Use of precise point positioning techniques in GNSS applications

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1 Abstract

Geodesy is the science in charge of accurately measuring and understanding the Earth’s geometric shape, orientation in space, and gravitational field. The field also incorporates studies of how these properties change over time and equivalent measurements for other planets. Geodetic phenomena include crustal motion, tides and polar motion, amongst other effects. All these phenomena ranges between tenths of a millimeters to a few millimeters. Therefore, we need very precise geodetic techniques to successfully measure and quantify these effects.

GNSS is one of the most prolific and important geodetic techniques in order to perform these measurements. A Global Navigation Satellite System uses satellites to provide autonomous geospatial positioning. It allows receivers to determine their location to high precision by using time signals transmitted from satellites. And to do so as precise as possible, carrier phase measurements are the best way to go, and the reason why they are used for geodetic applications, where the millimeter level is required. Nevertheless, this technique yields a problem that is related to the number of cycles (or wavelengths) between the satellite and the receiver: they cannot be measurable. This is called integer ambiguity, and needs to be fixed. Although historically such ambiguity has been fixed on double differenced GNSS phase measurements, an alternative called Precise Point Positioning (PPP) is also possible. In this technique, undifferenced phase measurements are used in combination with precise orbits and clocks to eventually solve the integer ambiguity and produce precise measurements. If this happens, then it is called Integer-PPP, or IPPP by its acronym.

This project will then try to use this technology by making use of the GINS tool, a precise orbitography software applied to space geodesy, developed and maintained by the CNES Space Geodesy team for its research activities in the Groupe de Recherche en Géodésie Spatiale (GRGS). With its help, a series of analysis in order to compare different geodetic models, alignments, orbit and clock products will be conducted.

As for the contents, a theoretical introduction to space geodesy and the four most important geodetic techniques are presented firstly. Then, we will be focusing on GNSS, its working principle and everything that is ultimately related to the Precise Point Positioning technique. Following that, a quick introduction to the different software tools that were used in order to carry out all the studies and analysis is done, right before showing the pertinent analysis and their corresponding results. Finally, the conclusions and future work and research that can still be done will be presented.
La géodésie est la science chargée de mesurer et de comprendre avec précision la forme géométrique, l'orientation dans l'espace et le champ gravitationnel de la Terre. Le champ comprend également des études sur l'évolution de ces propriétés dans le temps et des mesures équivalentes pour d'autres planètes. Les phénomènes géodésiques incluent le mouvement de la croûte terrestre, les marées et le mouvement polaire, entre autres effets. Tous ces phénomènes vont de quelques dixièmes de millimètres à quelques millimètres. Par conséquent, nous avons besoin de techniques géodésiques très précises pour mesurer et quantifier avec succès ces effets.

Le GNSS est l'une des techniques géodésiques les plus prolifiques pour effectuer ces mesures. Un système mondial de navigation par satellite, ou GNSS pour ses sigles en anglais, utilise des satellites pour fournir un positionnement géospatial autonome. Il permet aux récepteurs de déterminer leur position avec une grande précision en utilisant les signaux horaires transmis par les satellites. Et pour que cela soit aussi précis que possible, les mesures de la phase porteuse sont la meilleure façon de procéder, et sont la raison pour laquelle elles sont utilisées pour des applications géodésiques, où le niveau millimétrique est requis. Néanmoins, cette technique pose un problème lié au nombre de cycles (ou longueurs d'onde) entre le satellite et le récepteur: ils ne peuvent pas être mesurables. Ceci est appelé ambiguïté entière et doit être corrigé. Bien que, dans le passé, cette ambiguïté ait été corrigée pour les mesures de phase GNSS à double différenciation, une alternative appelée Precise Point Positioning (PPP) est aussi possible. Dans cette technique, les mesures de phase indifférenciées sont utilisées en association avec des orbites et des horloges précises pour résoudre l'ambiguïté des nombres entiers et produire des mesures précises. Si cela se produit, il s'appelle alors Integer-PPP, ou IPPP pour son sigle en anglais.

Ce projet tentera ensuite d'évaluer cette technologie en utilisant l'outil GINS, un logiciel d'orbitographie précis appliqué à la géodésie spatiale, développé et mis à jour par l'équipe de géodésie spatiale du CNES pour ses activités de recherche dans le cadre du Groupe de Recherche en Géodésie Spatiale (GRGS). Avec son aide, une série d'analyses afin de comparer différents modèles géodésiques, alignements, orbites et horloges seront réalisées.

Quant au contenu, une introduction théorique à la géodésie spatiale et les quatre techniques géodésiques les plus importantes sont présentées. Ensuite, nous nous concentrerons sur le GNSS, son principe de fonctionnement et tout ce qui est finalement lié à la technique de positionnement précis de points. Ensuite, une introduction rapide aux différents outils logiciels utilisés pour mener à bien toutes les études et analyses est faite, juste avant de montrer l'analyse pertinente et les résultats correspondants. Enfin, les conclusions, les recherches potentielles futures et les travaux pouvant encore être effectués seront présentés.
2 Motivation and objectives of the internship

The internship on which this project is part of the activities that are carried out by the Groupe de Recherche de Géodésie Spatiale (GRGS), in the Géosciences Environnement Toulouse (GET) laboratory that belongs to the Observatoire Midi-Pyrénées (OMP), in Toulouse, France. The team that I have been working with for the past six months covers a broad spectrum of skills in highly complementary fields of study of the field of gravity, GNSS positioning, surface deformations or the internal structure of the Earth amongst others. This work is also set within the context of the CNES Analysis Center, which is responsible for providing daily geodetic products from a global network of stations. In particular, in 2020, the team will contribute to a massive historical GNSS data reprocessing campaign called repro3, with the aim of providing international services and users with improved geodetic products.

