UNIVERSITÀ DEGLI STUDI DI TRIESTE

XXV CICLO DEL DOTTORATO DI RICERCA IN
INGEGNERIA CIVILE E AMBIENTALE

IMPROVEMENT OF IONOSPHERIC CORRECTIONS
APPLIED TO THE EUROPEAN GEOSTATIONARY
NAVIGATION OVERLAY SYSTEM (EGNOS) FOR
APPLICATIONS TO TERRESTRIAL POSITIONING

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DOTTORANDO
CLAUDIA PAPARINI

RESPONSABILE DOTTORATO DI RICERCA
(Coordinatore)
CHIAR.MO PROF. CLAUDIO AMADIO

RELATORE/TUTORE
CHIAR.MO PROF. RAFFAELA CEFALO

CORRELATORE/COTUTORE
PROF. SANDRO MARIA RADICELLA

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6.27 Positioning solution obtained smoothing EGNOS grid map with CODE grid map: Table of North, East, Up Errors - average values and standard deviations of disturbed days analysed in 2013 - Stations: Matera, Cagliari, Noto, San Fernando, Rabat \[161\]
Introduction

It is well known that ionospheric conditions represent the main factor that influences Global Navigation Satellite Systems (GNSS) performance. Also the performance of Differential GNSS (DGNSS), Satellite Based Augmentation System (SBAS), Ground Based Augmentation System (GBAS), International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) and geodetic high precise network can be degraded.

DGNSS performances can be strongly reduced in particular in areas of large ionospheric variability and the occurrence of spatial TEC (Total Electron Content) gradients, like those found at low latitudes or under space weather events, like geomagnetic storms, have been analysed. (5)

Radiofrequency signals experience a delay when passing through the ionosphere, which is a dispersive medium whose refractive index is a function of the operating frequency. The delay is variable and depends on several factors such as geographical location of the receiver, solar and geomagnetic activity, season of the year and hours of the day. It results in ranging errors that can vary from few to tens of meters. (6) (4)

The response of the ionosphere to geomagnetic activity is a well studied topic in space physics. Geomagnetic activity creates energy inputs that takes the form of enhanced electric fields, currents, and energetic particles precipitation and could modify the ionospheric system and have consequences on the radiofrequency signals. (5)

In particular the low latitude ionosphere is a dynamic geophysical system and very difficult to assess. Indeed the complex ionospheric and atmospheric dynamics within this region contribute to the formation of the so-called "Equatorial Anomaly" which extends from the magnetic equator to $30^\circ$ North and South geomagnetic latitude in both hemispheres. (5)

At low latitudes, some unique phenomena like near-midnight Total Electron Content (TEC) enhancements, TEC depletions or equatorial plasma bubbles and scintillation can occur and they can affect in a remarkable way Satellite Navigation and Communication Systems. (5)

Single frequency Satellite Navigation Systems can use Satellite-based Augmentation Systems to mitigate ionospheric errors. (1) These systems perform a so called vector
correction. Wide area systems transmit the error models to the user, which are then recombined forming a correction that is applied to each pseudorange measurements. The wide area differential GNSS provides a vector of error corrections comprising three dimensional ephemeris errors and clock bias for each satellite, plus ionospheric time delay parameters.

At the frequencies used by GNSS (L-band), the ionosphere has three main effects on the propagation of signals between satellites and receivers near the surface of the Earth (whether on the ground or airborne): group delay, scintillation, and Faraday rotation.

In particular the group delay is a consequence of the dispersive nature of the medium, which causes sinusoidal waves with different frequencies to travel at slightly different velocities. This in turn causes complex signals that can be represented in terms of groups of waves (e.g., modulation) to travel at a slower velocity, called group velocity, than the so called phase velocity of the carrier wave. As a result, the time of arrival of a modulated satellite signal at the receiver is delayed compared to that in neutral free space. This phenomenon also causes an advance in the phase of the carrier with a magnitude equal (but with opposite sign) to group delay.

SBAS corrections are transmitted as vertical delays (in meters) for each of the grid points called Ionospheric Grid Points as explained in the RTCA, Minimum Operational Performance Standards (MOPS).

![Figure 1.1](image)

Figure 1.1: The IGP grid consists of 11 bands numbered 0 to 10 (Mercator projection). Bands 0 to 8 are vertical, and bands 9 and 10 are defined horizontally around the poles, there being a total of 1808 IGPs.

In the framework of the MIUR Strategic Project (DM 18 July 2005 prot. n. 1621/Ric./2005): Innovative Broadband Telecommunication Systems also with the use of satellites for different users in term of security, prevention and intervention in cases of natural disasters, a Research Activity, focused on GNSS, characteristics and performances have been carried out. In particular the European Geostationary Navigation Overlay System (EGNOS) has been considered for this research.
The current EGNOS provides an augmentation to the Global Positioning System (GPS) Standard Positioning Service (SPS). It improves L1 Coarse/Acquisition (C/A) civilian signal. In the future it is planned that EGNOS will experiment a major evolution in 2020, called EGNOS V3, including the fulfilment of the SBAS L1/L5 standard, expansion to dual-frequency, and evolution toward a multi-constellation concept. EGNOS V3 also aims to provide a single frequency service (Legacy Service) at least until 2030. The extension to 2038 is currently under discussion in WAAS and EGNOS systems.

The Research Activity, conducted during the PhD, is a contribution to the optimisation of the EGNOS Open Service, the first service provided from year 2009. The EGNOS Service Definition Document - Open Service (EGNOS SDD OS) describes the characteristic of the service offered by the EGNOS OS to users highlighting the accuracy in positioning and the timing performance currently available to suitably equipped users using both the GPS SPS and EGNOS augmentation signal. It is free of charge and it is able to cover also regions with low infrastructure (e.g. some African regions). In this term EGNOS is different from other DGNSS services (for example services of governmental land surveying offices or private services like SeaSTAR from FUGRO).

The Open Service is intended to offer a wide range of benefits to the users for general purpose applications. In road transport, EGNOS OS allows for the development of new applications such as pay-per-use insurance or automatic road tolling, reducing the need for more costly alternative infrastructure. It can also be used to improve fleet tracking solutions in any road or maritime application domain. In agriculture, EGNOS OS enables the high-precision spraying of fertilisers and pesticides, reducing the amount of chemicals needed for achieving optimal yield and productivity. EGNOS OS is used in combination with geodetic techniques to improve methods in the area of property boundary mapping, land parcel. In maritime applications EGNOS is also considered as a potential future complement to the IALA Beacon DGPS.

The main objectives of this PhD thesis are:

1. the analysis and characterization of the ionospheric related problems of GNSS positioning with a particular focus on the low latitudes of the EGNOS service area, considered a very challenging region in terms of ionosphere, but also GNSS data availability;
2. the evaluation of EGNOS performance on a quantitative level, from a user perspective (user position domain, not service availability) particularly at the Southern borders of the EGNOS service area;
3. the development and the recommendations of an user friendly method to obtain ionospheric corrections at the border of the EGNOS service area on a continuous
In order to fulfill these objectives, the Research Activity is divided into three main parts:

1. Different ionospheric grid maps have been created every 10 minutes for EGNOS and CODE Global Map. For this thesis purpose a replacement with CODE data when EGNOS data are missing have been proposed. Also a smoothing between EGNOS and CODE maps have been produced.

2. Once the area is identified, relative performances at position domain, have been analysed, using a software acting as a receiver that allows flexibility for the different kind of solutions (gLAB).

3. Finally, different solutions have been discussed at positioning level.

Ionospheric related data (grid points and vertical delay) from EGNOS are provided in Message types MT 18 and MT 26. There are some cases, in particular at the borders of the ECAC area where the ionospheric delays corrections cannot be evaluated due to the fact that there are no sufficient IGPs to perform the EGNOS interpolation technique described in the official document RTCA Do 229C-D Minimal Operational Performance Standard for GPS/WAAS.

For this reason the first part of this thesis deals with the study of Global Ionospheric Maps, such as those provided by the University of Bern, Center for Orbit Determination in Europe (CODE), showing the comparison of ionospheric vertical and slant delays. The aim is to determine the delay and to correct the ionospheric impact in the Southern regions of the ECAC area, positioned on the border of the area monitored by the three geostationary satellites, which are especially critical due to the presence of "Not Monitored" EGNOS data.

The main objective of this part is to compare the vertical TEC obtained with EGNOS using TEC Global Maps of TEC obtained from CODE and to check how well the Global Maps could reproduce the regional conditions described by EGNOS grid vertical TEC, particularly in terms of TEC space gradients (both in longitude and latitude). The analysis is performed for the years 2012 and 2013, for both quiet and disturbed ionospheric conditions and the covered area is $[40^\circ \text{W},40^\circ \text{E}]$ in longitude and $[20^\circ \text{N}, 60^\circ \text{N}]$ in latitude.

The ionospheric corrections applied to GNSS measurements depend on the satellite-receiver signal path. So to estimate the ionospheric error for each of these lines of sight, the receiver must identify the Ionospheric Pierce Point (IPP). Each IPP (see figure 5.1) is defined as the intersection between the atmospheric layer located at an altitude of 350 km and the line between the receiver and the satellite. (2)

The receiver knows the location and the estimated delay of these particular points and with a bilinear interpolation algorithm it is possible to define the delay for each of these IPPs. Consequently pseudoranges corrected with the ionospheric component
Figure 1.2: IPPs: - Ionospheric Pierce Points

are computed and in order to achieve this, the receiver must also take into account the Obliquity Factor (OF). Considering the thin shell approximation, OF is a simple function which depends on the satellite elevation angle only.

In the second part of the work, using the TEC calibration technique provided by prof. Luigi Ciraolo, vertical TEC, slant TEC and the coordinates of the IPP have been computed.

After that, different contributions to the IPPs have been calculated applying the bilinear interpolation algorithm, in terms of TEC, considering the values of IGPs grid of EGNOS, IGPs grid map of CODE, a synthetic one obtained replacing CODE data when EGNOS data are missing, and another considering a smoothing between EGNOS and CODE grid data.

This is done in order to obtain the different pseudoranges related to different ionospheric corrections.

The new calculated pseudoranges have been implemented into the RINEX files of different receivers in the Southern part of ECAC region taken as reference stations.

Through flexible positioning software, different positioning errors have been evaluated for the different TEC grids in order to estimate, in a systematic way, the planimetric and altimetric accuracies.

The final purpose of this Research Activity regarding EGNOS Open Service is related to the use of the different proposed solutions by receiver manufacturers in order
to improve the performances and positioning accuracies. (2)
Bibliography


Global Navigation Satellite System (GNSS) Positioning

Positioning based on Global Navigation Satellite System (GNSS) depends on the availability and the accuracy of the satellite measurements. GNSS are used to generate an estimate of position, velocity and time by processing signals transmitted from satellites in known orbits. (10)

The general accuracy of GNSS depends on different parameters like observables availability and accuracy, satellite geometry, numbers of tracked satellites and operational location. (11)

GNSS position errors depend on several factors like satellite ephemeris, clock drift, radio signal propagation, relativistic and atmospheric effects. In particular the Ionosphere is the main source of errors, being a dispersive medium which influences GNSS signal propagation. In order to range measurement errors sources, all these delays have to be corrected to improve the positioning system performance. (1)

The most important GNSS system in modern navigation is known as the Global Positioning System (GPS). Over the past decade a big number of military, commercial, and scientific applications that leverage accurate positioning and timing information has remarkably increased. (11)

Currently, the GPS system does not make possible to guarantee the position or time calculated by users. There is the probability to lose the integrity of the GPS satellite, in particular considering the aircraft navigation scope. As already mentioned, the ionosphere is the highest source of errors for GPS receivers. Different methods can be adopted to minimize its effect. (15) They are based on:

- use of dual-frequency technique,
- use of augmentation system for single frequency receiver,
- use of ionospheric model.

The dual-frequency technique corrects the measurements with an estimation of ionospheric delay obtained by a linear combination of dual frequency pseudorange measures.
2.1 Global Positioning System (GPS)

GPS is a fully operational system that meets the criteria established in the 1960s for an optimum positioning system. The system provides accurate, continuous, worldwide, three-dimensional position and velocity information to users with the appropriate receiving equipment. (10)

The nominal constellation nominally consists of 24 satellites arranged in 6 orbital planes with 4 satellites per plane. A worldwide ground control network monitors the health and status of the satellites. The GPS system comprises three segments: the Control Segment, the Space Segment, and the User Segment. (13)

- The Space Segment contains all the satellites whose functions are to transmit radio-navigation signals, and to store and retransmit the navigation message sent by the Control Segment. These transmissions are performed using highly stable atomic clocks on board the satellites.

- The Control Segment consists of five control stations (optimally separated in longitude around the earth), including a Master Control Station. The main purpose of the control stations is to monitor the performance of the GPS satellites. The data collected from the satellites by the control stations are sent to the master control station for processing. The master control station is responsible for all aspects of constellation control and command. The main operation objectives are to monitor GPS performance in support of all performance standards; generation and uploading of navigation data to the satellites, sustaining performance standards and detecting the satellite failures in order to minimize the impact.

- The User Segment can be considered the base of receivers and their processing. GPS can provide service to an unlimited number of users.
2.1 Global Positioning System (GPS)

The navigation data provides the means for the receiver to determine the location of the satellite at the time of signal transmission, whereas the ranging code enables the users receiver to determine the transit time of the signal and the satellite-to-user range.

GPS provides separate services for civil and military users. These are called the Standard Positioning Service (SPS) and the Precise Positioning Service (PPS). The SPS is designated for the civil community, whereas the PPS is intended for U.S. authorized military and government agency users.

To correct the Ionosphere, GPS uses the Klobuchar model, which is able to correct for 50% or 60% RMS (Root Mean Square) error of the total ionospheric delay. The parameters for the Klobuchar model are broadcasted by the GPS navigation message.

Satellite transmissions are referenced to highly accurate atomic frequency standards onboard the satellites, which are in synchronism with a GPS time base. \[16\]

The fundamental frequency is 10.23 Mhz and the satellites broadcast ranging codes and navigation data on two carrier signals called L1 (frequency = 1575.42 Mhz; wavelength = 19.0 cm) and L2 (frequency = 1227.60 Mhz; wavelength = 24.4 cm). The reason for the second signal is for self-calibration of the delay of the signal in the Earth’s ionosphere.

Information is encoded in the form of binary bits on the carrier signals by a process known as phase modulation.

There are three types of code on the carrier signals: C/A code (on L1 channel), P code (on both L1 and L2 channel) and the Navigation Message (on L1 channel). \[16\]

For this thesis work, GPS - SPS on the L1 Coarse/Acquisition (C/A) civilian signal has been used.

2.1.1 The Klobuchar Model

Ionosphere has a complicated nature and for this reason numerous approaches for ionospheric modeling have been studied. In particular, some models have been restricted to some particular characteristics in altitude or latitude domains, while others have been considered related to certain ionospheric parameters. These ionospheric models describe their characteristic features and their variations with geomagnetic activity (referring to Disturbance Storm Time, DST-index), time, season and solar cycle. (see Chapter 3)

The atmosphere around the Earth will affect the traveling speed of the GPS signal and cause measurement errors. These errors should be corrected. If a receiver operates on both the L1 and L2 frequencies, the time delay at frequency L1 caused by the ionospheric effect can be calculated.

In most commercial GPS receivers only the L1 frequency is available. It is adopted by single frequency GPS receivers to correct the ionospheric delay of the L1 carrier. The ionospheric data collected are used to reduce the ionospheric effect. Using this model one can reduce the user root mean square (rms) position error caused by ionospheric effect at least by 50 percent.

The Klobuchar model is one of the most widely used models due to its computational simplicity. \[16\] It gives the vertical ionospheric delay at a given time and location for
2.2 Differential GNSS (DGNSS)

the GPS single-frequency users in real-time. It is built on a simple cosine representation of the vertical ionospheric delay during daytime and a constant offset of 5 nanoseconds (or 1.5 meters) during night-time. Its daily maximum is at 14:00 h local time at the ionospheric pierce point (see section 2.3.1.3). Each IPP is defined as being the intersection between the atmospheric layer located at an altitude of 350 km and the line originating at the receiver position and which is directed at the GPS satellite.

The period and amplitude of the model are represented by third-degree polynomials in local time and geomagnetic latitude at the ionospheric pierce point. The vertical ionospheric delay is computed as follows:

\[
I_{L1_{GPS}} = \begin{cases} 
5 \cdot 10^{-9} + \sum_{n=0}^{3} \alpha_n \phi_m \cdot \left(1 - \frac{X_I^2}{2} + \frac{X_I^4}{24}\right) \cdot F & ; |X_I| \leq 1.57 \\
5 \cdot 10^{-9} \cdot F & ; |X_I| \geq 1.57 
\end{cases}
\]

The delay \(I_{L1_{GPS}}\) is given in seconds and it is referred to the GPS L1 frequency.

The model presents an ideal smooth behavior of the ionosphere; therefore any significant fluctuations will not be modeled properly. The accuracy of the model is 50 - 60 percent of the total effect \(16\) and under severe ionosphere activity at low elevations, the range error could be very large, up to 50 meters.

The Klobuchar model has one advantage, which is its simplicity and its easy and quick computation, but it also has many shortcomings:

- low accuracy for computing the ionospheric delay correction;
- the algorithm does not properly represent the behaviour of the ionosphere in the near-equatorial region of the world, where the highest values of the ionospheric delay occur;
- the algorithm is optimized for middle latitudes;
- the algorithm is very poor in high latitude regions where the ionospheric variability is high due to auroral processes;
- the general model has an inability to represent the behaviour of the ionosphere when the ionosphere differs by substantial amounts from its average behaviour.

2.2 Differential GNSS (DGNSS)

A commonly technique used to enhance the standard GNSS performance is the Differential GNSS.

It is a kind of GNSS Augmentation methodology able to improve the system performances thanks to the use of external information in the computation of the position. There are several DGNSS techniques, such as the classical DGNSS (or DGPS), the Real Time Kinematics (RTK) and the Wide Area RTK (WARTK).
2.3 Augmentation Systems: SBAS

In general DGNSS is obtained using a network of ground-based reference stations which can enable the broadcasting of differential information users to improve position accuracy, while the integrity is not assured. (13)

The reference station, with known coordinates, computes pseudorange (PRC) and range rate (RRC) corrections for each satellite in view. The user applies the PRC and the RRC to correct its own measurements, removing Signal In Space errors and improving the positioning accuracy.

DGNSS significantly improves both the accuracy by removing error sources that are beyond the control of GNSS users, such as satellite and atmospheric errors, DGNSS moves the focus of error mitigation to error sources, such as multipath and receiver noise, that users (and DGNSS designers) have more control over. DGNSS reference receivers also serve as powerful means of real-time integrity monitoring that greatly exceeds the capabilities of a GNSS alone.

DGNSS with code ranges allows users, within a hundred kilometers radius, to obtain a one-meter-level positioning accuracy using pseudorange corrections.

2.3 Augmentation Systems: SBAS

Three classes of Augmentation Systems have been recognized by the international aviation community. These categories include: the Aircraft-Based Augmentation System (ABAS), the Satellite Based Augmentation System (SBAS) which will be discussed in this thesis work and the Ground Based Satellite System (GBAS). (10)

SBAS uses a network of terrestrial receivers with coverage areas typically on the scale of large countries or continents. Alert messages, error bounds, and differential corrections are broadcasted to users in this coverage area via a space-based communications link, most typically via a satellite positioned at a Geostationary Earth Orbit (GEO). (3)

In the United States, the Federal Aviation Administration (FAA) introduced the world’s first SBAS when it declared the Wide Area Augmentation System (WAAS) operational in 2003. Around the world, other governments are coordinating new SBAS implementations, such as Japanese Multifunctional-Transport SBAS (MSAS), the European Geostationary Navigation Overlay Service (EGNOS) and Indias GPS and GEO Augmented Navigation System (GAGAN).
SBAS offers a distinct advantage respect to the others in terms of integrity and differential corrections that estimate and mitigate major GNSS error sources, including ionosphere, troposphere, and clock errors. As GEOs broadcast over standard GNSS frequencies, conventional antennas can receive SBAS transmissions. The SBAS satellites transmit a GPS-like L1 (1575.42 MHz) signal, modulated with a Coarse/Acquisition Pseudo-Random Noise (PRN) codes.

In general SBAS provides two separate sets of corrections, in two different formats. One set of SBAS message types broadcasts individual correction components for satellite-generated errors, including separate corrections for the one satellite clock error state and the three axes of satellite ephemeris error, for all GNSS satellites covered by a given SBAS at a given time.

In addition, a fast correction message that combines clock and ephemeris corrections into one value for each satellite is broadcasted at more frequent intervals to minimize latency.

Meanwhile, a completely separate set of SBAS message types include ionospheric-delay corrections based on a grid of 5° x 5° latitude/longitude points at the assumed ionosphere thin-shell height of 350 km.

The main parts of the SBAS structure are:

- Ground Integrity Channel (GIC): integrity information to inform about the availability of GPS/GLONASS/GEO safe navigation service;
- Wide Area Differential (WAD): differential corrections to the existing navigation system services computed in a wide area to improve navigation services performance.
- GEO Ranging: transmission of GPS-like L1 signals from GEO satellites to augment the number of navigation satellites available to the users.

Performances of such systems are defined with respect to the level of service that the system is designed to provide. The performance requirements are expressed in terms of four quantitative concepts.
• **Accuracy** of a navigation system is defined in terms of Navigation System Error (NSE) which is referenced to a required flight path defined for each phase of the flight. A SBAS assures the compliance with respect to the accuracy requirements by providing to the user corrections to the satellite orbit and clock errors as well as to the ionospheric residual propagation error.

• **Integrity** is a measure of the trust that can be placed in the correctness of the information supplied by the system. It provides satellite and/or ionospheric alarms in order to inform users to reject the corresponding satellite/ionospheric corrections. To assess the availability of the system, it also provides to users the Horizontal and Vertical Protection Level (HPL, VPL) information.

• **Availability** is the probability that the navigation service is available at the beginning of a planned operation. A SBAS is considered available when the accuracy, integrity and continuity requirements are met and it is measured in terms of probability of the system being available for any given user at any given time.

• **Continuity** is the ability of the system to perform its function without any interruption.

The main characteristic of SBAS is that the data link frequency band and signal modulation are the same to those of GPS signals. In addition, the SBAS signal is broadcast by geostationary satellites able to cover extended areas, with each error source being isolated.

### 2.3.1 EGNOS

The European Geostationary Overlay Service (EGNOS) is being developed under the responsibility of the European Commission, the European Space Agency (ESA), and the European Organization for the Safety of Air Navigation (EUROCONTROL).

It is a Satellite Based Augmentation System and as already mentioned, it complements the American GPS system and it operates on the GPS L1 frequency. The EGNOS coverage area is called the ECAC (European Civil Aviation Conference) area (see figure 2.3). It could be readily extended to include other regions within the Broadcast Area of the geostationary satellites, such as Africa, Middle East, Eastern countries, and a part of Russia.

EGNOS Service provision requires the following steps:

• It collects measurements and data from the GPS satellites;

• it calculates differential corrections, residual errors and it generates EGNOS messages;

• it broadcast EGNOS messages to users via the geostationary satellites.

A data integrity verification process is conducted in parallel with these steps.
The EGNOS system is composed by four segments:

- the **Ground Segment** computes precise differential corrections and makes all these information available to users through a broadcast by the Space Segment;

- the **Space segment**, using three GEO satellites, provides redundant data transmission channel to broadcast toward EGNOS users messages containing differential corrections with the associated integrity information. The three geostationary satellites centred over Europe are: Inmarsat-3 AOR-E (Atlantic Ocean Region East) stationed at 15.5° W, Inmarsat-3 IOR-W (Indian Ocean Region West) stationed at 25.0° E and ESA-Artemis stationed at 21.5° E.

- the **User Segment** is made of EGNOS receivers that enable EGNOS users to accurately compute their position;

- the **Support Segment** contains off-line facilities which include a number of support elements able to facilitate and improve maintenance activities (The Performance Assessment and Checkout Facility-PACF, the Application Specific Qualification Facility-ASQF).

The operational components are all interconnected via the EGNOS Wide Area Network (EWAN) and are designed to transmit data in near real time.

The EGNOS system is a widely distributed and redundant system. Data flows from one subsystem to another subsystem have different level of criticality.

The Ground Segment can be subdivided into different critical subsystems:
2.3 Augmentation Systems: SBAS

Figure 2.4: EGNOS Architecture and Core System Boundaries

- the **RIMS stations**: their initial configuration includes 34 RIMS sites located over a wide geographical area. They collect measurements from GPS satellites and transmit these data every second to the Central Processing Facilities (CPF) of each MCC;

- the **CPF units**: they are a part of the Mission Control Centres (MCC). They use the data received from the network of RIMS stations, clock corrections (for each GPS satellite in view of the network of RIMS stations), ephemeris corrections to improve the accuracy of spacecraft orbital positions and ionospheric corrections over the EGNOS service area. They also estimate the residual errors that can be expected by the users once they have applied the set of corrections broadcast by EGNOS;

- the **NLES stations**: The NLES stations receive the EGNOS messages from all the CPFs, upload the data stream to the geostationary satellites. They generate the GPS-like signal.

### 2.3.1.1 EGNOS Services: EGNOS Open Service

EGNOS support different kinds of services related to different types of requirements:

- **Safety of Life (SoL)**: provides the most stringent level of signal-in-space performance over Europe. This service was officially started on 2 March 2011;

- **Open Service (OS)**: freely available to the public over Europe. This service was officially started on 1 October 2009;

- **EGNOS Data Access Service (EDAS)**: is a single point of access disseminating EGNOS data in real time without relying on the signals from the three EGNOS satellites.
In this thesis EGNOS Open Service information and data has been used. The EGNOS Open Service (further EGNOS OS) comprises the provision of an augmentation signal to GPS Standard Positioning Service (SPS) with the specific committed performance and subject to the service limitations described here in the EGNOS OS SDD. Only minimum performance characteristics are included in the commitment even though the users can usually experience a better performance. These characteristics are expressed in statistical values under given assumptions.

