This information may be variable depending on which module(s) is executed.

The log-file for the conversion – Contains the execution of LOG

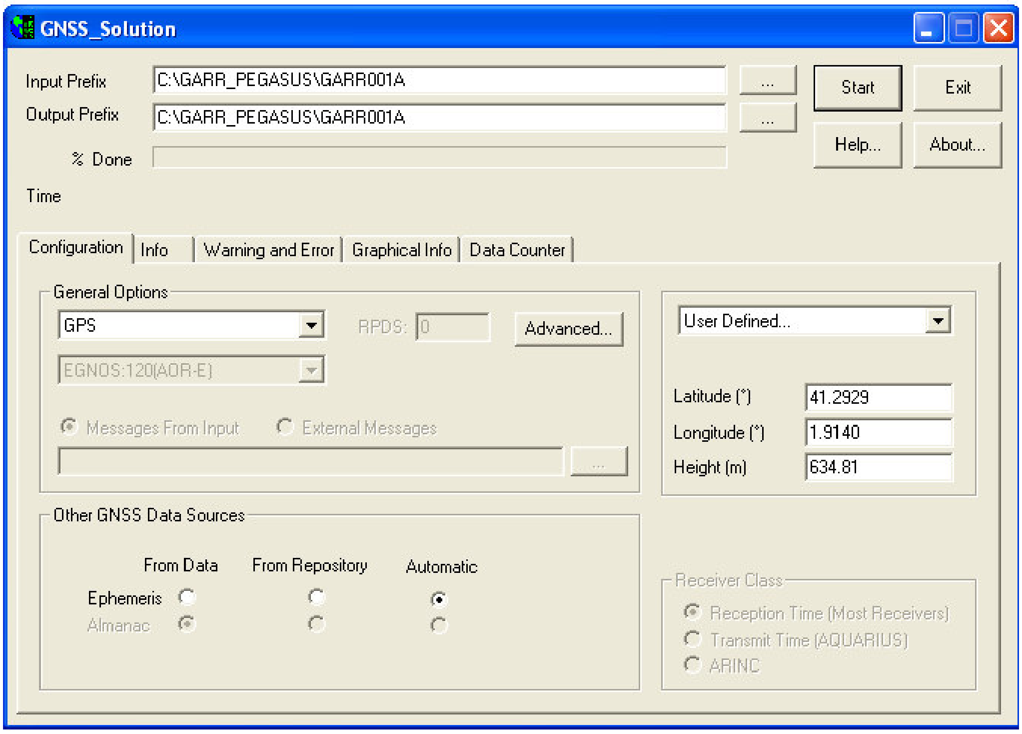
Data file containing range-data – Intermediate range results.

The next step is to rename the ephemeris file with the same as the LOG file.In our case, the file **GARR001A.07n** will be changed into **GARR001A_cnv.07n**.

GNSS Solution

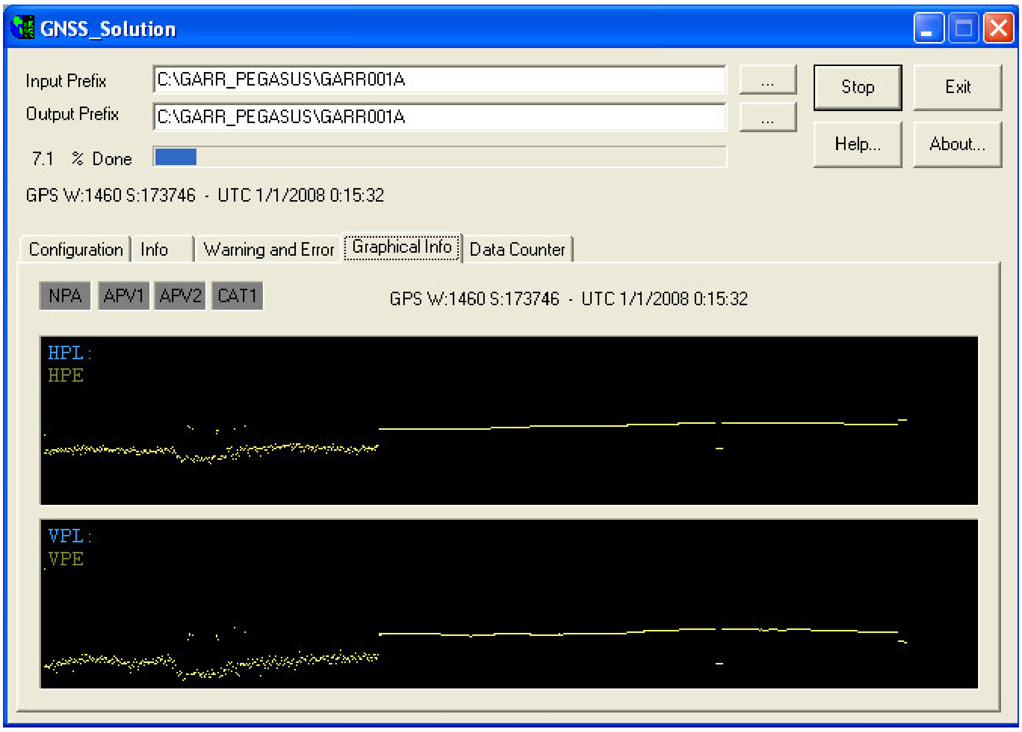
This module generates the positioning solution of the gps receiver.
The **.rng** ouput file extracted from the convertor will be the input prefix.
Additionally, you have to select the GPS station that will be used.

Coordinates (Latitude, Longitude and Height) must be specified if the GPS station if the station does not appear on the list option as it happens in our case.

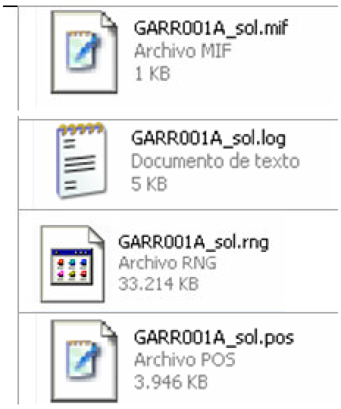


Afterwards, the process will begin:

If at any time, during the process execution, any error is found, the program may be interrupted showing the second where the mistake has occurred.



The output of the GNSS solution module consists of several files that provide information on the position domain, the range domain and useful log information. After this process, generated files have earned a "_sol" tag, indicating they contain information with the solution.



Module information file – Contains relevant information of the processing. This information may be variable depending on which module(s) is executed.

The log-file for the conversion – Contains the execution of LOG (22 error codes)

Data file containing range-data – Intermediate range results. (90 param.)

Position solution and integrity – Position solution for each epoch where measurements have been received. (40 param.)

When this module has finished, the **.rng** file contains information that must be ordered and organized to be understood. We have undertaken this process by:

- Importing **.rng** with a Text Editor such as UltraEdit. Some actions are needed to classify properly the information such as split fields by semicolons (**;**), deleting (**""**), delete letter "C" from GNSS_STATUS field.
- Importing modified data file into matlab.
- Making up an m-file (read_pegasus_data) which would allow us to classify information by epochs and satellites in the same way we deal with information in catgos project's structures.