The motivations behind this thesis contemplates the work that has and is being done in the group, as well as the future that resides particularly with the arrival of Galileo. As previously mentioned, GNSS is the most important source of information for geodetic applications, but as any other technique, it has errors. In this context, Galileo has become an opportunity to compare the solutions and errors that both systems yield in order to produce better results, from a better understanding of the impact of different geodetic models to more precise and accurate orbit and clock products. A gain in performance is anticipated on one hand because of the features of the signals transmitted and on the other hand because of the possibilities of hybridization between GPS and Galileo. Multi-GNSS analysis are becoming very interesting approaches, and along with techniques such as PPP or IPPP, the results that are being produced are more and more accurate every time.

Ultimately, the main objective of this thesis is to improve the positioning by modelling physical phenomena and testing new products. Precise point positioning techniques in GNSS applications will be evaluated, with a key interest in Galileo, in such a way that we can quantify its contribution to fundamental geodetic studies. All this can be addressed through, for example:

- The analysis of the solutions of the various estimated parameters such as station coordinates, orbits, orientation of the Earth at long periods and the impact on the realization of a terrestrial frame, such as the ITRF.
- The study of the origin and the reduction of errors impacting the geodetic products at different periods, by looking, for example, at the noise level, the percentage of ambiguities fixed or the residuals.

To do so, the GINS scientific software will be widely used (see point 5.1 for further explanation) and complemented with SARI (point 5.2). With these two tools, we will be able to retrieve the solutions that we are interested in (station coordinate corrections with respect to the a priori ones), for both GPS and Galileo, whether it is for PPP or IPPP. To analyse and evaluate the results, we will compute not only the temporal evolution of the corrections, but also the periodograms, in order to see possible periodic events in the time series. This can be very helpful to observe the behaviour of different geodetic models, alignments or orbit and clock products, but also to detect errors related to those features.
3 Introduction to space geodesy

3.1 What is geodesy?

Earth observation is fundamental to addressing scientific challenges pertaining to the quantification of changes that are affecting the Earth system. How is the Earth deforming due to plate tectonics, crustal motion, tides or current ice melting? How to accurately determine point positions at the Earth surface that is constantly deforming? What is the rate of sea level rise? Geodesy is the science discipline in charge of accurately measuring and understanding the Earth’s geometric shape, orientation in space, and its gravitational field. It also provides the standard in which the changes and their variability are quantified and properly referenced. In order to answer these scientific questions, fundamental to understanding the Earth dynamics, it is critically important to ensure the continuous availability and updates of an accurate, long-term stable and truly global Terrestrial Reference Frame, such as the International Terrestrial Reference Frame (ITRF).

3.2 International standards and organizations

The International Association of Geodesy (IAG), along with its Global Geodetic Observing System (GGOS) service, foster the development of geodetic activities and infrastructure in all regions of the world. Another important organization is the International Earth Rotation and Reference Systems Service (IERS), which is responsible for maintaining global time and reference frame standards, notably through its Earth Orientation Parameter (EOP) and International Celestial and Terrestrial Reference Frames (ICRF and ITRF). The GGOS enables research in three fundamental areas of geodesy:

- The geometric shape of the Earth as well as its variation in time.
- The orientation of the Earth in inertial space as a function of time.
- The Earth’s gravity field and its temporal variations.

3.3 Celestial and Terrestrial frames

In physics, a frame of reference (or reference frame) consists of an abstract coordinate system and the set of physical reference points that uniquely fix (locate and orient) the coordinate system and standardize measurements. The International Earth Rotation and Reference Systems Service (IERS) was created in 1988 to establish and maintain a reference frame with the help of the ICRF and ITRF. The Earth Orientation Parameters (EOP) connect these two frames together. These frames provide a common reference to compare observations and results from different locations.

In our study case, we are interested only in the ITRF, which is the realization of the International Terrestrial Reference System (ITRS). The Earth is constantly changing shape, so in order to understand it, it must be referenced. The ITRF provides a set of coordinates of some points located on the Earth’s surface. It can be used to measure plate tectonics, tides, crust deformation and Earth’s rotation in space.
Nowadays, four main geodetic techniques are used to compute accurate coordinates: VLBI, SLR, GNSS and DORIS. Since such techniques are evolving and the period of data available increases with time, the ITRF is constantly being updated. 11 realizations of the ITRF have been set from 1988, being the ITRF2014 the latest update. It has been generated with an enhanced modeling of nonlinear station motions, including seasonal (annual and semiannual) signals of station positions and postseismic deformation for sites that were subject to major earthquakes. ITRF2014 is demonstrated to be superior to past ITRF releases, as it precisely models the actual station trajectories leading to a more robust secular frame and site velocities. The ITRF2014 long-term origin coincides with the Earth system center of mass. The estimated accuracy of the ITRF2014 origin is at the level of less than 3 mm at epoch 2010.0 and less than 0.2 mm/yr in time evolution, according to Z. Altamimi et al. (2016).