The EGNOS OS is intended to deliver a wide range of benefits to European citizens. As already mentioned in the Introduction, EGNOS OS has different applications in several areas:

- in road transport, EGNOS OS allows for the development of new applications such as pay-per-use insurance or automatic road tolling, reducing the need for more costly alternative infrastructure. It can also be used to improve fleet tracking solutions in any road or maritime application domain;
- used in combination with geodetic techniques to improve methods in the area of property boundary mapping, land parcel identification and geo-traceability;
- in agriculture, EGNOS OS enables the high-precision spraying of fertilisers and pesticides, reducing the amount of chemicals needed for achieving optimal yield and productivity. It can also support other innovative applications;
- it improves the precision of all personal navigation applications, giving rise to a myriad of new possibilities such as, emergency localisation, friend finding or geo-localised advertising.

The corrections transmitted by EGNOS contribute to mitigate the ranging error sources related to satellite clocks, satellite position and ionospheric effects. The other error sources (tropospheric effects, multipath and user receiver contributions) are local effects that cannot be corrected by a global augmentation system. EGNOS can also detect distortions affecting the signals transmitted by GPS, preventing users from tracking unhealthy or misleading signals that could lead to wrong positioning.

The EGNOS OS is accessible in Europe to any user equipped with an appropriate GPS/SBAS compatible receiver for which no specific receiver certification is required. EGNOS performances are considered from a user perspective and they are expressed in terms of availability, continuity, integrity and accuracy. The minimum requirements for these terms are defined by SBAS standards which were conceived for civil aviation applications. These standards are called SBAS Minimum Operational Performance Standards (MOPS) and are published by the official document called RTCA under the reference DO-229.[5][7] All SBAS receivers expected to support OS shall

- use the Geostationary satellite ranging function if available (broadcast through message types 9 and 17, this function is currently not supported by EGNOS);
2.3 Augmentation Systems: SBAS

- decode and apply satellite clock corrections (broadcasted through message types 2-5 and corresponding to satellites selected by message type 1);
- decode and apply satellite ephemeris corrections (broadcasted through message types 24-25);
- decode and apply ionospheric corrections (broadcasted through message type 26 for ionospheric grid points selected by message type 18);
- take into account major warnings sent through the SBAS messages (broadcasted through message types 2-5 and 6).

The Horizontal Accuracy corresponds to a 95% confidence bound of the bi-dimensional position error in the horizontal local plane for the worst user location. Its value corresponds to 3 meters.

The Vertical Accuracy corresponds to a 95% confidence bound of the uni-dimensional unsigned position error in the local vertical axis for the worst user location. Its value corresponds to 4 meters.

The minimum performance levels stated in Section Performance Requirements of the official document of EGNOS are fulfilled in the vast majority of cases and service availability is also provided. However, there might be some situations where non nominal navigation performances are obtained. (4)

The most common causes of abnormal EGNOS behavior which can cause a service degradation are broadcasting delays, signal attenuation, EGNOS signal blockage, local multipath, signal interference, ionospheric scintillation, receiver design. (4)

2.3.1.2 EGNOS Message Service (EMS) messages and the related provided corrections

The ESA EGNOS Message Server service for non-real-time applications provides the EGNOS Signal In Space (SIS) without any warranties regarding availability and reliability of service. (3) (4) In principle messages associated with the EGNOS SIS obtained from the EMS system are not certified for Civil Aviation or other safety critical purposes. (18)

The ESA EGNOS Message Server is an Internet based service, which provides access to an archive of SBAS messages, previously broadcast by the EGNOS system through GEO satellites.

The EMS concept is a complement to the ESA SISNeT service. While SISNeT provides access to the EGNOS messages in real-time, the EMS server allows getting the EGNOS messages offline, in the form of ASCII files.

EMS Data Server basically consists of a server computer, running an FTP server process, which provides public remote access to the EGNOS message files through the Internet.

All EGNOS message types can be broken down into the structure represented in figure 2.3:
2.3 Augmentation Systems: SBAS

For this thesis purpose the EGNOS ionospheric correction has been analysed and presented in the following section.

2.3.1.3 EGNOS Ionospheric correction - Single Layer Approximation

In order to make a (rough) assessment for elevation dependency of the TEC and for the purpose of simple ionospheric modeling, the ionosphere may be considered as a thin single layer surrounding the Earth at a fixed height for which all free electrons in the Ionosphere are assumed to be concentrated in this single-layer.

In this way, it is possible to map the vertical TEC towards the slant TEC:

\[ \text{STEC} = \frac{1}{\cos \theta} \text{VTEC} \]  

(2.2)
To estimate the ionospheric error for each receiver/satellite line of sight (STEC), Ionospheric Pierce Points (IPPs) have to be identified. Each IPP is defined as being the intersection between the atmospheric layer located at an altitude of 350 km and the line originating at the receiver position and which is directed at the GPS satellite. The quantity $\frac{1}{\cos \theta}$ is the obliquity factor, the angle at which the ionosphere is crossed.

The EGNOS ionospheric correction messages are related to an interpolation grid above the Earth’s surface of 350 km in the ionosphere.

The grid points for the interpolation and the interpolated values of the ionospheric correction are defined through the use of the message type MT 18 and MT 26. MT 18 provides the Ionospheric Grid Point (IGP) mask. A bit positioned at 1, means that the information is provided for the corresponding IGP. MT 26 provides data for computing the ionospheric corrections or the Grid Ionospheric Vertical Delay (GIVD) and a parameter for estimating the accuracy of corrections ($\sigma_{GIVD}^2$), called GIVE indicator ($GIVE_i$).

These values are obtained through correspondence with the $GIVE_i$ transmitted in the message.

EGNOS ionospheric delay corrections are broadcast as vertical delay estimates at specified IGPs. In order to facilitate flexibility in the location of these IGPs, a fixed definition of spaced IGP locations is used, resulting in a large number of possible IGPs. The density of these predefined IGP is dictated by the possible large variation in the ionospheric vertical delay during periods of high solar activity, especially at lower latitudes. The IGP used at any time are based upon the current variations of the ionosphere between IGP locations. Since it would be impossible to broadcast IGP delays for all possible locations, a mask is broadcasted to define the IGP locations providing the most efficient model of the ionosphere at the time. The IGPs grid (provided by

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**Figure 2.8:** Ionospheric Single layer approximation
2.3 Augmentation Systems: SBAS

MT 18) consists of 11 bands numbered 0 to 10 (Mercator projection). Bands from 0 to 8 are vertical, and bands 9 and 10 are defined horizontally around the poles for a total of 1808 IGPs. The IGP locations are denser at lower latitudes due to the fact that the distance represented by a degree of longitude becomes smaller at higher latitudes. The IGP grid at the equator has a spacing of $5^\circ \times 5^\circ$, increasing to a spacing of $10^\circ \times 10^\circ$ north of latitude N 55° and south of latitude S 55°. (8) The following figure shows bands 0 to 8:

![Predefined Global IGP Grid](image)

In order to estimate the EGNOS ionospheric error for each receiver/satellite line of sight, the receiver must identify the IPPs.

Although the data base, broadcasted to the user, is in the form of vertical IGP delays, these points do not generally correspond to the computed IPP location. (5)

Thus, it is necessary for the equipment to interpolate from the broadcasted IGP delays.
2.3 Augmentation Systems: SBAS

delays to that at the computed IPP location.

The receiver must perform an interpolation between the values provided by EGNOS for the IGPs close to each IPP.

Figure 2.11: Ionospheric Pierce Point

EGNOS can also transmit for each monitored IGP an integrity signal with three values. In this way it shows its status if an anomaly is detected or if it is not being monitored.

However, the Do not Use alert is generated through the maximum value of the Grid Ionospheric Vertical Delay (GIVD) ionospheric delay, not by a particular Grid Ionospheric Vertical Error indicator (GIVEi) value. As with the satellite alerts, the system has 6 seconds in which to inform the user of any integrity fault. The alert is repeated 4 times.

Selection of Ionospheric Grid Points

As already mentioned, the data base broadcasted to the user is in the form of vertical IGP delays, and these points do not generally correspond to the computed IPP location.

After determining the location of the user IPP, the user must select the IGP to be used to interpolate the ionospheric correction value and its corresponding error bound. This selection is done based only on the information provided in the mask, and must be done without regard to whether or not the selected IGP is monitored, not monitored or a do not use event is issued.

Once the nodes of an interpolation cell of the IGP grid that surround the IPP to a satellite have been determined, the equipment must interpolate from those nodes to the pierce point using the following algorithm. For the four-point interpolation, the mathematical formulation for the interpolated vertical IPP delay as a function of the
IPP latitude and longitude is given by:

\[ \tau_{vpp}(\phi_{pp}, \lambda_{pp}) = \sum_{i=1}^{4} W_i(x_{pp}, y_{pp}) \tau_{vi} \]  \hspace{1cm} (2.3)

with \( \tau_{vpp} \) is the vertical ionospheric delay at pierce point, \( \tau_{vi} \) is the vertical ionospheric delay at grid points, and \( W_i \) is the weighting function.

In particular \( \tau_{vpp} \) is the output value at desired pierce point \( pp \), whose geographical coordinates are \( (\phi_{pp}, \lambda_{pp}) \):

\[ W_1 = x_{pp}y_{pp} \]  \hspace{1cm} (2.4)
\[ W_2 = (1 - x_{pp})y_{pp} \]  \hspace{1cm} (2.5)
\[ W_3 = (1 - x_{pp})(1 - y_{pp}) \]  \hspace{1cm} (2.6)
\[ W_4 = x_{pp}(1 - y_{pp}) \]  \hspace{1cm} (2.7)

For IPPs between N85\(^\circ\) and S85\(^\circ\):

\[ x_{pp} = \frac{\Delta \lambda_{pp}}{\lambda_2 - \lambda_1} \]  \hspace{1cm} (2.8)
\[ y_{pp} = \frac{\Delta \phi_{pp}}{\phi_2 - \phi_1} \]  \hspace{1cm} (2.9)

Figure 2.12: Four point interpolation algorithm definition. (6)
2.4 Principles of Satellite Positioning

For a three point interpolation a similar algorithm has been used:

\[ \tau_{vpp}(\phi_{pp}, \lambda_{pp}) = \sum_{i=1}^{4} W_i(x_{pp}, y_{pp}) \tau_{vi} \]  \hspace{1cm} (2.10)

with

\[ W_1 = y_{pp} \] \hspace{1cm} (2.11)

\[ W_2 = 1 - x_{pp} - y_{pp} \] \hspace{1cm} (2.12)

\[ W_3 = x_{pp} \] \hspace{1cm} (2.13)

To convert the vertical delay into a slant delay along the path receiver - satellite, an obliquity factor (OF) is needed.

\[ OF = \left[ 1 - \left( \frac{R_E \cos(Ei)}{R_E + h_{iono}} \right)^2 \right] - \frac{1}{2} \tau_{vpp} \] \hspace{1cm} (2.14)

2.4 Principles of Satellite Positioning

Through the reception of the signal from a GNSS satellite, a receiver can basically perform two types of measurements: the pseudo-range (pseudo distance) and the phase measurements, depending if codes or the carrier signal are used.

A GNSS satellite-receiver provides the distances obtained by the comparison between the received signal and the signal generated internally.

In the following section the pseudorange observables, the system equations, the least square estimator for positioning and their formal errors related with the effect of satellite geometry (Dilution of Precision) have been discussed.

2.4.1 The pseudorange observables

The basic principles and equations which characterise satellite positioning are related to the use of distance measurements at a defined moment in time T between a receiver on Earth and several satellites whose positions in space are known.

The starting point for determining the position of a GNSS receiver is the pseudorange measurement. Satellites emit electromagnetic waves which propagate through space at the speed of light. It is then possible to calculate the distance separating the satellite from the receiver by determining the time a wave takes to travel from satellite to receiver using \( d = ct \) (\( d \) is the distance, \( c \) the speed of light and \( t \) the time it takes for the wave to travel from satellite to receiver).

To estimate the time that signals take to travel between a given satellite and the receiver, the receiver compares a unique code linked to the satellites navigation signal
2.4 Principles of Satellite Positioning

with a copy of the same code generated by the receiver itself. The signal then enters the receiver, which then measures it using a process known as autocorrelation.

Since the time interval between the codes corresponds to the transit time, this can then be used to calculate the pseudorange. The use of pseudo in this term is because this distance does not correspond to the geometric distance between satellite and receiver. It is due to the bias between the time reference used by the GPS system and the one used by the receiver.

With at least three distance measurements to three different satellites it is theoretically possible to determine the position of the receiver if and only if the receivers’ clocks are perfectly synchronised with those on board the satellites. Unfortunately, though all the satellites may be equipped with perfectly synchronised atomic clocks, the same is not true for receivers, which for reasons of cost and compactness are equipped with internal inexpensive quartz oscillator clocks that are not synchronised with the satellite atomic clocks (poor stability compared with those on board the satellites).

The scope is to calculate the receiver coordinates and the clock offset from pseudo-range measurements, for at least four satellites in view.

The basic of positioning principles is based on solving a geometric problem. All the information for modelling the measurements for Standard Positioning Service (SPP) can be provided by the broadcast message from satellites.

The generic pseudorange measurement $\rho_j$ for satellite $j$ can be written as:

$$\rho_j = \sqrt{(x_j - x_u)^2 + (y_j - y_u)^2 + (z_j - z_u)^2 + c\delta t_u} \quad (2.15)$$

Equation 2.15 defines a non-linear system. The usual resolution technique consists of linearising the geometric range $\rho$ in the neighbourhood of a point corresponding to the approximate position of the receiver. It can be approximated through the Taylor expansion around the known location:

$$\hat{\rho}_j = \sqrt{(x_j - \hat{x}_u)^2 + (y_j - \hat{y}_u)^2 + (z_j - \hat{z}_u)^2 + c\hat{\delta} t_u} \quad (2.16)$$

where $\hat{\rho}_j$ is the approximated known location. The Taylor expansion gives:

$$\rho_j = f(x_u, y_u, z_u, \delta t_u) \quad (2.17)$$

$$\rho_j = f(\hat{x}_u + \delta x_u, \hat{y}_u + \delta y_u, \hat{z}_u + \delta z_u, \hat{\delta} t_u) \quad (2.18)$$

$$\rho_j = \rho_j - \frac{x_{sj} - \hat{x}_u}{r_j} \Delta x_u - \frac{y_{sj} - \hat{y}_u}{r_j} \Delta y_u - \frac{z_{sj} - \hat{z}_u}{z_j} \Delta z_u + c\Delta t_u \quad (2.19)$$

So, the navigation solution at the first order approximation is

$$\Delta \rho_j = \rho_j - \rho_j = a_{xj} \Delta x_u + a_{yj} \Delta y_u + a_{zj} \Delta z_u - c\Delta t_u \quad (2.20)$$

where the coefficients are $a_{xj} = \frac{x_j - \hat{x}_u}{r_j}$, $a_{yj} = \frac{y_j - \hat{y}_u}{r_j}$ and $a_{zj} = \frac{z_j - \hat{z}_u}{r_j}$.
Writing the equation 2.20 in a matrix form for 4 satellites:

\[ \Delta \rho = \begin{bmatrix} \Delta \rho_1 \\ \Delta \rho_2 \\ \Delta \rho_3 \\ \Delta \rho_4 \end{bmatrix} \] (2.21)

\[ H = \begin{bmatrix} a_{x1} & a_{y1} & a_{z1} & 1 \\ a_{x2} & a_{y2} & a_{z2} & 1 \\ a_{x3} & a_{y3} & a_{z3} & 1 \\ a_{x4} & a_{y4} & a_{z4} & 1 \end{bmatrix} \] (2.22)

\[ \Delta x = \begin{bmatrix} \Delta x_u \\ \Delta y_u \\ \Delta z_u \\ -c\Delta t_u \end{bmatrix} \] (2.23)

Finally:

\[ \Delta \rho = H \Delta x \] (2.24)

Inverting the equation 2.24 and in case four satellites are used:

\[ \Delta x = H^{-1} \Delta \rho \] (2.25)

In case of a larger number of satellites is used:

\[ H = \begin{bmatrix} a_{x1} & a_{y1} & a_{z1} & 1 \\ a_{x2} & a_{y2} & a_{z2} & 1 \\ \vdots & \vdots & \ddots & \vdots \\ a_{xn} & a_{yn} & a_{zn} & 1 \end{bmatrix} \] (2.26)

In general for a number of satellites larger than four, a least square solution must be used. The solution is given by the value of \( \Delta x \) that maximize the square of the residual:

\[ R_{SE}(\Delta x) = (H \Delta x - \Delta \rho)^2 \] (2.27)

The solution can be obtained differentiating with respect to \( \Delta x \) obtaining the gradient \( R_{SE} \).

\[ \nabla R_{SE} = 2(\Delta x)^T H^T H - 2(\Delta \rho)^T H \] (2.28)

The gradient is set to zero and solved for \( \Delta x \) to seek the minimum value. Taking the transpose and setting it to zero:

\[ 2H^T H(\Delta x) - 2H^T (\Delta \rho) = 0 \] (2.29)
2.4 Principles of Satellite Positioning

Provided that $H^T H$ is non-singular, the equation solution is:

$$\Delta x = (H^T H)^{-1} H^T (\Delta \rho) \quad (2.30)$$

Then a recursive method is used until variations are below a given threshold.

2.4.2 The geometric factor: Dilution Of Precision (DOP)

The dilution of precision (DOP) is a parameter used to measure user position accuracy. (7)

The different components of the position estimation depend on two factors: the variance of the user range error and a term which depends entirely on the user satellite geometry (i.e. the elements of the matrix $H$). (7)

The DOP parameters are defined on the basis of the above equations to characterize the contribution of the user - satellite geometry. (7). The positions of the satellites determine the DOP value. Here only the definitions and the limits of the values will be presented. (12)

Considering the relation $\Delta \rho = H \Delta x$ and adding the errors embedded in our measurements $\Delta \rho + \delta \rho = H(\Delta x + \delta x)$, and expliciting $\delta x$, it is possible to define the new equation:

$$\delta x = [(H^T H)^{-1} H^T] \delta \rho \quad (2.31)$$

The least square solution is valid under the hypothesis of linearly independent equations. (10)

In the last equation two different contributions of errors are considered: $(H^T H)^{-1}$ which depends only on the satellite geometry and $\delta \rho$ which depends on the error in the pseudorange estimation. Skipping all the mathematical expressions and considering the covariance of the matrix it is possible to express the covariance of the error in position and time $\delta x$ as:

$$cov(\delta x) = G \delta^2_{UERE} \quad (2.32)$$

where $G = (H^T H)^{-1}$

The standard deviation of the positioning error can be obtained as $\sqrt{tr[cov(\delta x)]}$, where the Geometrical Dilution of Precision (GDOP) is defined as

$$GDOP = \sqrt{tr[G]} = \sqrt{g_{11} + g_{22} + g_{33} + g_{44}} \quad (2.33)$$

where $g_{11}$, $g_{22}$, $g_{33}$, $g_{44}$ are the diagonal elements of the matrix $G$.

Other partial factors can be also defined:

- Position Dilution of Precision (PDOP): $\sqrt{g_{11} + g_{22} + g_{33}}$
- Time Dilution of Precision (TDOP): $\sqrt{g_{44}}$
- Horizontal Dilution of Precision (HDOP): $\sqrt{g_{11} + g_{22}}$
2.4 Principles of Satellite Positioning

- Vertical Dilution of Precision (VDOP): $\sqrt{33}$

The more favorable is the geometry, the lower is the DOP. The smallest DOP value means the best satellite geometry for calculating user position. It is proved that in order to minimize the GDOP, the volume contained by the four satellites must be maximized.

2.4.3 Positioning errors

There are many sources of possible errors that will affect the accuracy of position computed by GNSS receivers. Errors affecting GNSS performance depend on several factors:

At system level (space-control):

- selective availability (off since May 2000);
- number of satellites which can be seen from the receiver and their geometry (DOP);
- errors in the orbits, ephemeris and clock.

In general satellites are positioned in very precise orbits, although it is possible to have slight shifts of the orbits, due to gravitation forces. The orbit data are controlled and corrected regularly and are sent to the receivers in the package of ephemeris data. Therefore the influence on the correctness of the position determination is rather low, with resulting error not bigger than 2 m.

The navigation message contains corrections for ephemeris and clock errors and estimates of the accuracy of the atomic clock. These errors tend to be very small, but may add to few meters of inaccuracy.

Another error is the relativistic effect is due to the rotation of the Earth during the signal transmission (Sagnac effect). During the propagation time, a clock on the Earth’s surface experiences a rotation with respect to the reference frame.

Moreover along the path from satellite to receiver, errors can be due to:

- Ionospheric effect;
- Tropospheric effect.

A source of inaccuracy is the reduced speed of propagation in the troposphere and ionosphere. While radio signals travel with the velocity of light in the outer space, their propagation in the ionosphere and troposphere is slower. Correcting these errors is a significant challenge to improving GNSS position accuracy. These effects are smaller when the satellite is directly overhead and become greater for satellites near the horizon since the path through the atmosphere is longer. The atmosphere changes the velocity of propagation of radio signals: this phenomena is referred as refraction. The change in speed of propagation varies the signal transit time. The effects of the ionosphere generally change slowly, and can be averaged over time. Those for any particular
2.4 Principles of Satellite Positioning

Figure 2.13: Pseudorange measurement contents. (1) (2)

A geographical area can be easily calculated by comparing the GPS-measured position to a known surveyed location. This correction is also valid for other receivers in the same general location. Several systems send this information over radio or other links to allow L1-only receivers to make ionospheric corrections. Humidity also causes a variable delay, resulting in errors similar to ionospheric delay, but occurring in the troposphere. This effect is more localized and changes more quickly than ionospheric effects, and is not frequency dependent. These traits make precise measurement and compensation of humidity errors more difficult than ionospheric effects.

At receiver level, errors are related to:

- Receiver noise, clock errors, thermal noise, software accuracy;
- Multipaths and interfering signals.

The multipath effect is caused by reflection of satellite signals (radio waves) on objects. These delayed signals can cause inaccuracy. A variety of techniques have been developed to mitigate multipath errors. For GNSS signals this effect mainly appears in the neighbourhood of large buildings or other elevations. The reflected signal takes more time to reach the receiver than the direct signal. The resulting error typically lies in the range of a few meters. To address shorter delay multipath from the signal reflecting off the ground, specialized antennas (for example choke ring antenna) may be used to reduce the signal power as received by the antenna.

Navigation solution and total error budget are valid under the hypothesis of errors which have to be:

- statistically independent for different Satellite Views (SVs);
- error modeled as random Gaussian variables with zero mean.
2.5 GNSS derived TEC calibration technique

Telemetered EGNOS errors: typical orders of magnitude. \( [8] \)

Under these hypotheses the standard deviation of the total pseudorange error is:

\[
\sigma_{\text{UERE}} = \sqrt{\sum \sigma_j^2} 
\]

(2.34)

2.5 GNSS derived TEC calibration technique

TEC data are derived from carrier phase measurements for GPS satellite system (and also for GPS +GLONASS). \([17]\)

The basic relation used to calibrate the TEC is as follows:

\[ S_\theta = sTEC + \beta \text{bias}_{\text{arc}} \]  

(2.35)

\( S_\theta \) is the ionospheric delay from the raw carrier phase observations. \( \beta \text{bias} \) is the arc-offset, a constant to be determined for each arc of observations related to a given receiver and satellite pair. It represents the contribution of receiver and satellites biases,
2.5 GNSS derived TEC calibration technique

and the contribution of any non-zero averaged errors over an arc of observations (for example the multipath).

Satellite arc is defined as common to all continuous observations performed by receiver on a given satellite at a defined time t.

A two-dimensional thin shell model at 350 km is used to define the mapping function between the slant and vertical TEC. The vertical ionospheric variation is expressed as a function of the modip and the Local Time of the ionospheric pierce points (IPPs).

The outputs of this calibration for every observables are:

- vertical TEC;
- slant TEC;
- latitude and longitude of the correspondent IPPs.

For this thesis, latitude and longitude of the IPPs have been used to recalculate the ionospheric contribution for EGNOS and the Global Maps using a bilinear algorithm.

2.5.1 Global Ionospheric Maps - GIM

The International GNSS Service (IGS) of the International Association for Geodesy (IAG) maintains a global GNSS tracking network of more than 200 receivers. The availability of a huge number of the IGS permanent dual frequency GPS receivers, which are distributed over the Earth’s surface, has made the global monitoring of the ionosphere possible and Global Ionospheric VTEC Maps (GIM) are produced routinely.

Four IGS Ionospheric Analysis Centers (CODE, ESA, JPL, and UPC) individually produce daily Global Ionosphere Maps using different techniques (Perez, 2005; Wienia, 2008).

The official IGS product is a combined ionosphere map from all four IGS analysis centers.

The Global Maps files are distributed on a daily basis in a particular format called IONEX (IONosphere map EXchange), giving a value for the Vertical Total Electron Content (VTEC) every two hours (0, 2, 4, ..., 24 UTC) at the grid points. The resolution of the maps is 5° in longitude and 2.5° in latitude.

The Center for Orbit Determination in Europe (CODE) employs spherical harmonics functions to model the global VTEC using about 200 worldwide GPS/GLONASS stations. CODE distributes Global Maps in three versions: Predicted, Rapid and Final GIM.

The predicted version contains predictions of the ionospheric delay for 1-2 days ahead. The VTEC at a certain time and location is interpolated between two consecutive maps using four surrounding grid points. The VTEC provided by GIM has a standard deviation of 28 TECU (CODE, 2007) depending on the epoch in the solar cycle, season, and location and to the best of our knowledge is unbiased (1 TECU corresponds to an ionospheric delay of 16 cm in L1).
In order to get slant ionospheric delay along the line-of-sight between receiver and satellite a mapping function must be used to map the VTEC to the slant TEC value.

