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Ph.D. Thesis

Doctoral Program Aerospace Science and Technology

# Consolidation and assessment of a technique to provide Fast and Precise Point Positioning (Fast-PPP)

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UNIVERSITAT POLITÈCNICA DE CATALUNYA
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**Curs acadèmic:** 2015/2016

## Acta de qualificació de tesi doctoral

| | |
|---|---|
| Nom i cognoms | Adrià Rovira Garcia |
| Programa de doctorat | Ciència i Tecnologia Aerospacial |
| Unitat estructural responsable del programa | Departament de Física |

## Resolució del Tribunal

Reunit el Tribunal designat a l'efecte, el doctorand / la doctoranda exposa el tema de la seva tesi doctoral titulada Consolidation and assessment of a technique to provide Fast and Precise Point Positioning(Fast-PPP).

Acabada la lectura i després de donar resposta a les qüestions formulades pels membres titulars del tribunal, aquest atorga la qualificació:

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- Com a secretari/ària del tribunal faig constar que la tesi s'ha defensat en part, i com a mínim pel que fa al resum i les conclusions, en una de les llengües habituals per a la comunicació científica en el seu camp de coneixement i diferent de les que són oficials a Espanya. Aquesta norma no s'aplica si l'estada, els informes i els experts provenen d'un país de parla hispana.

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# Abstract

**UNESCO Codes:** 1203.21, 2501.18, 2504.03, 2504.07

The research of this paper-based dissertation is focused on the Fast Precise Point Positioning (Fast-PPP) technique. The novelty relies on using an accurate ionosphere model, in combination with the standard precise satellite clock and orbit products, to reduce the convergence time of state-of-the-art high-accuracy navigation techniques from approximately one hour to few minutes.

My first contribution to the Fast-PPP technique as a Ph.D. student has been the design and implementation of a novel user navigation filter, based on the raw treatment of undifferenced multi-frequency code and carrier-phase Global Navigation Satellite System (GNSS) measurements. The innovative strategy of the filter avoids applying the usual ionospheric-free combination to the GNSS observables, exploiting the full capacity of new multi-frequency signals and increasing the robustness of Fast-PPP in challenging environments where the sky visibility is reduced. It has been optimised to take advantage of the corrections required to compensate the delays (i.e., errors) affecting the GNSS signals. The Fast-PPP corrections, and most important, their corrections uncertainties (i.e., the confidence bounds) are added as additional equations in the navigation filter to obtain Precise Point Positioning (PPP) in few minutes.

A second contribution performed with the new user filter, has been the consolidation of the precise ionospheric modelling of Fast-PPP and its extension from a regional to a global scale. The correct use of the confidence bounds has been found of great importance when navigating in the low-latitude areas of the equator, where the ionosphere is difficult to be accurately modelled. Even in such scenario, a great consistency has been achieved between the actual positioning errors with respect to the formal errors, as demonstrated using similar figures of merit used in civil aviation, as the Stanford plot.

A third contribution within this dissertation has been the characterisation of the accuracy of different ionospheric models currently used in GNSS. The assessment uses actual, unambiguous and undifferenced carrier-phase measurements, thanks to the centimetre-level modelling capability within the Fast-PPP technique. Not only the errors of the ionosphere models have been quantified in absolute and relative terms, but also, their effect on navigation.

# Resum

**Codis UNESCO:** 1203.21, 2501.18, 2504.03, 2504.07

La investigació d'aquesta Tesi Doctoral per compendi d'articles es centra en la tècnica de ràpid Posicionament de Punt Precís (Fast-PPP). La novetat radica en l'ús d'un model ionosfèric precís que, combinat amb productes estàndard de rellotge i de l'òrbita de satèl·lit, redueix el temps de convergència de les actuals tècniques de navegació precisa d'aproximadament una hora a pocs minuts.

La meva primera contribució a la tècnica Fast-PPP com a estudiant de Doctorat ha estat el disseny i la implementació d'un filtre de navegació d'usuari innovador, basat en el tractament de múltiples freqüències de mesures de codi i fase sense diferenciar (absolutes). La estrategia del filtre de navegació evita l'aplicació de l'habitual combinació lineal lliure de ionosfera per a aquests observables. Així, s'explota la capacitat completa dels senyals multi-freqüència en el nous Sistemes Globals de Navegació per Satèl·lit (GNSS) i s'augmenta la robustesa del Fast-PPP en entorns difícils, on es redueix la visibilitat del cel. S'ha optimitzat per tal de prendre avantatge de les correccions necessàries per a compensar els retards (és a dir, els errors) que afecten els senyals GNSS. Les correccions de Fast-PPP i més important, les seves incerteses (és a dir, els intervals de confiança) s'afegeixen com a equacions addicionals al filtre per aconseguir Posicionat de Punt Precís (PPP) en pocs minuts.