3.4 Space geodetic techniques

3.4.1 Very-long-baseline interferometry (VLBI)

Very-long-baseline interferometry (VLBI) is a type of astronomical interferometry used in radio astronomy. In VLBI a signal from an astronomical radio source, such as a quasar, is collected at multiple radio telescopes on Earth. The distance between the radio telescopes is then calculated using the time difference between the arrivals of the radio signal at different telescopes. This allows observations of an object that are made simultaneously by many radio telescopes to be combined, emulating a telescope with a size equal to the maximum separation between the telescopes.

VLBI is best known for imaging distant cosmic radio sources, spacecraft tracking, and for applications in astrometry. However, since the VLBI technique measures the time differences between the arrival of radio waves at separate antennas, it can also be used “in reverse” to perform earth rotation studies, precise map movements of tectonic plates, and other types of geodesy. Using VLBI in this manner requires large numbers of time difference measurements from distant quasars observed with a global network of antennas over a period of time.

The International VLBI Service for Geodesy and Astrometry (IVS) is an international collaboration whose purpose is to use the observation of astronomical radio sources using VLBI to precisely determine Earth Orientation Parameters (EOP) and the International Celestial and Terrestrial Reference Frames or ICRF and ITRF by their acronyms.

3.4.2 Satellite Laser Ranging (SLR)

Satellite Laser Ranging (SLR) and Lunar Laser Ranging (LLR) use short-pulse lasers and state-of-the-art optical receivers and timing electronics to measure the two-way time of flight (and hence distance) from ground stations to retroreflector arrays on Earth orbiting satellites and the Moon. SLR and LLR are proven geodetic techniques with significant potential for important contributions to scientific studies of the earth/atmosphere/ocean system.
The International Laser Ranging Service (ILRS) is an established service whose primary objective is to provide a service to support, through Satellite and Lunar Laser Ranging data and related products, geodetic and geophysical research activities including precise geocentric positions and motions of ground stations, satellite orbits, components of Earth’s gravity field and their temporal variations, Earth Orientation Parameters (EOP), precise lunar ephemerides and information about the internal structure of the Moon.

### 3.4.3 DORIS

Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) is a French satellite system used for the determination of satellite orbits. The idea is that ground-based radio beacons emit a signal which is picked up by receiving satellites. Then, a frequency shift of the signal occurs due to the movement of the satellite (Doppler effect). From this observation, satellite orbits, ground positions as well as other parameters can be derived. The ground segment includes about 50-60 ground stations, equally distributed over the earth and ensure a good coverage for orbit determination. The best known satellites equipped with DORIS receivers are the altimetry satellites TOPEX/Poseidon, Jason 1, Jason 2, and Jason 3. They are used to observe the ocean surface as well as currents or wave heights.

The International DORIS Service (IDS), as any other geodetic technique, is a service that provides support, through DORIS data and data products, to geodetic and geophysical research activities. The IDS collects, archives and distributes DORIS observation data sets of sufficient accuracy to satisfy the objectives of a wide range of applications. From these data sets, products such as coordinates and velocities of the IDS tracking stations, improvement of the ITRF, ionospheric information, high accuracy ephemerides of DORIS satellites and EOP can be derived.

### 3.4.4 Global Navigation Satellite System (GNSS)

A satellite navigation system uses satellites to provide autonomous geospatial positioning. It allows receivers to determine their location (longitude, latitude, and altitude/elevation) to high precision using time signals transmitted along a line of sight by radio from satellites. The signals also allow the receiver to calculate the current local time to high precision, which allows time synchronisation.

A satellite navigation system with global coverage may be termed a Global Navigation Satellite System (GNSS). As of October 2018, the US’ GPS and Russia’s GLONASS are fully operational systems, with China’s BeiDou and the European Union’s Galileo systems scheduled to be fully operational by 2020. Global coverage for each system is generally achieved by a constellation of 18–30 medium Earth orbit (MEO) satellites spread between several orbital planes. The actual systems vary, but use orbital inclinations of around 50° and orbital periods of roughly twelve hours.

GNSS systems were originally designed for Earth-based positioning and navigation. However, these systems offer important contributions in a variety of scientific research domains, such as Geodesy and Geodynamics, Precise Orbit Determination, Remote Sensing, Satellite Realtime Navigation and Timing, Land Surveying and
more. The service that provides the means to use GNSS data is the International GNSS Service (IGS) that nowadays has a fundamental contribution to the overall GNSS community since provides the highest quality data and products as the standard for GNSS. As a component of the Global Geodetic Observing System, the IGS operates a global network of GNSS ground stations (see Figure 1), data centers, and data analysis centers to provide data and derived data products that are essential for Earth science research. IGS products include GNSS satellite ephemerides, EOPs, global tracking station coordinates and velocities, satellite and tracking station clock information, zenith tropospheric path delay estimates and global ionosphere maps. These products support Earth science analyses and other efforts, such as:

- Improving and extending the International Terrestrial Reference Frame (ITRF) maintained by the International Earth Rotation and Reference Systems Service (IERS).
- Monitoring deformation of the Earth as well as its rotation.
- Monitoring the troposphere and ionosphere.
- Determining orbits of scientific satellites.