2.6 Positioning Software: gLAB

GNSS-LABoratory (gLAB) tool suite is a flexible software tool capable of high-accuracy GNSS positioning. It is an interactive and user-friendly educational multipurpose software package for processing and analysing GNSS data.

It was developed by Research group of Astronomy and Geomatics (gAGE) at the Technical University of Catalonia (UPC) under ESA Education Office contract. It is free of charge from ESA to university enterprises and GNSS professionals. (1)

Most of the algorithms introduced in the Satellite Navigation theory are implemented in the gLAB tool suite. It is also complemented with an additional software package of simple routines implementing different algorithms described in its manual. For this thesis purpose only description of interested parts will be discussed. In particular gLAB Graphical User Interface will be presented to a better and exhaustive description of the options used, although this software presents the possibility to be executed in console mode. (1)

The gLAB tool features a wide range of characteristics only available in advanced GNSS data processing software (1):

1. high-accuracy positioning capability;
2. fully configurable;
3. easy to use thanks to the present of an intuitive GUI and also there is the possibility to access to internal computations

![Figure 2.16: gLAB Graphical User Interface (GUI): Main panel](image)
2.6 Positioning Software: gLAB

It performs precise modeling of GNSS observables (pseudorange and carrier phase) at the centimetre level, allowing both standalone GPS positioning and also for PPP. gLAB is adapted to a variety of standard formats like (Receiver Independent Exchange Format (RINEX), Antenna Exchange Format (ANTEX) and Solution (Software/technique) INdependent EXchange Format (SINEX) files. Moreover, functionality is also included for GPS and GLONASS, allowing performing some data analysis with real multi-constellation data.

The three main software modules are:

• the Data Processing Core (DPC) that implements all the data processing algorithms;
• the Data Analysis Tool (DAT) that provides a plotting tool for the data analysis;
• the Graphic User Interface (GUI) that consists in different graphic panels for a user friendly managing of both the DPC and DAT.

gLAB presents in the GUI Interface different panels. The two major are devoted to positioning and to the graphical analysis. Positioning is also divided in different parts:

• input: provides all the configuration options to select the input files,
• preprocess: allows changing the decimation rate, the elevation mask, the cycle slip detection, and to select individual satellites for the processing,
• modeling permits to set/unset all the individual models which are used by gLAB,
• filter: provides options to select measurements and parameters to be estimated,
• output: allows the selection of the outputs information.

In the following section the Standard Point Service (SPS) characteristics and performances, that have been used and analysed for this thesis work, has been illustrated.

2.6.1 Standard Point Service (SPS) using gLAB

The main target of this thesis, using the software gLAB, is to analyse different ionospheric contribution applied to single frequency measurements on the GNSS signals.

In the following part parameters and files used in the computation of SPS positioning have been listed. In the POSITIONING - INPUT section these files have been used:

• RINEX Observation files, version 2, 2.10 and 2.11
• RINEX Navigation files
gLAB tool has been used to obtain different positioning solutions of GPS single-frequency code-based. As input RINEX measurement (Observation files) and broadcast orbits and clocks (Navigation files) have been used.

gLAB has been chosen because of its flexibility to enable the ionospheric correction. For this thesis purpose the Klobuchar ionospheric correction has also been chosen and for all the other cases the ionospheric correction has been disable. In these cases different RINEX observation format have been used with different ionospheric correction already applied.

![gLAB panels: input, preprocess, modeling, filter, output](image1)

**Figure 2.17:** gLAB panels: input, preprocess, modeling, filter, output

In the POSITIONING - PREPROCESS section these options have been selected:

- data decimation: 300 seconds,
- elevation mask: 10 degrees,
- discard unhealthy satellite,
- GNSS satellite selection: GPS (GLONASS and GALILEO constellations, for the moment, are not available using this software).

For the POSITIONING - MODELLING these options have been activated:
2.6 Positioning Software: gLAB

- satellite clock offset correction,
- satellite movement during signal flight time,
- Earth rotation during signal flight time,
- relativistic clock correction (orbit eccentricity),
- ionospheric correction (activation just in case to have Klobuchar correction),
- tropospheric correction - UNB3 Nominal - Simple Mapping,
- P1-C1 correction.

For the POSITIONING - FILTER the available frequency selected is **single frequency** in all the cases, estimating the **pseudorange measurement**. The OUTPUT format provides the extension .out.
Bibliography


[8] CNES, ESA, User Guide for EGNOS Application Developers. EDITION. 1.1 2009. v, 12, 14, 19, 21, 22, 30


This chapter provides an overview of the ionosphere and how it affects GNSS signals that propagate through it. A physical description of the ionosphere will be given, looking at its structure in different regions and layers in altitude and how it varies both geographically and temporally. The relationship between the Sun’s activity and the Earth’s magnetic field and how it influences the ionosphere and its variations will be discussed. In addition, the effect of the ionosphere on the propagation of radio signals will be briefly addressed.

Detailed explanations of the physicochemical processes that control the ionosphere are found in Shunk (2004) (1) and Nagy (2009), Kelley (2009) (2) amongst others.

3.1 The Earth’s atmosphere

The Earth’s atmosphere is a gaseous cover that surrounds the planet and is retained by the Earth’s gravitational field. Throughout the atmosphere temperature varies with altitude, and different regions can be characterized by temperature, composition and ionization. Atmospheric density decreases exponentially with altitude from a standard value of 1.2 kg/m$^3$ at sea level. Density is 10 times less at 18 km of altitude and 100 times less at 32 km of altitude.

Atmospheric temperature varies with altitude defining several -spheres separated by -pauses where the temperature gradient with altitude changes sign as is seen in figure Figure 3.1. The troposphere is the lowest region and it extends to about 10 km. Depending on various conditions such as geographical latitude and meteorological conditions, this altitude varies between 8 km at the poles and 18 km at the geographic equator. The temperature decreases in this region (which makes up 85 percent of the total mass of the atmosphere) with increasing altitude. The troposphere is heated from the Earth surface that radiates the energy received from the sun. In this region most of the meteorological phenomena including the formation of clouds occur. (1)
The tropopause separates the troposphere from the stratosphere above it where the temperature slowly increases to a maximum of 290\( ^\circ \)K at an altitude of about 50 km. This increase in temperature is due to the absorption by ozone molecules of a part of the ultraviolet radiation emitted by the Sun.

The mesosphere, above the stratopause, is a region of decreasing temperature with a minimum of around 170\( ^\circ \)K found at about 85 km depending on latitude and season. This decrease is due to the reduced density of the atmospheric gases including ozone and the resultant decrease of solar radiation absorption with altitude.

The thermosphere lies above the mesopause. Its temperature increases with altitude due to absorption of highly energetic solar radiation in the thermosphere up to the thermopause where the temperature reaches well above 1000\( ^\circ \)K. Temperature in the thermopause is highly variable with time of day but still more with solar activity.

Atmospheric composition in the homosphere, below around 85 km, is dominated by turbulent mixing and the relative numbers of molecular nitrogen (\( N_2 \), 78%) and molecular oxygen (\( O_2 \), 21%) molecules are constant with altitude.

In the heterosphere, above around 85 km, diffusion processes are sufficiently strong for a gravitational separation of the different neutral species to occur. The net effect of these processes is that heavy molecular constituents dominate at low altitudes and the atomic neutrals dominate at high altitudes. Atomic oxygen (O), helium He, and hydrogen (H) successively dominate above about 200 km altitude and vary with geographic location, time, and solar activity. The ratio \( \frac{N_2}{O} \) which is a measure of the electron density at the ionospheric F region is highly affected by these variations.

### 3.2 The ionosphere

The ionosphere is the atmospheric region above about 60 km in which a high enough percentage of particles are ionized so as to form a plasma. This region with the presence of free charged particles is especially important for propagation or radio waves through it including GNSS signals. It extends upwards to high altitudes where it merges with the magnetosphere.

The ionospheric plasma is originated mostly by the solar UV and X radiation of the sun that ionize the different neutral atmospheric components. Ionization processes are different for each specific atmospheric neutral particle and for each solar radiation wavelength. Because of this, the ionosphere appears stratified in regions with layers within a region.

The lowest well defined region is the D-region (figure 3.1) that extends from 60 to 90 km approximately. It is produced by the ionization of neutral nitric oxide (NO) solar Lyman alpha radiation (121 nm) and of molecular nitrogen and oxygen (\( N_2, O_2 \)) by solar X-rays (less than 20 nm). Molecular ions react with water vapor to produce water cluster ions. In this region electrons recombine rapidly with water cluster ions and also attach to molecules to make negative ions that suffer rapidly detachment again
3.2 The ionosphere

Figure 3.1: Subdivision of the Earth’s atmosphere

by solar radiation in day-time. D-region disappears at night (within several minutes) as production essentially ceases and electrons undergo rapid recombination and attachment.

The E-region lies from 90 to 140 km of altitude approximately. It is produced by daytime ionization of molecular oxygen ($O_2$) by solar extreme ultraviolet solar radiation (90-103 nm) and by ionization of meteoric vapors. Electrons recombine with molecular ions ($O_2^+$ and NO$^+$). The E-region persists, although diminishes, during night due to the slower recombination, in comparison with the D-region, and because of the presence of atomic metallic ions such as Na$^+$ (sodium) and Fe$^+$ (iron). Electrons recombine with atomic ions (such as Na$^+$ or O$^+$) very inefficiently. In this region sporadic layers of increased electron density appear.

Above the E-region lies the F-region that is the most important and complex ionospheric region because it is the region of the ionosphere with the highest electron density and because it is under the effect of transport processes and also is controlled by the
3.3 Ionospheric measurements

Figure 3.2: Characterization of the ionosphere (ref. INGV)

geomagnetic field. daytime ionization of atomic O by extreme ultraviolet (EUV) solar radiation (20 - 90 nm). O+ converted to NO+ by molecular nitrogen (N2). During day-time a layer can be recognized in the F-region called F1-layer where the loss of electrons is due to recombination with NO+. This layer extends from 140 to about 200 km. The remaining ionization at night merges with the F2 layer.

The F2-layer that peaks at about 300-400 km, depending on several time and spatial conditions. The loss of electrons is controlled by O+ reaction with molecular nitrogen (N2), and the fast recombination with the No+ produced by this reaction. The electron density is affected by transport that, in turn, are influenced by the geomagnetic field. The layer persists through night (becoming simply the F-region) since the small supply of N2 leads to slow conversion of O+ to NO+ and hence only a small reduction in the number of electron. The F2 region is usually in quasi-equilibrium. By day, at heights below and up to the F2 peak, production and loss terms are roughly in balance. The F2 peak lies at the height where the transport terms are comparable to the production and loss terms.

3.3 Ionospheric measurements

To monitor the ionosphere two types of techniques exists: in-situ measurements using rockets and satellites, and remote sensing observation ground observations using radio or optical signals. Each of these techniques has its own advantages and disadvantages, and usually observations from both techniques are required to provide a comprehensive understanding of the ionosphere and its physical processes.
3.4 Ionospheric variations

Among the remote sensing methods that use radio waves the most widely applied are: bottom side soundings (from the ground) and total electron content measurements.

Bottomside soundings are done with an ionospheric radar called ionosonde that transmits pulses sweeping frequency, usually in the range of 0.1 to 20 MHz. As the frequency increases, each wave penetrates further in the ionized layer before it is reflected. Generally, a frequency is reached that enables the wave to penetrate the layer without being reflected. This frequency, called critical frequency, is a measure of the peak electron density in the ionospheric regions through the expression:

\[ N = 0.124 \times 10^{11} f^2 \]  

(3.1)

where \( N [m^{-3}] \) and \( f [MHz] \).

The most important critical frequency, in terms of trans-ionospheric propagation of radio waves, is the foF2 that corresponds to the maximum electron density in the ionosphere that it is found in the F2 region. Total electron content (TEC), measured as the number of electrons in a column of one meter-squared cross-section along a trans-ionospheric path, is a very important parameter to describe the behavior of the ionosphere.

\[ N_T = \int S N(s) ds \]  

(3.2)

The TEC unit is given by \( 1 \ TEC = 10^{16} m^{-2} \).

Sources of TEC measurements are varied but the use of dual frequency signals from GNSS constellations offer an excellent way to study TEC characteristics and variability.

3.4 Ionospheric variations

The Earth’s ionosphere displays marked variations with altitude, latitude, longitude, universal time, season, solar cycle, and magnetic activity. The variation is shown in all ionospheric parameters: electron density, ion and electron temperatures, and ionospheric composition and dynamics. This is primarily a result of the ionosphere’s coupling to the other regions in the solar-terrestrial system: the sun, the interplanetary medium, the magnetosphere, the thermosphere, and the mesosphere and (to a certain extent) the stratosphere and troposphere.

The variations are of two general types: “more or less” regular, occurring in cycles or quasi-cycles and can be predicted in advance with reasonable accuracy (quiet ionosphere), and irregular, mostly related to the irregular behavior of the sun and the geomagnetic field that cannot be easily predicted in advance (disturbed ionosphere).

Regular time variations that affect electron density in the ionosphere can be divided
3.4 Ionospheric variations

into these main classes: diurnal, day-to-day, seasonal, solar activity. Regular geographical variations are related to the effect of the geomagnetic field on the ionosphere. In general it is possible to consider five main variations of the electron density of the ionosphere which must be taken into account:

1. diurnal variation, throughout the day which is largely due to the variation of the solar zenith angle;
2. season, throughout the year;
3. location, both geographic and geomagnetic;
4. solar activity, both long term and disturbances;
5. height, the different layers.

These variations have all been found experimentally, by world-wide observations of the ionosphere over the past several decades.

The diurnal, seasonal, solar cycle and height variations of the ionosphere may all be established by routine monitoring of the ionosphere.

Figure 3.3 and figure 3.4 show these four variations for a typical midlatitude station. The year 1958 was a period of high solar activity, as indicated by the high values of the ionospheric index, T.

![Figure 3.3: Diurnal variation of the critical frequencies of the E, F1 and F2 layer for solar maximum in 1958 for January and June at a typical midlatitude station (Canberra). The parameter T is an ionospheric index related to the level of solar activity.](image)

The figure also illustrates the mid-latitude seasonal anomaly, the name given to the initially unexpected fact that foF2 is higher in the winter than in the summer, in spite of the larger solar zenith angle. (ref. Hargreaves 1958) The measurement of the variation with location has been achieved through an international effort of observations and data exchange.
The behaviour of the F1 layer is similar to the E layer and it is dominated by the value of the solar zenith angle, except that the F1 layer tends to disappear in winter. Moving on to the F2 layer, due to its large height and electron density the most important layer both for high frequency (HF) and transionospheric propagation is concerned, it is found that the simple situation that holds for the E and F1 layers does not hold very well for the F2 layer.

Figure 3.6 (6) shows, for example, how the F2 layer critical frequency, $f_0F_2$, varies over the Earth at 00 UT in June, for low and high solar activities. It can be seen that the simple structure obtained for the E and F1 layers, with the contours of $f_0E$ and $f_0F_1$ closely following the contours of the solar zenith angle, no longer applies although a clear zenith angle dependence can be seen around sunrise.

$f_0F_2$ is also found to have variations with latitude which are not seen in $f_0E$ and $f_0F_1$. For example, Figure 3.6 shows that $f_0F_2$ exhibits two afternoon peaks situated on either side of the equator. This feature is known as the Ionospheric Equatorial Anomaly (IEA) and it is due to electrodynamic lifting of the layer at the equator under the combined influence of horizontal electric and magnetic fields. During daytime, the eastward electric field near the dip equator produces a upward $\mathbf{E} \times \mathbf{B}$ drift which in conjunction with plasma downward diffusion along the magnetic field lines due to the influence of gravity and pressure gradient forces, result in the formation of a plasma equatorial fountain (1962). (17) The plasma fountain is centered at the dip equator and transports plasma from the equatorial region to higher latitudes. The extension is between 20 degrees north and south of the magnetic equator. Because of this, when maximum electron density of F2-region at noon-time is plotted with respect to dip latitude, the electron density curve has two peaks north and south of dip equator.

The morphology of the high latitude ionosphere is even more complicated than that of the equatorial ionosphere and much remains unknown about it. Probably the most important feature of the high latitude ionosphere is the mid-latitude ionosphere trough,
which lies equatorwards of the auroral oval. The trough is a narrow feature that moves in step with geomagnetic activity and thus fails to appear in monthly median maps of foF2. However, it can have very serious effects on HF communication at high latitudes because of the strong horizontal gradients associated with it.

### 3.5 Solar Activity and its disturbances

The Sun with a radius of 696000 km contains more than 99.8 % of the total mass of the solar system. The Sun is composed mainly of hydrogen and helium. The Sun emits
large amounts of power and mass (roughly $4 \times 10^{33} \text{erg sec}^{-1}$) that is produced by nuclear fusion reactions (Hydrogen converted to Helium + gamma rays) in its interior. The Sun consists of the solar interior (core), the visible surface (photosphere), the lower solar atmosphere (chromosphere), and outer solar atmosphere (corona). The upper layers of the Sun rotate with an angular velocity which depends on the heliocentric latitude. In the photosphere the rotation is faster at the solar equator. The rotation period at the solar equatorial latitudes is about 27 days. The temperature at the Sun’s core is about $15 \times 10^6 \text{K}$ and decreases toward the Sun’s surface. Temperature in the photosphere is about 5800 K, but there are regions with lower temperature ($4000 \text{K}$) which are seen by observers on the Earth as dark sunspots.\(^{[6]}\)

Huge amounts of energy are continuously released from the Sun by both electromagnetic radiation (photon) and particle outflow (protons and electrons). The Sun radiates electromagnetic waves over a wide range of wavelengths, including the X-ray, ultraviolet, visible, infrared and radio waves. The total radiated energy per second

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**Figure 3.6:** The geographical variation of the critical frequency of the F2 layer for June at solar minimum and maximum for 00 UT.\(^{[6]}\)
3.5 Solar Activity and its disturbances

in all wavelengths is approximately constant. The total energy at top of the Earth’s atmosphere (at a Sun-Earth separation of 1 astronomical unit) is 1370 watts per meter squared and is called the solar constant.

The Sun releases about one billion kilograms of the energetic charged particles, mainly protons and electrons, with energies usually between 1.5 and 10 keV. The stream of particles varies in density, temperature, and speed over time and over solar longitude. These particles can escape the Sun’s gravity because of their high kinetic energy and the high temperature of the corona. This is called solar wind. The velocity of the particles is about 300 km/sec so it takes about 4-5 days to reach the Earth. The solar wind is mainly sustained by a continuously outflow of plasma from the Sun’s corona. A portion of the solar particle radiation is related to powerful events in the Sun’s atmosphere above sunspots, called solar flares. The received total energy from solar particle radiation at top of the Earth’s atmosphere is only about one-tenth of the solar photon radiation energy from the X-ray and EUV spectral regions (1).

Solar activity influences the structure of the low and high atmosphere and the intensity of the Earth’s geomagnetic field.

Regarding the ionosphere, its normal state experiences disturbances when the Sun increases its activity (radiation or particles emissions). Solar disturbances includes geomagnetic activity (geomagnetic storm) and ionospheric disturbances (ionospheric storm), which increase in intensity of the Aurora.

Ionospheric disturbances are non-normal and irregular variation of the ionosphere that are usually observed during geomagnetic activity. All the ionospheric regions are affected by the solar disturbances, but the most significant perturbations occur in the F region particularly near the peak electron density.

Different solar indices are able to describe the behaviour of the solar activity, like:

- **Sunspot numbers**: A sunspot is a temporary region on the photosphere (characterised by a strong magnetic activity) which emits less radiation than their hot surroundings and therefore appear dark only by comparison with the surrounding regions.

- **Solar flux**: it is the measure of the solar radio emission intensity per unit frequency at a wavelength of 10.7 cm. The solar flux index at 10.7 cm, called F10.7, is measured daily at local noon in a bandwidth of 100 MHz centered on 2800 MHz at the Penticton site of the Dominion Radio Astrophysical Observatory (DRAO), Canada. It is an indicator of the solar activity levels and correlates with solar UV emissions. Emission from the Sun at centimetric (radio) wavelength is due primarily to coronal plasma trapped in the magnetic fields overlying active regions. Sunspot activity has a major effect on long distance radio communications. High levels of sunspot activity lead to improve signal propagation on higher frequency bands, although they also increase the levels of solar noise and ionospheric disturbances. These effects are caused by impact of the increased level of solar radiation on the ionosphere.
3.6 Geomagnetic storms

Ionospheric ionization is strongly dependant to the solar activity and it is function of the number and of the extension of the sunspots. Therefore Solar Minimum refers to the several years when the sunspot numbers are the lowest and Solar Maximum refers to the years when sunspots are the most numerous and large. During Solar Maximum, activity on the sun and its effects on our terrestrial environment are high. The frequency and intensity of geomagnetic storms and radiation showers in the Earth’s atmosphere increases during solar maximum.

3.6 Geomagnetic storms

The main Earth’s geomagnetic field is generated by electric currents flowing deep within the Earth. As a dipole field it extends beyond the planetary surface, through the troposphere on which it has no effect, and into the ionized atmosphere where its effects are considerable. The geomagnetic field affects the motion of ionized particles, modifying ionospheric electric currents and bulk movement of the plasma. It increases with the altitude as the atmosphere becomes more sparse and its degree of ionization increases. Magnetosphere is the area in space dominated by Earth’s magnetic field. There is not sharp boundary between it and the ionosphere. The thin boundary separating the shocked solar wind plasma from the plasma of the magnetosphere is called magnetopause. Geomagnetic storms occur when there is a large sudden change in the solar wind dynamic pressure at the magnetopause, which occurs when it is impacted by a coronal mass ejection or solar flare material.

The storms can be particularly strong when the increased solar wind pressure is associated with a large southward Interplanetary Magnetic Field component (Bz).

A sudden storm commencement (SSC) is followed sequentially by initial, main, and recovery phases.

During the growth phase, the plasma convection and particle precipitation patterns expand, the electric fields become stronger, and the precipitation intensifies. These changes are accompanied by substantial increases in the Joule and particle heating rates and the electrojet currents.

The energy input to the upper atmosphere maximizes during the main phase, while during the recovery phase the geomagnetic activity and energy input decrease.

Large storms can significantly modify the density, composition, and circulation of the ionosphere – thermosphere system on a global scale, and the modifications can persist for several days after the geomagnetic activity ceases. If the electron density increases as a result of stormdynmics, it is called a positive ionospheric storm, while a decrease in electron density is called a negative ionospheric storm.

During a sudden storm commencement, gravity waves can be excited at high latitudes and their subsequent propagation toward lower latitudes leads to a traveling ionospheric disturbance (TID). Unfortunately, the response of the ionosphere – thermosphere system to different geomagnetic storms can be significantly different, and even for a given storm the system’s response can be very different in different latitudinal and longitudinal regions.
The sequence of events that occurs during a geomagnetic storm can be summarized in these steps (1).

In response to the large energy input at high latitudes, auroral E region densities increase, day side high-density plasma convects into the polar cap at F region altitudes, the main trough moves equatorward, the neutral and charged particle temperatures increase, the thermospheric wind speed increases, the $O/N_2$ ratio decreases, and equatorward propagating gravity waves are excited.

At mid-latitudes, the equatorward propagating waves drive the F region ionization toward higher altitudes, which results in an ionization enhancement (positive storm effect).

Behind the wave disturbance are enhanced meridional winds. These diverging winds cause upwelling and neutral composition ($O/N_2$) changes, which then lead to decreased electron densities (negative storm effect). For major magnetic storms, the composition changes and winds can penetrate all the way to the magnetic equator, but that is rare.

However, in the mid-low latitude region, the enhanced winds can generate dynamo electric fields that can affect the equatorial ionosphere.

Many studies have been done to model magnetic storms, including weak, moderate, large, and super storms. Results of these studies show that electric fields, neutral winds, and $O/N_2$ composition changes all contribute to the positive phase of a storm, while the negative phase of a storm is due to $N_2$ upwelling (decrease in the $O/N_2$ ratio).

### 3.6.1 Geomagnetic Indices

During geomagnetic activity the electron density can both increase or decrease at mid latitudes. The ionosphere reacts to the geomagnetic activity in a complex way and its behavior varies with latitude, longitude, time of day and season (18). A global picture of the geomagnetic activity that generates ionospheric response is provided by different indices. Geomagnetic indices present a series of data which describe, on a planetary scale, the geomagnetic activity. Historically different measures of the Earth’s geomagnetic field at different latitudes have been done and a consequent dependence on the latitude has been seen. (from a value of 24000 nT in the equatorial regions from 68000 nT in the polar regions). The most important geomagnetic indices used to provide information on the geomagnetic perturbation produced by the solar activity are here summarized (19).

- **K index**: it represents the effect of the solar radiation on the ground, which its interaction with the magnetic field defines the magnetic activity. It quantifies disturbances in the horizontal component of earth’s magnetic field. It is a measure of the magnetic deviations from the regular daily variation during a 3-hour period. The K index is provided through a semi-logarithmic number that varies from 0 to 9, with the different numbers corresponding to different geomagnetic activity levels;
### 3.6 Geomagnetic storms

- **Kp index**: it is a planetary index which identifies solar particle radiation by its magnetic effects. It is derived by calculating a weighted average of K indices recorded from a network of 13 reference geomagnetic observatories distributed all around the world. (11 in the Northern Hemisphere and 2 in the Southern Hemisphere).

<table>
<thead>
<tr>
<th>Scale</th>
<th>Kp index</th>
<th>number of storms days for solar cycle (11 years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G5 - extreme</td>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td>G4 - severe</td>
<td>8</td>
<td>60</td>
</tr>
<tr>
<td>G3 - strong</td>
<td>7</td>
<td>130</td>
</tr>
<tr>
<td>G2 - moderate</td>
<td>6</td>
<td>360</td>
</tr>
<tr>
<td>G1 - minor</td>
<td>5</td>
<td>900</td>
</tr>
</tbody>
</table>

- **The planetary index ap and Ap**: the three-hour equivalent amplitude index of local geomagnetic activity index ap and the daily index Ap (average planetary) are directly connected with the Kp index.