La segona contribució ha estat la consolidació del modelat ionosfèric precís de Fast-PPP i la seva extensió d'un abast regional a una escala global. La correcta determinació i ús dels intervals de confiança de les correccions Fast-PPP ha esdevingut de gran importància a l'hora de navegar en zones de baixa latitud a l'equador, on la ionosfera és més difícil de modelar amb precisió. Fins i tot en aquest escenari, s'ha aconseguit una gran consistència entre els errors de posicionament reals i els nivells de protecció dels usuaris de Fast-PPP, tal com s'ha demostrat amb figures de mèrit similars a les utilitzades en l'aviació civil (els diagrames de Stanford).

La tercera contribució d'aquesta Tesi Doctoral ha estat la caracterització de l'exactitud dels models ionosfèrics utilitzats actualment en GNSS. L'avaluació utilitza mesures de fase, sense ambigüitats i sense diferenciar, gràcies a la capacitat de modelatge centímetric emprat a la tècnica de Fast-PPP. No només els errors dels models de la ionosfera han estat quantificats en termes absoluts i relatius, sinó també, el seu efecte sobre la navegació.

# Thesis Breakdown

The structure of the dissertation is the following:

**Chapter 1** briefly introduces the satellite navigation topic, giving essential references for anyone eager to acquire a strong background on GNSS. Then, the state-of-the-art of current high-accuracy positioning techniques is reviewed. The reader can understand not only their benefits but also the drawbacks and current limitations that justify the new approach of the Fast-PPP technique.

**Chapter 2** describes the results obtained in this Ph.D. study. A number of findings have contributed to the assessment and consolidation of the Fast-PPP technique, as intended.

**Chapter 3** is aimed to provide evidence of the quality of the research of this dissertation. The results have been validated by the international scientific community through a number of international conferences and peer-reviewed journals. This chapter lists the publications together with a selection of quality indexes for each journal.

**Chapter 4** consists of the different conclusions reached through this research. In addition, future research directions are suggested, based on the outcomes of this doctorate thesis.

**Chapter 5** contains the original manuscripts.

# Contents

# List of Figures

## Chapter 1

# Introduction

Three classical introductory books to the Global Navigation Satellite System (GNSS) are Parkinson et al (1996), Misra and Enge (2001) and Hofmann-Wellenhof et al (2008). They should be consulted to acquire a solid background of satellite navigation. The particular topic of the GNSS Data Processing is extensively treated in Sanz et al (2013b), in which this chapter is based on.

The positioning principle by means of GNSS satellites is illustrated in Fig. 1.1. A constellation of satellites orbiting at an approximately altitude of twenty thousand kilometres over the Earth surface transmits radio-navigation signals, see Hegarty (2012). Using these signals, any GNSS receiver is able to determine the distance ($\rho$) to each of the satellites in view together with the satellite coordinates $(X_s, Y_s, Z_s)$, see Fig. 1.1.

The user estimates its time and coordinates $(X, Y, Z)$ after solving the geometric problem involving the distances (ranges) to a minimum set of four GNSS satellites with known coordinates, see Kaplan (1996).

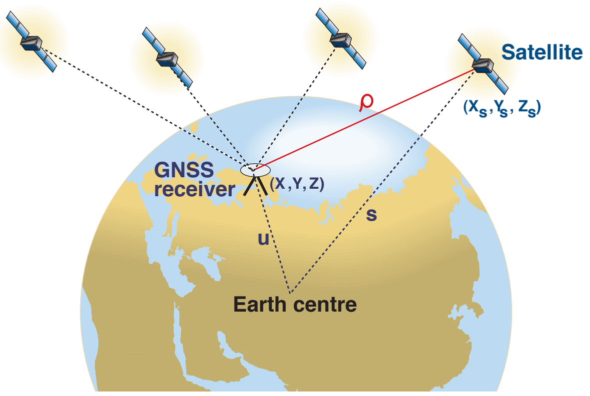


Figure 1.1: Geometric concept of GNSS positioning from Sanz et al (2013b).