Figure 1: IGS network of ground stations
4 GNSS positioning working principle

Navigation satellites work on the principle of trilateration. Position of an object is determined by its latitude, longitude on the spheroid and height above Mean Sea Level. If at the time of measurement, the instantaneous position of three satellites are known and the distance of the point of measurement from each of these three satellites is known, then the latitude, longitude and height of the point can be determined using simple distance formula. In practice, a fourth satellite is needed to adjust for timing biases. Each distance measurement, regardless of the system being used, places the receiver on a spherical shell at the measured distance from the broadcaster. By taking several measurements and then looking for a point where they meet, a fix is generated. Satellite navigation receivers must also take into account relativistic considerations as well as the effect of the ionosphere and troposphere. This can be done by using combinations of signals from multiple satellites and correlators.

Also, without the ability to condense the huge amount of data into a manageable number of components, GNSS processors would be overwhelmed. That is why estimators are used in the uploading process to reduce the data to the satellite clock offset and drift, 6 orbital parameters, 3 solar radiation pressure parameters, biases of the monitoring stations clock, and a model of the tropospheric effect and earth rotational components. Most, if not all, GNSS receivers compute their positions using Kalman filtering or least-squares estimation algorithms. Basically, least-squares is based on minimizing the measurement residuals (i.e., the difference between the actual and predicted measurements) whereas the Kalman filter is derived based on minimizing the mean-square error of the solution.

4.1 Code measurements vs. Carrier phase measurements

In the case of code measurements, a GPS receiver determines the travel time of a signal from a satellite by comparing the "pseudo random code" it is generating, with an identical code in the signal from the satellite. The receiver "slides" its code later until it syncing up with the satellite’s code. The amount it has to slide the code is equal to the signal’s travel time. The problem is that the pulses (or cycles) of the pseudo random code are so wide they are not perfectly synced. As a result, code measurements are precise to the meter level.

The carrier phase measurement is much precise since its pulses/cycles are much closer together and therefore can lead to more accurate results. The pseudo random code has a bit rate of about 1 MHz but its carrier frequency has a cycle rate of over a GHz. At the speed of light, the 1.57 GHz L1 GPS signal has a wavelength of 19 centimeters, so the carrier signal can act as a much more accurate reference than the pseudo random code itself. That is why carrier phase measurements are used for geodetic applications, in which the millimeter level is required. However, the whole number of cycles between satellite and receiver is not measurable, leading to an ambiguity called integer ambiguity that needs to be fixed.
4.2 Ambiguity fixing of the carrier phase measurements

Ambiguity fixing to integer numbers of the phase measurements has been proven to enhance the accuracy of GNSS data processing. Up until now there are two strategies to achieve ambiguity resolution: by forming double differences and by using undifferenced phase measurements. In this case, we will be focusing on the latter.

The undifferenced ambiguity fixing method is based on the following model of equations for code ($P_i$ and $P_j$) and carrier phase ($L_i$ and $L_j$) (Laurichesse et al., 2009 and Katsigianni et al., 2019):

\[
\begin{align*}
P_i &= D_{P_i} + e + \Delta h_P + \Delta \tau_P \\
P_j &= D_{P_j} + \gamma e + \Delta h_P + \gamma \Delta \tau_P \\
\lambda_i L_i &= D_{L_i} + \lambda_i W - e + \Delta h_L + \Delta \tau_L - \lambda_i N_i \quad (1c) \\
\lambda_j L_j &= D_{L_j} + \lambda_j W - \gamma e + \Delta h_L + \gamma \Delta \tau_L - \lambda_j N_j \\
\end{align*}
\]

where

- $D_{P_i}$, $D_{L_i}$, $D_{P_j}$ and $D_{L_j}$ are the geometrical propagation distances between the satellite and the receiver for code and carrier phase measurements, for two frequencies $f_i$ and $f_j$ respectively.
- $\lambda_i$ and $\lambda_j$ are the wavelengths for each frequency and $\gamma = \lambda_j^2/\lambda_i^2 = f_i^2/f_j^2$.
- $e$ is the ionospheric delay.
- $\Delta h_P$ and $\Delta h_L$ are ionosphere-free phase clock differences between the satellite and the receiver for code and carrier phase measurements respectively.
- $\Delta \tau_P$ and $\Delta \tau_L$ are the offset differences between the satellite and the receiver for code and carrier phase measurements (Loyer et al., 2012, Laurichesse and Mercier, 2007, Collins, 2008).
- $W$ is the phase wind-up effect contribution (in cycles).
- $N_i$ and $N_j$ are the carrier phase ambiguities (in cycles).

From these four equations it is possible to form a Melbourne-Wübbena linear combination that has the identity to reduce measurement noise and cancel out any geometric, ionospheric and clock terms. This combination can be written as follows (Loyer et al., 2012 and Katsigianni et al., 2019):

\[
MW = \lambda_{WL}(L_j - L_i) - \lambda_{NL}(P_i/\lambda_i + P_j/\lambda_j) = \lambda_{WL}(N_{WL} + WSB - WRB) 
\]  \hspace{1cm} (2)

where

- $\lambda_{WL} = c/(f_i-f_j)$ is the wide-lane wavelength.
- $\lambda_{NL} = c/(f_i+f_j)$ is the narrow-lane wavelength.
- \( N_{WL} = N_j - N_i \) is the wide-lane ambiguity, and according to Laurichesse et al. (2009) is an integer number.

- WSB are the WL satellite biases.

- WRB are the WL receiver biases.