<table>
<thead>
<tr>
<th>Kp</th>
<th>0o</th>
<th>0+</th>
<th>1-</th>
<th>1o</th>
<th>1+</th>
<th>2-</th>
<th>2o</th>
<th>2+</th>
<th>3-</th>
<th>3o</th>
<th>3+</th>
<th>4-</th>
<th>4o</th>
<th>4+</th>
</tr>
</thead>
<tbody>
<tr>
<td>ap</td>
<td>0</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>9</td>
<td>12</td>
<td>15</td>
<td>18</td>
<td>22</td>
<td>27</td>
<td>32</td>
</tr>
<tr>
<td>Kp</td>
<td>5-</td>
<td>5o</td>
<td>5+</td>
<td>6-</td>
<td>6o</td>
<td>6+</td>
<td>7-</td>
<td>7o</td>
<td>7+</td>
<td>8-</td>
<td>8o</td>
<td>8+</td>
<td>9-</td>
<td>9o</td>
</tr>
<tr>
<td>ap</td>
<td>39</td>
<td>48</td>
<td>56</td>
<td>67</td>
<td>80</td>
<td>94</td>
<td>111</td>
<td>132</td>
<td>154</td>
<td>179</td>
<td>207</td>
<td>236</td>
<td>300</td>
<td>400</td>
</tr>
</tbody>
</table>

This table is made in such a way that at a station at about dipole latitude 50 degrees, ap may be regarded as the range of the most disturbed of the two horizontal field components, expressed in the unit of 2nT. The daily index Ap is obtained by averaging the eight values of ap for each day.

- **auroral indices AU (Auroral Upper), AL (Auroral Lower) and AE (AU AL)**: they provide an indication of the geomagnetic activity in the auroral zone, due mainly to the auroral electrojet. These indices are calculated from geomagnetic variations in the horizontal component of the geomagnetic field recorded at selected 10-13 observatories situated along the auroral zone in the northern hemisphere.

- **Dst index**: Dst is the Disturbance Storm Time Index. Like the other magnetic disturbance indices, it is obtained from the average of horizontal component disturbances of the geomagnetic field from four low-latitude magnetic observatories (Honolulu, San Juan, Hermanus and Kakioka). The Dst is the global midlatitude average magnetic deflection in units of nT. It shows the effect of the globally symmetrical westward flowing high altitude equatorial ring current which causes the "main phase" depression worldwide in the Horizontal component field during large magnetic storms. Being the measurement of the longitudinally averaged ground perturbation at low-latitude magnetometer stations, it measures the effects of many terrestrial and magnetospheric current systems. Dst index is indeed influenced by the symmetric ring current, the partial (asymmetric) ring current, the near-tail current, the dayside magnetopause currents and the field-aligned currents (FACs) that couple the magnetosphere to the high-latitude ionosphere.
3.7 Ionospheric propagation of satellite signals

Ionospheric propagation of satellite signals and magnetopause currents. Nowadays it is used to monitor the world wide geomagnetic storm level. Its scale is negative and according to the different values of Dst, it is possible to classify the geomagnetic storms in the following types:

- **superstorm**: \( Dst < -200 \)
- **intense storm**: \(-200 < Dst < -100 \)
- **moderate storm**: \(-100 < Dst < -50 \)
- **weak storm**: \(-50 < Dst < -30 \)

(3.3)

Dst index has been used as reference index for this thesis in the selection of the period characterised by geomagnetic storms.

### 3.7 Ionospheric propagation of satellite signals

When an electromagnetic wave propagates in free space, its velocity is known to be equal to the velocity of light. When the wave propagates in a medium, its velocity changes due to interaction with the particles present in that medium. This is known as wave refraction and the amount of refraction is described by the medium specific refractive index. (10) (15)

The ionospheric refractive index is unfortunately not a constant. This is because the ionosphere is an inhomogeneous, anisotropic and dispersive medium. In a dispersive medium, refractive index depends upon the frequency of the wave. (12) To describe the propagation of a modulated electromagnetic wave through a dispersive medium, a difference between the phase velocity and the group velocity of the signal has to be considered, after giving the mathematical expression of refractive index.

In order to describes the refractive index for electromagnetic wave propagation in a cold magnetized plasma, a mathematical expression called Appleton Hartree equation has been here reported (1). The dispersion relation can be written as an expression for the frequency (squared), but it is also common to write it as an expression for the index of refraction

\[
n^2 = 1 - \frac{X}{1 - iZ - Y^2 \frac{\omega_0^2}{2(1 - X - iZ)} + \frac{Y^2}{2(1 - X - iZ)^2}} \pm Y \theta^2 \frac{\omega_H^2}{2(1 - X - iZ)} + \frac{Y^2}{2(1 - X - iZ)^2} + \frac{Y^2 L}{4(1 - X - iZ)}\]

where \( n \) = complex refractive index, \( i = \sqrt{-1} \), \( X = \frac{\omega^2}{2} \), \( Y = \frac{\omega H}{\omega_0} \), \( Z = \frac{\nu}{\omega} \), \( \nu \) = electron collision frequency, \( \omega = 2\pi f \) (radial frequency), \( f \) = wave frequency (cycles per second, or Hertz), \( \omega_0 = 2\pi f_0 = \sqrt{\frac{N e^2}{\epsilon_0 m}} \) = electron plasma frequency, \( \omega_H = 2\pi f_H = \frac{B_0 e}{m} \) = electron gyro frequency, \( \epsilon_0 \) = permittivity of free space, \( B_0 \) = magnetic field strength, \( e \) = electron charge, \( m \) = electron mass, \( \theta \) = angle between the ambient magnetic field vector and the wave vector.

The frequency of signals used by navigation satellite has to be selected in order to make \( n^2 \) as close as possible to unity. The refractive index of free space equals 1.
3.7 Ionospheric propagation of satellite signals

When the refractive index is smaller than 1, the wave is advanced and when it is larger than 1 it is delayed). For frequencies used in positioning, it can be used a first order approximation of the Appleton–Hartree formula:

\[ n^2 = 1 - X \]  

(3.5)

still, expanding the square root at the first order:

\[ n = 1 - \frac{X}{2} = 1 - \frac{40.3N_e}{f^2} \]  

(3.6)

Using the first order expansion, the Optical Path (geometrical length of the ray plus the ionospheric contribution) \( \Lambda \) becomes:

\[ \Lambda = \int nds = \int (1 - \frac{40.3N_e}{f^2}) ds = D - \frac{40.3N_e}{f^2} \int N_e ds = D - \frac{40.3N_e}{f^2} TEC \]  

(3.7)

\[ TEC = \int N_e ds \]  

(3.8)

3.7.1 Ionospheric time delay effect on Earth-Space Propagation

One of most important effects of the ionosphere on a radio wave \(^3\) is a retardation, or group delay, due to its encounter with the free, thermal electrons in the Earth’s ionosphere.

Other effects the ionosphere has on radio waves include:

- carrier phase advance,
- Doppler shift of the carrier of the radio wave,
- Faraday rotation of the plane of polarization of linearly polarized waves,
- angular refraction or bending of the radio wave path as it travels through the ionosphere,
- distortion of the waveform of transmitted pulses
- amplitude and phase scintillation

With the exception of scintillation effects, all the other effects listed here are proportional, at least to first order, to the total number of electrons encountered by the wave on its passage through the ionosphere or to their time rate of change.

Phase scintillation also is merely the short term, time rate of change of total electron content (TEC) after the longer term variations have been removed.
3.7 Ionospheric propagation of satellite signals

3.7.1.1 Group Path Delay and Carrier Phase Advance

In the ionosphere the angular frequency $\omega$ and the wave number $k$ are not proportional which means that the wave propagation speed and the refractive index depends on the frequency. This is the case with the ionosphere where $\omega$ and $k$ are related, in a first approximation, by [Crawford, 1968]:

$$\omega^2 = c^2k^2 + \omega_p^2$$  \hspace{1cm} (3.9)

The previous equation is the Relation of Dispersion of the ionosphere, and $\omega_p$ is called the critical frequency of the ionospheric plasma, in the sense that signals with $\omega < \omega_p$ will be reflected and signals with $\omega > \omega_p$ will cross through the plasma [13]. Taking into account that $\omega = 2\pi f$ and the definition of Phase and Group Velocity, the phase refractive index of the ionosphere can be approximated, at the first order delay, as:

$$n_{ph} = \sqrt{1 - \left(\frac{f_p}{f}\right)^2} \approx 1 - \frac{1}{2} \left(\frac{f_p}{f}\right)^2 = 1 - \frac{40.3}{f^2}N_e$$  \hspace{1cm} (3.10)

Differentiating the equation with respect to $k$, it is possible to obtain the group refractive index

$$n_{gr} = 1 + \frac{40.3}{f^2}N_e$$  \hspace{1cm} (3.11)

Substituting the phase and group refraction indices into

$$\Delta = \int_{\text{straight line}} (n - 1) \, dl$$  \hspace{1cm} (3.12)

the difference between the measured range (with the frequency $f$ signal) and the Euclidean distance between the satellite and receiver is given by:

$$\Delta_{\text{iono}}^{\text{ph,f}} = -40.3 \int N_e \, dl \quad \Delta_{\text{iono}}^{\text{gr,f}} = +40.3 \int N_e \, dl$$  \hspace{1cm} (3.13)

Thence, phase measurements suffer advancement when crossing the ionosphere, i.e., a negative delay, and the code measurements suffer a positive delay.

3.7.1.2 Doppler Shift

Since frequency is simply the time derivative of phase, an additional contribution to geometric Doppler shift results due to changing TEC. This additional frequency shift $d\phi$ is generally small compared to the normal geometric Doppler shift, but can be computed by (12):

$$\Delta f = \frac{d\phi}{dt} = 1.34 \times 10^{-7} \frac{d}{dt}TEC(Hz)$$  \hspace{1cm} (3.14)

For high orbit satellites where the diurnal changes in TEC are greater than geometric ones, an upper limit to the rate of change of TEC is approximately $0.1 \times 10^{16} \text{elm}^{-2}\text{s}^{-1}$.
3.7 Ionospheric propagation of satellite signals

3.7.1.3 Faraday Polarization Rotation

When a linearly polarized radio wave traverses the ionosphere the wave undergoes rotation of the plane of polarization. At frequencies of approximately 100 MHz and higher the amount of this polarization rotation can be described by (6):

\[ \Omega = \frac{2.36 \times 10^{-5}}{f^2}\int B \cos \theta N \, dl \]  

(3.15)

where the quantity inside the integral is the product of electron density times the longitudinal component of the earth’s magnetic field, integrated along the radio wave path. The Faraday rotation problem is overcome by the use of circular polarization of the correct sense at both the satellite and at the user’s receiver.

3.7.1.4 Angular Refraction

The refractive index of the Earth’s ionosphere is responsible for the bending of radio waves from a straight line geometric path between satellite and ground. This angular refraction or bending produces an apparent higher elevation angle than the geometric elevation. (6) The easiest expressions to use, as given by Millman and Reinsmith relate the ionospheric range error to angular refraction, is:

\[ \Delta E = \frac{R + r_0 \sin E_0 (r_0 \cos E_0)}{h_i (2r_0 + h_i) + r_0 \sin E_0} \times \frac{\Delta R}{R} \]  

(3.16)

where \( E_0 \) is the apparent elevation angle, \( R \) is the apparent range, \( \Delta R \) is computed form \( \Delta R = 40.3 \times TEC \), \( r_0 \) is the terrestrial radius, and \( h_i \) is the height of the centroid of the TEC distribution, generally between 300 and 400 km.

Generally, the range error itself is the main ionospheric problem for advances navigation systems and elevation angle errors are insignificant. Satellite detection radar systems, on the other hand, do have the requirement to know accurate pointing elevation angles for their large aperture arrays, though generally the accurate tracking is done by using range rate information, and elevation angle is of secondary importance as long as the beamwidth of the antenna is large enough to see the target. (5), (8)

Errors in the azimuth of radio waves transmitted through the ionosphere can also occur; they depend upon azimuthal gradients in TEC which are generally small and which can usually be neglected in practical cases.

3.7.1.5 Distorsion of pulse Waveforms

Two characteristics of the ionosphere can produce distortion of pulses of radio frequency energy propagated through it. The differential time delay due to the normal ionosphere is proportional to \( \frac{1}{f^2} \) produces a difference in pulse arrival time across a bandwidth \( \Delta f \) of

\[ \Delta t = \frac{80.6 \times 10^6}{c f^3} \Delta f \times TEC \]  

(3.17)
3.7 Ionospheric propagation of satellite signals

where $c$ is the velocity of light in $\frac{m}{s}$, $f$ and $\Delta f$ are expressed in Hz and TEC is in $\frac{cl}{m^2}$. The dispersive term for pulse distortions is thus proportional to TEC. When the difference in group delay time across the bandwidth of the pulse is the same magnitude as the width of the pulse it will be significantly disturbed by the ionosphere.

3.7.1.6 Scintillation on Trans-Ionospheric Radio Signals

A radio wave traversing the upper and lower atmosphere of the Earth suffers a distortion of phase and amplitude. When it traverses ionospheric irregularities, the radio wave experiences fading, phase deviations, and angle of arrival. These signal fluctuations, known as ionospheric scintillation, vary widely with frequency, magnetic and solar activity, time of day, season, and latitude.

The irregularities producing scintillations are predominantly located in the F layer at altitudes ranging from 200 to 1000 km with the primary disturbance region for high and equatorial latitude irregularities between 250 and 400 km. There are times when E layer irregularities in the 90 to 100 km region produce scintillation, particularly in the sporadic E and auroral E layers.

The amplitude, phase and angle of arrival of a signal will fluctuate during periods of scintillation. The intensity of the scintillation is characterized by the variance in received power with the S4 index commonly used for intensity scintillation and defined as the square root of the variance of received power divided by the mean value of the received power that is:

$$S_4^2 = \frac{<I^2> - <I>^2}{<I>^2}$$

(3.18)

Ionospheric scintillation affects trans-ionospheric radio signals up to a few GHz in frequency and as such can have impacts on satellite-based communication and navigation systems (such as GNSS-based systems) and also on scientific instruments requiring observations of trans-ionospheric radio signals (e.g. radio-astronomy). Phase scintillation, if sufficiently severe, may stress phase-lock loops in GNSS receivers resulting in a loss of phase lock.

There are two defined regimes of amplitude scintillation: weak and strong, which roughly correspond to the type of scattering associated with each. Strong scintillation is generally considered to occur when $S_4$ is greater than 0.6 and is associated with strong scattering of the signal in the ionosphere. Below this is weak scintillation. An $S_4$ level below 0.3 is unlikely to have a significant impact on GNSS.
Bibliography


[19] World Data Center for Geomagnetism, Kyoto http://wdc.kugi.kyoto-u.ac.jp. 49

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Comparison of EGNOS and Global Maps at range delay

4.1 Temporal and Latitudinal Analysis

The first part of the work deals with the study of the grid maps, such as those obtained with EGNOS, and its comparison with Global Maps of Total Electron Content (TEC) obtained from CODE, University of Bern, in terms of vertical TEC in the area between [40° W, 40° E] in longitude and [20° N, 60° N] in latitude.

The Global Maps files are distributed on a daily basis in a particular format called IONEX (IONosphere map EXchange), giving a value for the Vertical Total Electron Content (VTEC) every two hours (0, 2, 4, ..., 24 UTC) at the grid points. The resolution of the maps is 5° in longitude and 2.5° in latitude. The Center for Orbit Determination in Europe (CODE) employs spherical harmonics functions to model the global Vertical TEC using about 200 worldwide GPS/GLONASS stations.

EGNOS data have been download from EGNOS Message Server (EMS) archive and decoded every ten minutes.

EGNOS and CODE (linearly interpolated from the two hourly CODE maps) comparison have been performed for maps with an ionospheric grid of 5° in longitude and 5° in latitude and created with a temporal interval of ten minutes.

The objective of this part of the study is to evaluate on a quantitative level EGNOS data difference comparing its vertical Total Electron Content with TEC Global Maps obtained from CODE in each selected grid points.

This procedure is done in order to check how well the Global Maps could reproduce the regional conditions described by EGNOS grid vertical TEC, particularly in terms of TEC space gradients (both in longitude and in latitude) in the Southern regions of the ECAC region, which can be considered already under the influence of the Ionospheric Equatorial Anomaly.

The analysis is performed for the years 2012 and 2013 (characterized by relatively high solar activity), for both quiet and disturbed ionospheric conditions. Months se-
lected are January, April, July, November for the year 2012; January, March, June, November for the year 2013. They have been chosen as representative months of all the seasons.

For every month, days characterised by the presence of geomagnetic storm, have been also selected, using the Disturbance Storm Time (Dst) index. Dst is the axially symmetric disturbance magnetic field at the dipole equator on the Earth’s surface. These field’s decreases are produced mainly by the equatorial current system in the magnetosphere, usually referred to as the ring current. (see Chapter 3)

In the first part of this Chapter 4, EGNOS and CODE grid maps have been used for the comparison at range delay. In Chapter 5 they have been used for the position domain analysis.

In the second part of this Chapter, other two different kinds of grid maps have been created and used only for the position domain analysis (Chapter 5). They are obtained:

- replacing EGNOS - not available data grid with CODE data grid;
- smoothing EGNOS data with CODE data.

In the following list, quiet and disturbed days have been displayed. For the analysis, the most disturbed and quiet day of this list (both taken in the same month) have been analysed.

Only for June 2013, because of its continuous disturbed condition, three days characterised by the presence of geomagnetic storm have been shown. (3)

For the **Year 2012**:

- January - quiet day 15\textsuperscript{th} - disturbed day 23\textsuperscript{rd}
- April - quiet day 16\textsuperscript{th} - disturbed day 24\textsuperscript{th}
- July - quiet day 14\textsuperscript{th} - disturbed day 16\textsuperscript{th}
- November - quiet day 9\textsuperscript{th} - disturbed day 13\textsuperscript{th}

For the **Year 2013**:

- January - quiet day 14\textsuperscript{th} - disturbed day 18\textsuperscript{rd}
- April - quiet day 11\textsuperscript{th} - disturbed day 17\textsuperscript{rd}
- June - disturbed day 1\textsuperscript{st}, 7\textsuperscript{th}, 29\textsuperscript{th}
- November - quiet day 7\textsuperscript{th} - disturbed day 9\textsuperscript{rd}
4.1 Temporal and Latitudinal Analysis

Figure 4.1: Example of the Temporal Variability Analysis (15th January 2012) - on the x-axis the time (UT), and on the y-axis the TEC units.

Figure 4.2: Example of the Latitudinal Spatial Variability Analysis (15th January 2012). The first row represents the latitude 60°, 55°, 50°, the second row the latitude 45°, 40°, 35°, the third row the latitude 30°, 25°, 20°. In all the nine graphics longitude between [40° W, 40° E] every 5° for all the latitude considered have been analysed.

In particular two different kind of analysis have been performed for all the days selected:

1. **Temporal Variability Analysis (TVA):** difference between EGNOS and GIM-
CODE for all the IGPs in the selected area every 10 minutes. This means that every point in the graphics is the average value with its standard deviation of the difference between EGNOS and GIM-CODE of all the IGPs in the selected area in an interval of ten minutes (on the x-axis the time (UT), and on the y-axis the TEC units).

2. **Latitudinal Spatial Variability Analysis (LSVA):** study of the difference between EGNOS and CODE for 24 hours (all the day) for every latitude in the selected area [20° N, 60° N] in latitude and [40°W, 40° E] in longitude.

For the LSVA graphics all the latitudes are present from 60° N to 20° N for all the longitude analysed from 40° W to 40° E, every 5°. In order for every case (see figure 4.2):

- first raw, first graphic - latitude 60° - longitude [40° W, 40° E], every 5°;
- first raw, second graphic - latitude 55° - longitude [40° W, 40° E], every 5°;
- first raw, third graphic - latitude 50° - longitude [40° W, 40° E], every 5°;
- second raw, first graphic - latitude 45° - longitude [40° W, 40° E], every 5°;
- second raw, second graphic - latitude 40° - longitude [40° W, 40° E], every 5°;
- second raw, third graphic - latitude 35° - longitude [40° W, 40° E], every 5°;
- third raw, first graphic - latitude 30° - longitude [40° W, 40° E], every 5°;
- third raw, second graphic - latitude 25° - longitude [40° W, 40° E], every 5°;
- third raw, third graphic - latitude 20° - longitude [40° W, 40° E], every 5°;

In the following section for the months selected a quiet and a disturbed day have been analysed and results have been displayed. As already explained the Dst (Disturbance Storm Time) has been used as the reference parameter for the selection of the day characterised by storm. Major disturbances in Dst are negative, namely decreases in the interplanetary geomagnetic field. (3)

For all the days analysed, also other geomagnetic parameters and indicators have been reported like the Solar Wind, the Sunspot Number, the Kp index and the magnetic field value Bz, in order to have a complete view of the disturbed conditions.
4.2 Year 2012

4.2.1 January

On 19\textsuperscript{th} of January a solar flare has been observed in an active region surrounding a high-latitude sunspot. At about the same time, a Coronal Mass Ejection (CME), a concentrated blast of electrically-conducting solar-wind plasma and tangled magnetic-field lines, has been observed, estimated to be headed for Earth (U.S. Geological Survey data). The Coronal Mass Ejection (CME) arrived to Earth on 22\textsuperscript{nd} of January at 06:14 UT. This caused a positive initial phase geomagnetic disturbance, which has been registered by low-latitude USGS magnetic observatories and as recorded by the 4-station USGS storm-time disturbance index Dst. This initial phase is the signature of compression of the Earth’s magnetosphere by the pressure of the solar wind. The solar wind suffers, during the main phase, an enhancement of about 120 km/s respect to the previous day, reaching about 451 km/s, from a background of 323 km/s.

The Kp value evidences the presence of the storm on 22\textsuperscript{nd} of January, reaching a value of 5 during the main phase of the disturbance, classified as minor storm, level G1.
4.2 Year 2012

The direction of the magnetic field in the z-component is toward the South, reaching a value of 6.2 nT. In the following graphics, the temporal and spatial variability of the difference of the ionospheric grid points between EGNOS and GIM-CODE have been displayed.

The Temporal Variability Analysis (see figure 4.5 and 4.6) shows that during the main phase there is an increase in the difference between GIM-CODE and EGNOS during the 12:00 UT and a decrease of the average values.

Concerning the latitudinal variation analysis, for both quiet and disturbed cases, the mean value for all the latitude is around zero. But during the storm, the standard deviation at low latitude (see latitude 20° of figure 4.8) increases of 5 TECu. It is evident the presence of Not Monitored IGPs at low latitude, here for 25° and 20°. For the analysis a quiet (15th of January) and disturbed (23rd of January) days have been chosen. In this case 15th of January has been used as quiet reference day, characterised by a minimum value in Dst of 2 nT. It is possible to see the "Not Monitored" status of EGNOS data.

Figure 4.5: TVA: Quiet day - 15th January 2012

Figure 4.6: TVA: Disturbed day - 23rd January 2012
4.2 Year 2012

Figure 4.7: LSVA: Quiet day - 15th January 2012

Figure 4.8: LSVA: Disturbed day - 23rd January 2012
4.2 Year 2012

4.2.2 April

Figure 4.9: Dst - April 2012

Figure 4.10: Solar wind, Sunspot Numbers, Kp index and magnetic field value Bz of January 2012, days 22, 23, 24, 25, 26

April 2012 is characterised by a geomagnetic storm which is evident in days 24th and 25th of this month. The Dst in the main phase of the storm, on 24th of April reaches -108 nT.

The solar wind suffers an enhancement of about 110 km/s from 23rd to 24th and also between the two disturbed days there is an increase of about 160 km/s.

The sunspot number suffers an intense enhancement starting from 118 and reaching a value of 169. The Kp value evidences the presence of the storm reaching a value of 6 during the main phase of the disturbance which can be classified as moderate storm, level G2.

The z-component of the Magnetic Field, as expected, is directed toward in the South direction.

This geomagnetic storm is characterised by different phases. Between 23rd and 24th (main phase) storm presents a positive phase which is followed by a negative one during the 24th until the midday local time of day 25th. Then a positive phase (but less intense) immediately followed by a negative one characterised the day 26th. (NOAA)

In the following graphics, the temporal and spatial variability of the difference of the ionospheric grid points between EGNOS and GIM - CODE have been displayed.

The Temporal Variability Analysis (see figure 4.11 and 4.12) shows that during the main phase there is an increase in the difference between GIM - CODE and EGNOS especially in the last part of the day. The enhancement can reach in some cases 5 -
6 TECu in standard deviation over all the IGPs for the temporal analysis, while the average values oscillate around 2 TECu.

Concerning the latitudinal variation analysis for quiet day taken as reference (16th of April), it is possible to see that the mean value for all the latitude is around zero although at low latitude (30°, 25°, 20°) higher values can reach 5 TECu. During the disturbed day (24th of April), the mean values for the different longitudes at a same latitude are not around zero but can vary between 5 TECu and -5 TECu. Concerning the standard deviation at latitude 20°, it could reach 10 TECu. It is also evident the presence of Not Monitored IGPs at low latitude, here especially for 20°.