## 1.1 GNSS Architecture

Figure 1.2 depicts the three segments of any GNSS: i) the space segment, which comprises the satellites, ii) the ground (control) segment, which takes care of the proper system operation and iii) the user segment, which demands not only positioning but also precise timing.

This dissertation is focussed on the third segment. In particular, the presented algorithms are able to provide to GNSS users a high level of accuracy (i.e., decimetre or better) taking into account that user requirements greatly vary depending on the application, see European GNSS Agency (GSA) (2015).

Engineering surveyors and other geodesy users are concerned about the accuracy and robustness of the navigation solution, see Seeber (1993). In general, this group of users can afford high-end equipment with multi-constellation / multi-frequency receivers and even, local-error mitigating antennas.

Mass-market GNSS receivers (e.g., embedded in mobile phones) require a reasonable position with short convergence time. Tipically, an inexpensive patched antenna is used to acquire the GNSS signals in a unique frequency. Chapter 2 shows that the accuracy of single-frequency users is determined by the model chosen to correct the ionospheric delay, among other factors.

Safety-critical applications (e.g., civil-aviation) demand integrity, which is the ability of a positioning system to protect against hazardous anomalies. In this sense, the user computes not only its position but also the Protection Levels (PLs). The PLs take into account the uncertainty (i.e., the trust) associated with the information used (e.g., satellite orbits and clocks, receiver noise and multipath), following a well-established set of conventions by the International Civil Aviation Organization (ICAO), see the Annex 10 of ICAO (2006).

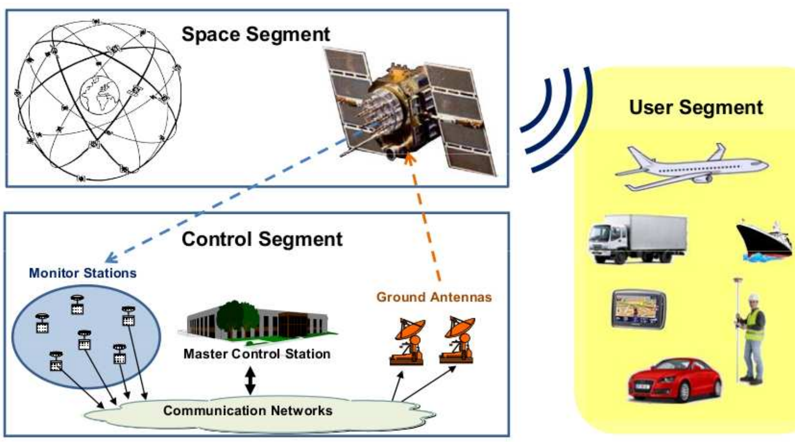


Figure 1.2: GNSS architecture from Sanz et al (2013b).

## 1.2 State-of-the-art

Two state-of-the-art High-Precision Positioning Services (HPPSs) offer positioning accuracy at the centimetre level: Real Time Kinematics (RTK) and Precise Point Positioning (PPP). Both techniques rely on carrier-phase measurements, typically more than two orders of magnitude more precise than pseudorange measurements. However, the carrier-phases contain the ambiguities as additional unknowns. In this section, RTK and PPP are briefly introduced, drawing special attention to their major benefits and drawbacks.

### 1.2.1 Real Time Kinematics

RTK is a high-accuracy technique in differential mode, involving two receivers, introduced by Remondi (1985). It is based on the idea that most of the delays affecting the GNSS signals (i.e., the errors) can be compensated by a close reference receiver.

The errors are classified in Table 1.1 according to their origin: space segment (satellite clocks and ephemeris), propagation effects (ionosphere and troposphere), and user segment (receiver noise and multipath). The magnitude of errors affecting standalone users is given in the left column and the right column depicts the temporal and spatial decorrelation of those errors.