It has been observed that WSB are stable over long periods of time for the GPS system satellites and can be considered as constant during at least one day (Mercier and Laurichesse et al., 2007). If enough satellites are in visibility, WSB can be estimated at each epoch and \( N_{WL} \) can be fixed to an integer value.

The next step is to form an ionosphere-free linear combination for code and carrier phase measurements (Loyer et al., 2012 and Katsigianni et al., 2019):

\[
\frac{\gamma P_i - P_j}{\gamma - 1} = \frac{\gamma D_{Pi} - D_{Pj}}{\gamma - 1} + \Delta h_P \tag{3a}
\]

\[
\frac{\gamma \lambda_i L_i - \lambda_j L_j - \lambda_j N_{WL}}{\gamma - 1} = \frac{\gamma D_{Li} - D_{Lj}}{\gamma - 1} + \lambda_{NL} W + \Delta h_L - \lambda_{NL} N_i \tag{3b}
\]

Then \( N_i \), which is the narrow-lane ambiguity (in cycles) is solved using the satellite constellation and a global network of stations. After the convergence of the global problem which includes satellite orbits, clocks and dynamic parameters, receiver clocks, tropospheric and ambiguity unknowns to float solutions, the corresponding linear system of equations is stored. Then the system of equations is reduced and only the ambiguities unknowns are kept. Finally, such system is solved and float ambiguities are fixed to integers by applying a bootstrapping method. The whole procedure is explained as a flowchart diagram in Figure 2.

![Figure 2: Procedure to fix ambiguities to integer values in undifferenciated phase measurements](image-url)
4.3 Precise Point Positioning (PPP)

Integer ambiguity resolution is routinely applied on double differenced GNSS phase measurements to achieve precise positioning. Double-differencing is very powerful because it removes most of the common errors between the different signal paths, including biases, making it easier to identify integer ambiguities. It also minimizes the size of the problem to be solved by removing all the clock contributions. This technique is the basis for very precise differential positioning. Precise Point Positioning (PPP) is an alternative approach to perform precise positioning. In this technique, undifferenced phase measurements are used in combination with precise orbits and clocks. The performance of the method is directly related to the quality of these input orbits and clocks, which are computed using data collected over a world-wide network of stations. PPP is a very powerful tool, in particular to track moving receivers.

It was until very recently though when PPP was able to directly fix integer ambiguities on zero-difference phase measurements. As previously described, the process is a two steps procedure. First of all, the difference of the two ambiguities (one for each frequency) is first fixed using the four observables from which the Melbourne-Wubbena combination is formed. Then, the remaining ambiguity is fixed in a global network solution, using the models and the ionosphere-free combination. When the ambiguities are fixed to integer values, this technique can be referred as Integer-PPP or IPPP.
5 Software tools

Over the course of the internship, I have made use of two software tools: GINS and SARI. Both of them are briefly described below:

5.1 GINS scientific software

The GINS software (Géodésie par Intégrations Numériques Simultanées) is a tool developed and maintained by the CNES Space Geodesy team for its research activities within the framework of the Space Geodesy Research Group (GRGS). It is a precise orbitography software applied to space geodesy that allows the restitution of many geodetic or physical parameters accessible by space observations. These parameters are of three types:

1. Geometrical (such as station and geocenter positions, rotation parameters of the Earth or planets)

2. Dynamics (such as the spherical harmonic coefficients of the gravity field or the tides, the coefficients of the surface forces, the parameters of the thermosphere, the thermo-optical characteristics of the satellite)

3. Measurement (such as corrections of tropospheric delay, dating, frequency)

For example, all the different geodetic models (ocean loading, solid tides, pole tides, atmospheric loading) and some other features such as orbit and clock products, sampling time and weighting or station a priori coordinates are specified in the director file within the GINS software, as shown in Figure 3 and 4.

![Figure 3: Director file in GINS](image)
A director file is generated every time a RINEX file is executed with the GINS function “exe.ppp”. In the field of geodesy, a RINEX file is an interchange format for raw satellite navigation system data. This allows the user to post-process the received data to produce a more accurate result. It is universal acceptable as it is a receiver independent. These RINEX files can be downloaded from the Internet and they are produced for every station on a daily basis. The most recent version of these files is v3.

GINS also includes a process of numerical integration of the differential equations of the movement of a satellite or a constellation of satellites in an inertial frame, taking into account all the gravitational and surface forces acting on the satellite as well as the specified attitude movement of the satellite according to its macro-model. It also allows the least-squares adjustment of the ephemerides and other parameters produced thanks to different geodetic techniques such as GNSS, DORIS, SLR or altimetry. GINS is a planetary geodesy tool too, so it can calculate the trajectory of an artificial satellite around any body in the solar system.
5.2 SARI. Interactive GNSS position time series analysis software

As specified in A. Santamaría-Gomez et al. (2019), GNSS position time series contain signals induced by Earth deformation, but also by systematic errors at different time scales, from sub-daily tidal deformation to inter-annual surface-loading deformation and secular tectonic plate rotation. This software allows users to visualize GNSS position time series, but also any other series, and interactively remove outliers and discontinuities, fit models and save the results. A comprehensive list of features is included to help the user extracting relevant information from the series, including spectral analysis with the Lomb–Scargle periodogram and wavelet transform, signal filtering with the Kalman filter and the Vondrák smoother, and estimation of the time-correlated stochastic noise of the residuals. The software can be run on a local machine if all the package dependencies are satisfied or remotely via a public web server with no requirement other than having Internet connection.
6 Analysis and results

6.1 1st analysis: Ocean loading model comparison

This first analysis consists in studying and comparing the corrected station coordinates of the BRUX station, in Brussels. We will consider two different ocean loading models (fes2014.cf and got4.10c, in order to make the comparison), but also solid tides and pole tides. Ocean loading is a secondary tidal effect due to the elastic response of the Earth’s crust to ocean tides, producing deformation of the sea floor and a surface displacement of an adjacent land. This study is a GPS static analysis of a time series in which the float solutions (PPP) will be presented.