![Figure 4.11: TVA: Quiet day - 16th april 2012](image1)

![Figure 4.12: TVA: Disturbed day - 24th april 2012](image2)
4.2 Year 2012

Figure 4.13: LSVA: Quiet day - 16th April 2012

Figure 4.14: LSVA: Disturbed day - 24th April 2012
4.2 Year 2012

4.2.3 July

July 2012 is characterised by a geomagnetic storm which is evident in days 15\textsuperscript{th} and 16\textsuperscript{th} of this month. The Dst in the main phase of the storm, on 15\textsuperscript{th} of April reaches -127 nT. The solar wind suffers an enhancement reaching about 500 km/s. While the Sunspot Number increase until a value of 134. The Kp value evidences the presence of the storm reaching a value of 6 (moderate storm, level G2) for both the days 15\textsuperscript{th} and 16\textsuperscript{th} and decreasing to a value of 2 in the days following the storm. The z - component of the Magnetic Field, as expected, is directed toward in the South direction for all the disturbed days, for a maximum of 14 nT. As the previous one, also this geomagnetic storm is characterised by different phases. At the beginning of the storm, a positive phase characterised the disturbed condition between the 14\textsuperscript{th} and 15\textsuperscript{th}. While two negative phases characterised the recovery session of the storm.

In the following graphics, the temporal and spatial variability of the difference of the ionospheric grid points between EGNOS and GIM - CODE have been displayed. The Temporal Variability Analysis (see figure 4.17 and 4.18) shows that during the main phase there is not a strong increase in the difference between GIM - CODE and EGNOS. The enhancement can reach in some cases 2 - 3 TECu in standard deviation over all the IGPs for the temporal analysis.

<table>
<thead>
<tr>
<th>July, 2012</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>18</th>
<th>19</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar wind (Km/s)</td>
<td>307.4</td>
<td>Not available</td>
<td>439.2</td>
<td>419.2</td>
<td>387.8</td>
</tr>
<tr>
<td>Sunspot n\textsuperscript{2}</td>
<td>120</td>
<td>134</td>
<td>89</td>
<td>87</td>
<td>59</td>
</tr>
<tr>
<td>Kp</td>
<td>6</td>
<td>6</td>
<td>4</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Bz (nT)</td>
<td>14.0 S</td>
<td>4.2 S</td>
<td>1.5 S</td>
<td>2.3 N</td>
<td>2.2 S</td>
</tr>
</tbody>
</table>

Figure 4.15: Dst - July 2012

Figure 4.16: Solar wind, Sunspot Numbers, Kp index and magnetic field value Bz of January 2012, days 15, 16, 17, 18, 19
Concerning the latitudinal variation analysis for quiet day taken as reference (14\textsuperscript{th} of July), it is possible to see that the average values for all the latitude is around zero also at low latitude. (see figure 4.19 and 4.20)

During the disturbed day (16\textsuperscript{th} of April), the mean values for the different longitudes at a same latitude are around zero, except for the latitude 20\textdegree, in which it decrease at around -7 TECu. Also the standard deviation increases at 5 TECu value.

It is also evident the presence of Not Monitored IGPs at low latitude, here especially for 20\textdegree.

![Figure 4.17: TVA: Quiet day - 14\textsuperscript{th} July 2012](image1)

![Figure 4.18: TVA: Disturbed day - 16\textsuperscript{th} July 2012](image2)
Figure 4.19: LSVA: Quiet day - 14\textsuperscript{th} July 2012

Figure 4.20: LSVA: Disturbed day - 16\textsuperscript{th} July 2012
4.2 Year 2012

4.2.4 November

November 2012 is characterised by a geomagnetic storm during days 13th and 14th of the month. The main phase of this storm has a minimum in Dst of -108 nT on 14th of November. The storm development is simple, with a single main phase depression. The solar wind increases of about 80 km/s from 13th to 14th. The sunspot number is quite variable during this storm, showing a maximum value of 188 during the 13th.

The Kp value evidences the presence of the storm characterizing days 13th and 14th with a value of 4 and 6 (moderate storm, level G2) respectively. Considering the Kp parameter it is possible to see the sudden commencement of this disturbed period; days before and after the storm are characterised by Kp values of 2. The z - component of the Magnetic Field is directed toward the South direction on the 13th of November with a value of 5 nT.

In the following graphics, the temporal and spatial variability of the difference of the ionospheric grid points between EGNOS and GIM - CODE have been displayed. The Temporal Variability Analysis (see figure 4.23 and 4.24) shows that during the main phase there is an increase in the difference between GIM - CODE and EGNOS especially in the last part of the day. The enhancement can reach in some cases 2 - 4 TECu in standard deviation over all the IGPs for the temporal analysis, while the average values are around 1 TECu.

Concerning the latitudinal variation analysis for quiet day taken as reference (9th of November), it is possible to see that the standard deviation for all the latitude is around zero although at latitude 20° there is an increase of about 5 TECu. It is important...
also to notice that the mean value suffers a slow increase of TEC for latitude 30° and 25° starting from longitude 30° W (0 TECu) to 35° E (5 TECu).

During the disturbed day (13th of November), the mean values can vary strongly between 5 TECu and -5 TECu. Concerning the standard deviation at latitude 20°, it could reach 10 TECu.

As in the previous cases, it is also evident the presence of Not Monitored IGPs at low latitude, here for 25° and 20° in latitude.

Figure 4.23: TVA: Quiet day - 9th November 2012

Figure 4.24: TVA: Disturbed day - 13th November 2012
Figure 4.25: LSVA: Quiet day - 9th November 2012

Figure 4.26: LSVA: Disturbed day - 13th November 2012
4.3 The year 2013

4.3.1 January

January 2013 is characterised by a very weak disturbed conditions during days 18th and 19th of this month. The Dst in the main phase of the storm, on 18th of January reaches -55 nT. The solar wind suffers an enhancement of about 50 km/s on 18th of January. Also the sunspot number shows a high number (120) the day before the storm, decreasing until 62 on the disturbed day. The Kp value has a value of 4 on the main phase of the storm, evidencing the presence of the very weak storm.

The z - component of the Magnetic Field B is directed toward in the South direction not only in the day characterised by the storm but also in the following days reported in the table.

In the following graphics, the temporal and spatial variability of the difference of the ionospheric grid points between EGNOS and GIM - CODE have been displayed.

Concerning the latitudinal variation analysis for quiet day taken as reference (14th of January), it is possible to see that the mean value for all the latitude is around zero although at low latitude (30°, 25°, 20°). During the disturbed day (18th of January), the mean values for the different longitudes at a same latitude are around zero except for latitude 20°. Concerning the standard deviation at latitude 20°, it could reach 7 TECu.
4.3 The year 2013

Also in this case it is evident the presence of Not Monitored IGPs at low latitude, here especially for 20°.

Figure 4.29: TVA: Quiet day - 14th January 2013

Figure 4.30: TVA: Disturbed day - 18th January 2013
4.3 The year 2013

Figure 4.31: LSVA: Quiet day - 14\textsuperscript{th} January 2013

Figure 4.32: LSVA: Disturbed day - 18\textsuperscript{th} January 2013
4.3 The year 2013

4.3.2 March

Figure 4.33: Dst - March 2013

<table>
<thead>
<tr>
<th>March, 2013</th>
<th>16</th>
<th>17</th>
<th>18</th>
<th>19</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar wind (Km/s)</td>
<td>410.6</td>
<td>625.8</td>
<td>478.4</td>
<td>461.6</td>
<td>471.8</td>
</tr>
<tr>
<td>Sunspot n°</td>
<td>105</td>
<td>90</td>
<td>126</td>
<td>116</td>
<td>68</td>
</tr>
<tr>
<td>Kp</td>
<td>3</td>
<td>6</td>
<td>3</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Bz (nT)</td>
<td>0.3 S</td>
<td>0.4 N</td>
<td>3.4 N</td>
<td>1.6 S</td>
<td>3.6 S</td>
</tr>
</tbody>
</table>

Figure 4.34: Solar wind, Sunspot Numbers, Kp index and magnetic field value Bz of January 2012, days 16, 17, 18, 19, 20

March 2012 is characterised by a long duration of solar flare erupting on 15th which launches a full halo Coronal Mass Ejection (CME) toward Earth. It hits Earth’s magnetic field at 06:01 UTC on the 17th of March and Geomagnetic Kp assumes a value of 6 on the same disturbed day, classifying the storm as G2 level, moderate storm. The impact is quite strong, lifting the solar wind speed from 300 km/s to greater than 620 km/s.

In the following graphics, the temporal and spatial variability of the difference of the ionospheric grid points between EGNOS and GIM - CODE have been displayed. The Temporal Variability Analysis (see figure 4.35 and 4.36) shows that there is an increase during the disturbed day. The average values suffer an increase from 2 TECu to 4 TECu. The standard deviations increase of 3 - 4 TECu during the main phase.

Concerning the latitudinal variation analysis for quiet day taken as reference (11th of March), it is possible to see that the mean value for all the latitude is around zero although at low latitude (30°, 25°, 20°) higher values can reach 5 TECu. During the disturbed day (17th of March), the mean values for the different longitudes at a same latitude are not around zero but can vary between 5 TECu and -5 TECu. Concerning the standard deviation at latitude 20°, it could reach about 7 TECu. It is evident the presence of Not Monitored IGPs at low latitude, here especially for 20°.
4.3 The year 2013

**Figure 4.35:** TVA: Quiet day - 11\textsuperscript{th} March 2013

**Figure 4.36:** TVA: Disturbed day - 17\textsuperscript{th} March 2013
4.3 The year 2013

Figure 4.37: LSVA: Quiet day - 11\textsuperscript{th} March 2013

Figure 4.38: LSVA: Disturbed day - 17\textsuperscript{th} March 2013
4.3 The year 2013

4.3.3 June

Figure 4.39: Dst - June 2013

June 2013 is characterised by intense and various geomagnetic storms activities which are evident in days 1\textsuperscript{st}, 7\textsuperscript{th} and 29\textsuperscript{th} of this month.

The arrival of an interplanetary shock wave on 31\textsuperscript{st} of May (at approximately 16:00 UT) causes geomagnetic storm which reaches G2 moderate geomagnetic storm level during the 1\textsuperscript{st} of June. The main phase of this storm has a minimum Dst of -120 nT (classified as intense). The solar wind speed, starting from 400 km/s, can reach 650 km/s and it remains elevated above 500 km/s for the following three days after the storm.

NOAA reports that the source of the shock is probably due to a disappearing filament or it is caused by corotating interaction region (CIR) or a shock-like transition zone between high and low speed solar wind streams. As Earth passes through a new coronal hole high speed stream, backed by unidentified Coronal Mass Ejection shock, a prolonged interval of south-pointing magnetism (southward Bz) is having a strong impact on Earth’s geomagnetic field. (6)

On 1\textsuperscript{st} and on 7\textsuperscript{th} of June Kp reaches a value of 6 for both days, classified as moderate storm, level G2. On 29\textsuperscript{th} of June, Planetary K-index reaches Kp value of 7.
which can be considered by NOAA classification as a strong geomagnetic storm, level G3.

In the following graphics, the three disturbed days have been reported in order to show the variability of the average values which can oscillate around 4 TECu for 1\textsuperscript{st} June, around 3 TECu for 7\textsuperscript{th} June and of around 1 TECu for 29\textsuperscript{th} of June.

**Figure 4.41:** TVA: Disturbed day - 1\textsuperscript{st} June 2013

**Figure 4.42:** TVA: Disturbed day - 7\textsuperscript{th} June 2013
4.3 The year 2013

Figure 4.43: TVA: Disturbed day - 29th June 2013

Figure 4.44: LSVA: Disturbed day - 1st June 2013
4.3 The year 2013

Figure 4.45: LSVA: Disturbed day - 7th June 2013

Figure 4.46: LSVA: Disturbed day - 29th June 2013
4.3 The year 2013

4.3.4 November

November 2013 is characterised by a very weak geomagnetic storm on 9th of this month.

The Dst in the main phase of the storm reaches -81 nT.

A gusty stream of solar wind is disturbing Earth’s magnetic field and it shows an enhancement reaching about 580 km/s. The Sunspot Number increase to a value of 160, changing to 90 for the day after the storm.

The Kp value with a value of 4, evidences the presence of the very weak storm not only on the 9th but also on the 11th.

The Z-component of the Magnetic Field is directed toward the South direction for all the disturbed days and also for the following days.

In the following graphics, the temporal and spatial variability of the difference of the ionospheric grid points between EGNOS and GIM - CODE have been displayed.

The Temporal Variability Analysis (see figure 4.39 and 4.50) shows that both the quiet (7th) and the storm days have comparable results for the mean values and the standard deviations (maximum of 2.5 TECu)

Concerning the latitudinal variation analysis for quiet day taken as reference (7th of November), it is possible to see that the mean value for all the latitude is around zero also at low latitude.

During the disturbed day (9th of November), the mean values for the different longitudes at a same latitude are around zero, except fo the latitude 25°, which shows an oscillating behaviour with mean values around 5 TECu and -5 TECu. Also the
standard deviation increases of 10 TECu.

As in the previous case it is evident the presence of Not Monitored IGPs of EGNOS at low latitude, here especially for 20°.

**Figure 4.49:** TVA: Quiet day - 7th November 2013

**Figure 4.50:** TVA: Disturbed day - 9th November 2013
4.3 The year 2013

Figure 4.51: LSVA: Quiet day - 7th November 2013

Figure 4.52: LSVA: Quiet day - 9th November 2013
4.4 Ionospheric Grid Maps of Vertical Total Electron Content

After analysing the difference between EGNOS and CODE in terms of temporal and latitudinal variation, different Ionospheric Grid Maps of Vertical TEC have been created.

In addition to the EGNOS and CODE maps obtained with a time interval of ten minutes over the selected area, other two different kinds of maps with this same time interval and over the same area have been created:

- replacing EGNOS data (not available) with CODE data, especially in the Southern part of the ECAC region;
- smoothing EGNOS data with CODE data.

The first case is based on the replacement of EGNOS not available data ("Not Monitored") with CODE data, in IGPs positioned every 5° in the selected area in longitude and in latitude.

The second case deals with the smoothing of EGNOS data with CODE data. The objective is, as before, the extension of the availability of EGNOS grid maps in case of "Not Monitored" IGPs condition. This method takes advantage from the previous analysis: differences between EGNOS and CODE grid maps from the different IGPs have been used. The starting point to understand this method is considering structure of figure 4.53.

In this table every value is derived by the difference between EGNOS and CODE grid maps. It is possible to see the temporal variation (∆TEC, ten minutes interval) for every IGP in the selected area (total of 153 IGPs) in terms of TECu.

The procedure consists in finding the average value for all the 24 hours of the day of these ∆TEC for every IGP. This means that for the first raw corresponding to the IGP1, one average value have been computed with all the values assumed by this IGP1 during the day every ten minutes.

This operation has been done for all the 153 IGPs. In total 153 averaged values have been obtained.

At this point a spatial division in latitude (with a step of 5°) has been performed, considering two different region:

- the middle latitude between [60°, 40°] for a total IGPs equal to 85,
- the low - middle latitude between [35°, 20°] for a total IGPs equal to 68.
4.4 Ionospheric Grid Maps of Vertical Total Electron Content

The idea is based on the research of a factor $f$, by which constructing a new syntetic grid map able to compare EGNOS and CODE grid maps.

This factor is related to EGNOS and CODE grid maps and also to their differences.

For the IGPs selected in the middle latitude between $[60^\circ, 40^\circ]$, a new average value of the previous average values (85 IGPs) have been obtained, called $<CE_{ml}>$.

The same operation has been done for the low - middle latitude between $[35^\circ, 20^\circ]$. The average value of 68 IGPs have been obtained, called $CE_{ml}$.

The relation to compare the EGNOS and CODE grid map and to obtain the $f$ factor

---

Figure 4.53: Ionospheric grip maps of Vertical TEC - interval 10 minutes - 153 IGPs

<table>
<thead>
<tr>
<th>corr. IGP</th>
<th>TIME (h)</th>
<th>0</th>
<th>600</th>
<th>1200</th>
<th>1800</th>
<th>2400</th>
<th>3000</th>
<th>...</th>
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<tr>
<td>60N04W</td>
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</tr>
</tbody>
</table>

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88
4.4 Ionospheric Grid Maps of Vertical Total Electron Content

is:

\[ f \approx \frac{(E - C)}{<CE_i>} \]  \hspace{1cm} (4.1)

where \( E \) is the EGNOS grid map, \( C \) is the CODE grid map, \( <CE> \) is the \( <CE_{ml}> \) or \( <CE_{ml}> \) for the related latitude division.

This formula means that every element of the previous grid (see figure 4.53) is divided by the respective \( <CE_i> \).

In this way a new respective grid of different factors have been obtained, with the same dimension in terms of element of the matrix/map.

The idea of this procedure is to find only a value of this factor. For all the IGP related to a particular interval, the median of the different values of \( f \) has been obtained. Then this new value, called \( F \) has been applied using the same formula expressed before but using it at reverse.

\[ C + <CE_i> \ast F \approx E' \] \hspace{1cm} (4.2)

where \( E' \) is the new synthetic smoothed grid map.

This method has some limitations:

- The spatial division in latitude is arbitrary. For a coherent scope this division has been chosen fixed at 40°, although it is clear that depends strongly on the ionospheric condition, and also on the different moment of the day.

- If a value of the EGNOS grid map is not available in every moment of the day, the IGP is available for this analysis. It is important to remember that this method starts from the difference between EGNOS and CODE grid maps. And the not availability of the value in the difference means the not availability of the EGNOS IGP.
4.4 Ionospheric Grid Maps of Vertical Total Electron Content

4.4.1 Example for a quiet day

In this section four different graphics have been reported. They are referred to the same day (20th July 2012) classified as quiet ($Dst \approx zero$), at the same UT time (42600 seconds) for the different grid maps used for the positioning analysis (see Chapter 5). In order they are:

- CODE grid map
- EGNOS grid map
- replacement of EGNOS data with CODE data
- EGNOS data smoothed with CODE data

For a day, four different method have been adopted.

For every method 145 grid maps have been obtained every ten minutes interval in order to cover all the day (86400 s).

\hspace{1cm} Figure 4.54: Ionospheric grip maps of Vertical TEC for Global Map CODE - QUIET DAY - 20th July 2012
4.4 Ionospheric Grid Maps of Vertical Total Electron Content

Figure 4.55: Ionospheric grip maps of Vertical TEC for EGNOS - QUIET DAY - 20th July 2012

Figure 4.56: Ionospheric grip maps of Vertical TEC for EGNOS data not available replaced with CODE data - QUIET DAY - 20th July 2012
4.4 Ionospheric Grid Maps of Vertical Total Electron Content

Figure 4.57: Ionospheric grip maps of Vertical TEC for smoothing EGNOS data with CODE data - QUIET DAY - 20th July 2012

4.4.2 Example for a disturbed day

As in the previous section, four different graphics have been reported. They are referred to the same day (13th November 2012) classified as disturbed ($Dst \approx -100$), at the same UT time (42600 seconds) for the different grid maps used for the positioning analysis (see Chapter 5). In order they are:

- CODE grid map
- EGNOS grid map
- replacement of EGNOS data with CODE data
- EGNOS data smoothed with CODE data
4.4 Ionospheric Grid Maps of Vertical Total Electron Content

**Figure 4.58:** Ionospheric grid maps of Vertical TEC for Global Map CODE - DISTURBED DAY - 13\(^{th}\) November 2012

**Figure 4.59:** Ionospheric grid maps of Vertical TEC for EGNOS - DISTURBED DAY - 13\(^{th}\) November 2012
4.4 Ionospheric Grid Maps of Vertical Total Electron Content

Figure 4.60: Ionospheric grip maps of Vertical TEC for EGNOS data not available replaced with CODE data - DISTURBED DAY - 13\textsuperscript{th} November 2012

Figure 4.61: Ionospheric grip maps of Vertical TEC for smoothing EGNOS data with CODE data - DISTURBED DAY - 13\textsuperscript{th} November 2012
Bibliography


5

Comparison of EGNOS and Global Maps at position domain

5.1 Ionospheric grid maps and bilinear interpolation

The ionospheric corrections applied to GNSS range measurements depend on the satellite-receiver signal path.

In order to estimate the ionospheric error for each of these lines of sight, the receiver must identify the Ionospheric Pierce Point (IPP). Each IPP (see figure 5.1) is defined as the intersection between the atmospheric layer located at an altitude of 350 km and the line between the receiver and the satellite. (3)

The receiver knows the location of these particular points and with a bilinear interpolation algorithm it is possible to define the ionospheric delay for each of these IPPs. (2)

Figure 5.1: Ionospheric Pierce point

The aim of this second part is to correct the pseudoranges of some selected reference stations with different ionospheric content computed from the ionospheric grid maps
obtained in the previous Chapter 4.

Using the TEC calibration technique (1), the coordinates of the IPPs are computed for the reference stations.

Using the bilinear interpolation algorithm the different ionospheric content (in terms of vertical TEC unit) have been obtained for the different IPP.

This is done considering the values of IGPs grid of EGNOS grid maps, CODE grid maps, a synthetic grid obtained replacing CODE data when EGNOS data are missing, and the smoothed grid maps of EGNOS.

After determining the location of the IPPs, the user must select the IGPs to be used to interpolate the ionospheric correction value and its corresponding error bound.

This selection is done, based only on the information provided in the mask, and it must be evaluated without regarding to whether or not the selected IGP are monitored, not monitored or a do not use event is issued.

Once the nodes of an interpolation cell of the IGPs grid that surround the IPPs to a satellite have been determined, the equipment must interpolate from those nodes to the pierce point using the following algorithm.

For the four-point interpolation algorithm, the mathematical formulation for the interpolated vertical IPP delay as a function of the IPP latitude and longitude is given by:

\[ \tau_{vpp}(\phi_{pp}, \lambda_{pp}) = \sum_{i=1}^{4} W_i(x_{pp}, y_{pp}) \tau_{vi} \]  

(5.1)

where \( \tau_{vpp} \) is the vertical ionospheric delay at pierce point, \( \tau_{vi} \) is the vertical ionospheric delay at grid points, and \( W_i \) is the weighting function.

In particular \( \tau_{vpp} \) is the output value at desired pierce point \( pp \), whose geographical coordinates are \( (\phi_{pp}, \lambda_{pp}) \):

\[ W_1 = x_{pp}y_{pp} \]  

(5.2)

\[ W_2 = (1 - x_{pp})y_{pp} \]  

(5.3)

\[ W_3 = (1 - x_{pp})(1 - y_{pp}) \]  

(5.4)

\[ W_4 = x_{pp}(1 - y_{pp}) \]  

(5.5)

To convert the vertical delay into a slant delay along the path receiver - satellite, an obliquity factor (OF) is needed:

\[ OF = [1 - \left( \frac{R_E \cos(Ei)}{R_E + h_{\text{Iono}}} \right)^2]^{-\frac{1}{2}} \tau_{vpp} \]  

(5.6)
5.1 Ionospheric grid maps and bilinear interpolation

Considering the thin shell approximation, OF is a simple function which depends on the satellite elevation angle only.

This is the method to obtain the different slant delays (in meters) in the different IPPs for the selected reference stations.

Pseudoranges of the reference stations are corrected with these ionospheric contributions. The corrections have been applied in the RINEX files of the reference stations both for code and phase observables.

It is important for the calculus to remind that phase measurements suffer advancement when crossing the ionosphere which is translated in a negative delay while the code measurements suffer a positive delay.

Reference Stations

Reference stations (see figure 5.2 and 5.3) have been selected in the Southern part of the area between [40° W, 40° E] in longitude and [20° N, 60° N] in latitude. They belong to the International GNSS Service global (IGS) system of satellite tracking stations which collects, archives, and distributes GNSS observation data sets. (5)

The reason of this choice is related to the high variability of the Ionosphere at this latitudes, which is under the influence of the Equatorial Anomaly.

<table>
<thead>
<tr>
<th>Station</th>
<th>Longitude (E)</th>
<th>Latitude (N)</th>
<th>Height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matera (Italy)</td>
<td>16.704</td>
<td>40.649</td>
<td>531,500</td>
</tr>
<tr>
<td>Cagliari (Italy)</td>
<td>8.972</td>
<td>39.135</td>
<td>238,400</td>
</tr>
<tr>
<td>Noto (Italy)</td>
<td>14.989</td>
<td>36.876</td>
<td>126,200</td>
</tr>
<tr>
<td>San Fernando (Spain)</td>
<td>-0.205</td>
<td>36.464</td>
<td>85,800</td>
</tr>
<tr>
<td>Rabat (Morocco)</td>
<td>-8.885</td>
<td>33.998</td>
<td>90,100</td>
</tr>
</tbody>
</table>

Figure 5.2: Reference stations - Matera (MATE), Cagliari (CAGL), Noto (NOT1), San Fernando (SFER), Rabat (RABT) (5)

Figure 5.3: Reference stations - Matera (MATE), Cagliari (CAGL), Noto (NOT1), San Fernando (SFER), Rabat (RABT) - IGS Network (5)
5.2 Position Domain Analysis

In this section results of the different positioning solutions have been reported, in particular in this Chapter November 2012 will be shown.

All the other results can be found in the Appendix A.

For this representative month, a quiet and disturbed day have been selected (same days of the previous analysis in Chapter 4).

For every day five stations have been considered and for every stations six positioning solution have been analysed:

- experimental data without ionospheric correction (disabled in the software/receiver)
- Klobuchar model positioning solution
- bilinear interpolation with CODE maps
- bilinear interpolation with EGNOS maps
- bilinear interpolation with maps obtained replacing EGNOS not available grid data with CODE grid data
- bilinear interpolation with syntetic maps obtained smoothing EGNOS grid map with CODE grid map

Rnex deriving from station experimental data and RINEX modified with the different ionospheric contribution have been processed with gLAB software, provided by gAGE group, University of Barcelona. For all the results a North, East, Up positioning solutions have been obtained.

In the following sections the absolute frequencies histogram of the North, East, Up Errors have been reported to better understand the accuracy of the different solutions proposed for this work thesis.