The less predictable error is by far, related to the satellite clock (specially with old atomic clocks technology). However, it can completely removed, provided

Table 1.1: Absolute errors (left) affecting GNSS and their decorrelation (right) in terms of time and distance, assuming Selective Availability is disconnected, sources: Parkinson et al (1996) and Misra and Enge (2001).

| **Error Source** | **Standalone** | **Decorrelation** | |
|---|---|---|---|
| | **Bias** $(\mathbf{m})$ | **Latency** $(\frac{\mathbf{m}}{\mathbf{s}})$ | **Distance** $(\frac{\mathbf{m}}{\mathbf{100\ km}})$ |
| Satellite Clock | 2.0 | 0.21 | 0.0 |
| Ephemeris | 2 to 10 | negl. | <0.05 |
| Ionosphere | 2 to 10 (times obliquity) | 0.02 | <0.2 |
| Troposphere | 2 (times obliquity) | negl | <0.1 |
| Receiver Noise | 0.5 | 0.0 | 0.0 |
| Multipath | 0.3 to 3.0 | 0.0 | 0.0 |

that the time-tagged measurements of the RTK user and the reference receiver are synchronised. The differential error produced by satellite orbits depends on the geometry, see Pervan and Gratton (2005), but in general, can be mitigated. On the other hand, local errors affecting the receivers (noise and multipath) are completely uncorrelated, thus local errors cannot be cancelled by RTK.

The relative positioning is limited by the de-correlation of propagation errors. The troposphere does not represent a major obstacle, because 90% of the Zenith Tropospheric Delay (ZTD) is predictable, see Leick (1994), and the remaining 10% can be estimated in real-time, see Zhang and Lachapelle (2001). However, the assumption of a differential ionospheric delay being either negligible or constant between the rover and the reference receiver is not valid for baselines greater than a few tens of kilometres, even under ionospheric favourable conditions such as in mid-latitudes or during minimum solar-cycle periods. Therefore, a large number of base stations would be required to provide a global service. In this regard, commercial companies offer different HPPSs over continental areas such as Europe and USA.

The differential positioning principle is illustrated in Fig. 1.3, where the user estimates the relative baseline vector to a reference station. Accuracies of centimetres are achieved in tens of seconds after the Double Difference (DD) of carrier-phase ambiguities are fixed to integer values. Ambiguities can be directly rounded to the nearest integer, or taking benefit from the correlations between ambiguities such as the Least-squares AMBiguity Decorrelation Adjustment (LAMBDA) method introduced by Teunissen (1996) or the Null Space method defined in Martin-Neira et al (1995).

A final remark on classical RTK must be made. If the required measurements from the reference station were broadcast using the Radio Technical Commission for Maritime Services (RTCM) standard defined in RTCM SC-104 (2001), large bandwidth would be required for a global HPPS based on RTK.

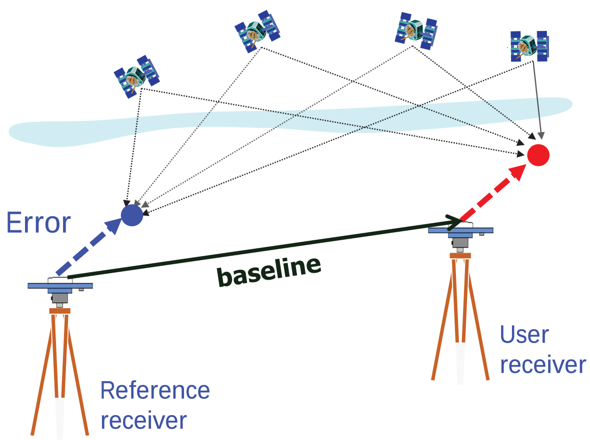


Figure 1.3: Concept of relative positioning from Sanz et al (2013a).

#### 1.2.1.1 Network RTK

RTK users can take advantage from a network of Continuously Operating Reference Stations (CORSs), by navigating with differenced measurements from the nearest CORS. This network processing is usually referred as Network RTK (NRTK), see Wubbena et al (1996). A commercial implementation of NRTK is the Virtual Reference Station (VRS), introduced in Wanninger (1996), where a virtual (non existing) reference station is generated ad-hoc to a VRS user, see Fig. 1.4. VRS is nowadays a trademark term of Trimble.

The network of receivers comprised in the NRTK or VRS technique presents two clear advantages. First, the correctness of measurements, satellite orbits and clocks is checked by the reference network before being distributed to the users. Second, the network data is used to generate an atmospheric modelling, see for instance Kashani et al (2004). The ionospheric modelling is interpolated by NRTK or VRS users, resulting in an enlargement of the baseline to the nearest CORSs up to 40 kilometres, see Rerscher (2002).