6.1.1 Methodology

The methodology that has been followed consists in doing a GNSS processing with GINS and SARI. First of all, we need to specify the time span under study. In this case, it will consist of two years of observations, between mid-2017 and mid-2019 (24500 and 25229 JD). With this in mind, we download the observation RINEX files associated with these days and the BRUX ground station.

Second of all, we run one RINEX file in order to generate a director file. This file will serve us as reference, and all the changes in terms of geodetic models, products and more features will be specified there. Right after, we can use the same function to run a series of RINEX files as well as selecting at the same time the reference director file in question. This way, all the outputs will be based on the same geodetic models, orbit and clock products and more features specified, making the analysis consistent.

Third of all, it is always a good practice to check the listing files (one of the produced outputs). We can do that by executing the function “listing_summarize” on a particular listing file. This will output a summary regarding the RINEX preprocessing, the loading corrections for each geodetic model specified in the director file, the first and last iterations as for the residuals, ambiguity resolution statistics if fixing ambiguities and various warnings as for the process.

After a quick examination of some listing files, we move on to the solutions, which is another produced output. The solution files contain a header with information on the processing, and three lines per station position with the date, the coordinates (absolute position of station and corrections) in FLH, XYZ and ENU, as well as their correlations. In our case, we will use the ENU (East-North-Up) coordinates, particularly the corrections with respect to the a priori station coordinates. Once this is finished, we need to concatenate the solutions in order to generate a complete solution for our time span, and eventually plot it with the GINS functions “plot_grace_PPP” or “xmgrace”.

Finally, we are also going to obtain the periodogram of the residuals through SARI. By doing that, we can easily see if there are periodic events in our time series in order to evaluate if the corrections behave as expected and the models applied help to correct the solutions or not.
6.1.2 Results

To begin with, we are going to show the temporal evolution of the corrections in the position of the BRUX station over the course of our time span, in the ENU coordinate system. Figure 5 corresponds to the corrections in the position taking into account the fes2014.cf ocean model, whereas Figure 6 corresponds to the corrections in the position considering the got4.10c model. Note that these corrections are with respect to the a priori station coordinates, so such temporal evolutions also represent the variation in the position of the station. For both figures, the x-axis is the epoch in Julian days and the y-axis the correction/variation in meters.

![Figure 5: Variation in the position of the BRUX station - fes2014.cf ocean model](image)

![Figure 6: Variation in the position of the BRUX station - got4.10c ocean model](image)
However, just by looking at the time series, not much can be deduced, since the differences that we are dealing with here are in the order of mm. That is why the difference between the two models needs to be quantified directly. Figures 7, 8 and 9 show this for the East, North and Up coordinates respectively. The x-axis is still the epoch in JD, but the y-axis this time shows the difference between the two models in meters.

![Figure 7: Difference in the E coordinate](image1)

![Figure 8: Difference in the N coordinate](image2)
We can see that, indeed, the difference between the two oceanic models is millimetric. Particularly, if we omit the outliers, for the E and U coordinate, the difference is up to 1 mm whereas for the N coordinate, it reaches up to 0.5 mm.

Regarding the periodograms, we will be showing the ones that belong to the difference of the models in order to be consistent with the analysis. These periodograms, shown in Figure 10, 11 and 12 for the East, North and Up coordinates respectively, give us an idea of the sensitivity of the observations with respect to the models. It can be seen that the impact that one model or the other has on the solution is minimal, since the amplitude is very low. What it is interesting though, is the fact that for the three coordinates there are spikes at around 9.6 and 14 days, unlike the individual periodograms, where they remain for the E coordinate but do not appear for the N and U coordinates, meaning that the effects of the ocean loading have been successfully corrected by the models. The periodograms that belong to the analysis where the \textit{fes2014.cf} and \textit{got4.10c} ocean loading models are applied individually can be found in the annex.

Figure 10: Periodogram of the difference in the E coordinate
It is important to have understood the idea of the analysis. What we are doing is applying, amongst other geodetic models - e.g. solid tides and pole tides, a theoretical ocean loading model that is trying to cancel out/correct the effects of the ocean loading phenomenon on the BRUX station coordinates. Then, we do the difference of the resulting periodograms. The theoretical corrections of both models, as well as the periodograms, are included in the annex. Those periodograms show spikes at around 9.6 and 14 days, meaning that they are supposed to correct all the periodic events that happen every 9.6 and 14 days for each coordinate. This is consistent with the expected periodic behaviour of the oceanic loading phenomenon.