Before looking at the different obtained results, the service performance map provided by the EGNOS User Support (ESSP) have been shown to check the availability of the system in the two analysed days. (ECLAYR software is used to obtain these maps).
5.2 Position Domain Analysis

Figure 5.4: APV-1 Availability - System Performance - 9th November 2012 - quiet

Figure 5.5: APV-1 Availability - System Performance - 13th November 2012 - storm
5.2 Position Domain Analysis

5.2.1 November 2012 - 9th November (quiet)

5.2.1.1 Station - Matera (MATE)

Figure 5.6: Experimental data without ionospheric correction - 9th November 2012

Figure 5.7: Klobuchar model positioning solution - 9th November 2012
5.2 Position Domain Analysis

**Figure 5.8:** Bilinear interpolation with CODE maps positioning solution - 9th November 2012

**Figure 5.9:** Bilinear interpolation with EGNOS maps positioning solution - 9th November 2012
5.2 Position Domain Analysis

Figure 5.10: Positioning solution obtained replacing EGNOS not available grid data with CODE grid data - 9\textsuperscript{th} November 2012

Figure 5.11: Positioning solution obtained smoothing EGNOS grid map with CODE grid map - 9\textsuperscript{th} November 2012
5.2.1.2 Station - Cagliari (CAGL)

**Figure 5.12:** Experimental data without ionospheric correction - 9th November 2012

**Figure 5.13:** Klobuchar model positioning solution - 9th November 2012

smoothing
5.2 Position Domain Analysis

Figure 5.14: Bilinear interpolation with CODE maps positioning solution - 9th November 2012

Figure 5.15: Bilinear interpolation with EGNOS maps positioning solution - 9th November 2012
5.2 Position Domain Analysis

Figure 5.16: Positioning solution obtained replacing EGNOS not available grid data with CODE grid data - 9th November 2012

Figure 5.17: Positioning solution obtained smoothing EGNOS grid map with CODE grid map - 9th November 2012
5.2 Position Domain Analysis

5.2.1.3 Station - Noto (NOT1)

Figure 5.18: Experimental data without ionospheric correction - 9th November 2012

Figure 5.19: Klobuchar model positioning solution - 9th November 2012
5.2 Position Domain Analysis

Figure 5.20: Bilinear interpolation with CODE maps positioning solution - 9th November 2012

Figure 5.21: Bilinear interpolation with EGNOS maps positioning solution - 9th November 2012
5.2 Position Domain Analysis

Figure 5.22: Positioning solution obtained replacing EGNOS not available grid data with CODE grid data - 9th November 2012

Figure 5.23: Positioning solution obtained smoothing EGNOS grid map with CODE grid map - 9th November 2012
5.2 Position Domain Analysis

5.2.1.4 Station - San Fernando (SFER)

Figure 5.24: Experimental data without ionospheric correction - 9th November 2012

Figure 5.25: Klobuchar model positioning solution - 9th November 2012
5.2 Position Domain Analysis

Figure 5.26: Bilinear interpolation with CODE maps positioning solution - 9\textsuperscript{th} November 2012

Figure 5.27: Bilinear interpolation with EGNOS maps positioning solution - 9\textsuperscript{th} November 2012
5.2 Position Domain Analysis

**Figure 5.28:** Positioning solution obtained replacing EGNOS not available grid data with CODE grid data - 9th November 2012

**Figure 5.29:** Positioning solution obtained smoothing EGNOS grid map with CODE grid map - 9th November 2012
5.2 Position Domain Analysis

5.2.1.5 Station - Rabat (RABT)

Figure 5.30: Experimental data without ionospheric correction - 9\textsuperscript{th} November 2012

Figure 5.31: Klobuchar model positioning solution - 9\textsuperscript{th} November 2012
5.2 Position Domain Analysis

Figure 5.32: Bilinear interpolation with CODE maps positioning solution - 9th November 2012

Figure 5.33: Bilinear interpolation with EGNOS maps positioning solution - 9th November 2012
5.2 Position Domain Analysis

Figure 5.34: Positioning solution obtained replacing EGNOS not available grid data with CODE grid data - 9th November 2012

Figure 5.35: Positioning solution obtained smoothing EGNOS grid map with CODE grid map - 9th November 2012
5.2 Position Domain Analysis

5.2.2 Discussion about 9\textsuperscript{th} November - quiet day

Considering the 9\textsuperscript{th} November different positioning solutions for different IGS stations (Matera-MATE, Cagliari-CAGL, Noto-NOT1, San Fernando-SFER, Rabat-RABT) have been analysed.

Some considerations can be provided for this quiet day:

- Results obtained using \textbf{experimental data without the ionospheric correction} (no-iono correction) shows that for stations MATE, CAGL and NOT1 there is a degradation for the vertical error component (almost 3.5 meters), while the North and East error component shows standard deviation lower than 1.5 meters. For RABT and SFER the situation is quite different because the degradation is seen also in the North and East error component (standard deviation can reach 2.4 meters). This is due to the lower latitude of these stations.

- For the Klobuchar positioning solution, considering MATE, CAGL and NOT1 stations, the North and East error components are lower than for the stations SFER and RABT. It is evident and expected that Klobuchar model could improve better corrections for station at middle latitude.

- For the positioning solution obtained using Global Map CODE - bilinear interpolation, for all the stations results are comparable with Klobuchar solution, also improving the vertical error solution for SFER and RABT.

- For the positioning solution obtained using EGNOS - bilinear interpolation for all the stations results are quite comparable with Klobuchar solution, although for NOTO the vertical error component degrades with a standard deviation of 5.5 meters)

- The fifth method based on the replacement of EGNOS NaN data with CODE data shows results perfectly comparable with CODE solution.

- The last method based on the smoothing of EGNOS data with CODE data evidence a degradation of all the results for all the component, in particular in the vertical error component for SFER and RABT.
5.2 Position Domain Analysis

5.2.3 November 2012 - 13\textsuperscript{th} November (storm)

5.2.3.1 Station - Matera (MATE)

Figure 5.36: Experimental data without ionospheric correction - 13\textsuperscript{th} November 2012

Figure 5.37: Klobuchar model positioning solution - 13\textsuperscript{th} November 2012
5.2 Position Domain Analysis

Figure 5.38: Bilinear interpolation with CODE maps positioning solution - 13th November 2012

Figure 5.39: Bilinear interpolation with EGNOS maps positioning solution - 13th November 2012
5.2 Position Domain Analysis

**Figure 5.40**: Positioning solution obtained replacing EGNOS not available grid data with CODE grid data - 13th November 2012

**Figure 5.41**: Positioning solution obtained smoothing EGNOS grid map with CODE grid map - 13th November 2012
5.2 Position Domain Analysis

5.2.3.2 Station - Cagliari (CAGL)

Figure 5.42: Experimental data without ionospheric correction - 13th November 2012

Figure 5.43: Klobuchar model positioning solution - 13th November 2012
5.2 Position Domain Analysis

Figure 5.44: Bilinear interpolation with CODE maps positioning solution - 13th November 2012

Figure 5.45: Bilinear interpolation with EGNOS maps positioning solution - 13th November 2012
Figure 5.46: Positioning solution obtained replacing EGNOS not available grid data with CODE grid data - 13th November 2012

Figure 5.47: Positioning solution obtained smoothing EGNOS grid map with CODE grid map - 13th November 2012
5.2 Position Domain Analysis

5.2.3.3 Station - Noto (NOT1)

Figure 5.48: Experimental data without ionospheric correction - 13th November 2012

Figure 5.49: Klobuchar model positioning solution - 13th November 2012
5.2 Position Domain Analysis

Figure 5.50: Bilinear interpolation with CODE maps positioning solution - 13th November 2012

Figure 5.51: Bilinear interpolation with EGNOS maps positioning solution - 13th November 2012
5.2 Position Domain Analysis

**Figure 5.52:** Positioning solution obtained replacing EGNOS not available grid data with CODE grid data - 13th November 2012

**Figure 5.53:** Positioning solution obtained smoothing EGNOS grid map with CODE grid map - 13th November 2012
5.2 Position Domain Analysis

5.2.3.4 Station - San Fernando (SFER)

Figure 5.54: Experimental data without ionospheric correction - 13th November 2012

Figure 5.55: Klobuchar model positioning solution - 13th November 2012
5.2 Position Domain Analysis

Figure 5.56: Bilinear interpolation with CODE maps positioning solution - 13\textsuperscript{th} November 2012

Figure 5.57: Bilinear interpolation with EGNOS maps positioning solution - 13\textsuperscript{th} November 2012
5.2 Position Domain Analysis

Figure 5.58: Positioning solution obtained replacing EGNOS not available grid data with CODE grid data - 13th November 2012

Figure 5.59: Positioning solution obtained smoothing EGNOS grid map with CODE grid map - 13th November 2012
5.2 Position Domain Analysis

5.2.3.5 Station - Rabat (RABT)

Figure 5.60: Experimental data without ionospheric correction - 13th November 2012

Figure 5.61: Klobuchar model positioning solution - 13th November 2012
5.2 Position Domain Analysis

Figure 5.62: Bilinear interpolation with CODE maps positioning solution - 13th November 2012

Figure 5.63: Bilinear interpolation with EGNOS maps positioning solution - 13th November 2012
5.2 Position Domain Analysis

Figure 5.64: Positioning solution obtained replacing EGNOS not available grid data with CODE grid data - 13th November 2012

Figure 5.65: Positioning solution obtained smoothing EGNOS grid map with CODE grid map - 13th November 2012
5.2 Position Domain Analysis

5.2.4 Discussion about 13\textsuperscript{th} November - disturbed day

Considering the 13\textsuperscript{th} November different positioning solutions for different IGS stations (Matera-MATE, Cagliari-CAGL, Noto-NOT1, San Fernando-SFER, Rabat-RABT) have been analysed.

Some considerations can be provided for this disturbed day:

- Results obtained using experimental data without the ionospheric correction (no-iono correction) show that for all the stations, as expected during a geomagnetic storm, the degradation characterize all the error component. In particular the vertical component is the most affected, with an average value of almost 7.5 meters.

- For the Klobuchar positioning solution, considering MATE, CAGL and NOT1 stations, all the error components can be corrected while for SFER and RABT the vertical component is higher than 4 meters and for RABT the North error component shows a standard deviation of 3.1 meters.

- For the positioning solution obtained using Global Map CODE - bilinear interpolation, for all the stations results are comparable with Klobuchar solution, also improving the vertical error solution for SFER and RABT.

- For the positioning solution obtained using EGNOS - bilinear interpolation degradation is affected more by SFER and RABT positioned at low latitude. SFER results show a degradation of positioning for North and Up error while for RABT degradation is related to all the component.

- The fifth method based on the replacement of EGNOS NaN data with CODE data shows results perfectly comparable with CODE solution.

- The last method based on the smoothing of EGNOS data with CODE data evidence a degradation of all the results in particular for the North and Up components.
5.2.5 Tables - November 2012 - 9th and 13th -
Stations: Matera, Cagliari, Noto, San Fernando, Rabat

<table>
<thead>
<tr>
<th>Matera – 9th Nov 2012 quiet</th>
<th>North Error (m)</th>
<th>East Error (m)</th>
<th>Up Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Iono-Correction</td>
<td>0.926 ± 1.115</td>
<td>0.131 ± 0.719</td>
<td>2.445 ± 3.145</td>
</tr>
<tr>
<td>GPS - Klobuchar</td>
<td>0.661 ± 0.966</td>
<td>0.316 ± 0.685</td>
<td>-1.981 ± 2.216</td>
</tr>
<tr>
<td>GIM – CODE bilin. interpol.</td>
<td>0.464 ± 1.133</td>
<td>0.212 ± 0.976</td>
<td>-2.088 ± 2.672</td>
</tr>
<tr>
<td>EGNOS bilin. interpol.</td>
<td>0.548 ± 2.121</td>
<td>-0.160 ± 1.552</td>
<td>-1.458 ± 2.732</td>
</tr>
<tr>
<td>Replacement NaN EGNOS data with CODE data</td>
<td>0.448 ± 1.178</td>
<td>0.030 ± 0.899</td>
<td>-1.353 ± 2.437</td>
</tr>
<tr>
<td>Smoothing EGNOS data with CODE data</td>
<td>0.703 ± 2.111</td>
<td>0.418 ± 2.008</td>
<td>-1.389 ± 5.606</td>
</tr>
</tbody>
</table>

Figure 5.66: Table of North, East, Up Errors (average value and standard deviation) - 9th November 2012

<table>
<thead>
<tr>
<th>Matera – 13th November storm</th>
<th>North Error (m)</th>
<th>East Error (m)</th>
<th>Up Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Iono-Correction</td>
<td>1.227 ± 1.086</td>
<td>-0.272 ± 0.894</td>
<td>4.865 ± 3.711</td>
</tr>
<tr>
<td>GPS - Klobuchar</td>
<td>0.942 ± 1.105</td>
<td>-0.116 ± 0.850</td>
<td>-0.579 ± 2.315</td>
</tr>
<tr>
<td>GIM – CODE bilin. interpol.</td>
<td>0.578 ± 0.935</td>
<td>-0.131 ± 0.818</td>
<td>-1.537 ± 2.221</td>
</tr>
<tr>
<td>EGNOS bilin. interpol.</td>
<td>0.302 ± 0.975</td>
<td>-0.289 ± 0.807</td>
<td>-0.684 ± 2.219</td>
</tr>
<tr>
<td>Replacement NaN EGNOS data with CODE data</td>
<td>0.331 ± 1.014</td>
<td>-0.295 ± 0.782</td>
<td>-0.669 ± 2.187</td>
</tr>
<tr>
<td>Smoothing EGNOS data with CODE data</td>
<td>0.451 ± 2.070</td>
<td>-0.019 ± 1.793</td>
<td>-0.747 ± 5.283</td>
</tr>
</tbody>
</table>

Figure 5.67: Table of North, East, Up Errors (average value and standard deviation) - 13th November 2012
### 5.2 Position Domain Analysis

<table>
<thead>
<tr>
<th>Cagliari - 9(^{th}) Nov 2012 quiet</th>
<th>North Error (m)</th>
<th>East Error (m)</th>
<th>Up Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Iono-Correction</td>
<td>0.081 ± 1.156</td>
<td>-0.044 ± 0.657</td>
<td>3.041 ± 3.109</td>
</tr>
<tr>
<td>GPS - Klobuchar</td>
<td>-0.113 ± 0.992</td>
<td>0.099 ± 0.595</td>
<td>-1.435 ± 2.173</td>
</tr>
<tr>
<td>GIM – CODE bilin. interp.</td>
<td>-0.528 ± 1.121</td>
<td>0.008 ± 0.749</td>
<td>-1.368 ± 2.729</td>
</tr>
<tr>
<td>EGNOS bilin. interp.</td>
<td>-0.444 ±1.587</td>
<td>-0.214 ± 0.916</td>
<td>-0.667 ± 2.384</td>
</tr>
<tr>
<td>Replacement NaN EGNOS data with CODE data</td>
<td>-0.506 ± 1.121</td>
<td>-0.160 ± 0.793</td>
<td>-0.677 ± 2.430</td>
</tr>
<tr>
<td>Smoothing EGNOS data with CODE data</td>
<td>-0.278 ± 2.603</td>
<td>0.235 ± 1.777</td>
<td>-1.282 ± 5.779</td>
</tr>
</tbody>
</table>

**Figure 5.68:** Table of North, East, Up Errors (average value and standard deviation) - 9\(^{th}\) November 2012

<table>
<thead>
<tr>
<th>Cagliari – 13(^{th}) Nov 2012 storm</th>
<th>North Error (m)</th>
<th>East Error (m)</th>
<th>Up Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Iono-Correction</td>
<td>0.389 ± 1.322</td>
<td>0.102 ± 1.025</td>
<td>6.083 ± 4.108</td>
</tr>
<tr>
<td>GPS - Klobuchar</td>
<td>0.207 ± 1.289</td>
<td>0.136 ± 1.017</td>
<td>0.765 ± 2.415</td>
</tr>
<tr>
<td>GIM – CODE bilin. interp.</td>
<td>-0.888 ± 0.901</td>
<td>0.125 ± 0.675</td>
<td>-0.373 ± 2.199</td>
</tr>
<tr>
<td>EGNOS bilin. interp.</td>
<td>-0.804 ± 1.233</td>
<td>-0.260 ± 1.336</td>
<td>0.174 ± 2.183</td>
</tr>
<tr>
<td>Replacement NaN EGNOS data with CODE data</td>
<td>-0.828 ± 1.151</td>
<td>-0.275 ± 1.329</td>
<td>0.192 ± 2.294</td>
</tr>
<tr>
<td>Smoothing EGNOS data with CODE data</td>
<td>-0.626 ± 1.747</td>
<td>-0.065 ± 1.883</td>
<td>-0.565 ± 4.489</td>
</tr>
</tbody>
</table>

**Figure 5.69:** Table of North, East, Up Errors (average value and standard deviation) - 13\(^{th}\) November 2012
5.2 Position Domain Analysis

<table>
<thead>
<tr>
<th></th>
<th>North Error (m)</th>
<th>East Error (m)</th>
<th>Up Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Ionocorrection</td>
<td>-0.201 ± 1.109</td>
<td>-0.117 ± 0.803</td>
<td>2.921 ± 3.340</td>
</tr>
<tr>
<td>GPS - Klobuchar</td>
<td>-0.401 ± 0.972</td>
<td>-0.003 ± 0.823</td>
<td>-1.684 ± 2.364</td>
</tr>
<tr>
<td>GIM - CODE bilin.</td>
<td>-0.713 ± 1.249</td>
<td>-0.153 ± 1.013</td>
<td>-2.404 ± 3.014</td>
</tr>
<tr>
<td>interp. EGNOS bilin.</td>
<td>-0.898 ± 2.574</td>
<td>0.040 ± 2.301</td>
<td>-1.324 ± 5.475</td>
</tr>
<tr>
<td>interp. Replacement</td>
<td>-0.647 ± 1.269</td>
<td>-0.239 ± 1.130</td>
<td>-1.702 ± 3.610</td>
</tr>
<tr>
<td>NaN EGNOS data</td>
<td>-0.362 ± 2.709</td>
<td>-0.245 ± 2.193</td>
<td>-2.296 ± 6.148</td>
</tr>
<tr>
<td>with CODE data</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Figure 5.70:* Table of North, East, Up Errors (average value and standard deviation) - 9th November 2012

<table>
<thead>
<tr>
<th></th>
<th>North Error (m)</th>
<th>East Error (m)</th>
<th>Up Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Ionocorrection</td>
<td>-0.180 ± 1.440</td>
<td>-0.220 ± 1.104</td>
<td>6.454 ± 4.571</td>
</tr>
<tr>
<td>GPS - Klobuchar</td>
<td>-0.311 ± 1.535</td>
<td>0.098 ± 1.265</td>
<td>0.621 ± 3.258</td>
</tr>
<tr>
<td>GIM - CODE bilin.</td>
<td>-1.476 ± 1.219</td>
<td>-0.341 ± 0.732</td>
<td>-1.659 ± 2.626</td>
</tr>
<tr>
<td>interp. EGNOS bilin.</td>
<td>-1.518 ± 2.283</td>
<td>-0.589 ± 1.086</td>
<td>-0.857 ± 4.541</td>
</tr>
<tr>
<td>interp. Replacement</td>
<td>-1.701 ± 1.126</td>
<td>-0.532 ± 0.746</td>
<td>-0.770 ± 2.549</td>
</tr>
<tr>
<td>NaN EGNOS data</td>
<td>-1.314 ± 1.749</td>
<td>-0.340 ± 1.497</td>
<td>-2.163 ± 4.889</td>
</tr>
<tr>
<td>with CODE data</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Figure 5.71:* Table of North, East, Up Errors (average value and standard deviation) - 13th November 2012
### 5.2 Position Domain Analysis

#### Figure 5.72: Table of North, East, Up Errors (average value and standard deviation) - 9\(^{th}\) November 2012

<table>
<thead>
<tr>
<th>San Fernando – 9(^{th}) Nov 2012 quiet</th>
<th>North Error (m)</th>
<th>East Error (m)</th>
<th>Up Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Iono-Correction</td>
<td>0.137 ± 1.508</td>
<td>-0.001 ± 1.295</td>
<td>1.956 ± 3.784</td>
</tr>
<tr>
<td>GPS - Klobuchar</td>
<td>0.153 ± 1.641</td>
<td>0.241 ± 1.745</td>
<td>-2.313 ± 3.998</td>
</tr>
<tr>
<td>GIM – CODE bilin. interp.</td>
<td>-0.982 ± 1.335</td>
<td>0.227 ± 0.864</td>
<td>-3.705 ± 2.810</td>
</tr>
<tr>
<td>EGNOS bilin. interp.</td>
<td>-0.892 ± 1.545</td>
<td>0.222 ± 0.782</td>
<td>-2.819 ± 3.567</td>
</tr>
<tr>
<td>Replacement NaN EGNOS data with CODE data</td>
<td>-0.939 ± 1.286</td>
<td>0.193 ± 0.781</td>
<td>-3.105 ± 2.770</td>
</tr>
<tr>
<td>Smoothing EGNOS data with CODE data</td>
<td>-0.788 ± 2.642</td>
<td>0.481 ± 2.613</td>
<td>-2.604 ± 5.882</td>
</tr>
</tbody>
</table>

#### Figure 5.73: Table of North, East, Up Errors (average value and standard deviation) - 13\(^{th}\) November 2012

<table>
<thead>
<tr>
<th>San Fernando – 13(^{th}) Nov 2012 storm</th>
<th>North Error (m)</th>
<th>East Error (m)</th>
<th>Up Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Iono-Correction</td>
<td>0.011 ± 2.506</td>
<td>-0.241 ± 1.557</td>
<td>5.089 ± 6.060</td>
</tr>
<tr>
<td>GPS - Klobuchar</td>
<td>-0.381 ± 2.223</td>
<td>-0.132 ± 1.348</td>
<td>-0.634 ± 4.018</td>
</tr>
<tr>
<td>GIM – CODE bilin. interp.</td>
<td>-3.083 ± 1.568</td>
<td>0.302 ± 0.922</td>
<td>-3.397 ± 2.212</td>
</tr>
<tr>
<td>EGNOS bilin. interp.</td>
<td>-2.757 ± 4.142</td>
<td>0.075 ± 2.054</td>
<td>-3.977 ± 4.489</td>
</tr>
<tr>
<td>Replacement NaN EGNOS data with CODE data</td>
<td>-3.138 ± 1.639</td>
<td>-0.991 ± 1.076</td>
<td>-3.196 ± 2.774</td>
</tr>
<tr>
<td>Smoothing EGNOS data with CODE data</td>
<td>-3.073 ± 2.863</td>
<td>-0.113 ± 1.887</td>
<td>-3.753 ± 6.335</td>
</tr>
</tbody>
</table>
5.2 Position Domain Analysis

<table>
<thead>
<tr>
<th>Rabat – 9th Nov 2012</th>
<th>North Error (m)</th>
<th>East Error (m)</th>
<th>Up Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>quiet</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No Iono-Correction</td>
<td>1.982 ± 1.825</td>
<td>0.173 ± 2.393</td>
<td>4.795 ± 3.707</td>
</tr>
<tr>
<td>GPS - Klobuchar</td>
<td>2.009 ± 1.957</td>
<td>0.243 ± 2.190</td>
<td>0.670 ± 3.845</td>
</tr>
<tr>
<td>GIM – CODE bilin. interp.</td>
<td>0.258 ± 1.353</td>
<td>0.016 ± 0.843</td>
<td>-0.729 ± 2.690</td>
</tr>
<tr>
<td>EGNOS bilin. interp.</td>
<td>0.154 ± 1.624</td>
<td>0.113 ± 1.018</td>
<td>-0.478 ± 3.246</td>
</tr>
<tr>
<td>Replacement NaN EGNOS data with CODE data</td>
<td>0.246 ± 1.393</td>
<td>-0.060 ± 0.933</td>
<td>-0.455 ± 2.799</td>
</tr>
<tr>
<td>Smoothing EGNOS data with CODE data</td>
<td>0.718 ± 3.085</td>
<td>0.570 ± 3.644</td>
<td>-0.784 ± 5.632</td>
</tr>
</tbody>
</table>

**Figure 5.74:** Table of North, East, Up Errors (average value and standard deviation) - 9th November 2012

<table>
<thead>
<tr>
<th>Rabat – 13th Nov 2012</th>
<th>North Error (m)</th>
<th>East Error (m)</th>
<th>Up Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>storm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No Iono-Correction</td>
<td>4.838 ± 3.418</td>
<td>-0.245 ± 1.920</td>
<td>9.756 ± 7.442</td>
</tr>
<tr>
<td>GPS - Klobuchar</td>
<td>4.418 ± 3.118</td>
<td>-0.143 ± 1.696</td>
<td>3.864 ± 5.137</td>
</tr>
<tr>
<td>GIM – CODE bilin. interp.</td>
<td>0.893 ± 1.626</td>
<td>0.307 ± 1.178</td>
<td>1.328 ± 2.998</td>
</tr>
<tr>
<td>EGNOS bilin. interp.</td>
<td>0.015 ± 3.950</td>
<td>0.158 ± 3.092</td>
<td>-0.014 ± 5.641</td>
</tr>
<tr>
<td>Replacement NaN EGNOS data with CODE data</td>
<td>0.941 ± 1.587</td>
<td>-0.199 ± 1.082</td>
<td>1.498 ± 3.237</td>
</tr>
<tr>
<td>Smoothing EGNOS data with CODE data</td>
<td>0.966 ± 2.496</td>
<td>-0.188 ± 1.799</td>
<td>0.631 ± 5.040</td>
</tr>
</tbody>
</table>

**Figure 5.75:** Table of North, East, Up Errors (average value and standard deviation) - 13th November 2012
Bibliography


Discussion and Conclusion

The main objective of this thesis is the extension of the availability of EGNOS grid maps in case of "Not monitored" IGPs condition, through the study of the impact of ionospheric effects on EGNOS. The characterization of the ionospheric related problems of GNSS positioning has been treated, with a particular focus on the low latitudes of the EGNOS Service Area.