However, a number of limitations exist to surveying with NRTK. First, there is a high cost of setting up and maintaining the reference network. This results into a subscription fee paid to the organisation in charge of the service. Moreover, in the case of the VRS, it is a dual-way active system with strong and critical interaction between users and the processing network facility, see Kisling (2011). Second, and more important is the data link to the user. Radio links are reliable and free of charge but operation in Ultra High Frequency (UHF)/Very High Frequency (VHF) band requires an appropriate license, whereas unlicensed radios are sensitive to obstruction and reach more limited distances. Cell phone or wireless coverage is limited and might not meet desired continuity.

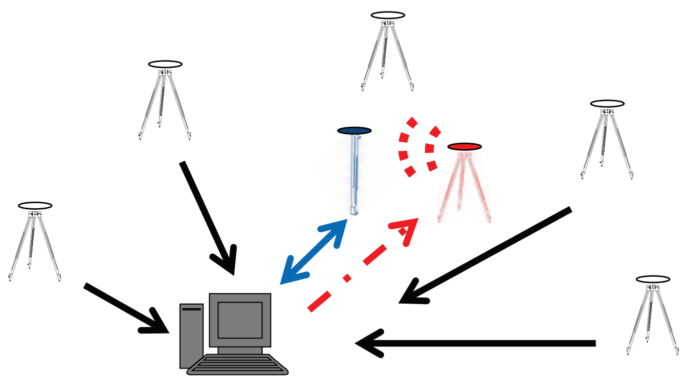

Figure 1.4: The Virtual Reference Station concept is an example of Network RTK, inspired in Landau et al (2002).

#### 1.2.1.2 Wide-Area RTK

The Wide-Area Real-Time Kinematics (WARTK) is a technique that extended the ambiguity fixing to wide-areas, introduced in Hernández-Pajares et al (2002) by the group of Astronomy and GEomatics (gAGE) at the Technical University of Catalonia (UPC). The main difference with respect to NRTK, is that a precise ionospheric model is calculated in a Central Processing Facility (CPF) in absolute (i.e., non-differenced) mode. The WARTK model requires a sparse network of permanent receivers with inter-station distances up to several hundreds of kilometres, similar to the existing European Geostationary Navigation Overlay System (EGNOS) Ranging and Integrity Monitoring Stations (RIMS), see Ventura-Traveset and Flament (2006).

At user level, the WARTK rovers navigate in differential mode, see Fig. 1.5. The WARTK rover uses the DD of code and carrier-phase measurements of a near reference station and the DD of the Slant Total Electron Content (STEC) model predictions (the $\nabla\Delta STEC$). The undifferenced ionospheric modelling extended the RTK ambiguity fixing from a local area (tenths of kilometres) to a continental area (hundreds of kilometres), see Juan et al (2012b). The WARTK technique is protected by several international patents; in 1999 the ionospheric part and in 2002 the extension to triple-frequency signals, see EP1576387 (A2).

The absolute processing in the WARTK CPF supports the space state representation of the errors listed in Table 1.1. Indeed, the present dissertation presents some contributions not only to the core of the technique (i.e., the ionospheric modelling), but also to the precise satellite orbit and clock computations and to the satellite Differential Code Bias (DCB) determinations. As a result, high-accuracy navigation with short convergence time is obtained, globally and in undifferenced mode (see Section 1.2.2.1).

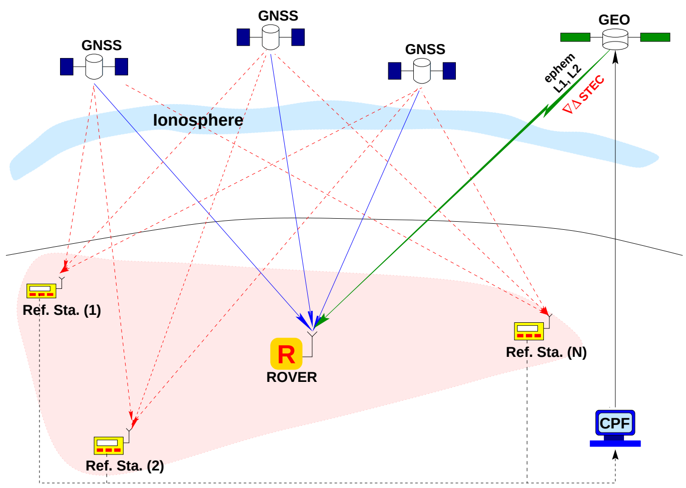


Figure 1.5: The WARTK technique extends the baselines of NRTK to hundreds of kilometres by means of an accurate non-differenced ionospheric modelling.