6.2 2nd analysis: GPS vs. Galileo positioning errors

The bulk of the work, however, resides in this second and last study. It consists of a PPP/IPPP static analysis with GPS and Galileo, 40 IGS stations and seven months of data (between 10/2018 and 04/2019). The stations vary slightly depending on whether we are doing a GPS or a Galileo analysis, as it can be seen in Figures 13 and 14.
The idea of this study is to analyse the noise level and the periodic errors in position time series with GPS and Galileo. To do so, we are going to obtain the periodogram of the residuals of the 40 stations individually, and then we are going to stack them in order to observe systematic peaks over the noise floor level that will provide information about periodic events in the time series. This a good way to test and validate different geodetic models as well as orbit and clock products. As a reminder, a periodogram only shows periods (frequencies) but not the phase. That is why when we accumulate and average the 40 individual periodograms, they do not cancel out, but build up, since all the stations have motions at the same frequency.
6.2.1 Methodology

Having in mind the methodology explained in point 6.1.1, let’s explain what the procedure is to proceed with this second analysis:

1. Execute in GINS all the RINEX files under the study case (40 stations, 7 months time span, GPS/Galileo, GRG/BRA products, static PPP/IPPP). Now, since we are dealing with more than one station, it is necessary to include a reference station file that contains all the a priori coordinates of all the stations involved in the analysis. This is done during the execution of the GINS function `exe_ppp`.

2. Align the solutions since each daily solution is not in the same frame, so they need to be aligned into a common frame, that is, the ITRF. This can be done following a Helmert transformation, that consists of a translation in origin, rotation in orientation and a scale in amplitude.

3. Retrieve the residuals and ENU corrections from the aligned solution files for every epoch and station. Then export them to SARI, where the outliers would be removed from the time series.

4. Finally, obtain the individual periodograms of the residuals for each coordinate and station, and average them with the function `lomb_onrequest.plx`.

It is also worth mentioning the fact that we are using the GRG products for GPS. However, for Galileo, given our time span, we need to use not only the GRG products but also the BRA products between 2018/322 DOY et 2019/033 DOY, since they were recalculated and yield better solutions.

6.2.2 Results

How important is the alignment?

In order to understand the importance of the alignment, we are going to show its influence. Figure 15 shows three periodograms, one per coordinate, each consisting of 7 months of data and averaged over 40 IGS stations, as previously introduced. They belong to a IPPP GPS solution, where the blue graph depicts the averaged periodogram without alignment, whereas the pink graph describes the same, but having applied the alignment. It can be seen how the alignment removes and/or softens the highest spikes, specially for the E coordinate.

The previous alignment was a GPS one. However, since it is still under investigation whether a GPS alignment is coherent with a Galileo analysis, we are going to use a Galileo alignment to avoid misleading results. The comparison between using a GPS or a Galileo alignment on an IPPP Galileo solution is shown in Figure 16. The blue graph shows the averaged periodogram with a GPS alignment, while the pink graph shows the same, but with a Galileo alignment.
Figure 15: From top to bottom: Averaged GPS periodograms for the East, North and Up coordinates, without alignment (blue) and with GPS alignment (red)

Figure 16: From top to bottom: Averaged Galileo periodograms for the East, North and Up coordinates, with GPS alignment (blue) and with Galileo alignment (red)
In a first approach, what is the actual difference between GPS and Galileo in this context?

Within the framework of this analysis, the difference between GPS and Galileo is shown in Figure 17. The GPS graphs consist of an IPPP analysis with a GPS alignment, while the Galileo graphs consist of an IPPP analysis with a Galileo alignment.

We can see that the noise level in the East component is similar for both Galileo and GPS. However, in the North and Up components, Galileo shows a higher noise level than GPS, specially below 10 days. Also, there are no remarkable spikes for any constellation, even though we know that for Galileo we should see a peak at 10 days due to its repeat cycle, and for GPS, a peak at 14 days should be spotted, as shown in Rebischung et al. (2016). The reason why we do not spot any of those peaks is the time span, which is seven months because we only had seven months of Galileo products available, which is not enough. For example, in Rebischung et al. (2016), the time span exceeded 15 years.

Also, it is worth mentioning that the Galileo constellation is not yet fully operational, meaning that there is still room for improvement as soon as new satellites are deployed. As a reminder, the Galileo space segment, once fully deployed, will include a constellation of a total of 30 Medium Earth Orbit (MEO) satellites, including 6 spares, in a so-called Walker 24/3/1 constellation. It is also important to point that, so far, all the Galileo analysis that have been conducted, have not considered the correct antex files, as they were not released by ESA on time. In the antex files, the antenna PCO (Phase Center Offset) and PCV (Phase Center Variation) are registered.

Figure 17: From top to bottom: Averaged GPS/Galileo periodograms for the East, North and Up coordinates, for GPS (blue) and for Galileo (red)
How do the new antex files/models affect the solutions?

At the end of the internship (mid-July), ESA released the new antex files with updated antenna PCOs and PCVs. A new analysis considering these new files was done in order to compare it with the old ones. Figure 18 shows this comparison. Both periodograms belong to an IPPP Galileo solution, with GRG and BRA products but without alignment. The only difference is that the blue graph represents the analysis with the old antex model, whereas the red plot follows the new antex models.