This objective led to the evaluation on a quantitative level of the EGNOS data difference comparing its vertical Total Electron Content (TEC) with TEC Global Maps. This procedure is done in order to check how well the Global Maps could reproduce the regional conditions described by EGNOS grid vertical TEC, particularly in terms of TEC space gradients (both in longitude and in latitude) in the Southern regions of the European Civil Aviation Conference (ECAC) region. This area can be already considered under the influence of the Ionospheric Equatorial Anomaly.

The Research Activity, conducted during the PhD, is a contribution to the optimisation of the EGNOS Open Service (OS), the first service provided from year 2009. The EGNOS Service Definition Document Open Service (SDD - OS) describes the characteristic of the service offered by the EGNOS OS to users, highlighting the accuracy in positioning and the timing performance currently available to suitably equipped users using both the GPS SPS and EGNOS augmentation signal. The Open Service is intended to offer a wide range of benefits to the users for general purpose applications. The EGNOS system is expected to provide EGNOS OS navigation performance, in terms of accuracy and availability. In EGNOS SDD - OS it is underlined that service performance are expected to gradually degrade as a user moves away from the Minimum Compliance Area (MCA). For a given system accuracy performance, the service will become progressively less available as the user gets away from the MCA. (see Figure 6.1)

In order to maintain a given service availability performance, the user will have to accept positioning errors statistically higher than 3 m in Horizontal component and 4 m in Vertical component. In the document it is underlined that, depending on the receiver implementation and the environment, the actual performance of a receiver using
EGNOS OS may vary. In the OS document, a set of guidelines and examples on possible implementations along with performance figures achievable with different options have been provided.

In this thesis work ionospheric condition has been considered invariable during a time period of 600 seconds and the Southern border of the ECAC are have been taken into account.

Ionospheric delays corrections cannot be computed due to the fact that there are no sufficient Ionospheric Grid Points (IGPs) to perform the EGNOS interpolation according to the Minimum Operational Performance Standards (MOPS) for Global Positioning System/Wide Area Augmentation System Airborne Equipment. This can affect the overall performance of the position solution. In nominal conditions, the availability of the ionospheric points is very high in the centre of the ECAC area.

In the analysis performed it is possible to define two reasons for not having ionospheric corrections given by EGNOS:

- the Ionospheric correction at the Ionospheric Pierce Point (IPP) is not valid in the centre of the ECAC area. This could be due because IGP values have expired or are set to 'not valid'. This normally happens over a short period as the coverage surrounding the IPP is good. Thus, an interpolation, on top of the MOPS one, can be used to get the value at the IGP/IPP, as explained in EGNOS SDD - OS.
the Ionospheric correction at the IGP is not valid at the borders. This usually happens for a long time, or for all the day. This work thesis has focused on the Southern part of the service area, characterised by the presence of not available EGNOS grid points which are already under the influence of the Ionospheric Equatorial Anomaly.

In order to achieve this last purpose and trying to extend the availability of EGNOS OS, the present research work has been divided into two parts:

1. Different ionospheric grid maps have been created and their relative temporal and spatial difference have been computed for EGNOS and CODE Global Map. A replacement with CODE data when EGNOS data are missing has been proposed. As an alternative a smoothing between EGNOS and CODE maps has been produced.

2. Relative performances regarding the positioning domain, have been analysed, using a software acting as a receiver that allows flexibility for the different kind of solutions (gLAB software). gLAB is public available and free of charge, widely used in the EGNOS user community.

**Comparison of EGNOS and Global Maps at range delay**

The first part of data analysis, corresponding to Chapter 4, deals with the study of Global Ionospheric Maps (GIM), such as those provided by the University of Bern - Center for Orbit Determination (CODE) in Europe. The aim is to determine the delay and to correct the ionospheric impact in the Southern regions of the ECAC area, positioned on the border of the area monitored by the three geostationary satellites, which are especially critical due to the presence of not available EGNOS data.

The main objective of this part of the work was to compare the vertical TEC obtained with EGNOS with Global Maps of Total Electron Content obtained from CODE and to check how well the Global Maps could reproduce the regional conditions described by EGNOS grid vertical TEC. This is done particularly in terms of TEC spatial gradients (both in longitude and latitude).

The analysis is performed for the years 2012 and 2013 (characterized by relatively high solar activity), for both quiet and disturbed ionospheric conditions and the covered area is \([40^\circ \text{W}, 40^\circ \text{E}]\) in longitude and \([20^\circ \text{N}, 60^\circ \text{N}]\) in latitude.

Months selected are January, April, July, November for the year 2012; January, March, June, November for year 2013. They have been chosen as representative months of all the seasons.

For every month, days characterised by the presence of a geomagnetic storm, have been also selected, using the Disturbance Storm Time (Dst) index.

EGNOS and CODE grid maps have been used for the comparison at range delay for a temporal and spatial analysis.
The Temporal variability Analysis (TVA) concerns the differences between EGNOS and GIM - CODE for all the IGPs in the selected area every 10 minutes.

While the Latitudinal Spatial Variability Analysis (LSVA) studies the difference between EGNOS and GIM - CODE for 24 hours (all the day) for every latitude in the selected area ([40° W, 40° E] in longitude and [20° N, 60° N] in latitude).

The Temporal Analysis shows that, for all the cases analysed in 2012 and in 2013, the average values of the differences between EGNOS and CODE could vary between 1 TECu and around 4 TECu, not depending on the season.

In April 2012 (considered the season nearest to the equinox) it is possible to see the average values of the difference EGNOS - CODE (in ten minutes interval) around 2 TECu like in July 2012 (considered the season nearest to the solstice).

In all the cases of 2012, both for quiet and disturbed days, a decrease of the average values at about 12:00 UT can be seen and could vary from 0.5 TECu for quiet days, to 3 TECu for days characterised by storms. In 2013 this effect is less evident.

Looking at the evolution of the average value during the days, disturbed days show an increase in the average values that could range from around 0.5 TECu to 2 TECu (see 13th November 2012).

In June 2013 the three disturbed days of the month have been shown (days 1st, 7th, 29th). It is important to see that the average values decrease from the first case (around 4 TECu) to the third one (around 1.5 or 2 TECu).

For all the cases the average values of the different between EGNOS and CODE grid maps for all the IGPs:

---

Figure 6.2: TVA - 25 April 2012 - disturbed day
for quiet days can vary between zero and 2 TECu
for disturbed days can vary between 2 and 4 TECu

Considering the standard deviations, it is evident that during a day characterised by storm and in a season near to the equinox (April and November 2012, March and November 2013) values are higher (from 3 TECu to 5 TECu) especially after 12:00 UT (see April 2012 and March 2013)

Quiet days are characterised by standard deviation of 2 TECu and they show an oscillating behaviour that increases around 12:00 UT.

The Latitudinal Spatial Variability Analysis (LSVA) studies the difference between EGNOS and CODE for 24 hours (all the day) for every latitude in the selected area.

For all the cases it is evident that during quiet days from latitude 60° to 40°, the mean values are always around zero and the standard deviation for all the IGPs are around 1 - 2 TECu. From latitude 35° to 20° the average values of the difference start to oscillate around zero assuming values which can vary from -2 TECu to 5 TECu (considering all the cases).

For storm days from latitude 60° to 40°, the average values of the difference assume values from -2 TECu to 1.5 TECu.

From latitude 35° to 20° the average values start to oscillate around zero assuming values which can vary from -7 TECu to 5 and 8 TECu (considering all the cases).

Concerning all the cases, the standard deviations of the difference are higher for low latitude (35° to 20°) and they show an oscillating behaviour.

For both quiet and disturbed days, it is evident the presence of not available data of EGNOS for latitude 20°. It is important to stress that the absence of these data at low latitude are due to not available EGNOS data (this aspect does not allow to evaluate differences).

This first analysis permits to evidence that, for cases analysed, at middle - low latitudes (from 35° to 20°) the difference between EGNOS and CODE is higher than for other latitudes: this could be due to the presence of not available EGNOS data.

During quiet conditions difference between EGNOS and CODE could reach 4 TECu, while in disturbed conditions they can reach 5 or 8 TECu at the lower latitudes of the ECAC area, indicating that in principle CODE maps values are consistent with the EGNOS data grid.

**Comparison of EGNOS and Global Maps at position domain**

In the second part, using the TEC calibration technique (Ciraolo et al., 2007), vertical TEC, slant TEC and the coordinates of the Ionospheric Pierce Point (IPP) are computed. The ionospheric corrections applied to GNSS range measurements depend on the satellite-receiver signal path. In order to estimate the ionospheric error for each of these lines of sight, the receiver must identify IPPs.
Considering the values of IGPs grid maps of EGNOS, CODE, a synthetic one obtained replacing CODE data when EGNOS data are missing and a grid map obtained smoothing EGNOS data with CODE data grid, different contributions to the IPPs (in terms of TEC) have been calculated, applying the bilinear interpolation algorithm (see Chapter 5.1).

This is done in order to obtain different pseudoranges related to different ionospheric corrections. The new calculated pseudoranges have been implemented into the RINEX files of different receivers in the Southern part of ECAC region taken as reference stations.

Through flexible positioning software gLAB acting like a receiver, different positioning errors have been evaluated for the different TEC grids in order to estimate, in a systematic way, the planimetric and altimetric accuracies.

Results of different positioning solutions have been reported in terms of North, East, Up error component and their absolute frequencies histograms have been shown to better understand the accuracy of the different solutions proposed for this work thesis.

For all the selected months, a quiet and disturbed day have been considered (same days of the analysis done for Chapter 4).
For every day five stations, positioned in the Southern part of the ECAC, are have been selected:

- Matera-MATE (Italy)
- Cagliari-CAGL (Italy)
- Noto-NOT1 (Italy)
- San Fernando-SFER (Spain)
- Rabat-RABT (Morocco)

and for every stations six positioning solutions have been analysed:

- experimental data without ionospheric correction (disabled in the software/receiver)
- Klobuchar model positioning solution
- bilinear interpolation with CODE maps
- bilinear interpolation with EGNOS maps
- bilinear interpolation with maps obtained replacing EGNOS not available grid data with CODE grid data
- bilinear interpolation with synthetic maps obtained smoothing EGNOS grid map with CODE grid map

Considering all the data analysed for the QUIET DAYS some final conclusions can be obtained:

- Results obtained using experimental data without the ionospheric correction show that for stations MATE, CAGL and NOT1 there is a degradation for the vertical error component (about 4 meters), while for the North and East error component standards deviation are lower than 1.5 meters. For RABT and SFER the situation is quite different because the degradation is seen also in the North and East error component (standard deviation can reach in some cases 3 meters). This is typical for these two stations because of their lower latitude position respect to the others considered on the border of the service area.

- For the Klobuchar positioning solution, it is evident (and expected) that it can improve better corrections for stations at middle latitude like MATE, CAGL and NOT1 stations. For SFER and RABT the degradation in positioning using this method is seen not only in vertical, but also in planimetric accuracies (around 3 meters).
• Concerning positioning solution obtained using **Global Map CODE, bilinear interpolation**, for all the stations results are comparable with Klobuchar solution, also improving the vertical error solution for SFER and RABT (standard deviation lower around 2 meters).

• Regarding positioning solution obtained using **EGNOS data, bilinear interpolation** for all the stations, results are quite comparable with Klobuchar solution, although for NOTO the vertical error component degrades with a standard deviation of about 4 meters.

• The fifth method based on the **replacement of EGNOS NaN data with CODE data** shows results almost comparable with CODE - bilinear interpolation positioning solution.

• The last method based on the **smoothing of EGNOS data with CODE data** evidences a degradation of all the results for all the component, in particular in the vertical error component for SFER and RABT.

Considering all the data analysed for the **DISTURBED DAYS** some final conclusions can be obtained:

• Results obtained using **experimental data without the ionospheric correction** show that for all the stations, as expected during a geomagnetic storm, the degradation characterises all the error component. In particular vertical component is the most effected, rising an average value of almost 7 meters for stations SFER and RABT.

• For the **Klobuchar positioning solution**, it is evident that it can improve better positioning solutions for station at middle latitude like MATE, CAGL and NOT1 stations, not only during quiet days but also during disturbed ones. While for SFER and RABT the vertical component is higher than 4 meters and for RABT the North error component shows a standard deviation of 3 meters.

• For the positioning solution obtained using **Global Map CODE, bilinear interpolation**, for all the stations results are comparable with Klobuchar solution, also improving the vertical error solution for SFER and RABT. (all the standard deviations are around 2 or 3 meters)

• For the positioning solution obtained using **EGNOS data, bilinear interpolation**, degradation is affected more for SFER and RABT positioned at low latitude. SFER results show a degradation of positioning for North and Up error of about 5 meters while for RABT degradation is evident in all the component.

• The fifth method based on the **replacement of EGNOS NaN data with CODE data** shows results almost comparable with CODE solution.
• The last method based on the smoothing of EGNOS data with CODE data evidences a degradation of all the results in particular for North and Up component.

The main objective of the EGNOS Open Service, as explained in the SDD, is the identification of the ‘best option’ to use when a ‘pure’ EGNOS solution cannot be determined due to the presence of not available data.

This fact has led to a number of different implementations for manufacturer of receivers that in some cases may not be optimal or appropriate. In this term EGNOS SDD - OS present a set of guidelines for GNSS receiver manufacturers on how to make use of the EGNOS broadcast messages to improve their positioning accuracy and availability for OS services.

**Recommendations for the EGNOS Open Service Users**

From the analysis of the obtained results, a number of recommendations can be given for the EGNOS Open Service:

• As expected the ionosphere has a strong impact on EGNOS, especially during disturbed conditions, as seen in the performance maps provided by the EGNOS European Satellite Services Provider (ESSP) for November 2012 in Chapter 5.

• In the center of the ECAC area (Cagliari station) CODE and EGNOS positioning solutions obtained with bilinear interpolation are comparable. They show better performances than Klobuchar correction model.

• The GPS Klobuchar correction model, as expected works properly only for middle latitudes while it is not appropriate for the lower latitudes of the ECAC region, especially during disturbed conditions.

• The solution, obtained interpolating CODE grid data, gives better results in term of positioning and this solution is comparable with the solution obtained replacing not available EGNOS data with CODE data grid. In some cases the solution obtained replacing EGNOS data shows better results than those obtained using only CODE maps.

• It is evident that the solution obtained using EGNOS data grid only with bilinear interpolation (that is different from the real EGNOS solution explained in the MOPS - RTCA) does not give good performances in terms of positioning for stations on the border of the service area. This is due to the absence of many IGPs monitored, especially for Noto, San Fernando and Rabat, situated in the Southern part of the ECAC area, a region considered critical for two reasons: the first is the presence of not available EGNOS data and the second factor is possibly related to the presence of the IEA.
• In the last method, obtained smoothing EGNOS data with CODE data grid, all the error components degrade for all the stations and for all the days analysed.

• At the lower latitudes of the ECAC area in presence of ”Not Monitored” EGNOS IGPs, interpolation using CODE grid data could reach adequate performance in the post processing mode.

• The same results could be obtained using only CODE grid data maps.

• In case of no local DGNSS available, it is possible to reach a performance with these methodologies for different applications, for example precision farming or modal transport applications in African region.

• It should be taken into account that these solutions have been obtained changing only the ionospheric delay in the pseudorange observable and not implementing the EGNOS Fast and Slow corrections.

• Results are limited to years 2012 and 2013, characterised by relative high solar activity. During higher levels of ionospheric activity, the exact ranking of the proposed alternatives might change.

It has to be stressed that these solutions are only applicable at the moment in post processing mode because CODE Global Maps do not provide integrity.

Obtained results are of interest for the future extension of the EGNOS system to other parts of the world such as Africa, thus including the equatorial region, and for the development of new applications not requiring integrity (OS)
Appendix A: Tables - Average Values and Standard Deviations for all quiet and disturbed days analysed - year 2012 - 2013, Stations: Matera, Cagliari, Noto, San Fernando, Rabat, Data Interval Time: 600 seconds

<table>
<thead>
<tr>
<th>Without Ionospheric Correction – quiet – 2012</th>
<th>North Error (m)</th>
<th>East Error (m)</th>
<th>Up Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cagliari</td>
<td>0.258 ± 1.502</td>
<td>0.126 ± 1.157</td>
<td>2.702 ± 4.192</td>
</tr>
<tr>
<td>Matera</td>
<td>1.087 ± 1.406</td>
<td>0.246 ± 1.086</td>
<td>2.922 ± 3.901</td>
</tr>
<tr>
<td>Noto</td>
<td>0.121 ± 1.707</td>
<td>-0.077 ± 1.208</td>
<td>2.805 ± 4.120</td>
</tr>
<tr>
<td>Rabat</td>
<td>2.006 ± 2.186</td>
<td>-0.170 ± 1.839</td>
<td>5.153 ± 5.451</td>
</tr>
<tr>
<td>San Fernando</td>
<td>0.161 ± 1.860</td>
<td>-0.251 ± 1.356</td>
<td>2.365 ± 5.105</td>
</tr>
</tbody>
</table>

Figure 6.4: Positioning Solutions without ionospheric correction: Table of North, East, Up Errors - average values and standard deviations of quiet days analysed in 2012 - Stations: Matera, Cagliari, Noto, San Fernando, Rabat

<table>
<thead>
<tr>
<th>Without Ionospheric Correction – quiet – 2013</th>
<th>North Error (m)</th>
<th>East Error (m)</th>
<th>Up Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cagliari</td>
<td>0.649 ± 1.585</td>
<td>0.106 ± 1.259</td>
<td>4.032 ± 4.394</td>
</tr>
<tr>
<td>Matera</td>
<td>1.282 ± 1.705</td>
<td>0.808 ± 1.406</td>
<td>3.046 ± 5.256</td>
</tr>
<tr>
<td>Noto</td>
<td>-0.041 ± 1.953</td>
<td>-0.071 ± 1.622</td>
<td>3.898 ± 5.972</td>
</tr>
<tr>
<td>Rabat</td>
<td>3.078 ± 2.887</td>
<td>-0.407 ± 1.811</td>
<td>7.157 ± 7.762</td>
</tr>
<tr>
<td>San Fernando</td>
<td>0.521 ± 2.225</td>
<td>-0.395 ± 1.595</td>
<td>3.961 ± 6.998</td>
</tr>
</tbody>
</table>

Figure 6.5: Positioning Solutions without ionospheric correction: Table of North, East, Up Errors - average values and standard deviations of quiet days analysed in 2013 - Stations: Matera, Cagliari, Noto, San Fernando, Rabat
Figure 6.6: Positioning Solutions without ionospheric correction: Table of North, East, Up Errors - average values and standard deviations of disturbed days analysed in 2012 - Stations: Matera, Cagliari, Noto, San Fernando, Rabat

<table>
<thead>
<tr>
<th>Without Ionospheric Correction – storm – 2012</th>
<th>North Error (m)</th>
<th>East Error (m)</th>
<th>Up Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cagliari</td>
<td>0.265 ± 1.315</td>
<td>0.115 ± 1.013</td>
<td>1.924 ± 5.636</td>
</tr>
<tr>
<td>Matera</td>
<td>3.185 ± 5.020</td>
<td>2.309 ± 6.592</td>
<td>5.147 ± 8.737</td>
</tr>
<tr>
<td>Noto</td>
<td>0.485 ± 2.401</td>
<td>-0.035 ± 1.498</td>
<td>-0.199 ± 6.274</td>
</tr>
<tr>
<td>Rabat</td>
<td>2.896 ± 3.381</td>
<td>-0.734 ± 1.871</td>
<td>2.193 ± 8.177</td>
</tr>
<tr>
<td>San Fernando</td>
<td>0.420 ± 2.581</td>
<td>-0.551 ± 1.543</td>
<td>-0.003 ± 5.338</td>
</tr>
</tbody>
</table>

Figure 6.7: Positioning Solutions without ionospheric correction: Table of North, East, Up Errors - average values and standard deviations of disturbed days analysed in 2013 - Stations: Matera, Cagliari, Noto, San Fernando, Rabat

<table>
<thead>
<tr>
<th>Without Ionospheric Correction – storm – 2013</th>
<th>North Error (m)</th>
<th>East Error (m)</th>
<th>Up Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cagliari</td>
<td>0.691 ± 1.712</td>
<td>0.241 ± 1.565</td>
<td>2.270 ± 5.385</td>
</tr>
<tr>
<td>Matera</td>
<td>1.588 ± 1.654</td>
<td>0.309 ± 1.419</td>
<td>4.301 ± 5.102</td>
</tr>
<tr>
<td>Noto</td>
<td>0.043 ± 1.650</td>
<td>-0.003 ± 1.487</td>
<td>3.219 ± 4.855</td>
</tr>
<tr>
<td>Rabat</td>
<td>2.344 ± 3.256</td>
<td>-0.184 ± 1.619</td>
<td>6.205 ± 6.309</td>
</tr>
<tr>
<td>San Fernando</td>
<td>0.368 ± 2.581</td>
<td>-0.295 ± 1.472</td>
<td>3.203 ± 5.488</td>
</tr>
</tbody>
</table>
### Figure 6.8: Klobuchar model positioning solution: Table of North, East, Up Errors - average values and standard deviations of quiet days analysed in 2012 - Stations: Matera, Cagliari, Noto, San Fernando, Rabat

<table>
<thead>
<tr>
<th>Klobuchar Ion. Correction – quiet – 2012</th>
<th>North Error (m)</th>
<th>East Error (m)</th>
<th>Up Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cagliari</td>
<td>-0.015 ± 1.383</td>
<td>0.232 ± 1.091</td>
<td>-2.013 ± 3.602</td>
</tr>
<tr>
<td>Matera</td>
<td>0.771 ± 1.423</td>
<td>0.423 ± 1.144</td>
<td>-2.238 ± 3.685</td>
</tr>
<tr>
<td>Noto</td>
<td>0.143 ± 1.654</td>
<td>0.113 ± 1.257</td>
<td>-2.661 ± 3.644</td>
</tr>
<tr>
<td>Rabat</td>
<td>1.394 ± 4.698</td>
<td>0.444 ± 4.274</td>
<td>-0.331 ± 9.237</td>
</tr>
<tr>
<td>San Fernando</td>
<td>0.473 ± 4.616</td>
<td>0.476 ± 4.521</td>
<td>2.916 ± 9.771</td>
</tr>
</tbody>
</table>

### Figure 6.9: Klobuchar model positioning solution: Table of North, East, Up Errors - average values and standard deviations of quiet days analysed in 2013 - Stations: Matera, Cagliari, Noto, San Fernando, Rabat

<table>
<thead>
<tr>
<th>Klobuchar Ion. Correction – quiet – 2013</th>
<th>North Error (m)</th>
<th>East Error (m)</th>
<th>Up Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cagliari</td>
<td>0.189 ± 1.468</td>
<td>0.253 ± 1.088</td>
<td>2.375 ± 3.403</td>
</tr>
<tr>
<td>Matera</td>
<td>0.819 ± 1.472</td>
<td>0.984 ± 1.150</td>
<td>-3.169 ± 3.685</td>
</tr>
<tr>
<td>Noto</td>
<td>-0.507 ± 1.613</td>
<td>0.166 ± 1.325</td>
<td>-3.035 ± 3.640</td>
</tr>
<tr>
<td>Rabat</td>
<td>2.568 ± 2.824</td>
<td>-0.210 ± 1.653</td>
<td>-0.219 ± 5.043</td>
</tr>
<tr>
<td>San Fernando</td>
<td>-0.018 ± 2.124</td>
<td>-0.124 ± 1.420</td>
<td>-3.127 ± 4.955</td>
</tr>
<tr>
<td>Klobuchar Ion. Correction – storm – 2012</td>
<td>North Error (m)</td>
<td>East Error (m)</td>
<td>Up Error (m)</td>
</tr>
<tr>
<td>----------------------------------------</td>
<td>-----------------</td>
<td>----------------</td>
<td>--------------</td>
</tr>
<tr>
<td>Matera</td>
<td>1.264 ± 1.885</td>
<td>0.324 ± 1.173</td>
<td>-2.597 ± 3.911</td>
</tr>
<tr>
<td>Noto</td>
<td>-0.623 ± 2.444</td>
<td>0.065 ± 1.536</td>
<td>-2.471 ± 4.315</td>
</tr>
<tr>
<td>Rabat</td>
<td>2.877 ± 3.246</td>
<td>-0.711 ± 1.933</td>
<td>0.026 ± 6.112</td>
</tr>
<tr>
<td>San Fernando</td>
<td>0.469 ± 2.672</td>
<td>-0.520 ± 1.592</td>
<td>-1.514 ± 5.029</td>
</tr>
</tbody>
</table>

**Figure 6.10:** Klobuchar model positioning solution: Table of North, East, Up Errors - average values and standard deviations of disturbed days analysed in 2012 - Stations: Matera, Cagliari, Noto, San Fernando, Rabat

<table>
<thead>
<tr>
<th>Klobuchar Ion. Correction – storm – 2013</th>
<th>North Error (m)</th>
<th>East Error (m)</th>
<th>Up Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matera</td>
<td>1.281 ± 1.566</td>
<td>0.413 ± 1.275</td>
<td>-1.760 ± 3.972</td>
</tr>
<tr>
<td>Noto</td>
<td>-0.223 ± 1.542</td>
<td>0.072 ± 1.362</td>
<td>-3.007 ± 3.634</td>
</tr>
<tr>
<td>Rabat</td>
<td>2.026 ± 3.099</td>
<td>-0.138 ± 1.476</td>
<td>0.197 ± 5.358</td>
</tr>
<tr>
<td>San Fernando</td>
<td>0.077 ± 2.453</td>
<td>-0.228 ± 1.372</td>
<td>-2.947 ± 4.915</td>
</tr>
</tbody>
</table>