### 1.2.2 Precise Point Positioning

PPP is the other high-accuracy technique, see Zumberge et al (1997). Unlike RTK, PPP uses undifferenced dual-frequency code and carrier-phase measurements to compute the position in absolute mode (i.e., not relative to a base station). After a centimetre-level modelling of the observables, typical accuracies in the order of a decimetre (kinematic mode) or centimetre (static mode) are achieved by current commercial PPP services, see Murfin (2013).

PPP is based on using satellite orbits and clocks approximately two orders of magnitude more accurate than those broadcast by the GNSS satellites, see Kouba and Héroux (2001). They are calculated using data from a permanent receiver network, e.g., the International GNSS Service (IGS), see Beutler et al (1999) and Dow et al (2009). Because orbits and clocks are only satellite-dependent, global coverage is achieved with a much lower bandwidth than in RTK, see Rizos et al (2012).

In PPP, the 99.9% of the ionospheric delay is cancelled thanks to the dual-frequency ionospheric-free combination, see Sanz et al (2013b). However, this combination amplifies the noise of the original measurements by a factor approximately 3 (using the L1 and L2 signals). This drawback contributes to the fact that classical PPP requires more time than RTK to achieve high-accuracy navigation. Indeed, the carrier-phase ambiguities are estimated as real numbers (i.e., undifferenced floated ambiguities) from the noise-amplified pseudorange measurements, instead of fixed double-differences from precise carrier-phase measurements.

The navigation accuracy can be further improved if the carrier-phase ambiguities are fixed to integer values, as in the aforementioned differential techniques. Two categories of developments added to PPP the capability of Integer Ambiguity Resolution (IAR) in undifferenced mode. The first type defines different satellite clocks for code and carrier-phases (Laurichesse and Mercier, 2007; Collins et al, 2008). The second category uses only the usual satellite code clock and uses Single Differences (SDs) of carrier-phases between satellites (Ge et al, 2008; Mervart et al, 2008). These IAR methods are compared in Shi and Gao (2014).

However, the largest drawback of PPP (fixing or floating the carrier-phase ambiguities) is the long convergence time to achieve decimetre-level of accuracy. Indeed, sufficient change must be observed in the satellite geometry to decorrelate (separate) the ambiguities from other parameters being estimated in the navigation filter (e.g., the coordinates and troposphere[1]). Generally, this process lasts almost one hour with only the Global Positioning System (GPS), although it is shorter in full multi-constellation environments.

[1]Like in RTK, the 90% of the ZTD is modelled and subtracted to the measurements, being estimated the remaining 10% of the ZTD, see Bevis et al (1992).

#### 1.2.2.1 Fast Precise Point Positioning

Fast Precise Point Positioning (Fast-PPP) is a high-accuracy navigation technique that tackles the drawback of the convergence time of PPP by using an accurate ionospheric modelling based on GNSS data, see Juan et al (2012a). The capability of the Fast-PPP CPF to determine the fractional part of the satellite ambiguities, enables integer ambiguity resolution as in RTK but with the word-wide coverage and low bandwidth of PPP.

The Fast-PPP technique was invented by the group of Astronomy and GEomatics (gAGE) at the Technical University of Catalonia (UPC). Since 2011, Fast-PPP is protected by several international patents funded by the European Space Agency (ESA), including the use of dual- and triple-frequency GNSS signals, see for instance PCT/EP2011/001512 (2011).

Fast-PPP corrections for high-accuracy navigation are computed in a unique CPF, with multi-frequency and multi-constellation capabilities, see Juan et al (2012a). The estimation of the Fast-PPP corrections is done using the three Kalman filters shown in Fig. 1.6. The geodetic, the ionospheric, and the fast filters work with updating times of minutes and seconds, respectively.

The Fast-PPP CPF is fed with GNSS data gathered by 3 different networks of receivers (see an example in Fig. 1.7). The first network (shown in black) includes all 172 receivers. Pseudorange and carrier-phase measurements are modelled to the centimetre level in a pre-processing stage, which includes cycle-slip detection and the computation of the ionospheric activity indicator named Along Arc TEC Rate (AATR), defined in Sanz et al (2014).