It seems that when we use the new antex files, either the highest spikes (originally at 14 days) are shifted towards the left, that is, to a lower period or they are corrected, even without applying any alignment. This is particularly evident for the E coordinate. We can also see that there are spikes at around 5, 3.3, 2.5 and 10 days. The 10-day spike, in coordinate E, is the repeat cycle of Galileo, whereas the other three seem to be the second, third and forth harmonic. Although this does seem to have sense, more work need to be done, especially applying the corresponding alignment.
Multi-GNSS analysis with GPS and Galileo

In such a multi-GNSS analysis, both GPS and Galileo data are processed concurrently. We are doing an IPPP study, with GRG products for GPS and GRG and BRA products for Galileo, and a GPS alignment. Figures 19, 20 and 21 show the corresponding periodograms, where the x-axis is the inverse of the period (frequency) and the y-axis the amplitude in meters. Note that, in multi-GNSS analysis, it is still unclear the alignment that needs to be used, so low-quality results are anticipated.

Figure 19: Averaged periodogram in the E coordinate

Figure 20: Averaged periodogram in the N coordinate
We can see that there are still spikes at 9.6 and 14 days in the E coordinate that go all the way up to 1-1.5 mm. For the N and U coordinate, the spikes can be said to be at the noise level. These results will be reanalysed in the future once the alignment of a multi-GNSS analysis with GPS and Galileo is found.
7 Conclusions and future work

This report focuses on the application of the undifferentiated ambiguity fixing method, as it is the case for Precise Point Positioning, to the GPS and Galileo system. The method consists of two steps: the first is calculating and fixing the wide-lane ambiguity and the second is fixing the narrow-lane ambiguity.

In the first analysis, we compared two different ocean loading models, and study with the help of the periodogram how these models show periodic events related with the ocean loading phenomenon. We have seen that the difference of the two periodograms has spikes at around 9.6 and 14 days for the three coordinates, as the own models themselves. It is true, though, that difference can be considered negligible, meaning that the impact that the models have on the solutions is basically the same.

The second analysis follows the results shown in Katsigianni et al., 2019, and it continues studying how the Galileo system behaves when doing PPP and IPPP, using GRG and BRA products, and a new antex model. We can say today that Galileo IPPP solutions are a bit noisier than the GPS ones for periods shorter than a few days, but similar for monthly periods (annual not yet observed). Also, the Galileo 10 and 14-days systematic variations not visible yet, probably because our time span of 7 months is not enough. However, we can be certain about the importance of the alignment for both GPS and Galileo. It is still under investigation whether they need different alignments or one can be coherent for both constellations. This will be very helpful to know while doing multi-GNSS processings. Finally, as for the new antex study, we can say that it yields good results, even if no alignment is applied. Some of the spikes are removed and the 10-day spike, typical of Galileo, finally appears. Nonetheless, work is ongoing to obtain new and more precise results, since such antex files were released just one month ago.

These preliminary results indicate that in the future undifferentiated Galileo phase observations could match the GPS ones. Future work will include extending the time span in order to analyse years, rather than months. This way the periodic coordinate variations will be spotted easily for the Galileo system. It will also include efforts in adding the new Galileo satellites, improving the orbit determination model and evaluating the impact of Multi-GNSS processing on Earth reference frame and orientation parameters.

And last but not least, by the start October 2019, the Analysis Centers of the International GNSS Service will begin the third data reprocessing campaign of GPS data collected by the IGS global network since 1994 in a fully consistent way using the latest models and methodology, being able to provide the most accurate products to date.
8 Bibliography

[1] Felix Perosanz. Introduction to Space Geodesy. GNSS data processing for geodetic applications


9 Annex

Periodograms with the \textit{fes2014.cf} ocean loading model

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{periodogram_E}
\caption{Periodogram in the E coordinate}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{periodogram_N}
\caption{Periodogram in the N coordinate}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{periodogram_U}
\caption{Periodogram in the U coordinate}
\end{figure}
Periodograms with the *got4.10c* ocean loading model

![Figure 25: Periodogram in the E coordinate](image1)

![Figure 26: Periodogram in the N coordinate](image2)

![Figure 27: Periodogram in the U coordinate](image3)
Temporal evolution of the theoretical corrections of the \textit{fes2014.cf} ocean loading model

Figure 28: Temporal evolution in the radial component

Figure 29: Temporal evolution in the latitudinal component
Figure 30: Temporal evolution in the longitudinal component
Periodograms of the theoretical corrections of the \textit{fes2014.cf} ocean loading model

Figure 31: Periodogram in the radial component

Figure 32: Periodogram in the latitudinal component

Figure 33: Periodogram in the longitudinal component
Temporal evolution of the theoretical corrections of the *got4.10c* ocean loading model

Figure 34: Temporal evolution in the radial component

Figure 35: Temporal evolution in the latitudinal component
Figure 36: Temporal evolution in the longitudinal component
Periodograms of the theoretical corrections of the *got4.10c* ocean loading model

Figure 37: Periodogram in the radial component

Figure 38: Periodogram in the latitudinal component

Figure 39: Periodogram in the longitudinal component
Averaged periodograms of a Galileo PPP solution with GRG products

The first two Galileo analysis that were conducted consisted on a PPP analysis, with only GRG products and a GPS alignment for the first case and no alignment for the second one. The corresponding averaged periodograms per coordinate are shown below.

PPP, GRG products and GPS alignment

Figure 40: Periodogram in the E coordinate

Figure 41: Periodogram in the N coordinate
PPP, GRG products and no alignment
Figure 44: Periodogram in the N coordinate

Figure 45: Periodogram in the U coordinate