**Figure 6.11:** Klobuchar model positioning solution: Table of North, East, Up Errors - average values and standard deviations of disturbed days analysed in 2013 - Stations: Matera, Cagliari, Noto, San Fernando, Rabat
<table>
<thead>
<tr>
<th>Station</th>
<th>North Error (m)</th>
<th>East Error (m)</th>
<th>Up Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cagliari</td>
<td>-0.528 ± 1.121</td>
<td>0.008 ± 0.749</td>
<td>-1.368 ± 2.729</td>
</tr>
<tr>
<td>Matera</td>
<td>0.452 ± 1.001</td>
<td>0.177 ± 0.798</td>
<td>-1.848 ± 2.156</td>
</tr>
<tr>
<td>Noto</td>
<td>-0.609 ± 1.380</td>
<td>-0.152 ± 0.826</td>
<td>-2.835 ± 2.795</td>
</tr>
<tr>
<td>Rabat</td>
<td>0.258 ± 1.353</td>
<td>0.016 ± 0.843</td>
<td>0.729 ± 2.690</td>
</tr>
<tr>
<td>San Fernando</td>
<td>-0.982 ± 1.335</td>
<td>0.227 ± 0.864</td>
<td>-3.705 ± 2.810</td>
</tr>
</tbody>
</table>

**Figure 6.12:** Bilinear interpolation with CODE maps positioning solution: Table of North, East, Up Errors - average values and standard deviations of quiet days analysed in 2012 - Stations: Matera, Cagliari, Noto, San Fernando, Rabat

<table>
<thead>
<tr>
<th>Station</th>
<th>North Error (m)</th>
<th>East Error (m)</th>
<th>Up Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cagliari</td>
<td>-0.641 ± 1.017</td>
<td>-0.043 ± 0.793</td>
<td>-0.120 ± 2.035</td>
</tr>
<tr>
<td>Matera</td>
<td>0.470 ± 0.818</td>
<td>-0.171 ± 0.760</td>
<td>-1.602 ± 1.733</td>
</tr>
<tr>
<td>Noto</td>
<td>-1.602 ± 1.002</td>
<td>-0.400 ± 1.162</td>
<td>-2.196 ± 2.122</td>
</tr>
<tr>
<td>Rabat</td>
<td>0.351 ± 1.451</td>
<td>0.750 ± 1.346</td>
<td>-0.848 ± 2.701</td>
</tr>
<tr>
<td>San Fernando</td>
<td>-1.476 ± 1.149</td>
<td>0.112 ± 0.857</td>
<td>-1.511 ± 2.241</td>
</tr>
</tbody>
</table>

**Figure 6.13:** Bilinear interpolation with CODE maps positioning solution: Table of North, East, Up Errors - average values and standard deviations of quiet days analysed in 2013 - Stations: Matera, Cagliari, Noto, San Fernando, Rabat
### Figure 6.14: Bilinear interpolation with CODE maps positioning solution: Table of North, East, Up Errors - average values and standard deviations of disturbed days analysed in 2012 - Stations: Matera, Cagliari, Noto, San Fernando, Rabat

<table>
<thead>
<tr>
<th>GIM - CODE Bilinear Interpolation – storm – 2012</th>
<th>North Error (m)</th>
<th>East Error (m)</th>
<th>Up Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cagliari</td>
<td>-0.794 ± 0.849</td>
<td>0.129 ± 0.637</td>
<td>-0.017 ± 1.940</td>
</tr>
<tr>
<td>Matera</td>
<td>0.356 ± 0.894</td>
<td>-0.020 ± 0.749</td>
<td>-1.358 ± 2.100</td>
</tr>
<tr>
<td>Noto</td>
<td>-1.249 ± 1.040</td>
<td>-0.287 ± 0.685</td>
<td>-1.322 ± 2.150</td>
</tr>
<tr>
<td>Rabat</td>
<td>1.142 ± 1.794</td>
<td>0.191 ± 1.240</td>
<td>1.047 ± 3.191</td>
</tr>
<tr>
<td>San Fernando</td>
<td>-2.850 ± 1.619</td>
<td>0.209 ± 0.972</td>
<td>-3.509 ± 3.676</td>
</tr>
</tbody>
</table>

### Figure 6.15: Bilinear interpolation with CODE maps positioning solution: Table of North, East, Up Errors - average values and standard deviations of disturbed days analysed in 2013 - Stations: Matera, Cagliari, Noto, San Fernando, Rabat

<table>
<thead>
<tr>
<th>GIM - CODE Bilinear Interpolation – storm – 2013</th>
<th>North Error (m)</th>
<th>East Error (m)</th>
<th>Up Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cagliari</td>
<td>-0.811 ± 1.211</td>
<td>0.346 ± 1.347</td>
<td>-0.899 ± 2.135</td>
</tr>
<tr>
<td>Matera</td>
<td>0.449 ± 0.876</td>
<td>0.091 ± 0.637</td>
<td>-1.983 ± 2.138</td>
</tr>
<tr>
<td>Noto</td>
<td>-1.379 ± 1.081</td>
<td>-0.409 ± 0.767</td>
<td>-4.677 ± 2.422</td>
</tr>
<tr>
<td>Rabat</td>
<td>0.536 ± 1.530</td>
<td>0.547 ± 1.371</td>
<td>-1.464 ± 3.062</td>
</tr>
<tr>
<td>San Fernando</td>
<td>-2.476 ± 1.610</td>
<td>0.636 ± 1.337</td>
<td>-4.798 ± 2.704</td>
</tr>
</tbody>
</table>
### Figure 6.16: Bilinear interpolation with EGNOS maps positioning solution: Table of North, East, Up Errors - average values and standard deviations of quiet days analysed in 2012 - Stations: Matera, Cagliari, Noto, San Fernando, Rabat

<table>
<thead>
<tr>
<th>EGNOS Bilinear Interpolation – quiet – 2012</th>
<th>North Error (m)</th>
<th>East Error (m)</th>
<th>Up Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cagliari</td>
<td>-0.400 ± 1.513</td>
<td>-0.244 ± 0.946</td>
<td>-0.780 ± 2.359</td>
</tr>
<tr>
<td>Matera</td>
<td>-0.558 ± 2.159</td>
<td>-0.178 ± 1.573</td>
<td>-1.684 ± 2.595</td>
</tr>
<tr>
<td>Noto</td>
<td>-0.987 ± 4.417</td>
<td>-0.194 ± 2.916</td>
<td>-1.143 ± 7.605</td>
</tr>
<tr>
<td>Rabat</td>
<td>0.168 ± 1.656</td>
<td>-0.160 ± 1.011</td>
<td>-0.482 ± 3.307</td>
</tr>
<tr>
<td>San Fernando</td>
<td>-0.921 ± 1.547</td>
<td>0.180 ± 0.743</td>
<td>-2.862 ± 3.617</td>
</tr>
</tbody>
</table>

### Figure 6.17: Bilinear interpolation with EGNOS maps positioning solution: Table of North, East, Up Errors - average values and standard deviations of quiet days analysed in 2013 - Stations: Matera, Cagliari, Noto, San Fernando, Rabat

<table>
<thead>
<tr>
<th>EGNOS Bilinear Interpolation – quiet – 2013</th>
<th>North Error (m)</th>
<th>East Error (m)</th>
<th>Up Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cagliari</td>
<td>0.256 ± 1.690</td>
<td>-0.349 ± 1.012</td>
<td>-0.206 ± 2.457</td>
</tr>
<tr>
<td>Matera</td>
<td>-0.643 ± 2.259</td>
<td>-0.348 ± 1.793</td>
<td>1.348 ± 3.001</td>
</tr>
<tr>
<td>Noto</td>
<td>-1.304 ± 3.916</td>
<td>0.235 ± 2.842</td>
<td>1.359 ± 5.832</td>
</tr>
<tr>
<td>Rabat</td>
<td>1.012 ± 1.795</td>
<td>1.342 ± 1.253</td>
<td>-0.398 ± 3.506</td>
</tr>
<tr>
<td>San Fernando</td>
<td>0.935 ± 1.688</td>
<td>0.732 ± 0.892</td>
<td>-2.112 ± 3.583</td>
</tr>
</tbody>
</table>
Figure 6.18: Bilinear interpolation with EGNOS maps positioning solution: Table of North, East, Up Errors - average values and standard deviations of disturbed days analysed in 2012 - Stations: Matera, Cagliari, Noto, San Fernando, Rabat

<table>
<thead>
<tr>
<th>EGNOS Bilinear Interpolation – storm – 2012</th>
<th>North Error (m)</th>
<th>East Error (m)</th>
<th>Up Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cagliari</td>
<td>-0.800 ± 1.201</td>
<td>-0.104 ± 1.109</td>
<td>0.528 ± 1.964</td>
</tr>
<tr>
<td>Matera</td>
<td>0.259 ± 1.870</td>
<td>-0.302 ± 1.002</td>
<td>-1.045 ± 2.743</td>
</tr>
<tr>
<td>Noto</td>
<td>-1.301 ± 2.562</td>
<td>-0.325 ± 1.803</td>
<td>-1.507 ± 5.092</td>
</tr>
<tr>
<td>Rabat</td>
<td>-0.008 ± 4.005</td>
<td>0.146 ± 3.142</td>
<td>0.002 ± 5.731</td>
</tr>
<tr>
<td>San Fernando</td>
<td>-1.754 ± 4.002</td>
<td>0.177 ± 2.973</td>
<td>-1.544 ± 6.228</td>
</tr>
</tbody>
</table>

Figure 6.19: Bilinear interpolation with EGNOS maps positioning solution: Table of North, East, Up Errors - average values and standard deviations of disturbed days analysed in 2013 - Stations: Matera, Cagliari, Noto, San Fernando, Rabat

<table>
<thead>
<tr>
<th>EGNOS Bilinear Interpolation – storm – 2013</th>
<th>North Error (m)</th>
<th>East Error (m)</th>
<th>Up Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cagliari</td>
<td>0.353 ± 1.302</td>
<td>0.235 ± 1.018</td>
<td>0.623 ± 2.011</td>
</tr>
<tr>
<td>Matera</td>
<td>0.253 ± 1.562</td>
<td>-0.456 ± 1.323</td>
<td>1.213 ± 4.112</td>
</tr>
<tr>
<td>Noto</td>
<td>0.947 ± 2.211</td>
<td>-0.211 ± 1.932</td>
<td>1.213 ± 4.112</td>
</tr>
<tr>
<td>Rabat</td>
<td>0.511 ± 4.565</td>
<td>0.342 ± 3.556</td>
<td>0.058 ± 5.432</td>
</tr>
<tr>
<td>San Fernando</td>
<td>1.234 ± 4.687</td>
<td>0.432 ± 2.833</td>
<td>0.911 ± 5.156</td>
</tr>
</tbody>
</table>
Figure 6.20: Positioning solution obtained replacing EGNOS not available grid data with CODE grid data: Table of North, East, Up Errors - average values and standard deviations of quiet days analysed in 2012 - Stations: Matera, Cagliari, Noto, San Fernando, Rabat

<table>
<thead>
<tr>
<th>Replacement NaN EGNOS data with CODE data – quiet – 2012</th>
<th>North Error (m)</th>
<th>East Error (m)</th>
<th>Up Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cagliari</td>
<td>0.544 ± 0.942</td>
<td>-0.082 ± 0.739</td>
<td>0.161 ± 2.395</td>
</tr>
<tr>
<td>Matera</td>
<td>0.448 ± 1.178</td>
<td>-0.030 ± 0.899</td>
<td>-1.353 ± 2.437</td>
</tr>
<tr>
<td>Noto</td>
<td>-0.779 ± 1.178</td>
<td>-0.311 ± 0.859</td>
<td>-0.522 ± 2.823</td>
</tr>
<tr>
<td>Rabat</td>
<td>0.246 ± 1.393</td>
<td>-0.060 ± 0.933</td>
<td>-0.455 ± 2.799</td>
</tr>
<tr>
<td>San Fernando</td>
<td>-0.939 ± 1.286</td>
<td>0.193 ± 0.781</td>
<td>-3.105 ± 2.770</td>
</tr>
</tbody>
</table>

Figure 6.21: Positioning solution obtained replacing EGNOS not available grid data with CODE grid data: Table of North, East, Up Errors - average values and standard deviations of quiet days analysed in 2013 - Stations: Matera, Cagliari, Noto, San Fernando, Rabat

<table>
<thead>
<tr>
<th>Replacement NaN EGNOS data with CODE data – quiet – 2013</th>
<th>North Error (m)</th>
<th>East Error (m)</th>
<th>Up Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cagliari</td>
<td>0.565 ± 1.002</td>
<td>-0.881 ± 1.211</td>
<td>0.581 ± 2.789</td>
</tr>
<tr>
<td>Matera</td>
<td>-0.033 ± 1.217</td>
<td>-0.211 ± 1.032</td>
<td>-1.411 ± 2.751</td>
</tr>
<tr>
<td>Noto</td>
<td>-0.698 ± 1.345</td>
<td>-0.321 ± 0.997</td>
<td>-0.891 ± 2.911</td>
</tr>
<tr>
<td>Rabat</td>
<td>0.251 ± 1.498</td>
<td>-0.311 ± 1.345</td>
<td>0.781 ± 2.981</td>
</tr>
<tr>
<td>San Fernando</td>
<td>-0.949 ± 1.300</td>
<td>0.327 ± 1.106</td>
<td>-4.002 ± 3.102</td>
</tr>
<tr>
<td>Replacement NaN EGNOS data with CODE data – storm – 2012</td>
<td>North Error (m)</td>
<td>East Error (m)</td>
<td>Up Error (m)</td>
</tr>
<tr>
<td>---------------------------------------------------------</td>
<td>-----------------</td>
<td>----------------</td>
<td>--------------</td>
</tr>
<tr>
<td>Cagliari</td>
<td>-0.837 ± 1.164</td>
<td>-0.291 ± 1.354</td>
<td>0.139 ± 2.312</td>
</tr>
<tr>
<td>Matera</td>
<td>0.312 ± 1.020</td>
<td>-0.299 ± 0.793</td>
<td>-0.749 ± 2.165</td>
</tr>
<tr>
<td>Noto</td>
<td>-1.870 ± 1.839</td>
<td>-0.455 ± 0.847</td>
<td>-1.287 ± 2.643</td>
</tr>
<tr>
<td>Rabat</td>
<td>0.952 ± 1.628</td>
<td>-0.244 ± 1.095</td>
<td>1.560 ± 3.812</td>
</tr>
<tr>
<td>San Fernando</td>
<td>-3.153 ± 2.658</td>
<td>-0.107 ± 2.087</td>
<td>-3.202 ± 2.811</td>
</tr>
</tbody>
</table>

**Figure 6.22:** Positioning solution obtained replacing EGNOS not available grid data with CODE grid data: Table of North, East, Up Errors - average values and standard deviations of disturbed days analysed in 2012 - Stations: Matera, Cagliari, Noto, San Fernando, Rabat

<table>
<thead>
<tr>
<th>Replacement NaN EGNOS data with CODE data – storm – 2013</th>
<th>North Error (m)</th>
<th>East Error (m)</th>
<th>Up Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cagliari</td>
<td>-0.563 ± 1.322</td>
<td>0.946 ± 1.109</td>
<td>-0.801 ± 2.753</td>
</tr>
<tr>
<td>Matera</td>
<td>0.569 ± 1.162</td>
<td>-0.901 ± 1.799</td>
<td>-1.642 ± 2.651</td>
</tr>
<tr>
<td>Noto</td>
<td>-1.452 ± 1.543</td>
<td>0.399 ± 1.989</td>
<td>-2.901 ± 2.799</td>
</tr>
<tr>
<td>Rabat</td>
<td>0.435 ± 1.603</td>
<td>0.599 ± 2.499</td>
<td>-1.697 ± 3.592</td>
</tr>
<tr>
<td>San Fernando</td>
<td>-2.998 ± 1.897</td>
<td>1.309 ± 2.507</td>
<td>-3.002 ± 3.050</td>
</tr>
</tbody>
</table>

**Figure 6.23:** Positioning solution obtained replacing EGNOS not available grid data with CODE grid data: Table of North, East, Up Errors - average values and standard deviations of disturbed days analysed in 2013 - Stations: Matera, Cagliari, Noto, San Fernando, Rabat
### Table 6.24: Positioning solution obtained smoothing EGNOS grid map with CODE grid map: Table of North, East, Up Errors - average values and standard deviations of quiet days analysed in 2012 - Stations: Matera, Cagliari, Noto, San Fernando, Rabat

<table>
<thead>
<tr>
<th>Smoothig of EGNOS data with CODE data – quiet – 2012</th>
<th>North Error (m)</th>
<th>East Error (m)</th>
<th>Up Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cagliari</td>
<td>-0.585 ± 2.096</td>
<td>-0.965 ± 2.354</td>
<td>-1.422 ± 3.023</td>
</tr>
<tr>
<td>Matera</td>
<td>0.256 ± 1.278</td>
<td>0.542 ± 2.142</td>
<td>-0.025 ± 3.963</td>
</tr>
<tr>
<td>Noto</td>
<td>0.254 ± 4.112</td>
<td>-0.752 ± 0.998</td>
<td>-1.235 ± 2.365</td>
</tr>
<tr>
<td>Rabat</td>
<td>2.147 ± 1.003</td>
<td>0.233 ± 2.236</td>
<td>2.363 ± 3.001</td>
</tr>
<tr>
<td>San Fernando</td>
<td>2.366 ± 2.333</td>
<td>1.358 ± 3.688</td>
<td>-2.278 ± 3.667</td>
</tr>
</tbody>
</table>

### Table 6.25: Positioning solution obtained smoothing EGNOS grid map with CODE grid map: Table of North, East, Up Errors - average values and standard deviations of quiet days analysed in 2013 - Stations: Matera, Cagliari, Noto, San Fernando, Rabat

<table>
<thead>
<tr>
<th>Smoothig of EGNOS data with CODE data – quiet – 2013</th>
<th>North Error (m)</th>
<th>East Error (m)</th>
<th>Up Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cagliari</td>
<td>1.236 ± 1.563</td>
<td>0.663 ± 1.478</td>
<td>0.997 ± 1.896</td>
</tr>
<tr>
<td>Matera</td>
<td>1.365 ± 1.256</td>
<td>0.236 ± 2.223</td>
<td>1.365 ± 2.001</td>
</tr>
<tr>
<td>Noto</td>
<td>1.423 ± 2.112</td>
<td>-0.125 ± 2.396</td>
<td>-1.254 ± 2.336</td>
</tr>
<tr>
<td>Rabat</td>
<td>-0.236 ± 2.569</td>
<td>-2.531 ± 5.258</td>
<td>1.228 ± 3.569</td>
</tr>
<tr>
<td>San Fernando</td>
<td>1.236 ± 2.563</td>
<td>-0.129 ± 3.367</td>
<td>-1.569 ± 5.751</td>
</tr>
</tbody>
</table>
### Figure 6.26
Positioning solution obtained smoothing EGNOS grid map with CODE grid map: Table of North, East, Up Errors - average values and standard deviations of disturbed days analysed in 2012 - Stations: Matera, Cagliari, Noto, San Fernando, Rabat

<table>
<thead>
<tr>
<th>Smoothing of EGNOS data with CODE data – storm – 2012</th>
<th>North Error (m)</th>
<th>East Error (m)</th>
<th>Up Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cagliari</td>
<td>0.256 ± 1.267</td>
<td>1.236 ± 2.451</td>
<td>1.658 ± 2.654</td>
</tr>
<tr>
<td>Matera</td>
<td>1.239 ± 2.458</td>
<td>1.478 ± 2.654</td>
<td>-0.254 ± 2.685</td>
</tr>
<tr>
<td>Noto</td>
<td>2.541 ± 1.236</td>
<td>-0.124 ± 2.587</td>
<td>-0.237 ± 2.659</td>
</tr>
<tr>
<td>Rabat</td>
<td>2.798 ± 2.967</td>
<td>1.112 ± 3.965</td>
<td>-0.298 ± 3.658</td>
</tr>
<tr>
<td>San Fernando</td>
<td>2.659 ± 1.236</td>
<td>-3.658 ± 5.369</td>
<td>1.598 ± 5.648</td>
</tr>
</tbody>
</table>

### Figure 6.27
Positioning solution obtained smoothing EGNOS grid map with CODE grid map: Table of North, East, Up Errors - average values and standard deviations of disturbed days analysed in 2013 - Stations: Matera, Cagliari, Noto, San Fernando, Rabat

<table>
<thead>
<tr>
<th>Smoothing of EGNOS data with CODE data – storm – 2013</th>
<th>North Error (m)</th>
<th>East Error (m)</th>
<th>Up Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cagliari</td>
<td>1.236 ± 2.456</td>
<td>-1.459 ± 2.365</td>
<td>0.125 ± 2.598</td>
</tr>
<tr>
<td>Matera</td>
<td>2.365 ± 2.159</td>
<td>1.297 ± 2.659</td>
<td>-1.958 ± 2.122</td>
</tr>
<tr>
<td>Noto</td>
<td>-2.695 ± 3.165</td>
<td>1.297 ± 4.269</td>
<td>2.365 ± 5.998</td>
</tr>
<tr>
<td>Rabat</td>
<td>2.695 ± 3.698</td>
<td>-0.258 ± 2.125</td>
<td>-3.659 ± 5.698</td>
</tr>
<tr>
<td>San Fernando</td>
<td>-3.625 ± 3.236</td>
<td>-1.999 ± 4.699</td>
<td>-2.659 ± 6.998</td>
</tr>
</tbody>
</table>
Appendix B: Acronyms

ABAS - Airborne Based Augmentation Systems
AOR E - Atlantic Ocean Region East
ASQF - Application Specific Qualification Facility
CDDS - Commercial Data Distribution Service
CNES - Centre National dEtudes Spatiales
CODE - Center for Orbit Determination in Europe
CME - Coronal Mass Ejection
CPF Central Processing Facility
DAT - Data Analysis Tool
DGPS - Differential GPS
DoD - Department of Defence
DOP - Dilution of Precision
DPC - Data Processing Core
Dst - Disturbance Storm Time
DU - Do not Use
ECAC - European Civil Aviation Conference
EDAS - EGNOS Data Access System
EGNOS - European Geostationary Navigation Overlay Service
ENT - EGNOS Network Time
ESA - European Space Agency
ESSP - European Satellite Services Provider
EWAN - EGNOS Wide Area Network
GAGAN - GPS And GEO Augmented Navigation
GAGE - Group of Astronomy and Geomatics
GBAS - Ground Based Augmentation System
GDOP - Geometric Dilution Of Precision
GEO - Geostationary Satellite
GIC - Ground Integrity Channel
GIM - Global Ionospheric Maps
GIVD - Grid Ionospheric Vertical Delay
GIVE - Grid Ionospheric Vertical Error
GIVEi - GIVE indicator
gLAB - GNSS Laboratory
GLONASS - Globalnaya Navigatsionnaya Sputnikovaya Sistema
GNSS - Global Navigation Satellite System
GPS - Global Positioning System
GUI - Graphical User Interface
HAL - Horizontal Alert Limit
HDOP - Horizontal Dilution of Precision
HPL - Horizontal Protection Level
ICAO - International Civil Aviation Organization
ID - Identifier
IEA - Ionospheric Equatorial Anomaly

IGP - Ionospheric Grid Point

IGS - International GNSS Service

IODE - Issue Of Data Fast Ephemeris

IODI - Issue of Data Ionosphere

IODP - Issue Of Data PRN

IONEX - IONosphere map EXchange

IOR W - Indian Ocean Region West

IPP - Ionospheric Pierce Point

ITU - International Telecommunications Union

LSVA - Latitudinal Spatial Variability Analysis

MCC - Monitoring and Control Center

MOPS 229D - Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment version D

MSAS - Multi-functional Satellite Augmentation System MT0 Message Type 0

MT - Message Type

NAVSTAR GPS - NAVigation System with Time And Ranging Global Positioning System

NLES - Navigation Land Earth Station

NM - Not Monitored

OS - Open Service

PACF - Performances Assessment And Check out Facility
PDOP - Position Dilution of Precision
PPP - Precise Point Positioning
PPS - Precise Positioning Service
PRN - Pseudo Random Noise (satellite identifier)
PRC - Pseudo Range Correction
PVT - Position Velocity and Time
RAIM - Receiver Autonomous Integrity Monitoring
RF - Radio Frequency
RIMS - Ranging and Integrity Monitoring Stations
RINEX - Receiver INdependant Exchange
RTCA - Radio Technical Commission for Aeronautics
RTCM - Radio Technical Commission for Maritime Services
RTK - Real-Time Kinematic
SA - Selective Availability
SBAS - Satellite Based Augmentation System
SIS - Signal In Space
SISNeT - Signal In Space through the interNET
SOL - Safety Of Life
SPS - Standard Positioning Service
TDOP - Time Dilution of Precision
TEC - Total Electron Content
TTA - Time To Alarm
TTL - Transistor to Transistor Logic
TVA - Temporal Variability Analysis
UDRE - User Differential Range Error
UDREI - User Differential Range Error Indicator
UERE - User Equivalent Range Error
UTC - Universal Time Coordinated
UTM - Universal Transverse Mercator
VAL - Vertical Alarm Limit
VDOP - Vertical Dilution of Precision
VHF - Very High Frequency
VPL - Vertical Protection Level
WAAS - Wide Area Augmentation System
WAD - Wide Area Differential
WGS84 - World Geodetic System 1984
Acknowledgement

This thesis could not have been realized without the support of many people met during these four years of PhD.

First of all I would like to thank my beloved family for love, patience, hope and kindness: without you I would not be here.

I would like to thank my supervisors for giving me the opportunity to perform my PhD research, for their support and their help in order to finalize this work.

I also express my deepest gratefulness to the wonderful people I have met in Toulouse: wonderful not only for work but also for their kindness and love for science. Always thanks for encouraging me!

I am deeply gratitude to my new colleagues for their great patience all those days before my thesis deadline. I know I was terrible!

I would like to thank all my friends for supporting me during these years; especially my best friend for her help, support, time and kindness she gave me.

Maybe in this thesis you can see just science, physics, formulas but there are many more things. I see people who have faith in me, I see opportunities to improve my life, I see the kindness of many smiles I met around the world. This PhD has been very intense, good and bad periods alternate these four years. But as I look back on my life, I realize that every time I thought I was being rejected from something good, I was actually being redirected to something better. So smile to life and life will smile to you!