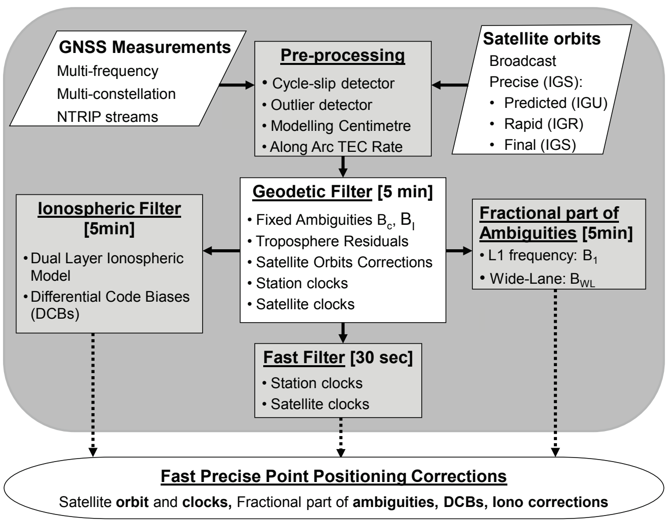


Figure 1.6: Top-level design of the Central Processing Facility used in the Fast Precise Point Positioning technique.

The pre-processed measurements are read by the geodetic filter to estimate every 5 minutes slow-varying parameters such as: the carrier-phase ambiguities, the troposphere residuals of the receiver network and the satellite orbit corrections to the input orbits (broadcast or precise). The main outputs of the geodetic filter are the carrier-phase measurements with fixed ambiguities, which are used by the other two filters (devoted to the estimation of the ionospheric model and satellite and receiver clocks).

The fast filter uses data from the second sub-network of 36 receivers, shown in blue in Fig. 1.7, to estimate the clocks of the satellites and receivers of the network with a high rate of 30 seconds. As it can be seen in Fig. 1.6, the fractional part of the ambiguities (for all receivers and satellites) is computed in a parallel module every 5 minutes.

Finally, a third ionospheric sub-network of 150 receivers (shown in red) is used to estimate the parameters of the Fast-PPP ionospheric model, originally described in Juan et al (1997). In the example presented in Fig. 1.7, the ionospheric sub-network covers the latitudinal range from -90 to 90 degrees and the longitudinal range from -130 to 130 degrees, but has been finally extended to all longitudes.

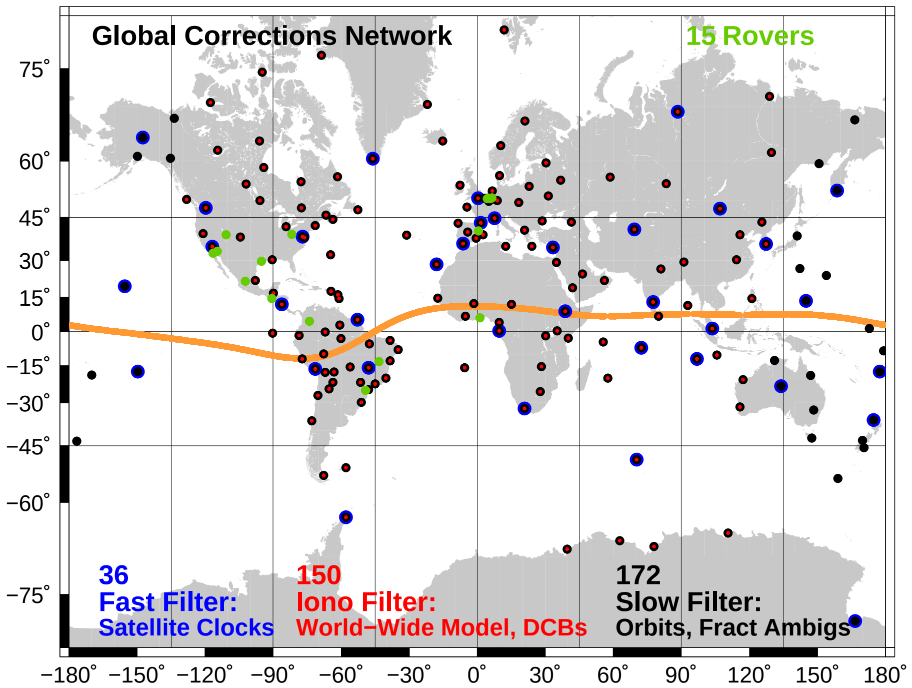


Figure 1.7: Example of a distribution of reference stations used to calculate Fast-PPP corrections. All reference receivers (black) are used to calculate orbit corrections, and fractional part of the ambiguities. The blue sub-network of stations is used to compute satellite clocks and the red sub-network to derive the ionospheric model. Stations in green are used as independent rovers. The geomagnetic equator is shown in orange.

The ionospheric estimation consists of a two-layer, irregular grid model, where the distances between Ionospheric Grid Points (IGPs) are maintained approximately 250 and 500 kilometres in the first and second layers, respectively. The first layer is devoted to represent the ionosphere and the second layer representing the plasmasphere (or upper ionosphere). The ionospheric filter updates the Total Electron Content (TEC) values of the IGPs and the satellite DCBs every 5 minutes, using the precise determination of the carrier-phase ambiguities performed in the geodetic filter.

## 1.3 Research Objectives

The aim of this dissertation is to assess and to consolidate the aforementioned Fast-PPP technique.

**Assessment:** To characterise the accuracy of the corrections involved in the Fast-PPP technique: satellite orbit and clocks, DCB, ionospheric corrections and fractional part of the ambiguities. In order to perform the assessment, standard products from the IGS have been used as a reference: the combined product or the individual contribution from different Analysis Centres (ACs).

For the products that are not accurate enough to be used as a reference, the internal self-consistency is examined. That is, comparing the day-to-day estimations for the fractional part of the ambiguities and analysing the agreement of the Fast-PPP ionospheric model (among others) with respect to actual, unambiguous and undifferenced carrier-phase measurements.

**Consolidation:** To extend the two-layer ionospheric model from a regional scale to a global scale and validate it with independent measurements from Radio Occultation (RO) of Low Earth Orbit (LEO) satellites.

In order to consolidate the navigation with the Fast-PPP corrections, a new user filter strategy has been implemented. The chosen approach optimises the new multi-frequency capabilities on-board the GNSS satellites and handles single-frequency users without any modification.

## 1.4 Methodology

A number of algorithms have been developed to process actual and simulated code and carrier-phase measurements, precise and broadcast satellite orbits, among other GNSS data. This required to write software applications in C, Fortran, Unix c-shell and gawk scripts. Especial care has been taken on practical implementation aspects such as their computational load, their real-time approach or their automatic data gathering and processing.

Chapter 2

# Results

The present chapter summarizes the main contributions obtained in the context of my Ph.D. study. The results presented in the following sections have been validated by the international scientific community through the assessment of papers published in peer-reviewed journals and international conference proceedings. A selection of quality indexes for each journal can be found in Chapter 3 and the original manuscripts are appended at Chapter 5.

## 2.1 Fast-PPP Corrections Assessment

It is of great importance to characterise the accuracy of the products generated at the CPF level. As mentioned in Section 1.3, standard products from the IGS have been used as a reference to assess the satellite orbits and clock corrections. Unfortunately, a standard product does not exists for the fractional part of the ambiguities. In the case of the ionospheric corrections, the existing standard product defined in Schaer et al (1998) has been shown to be not accurate enough to be used as a reference. The following sections detail how these limitations have been overcome.

### 2.1.1 Satellite Orbits

The Fast-PPP CPF orbit correction module can work from broadcast or IGS orbits, see Fig. 1.6. The real-time Fast-PPP orbit corrections have been assessed with respect to the IGS Rapid Products. The 3-D discrepancies (radial, cross-track and along-track) have been shown to be at the level of few centimetres, see Rovira-Garcia et al (2015a). This accuracy figure is in line with other ACs that compute satellite orbits in the IGS Real-Time Pilot Project (IGS-RTPP), see IGS Real Time Pilot Project (2014).

The capability of the Fast-PPP CPF to mitigate the degradation of the predicted IGS Ultra-Rapid (IGU) orbits as the prediction set becomes "older" has been confirmed. Indeed, the 3-D orbit error of the Fast-PPP determinations was maintained (in real-time) to few centimetres until a new prediction set was delivered. This IGU refresh occurs every 6 hours with a typical delay of 3 hours (i.e., the set of orbits predicted at $00^h$ becomes available at $03^h$).

### 2.1.2 Satellite Clocks

The global network of receivers shown as blue dots in Fig. 1.7 is used to estimate the satellite clocks on a fast rate (e.g., every 30 seconds), regardless of the orbit source (broadcast or IGS). The Fast-PPP satellite clocks determinations have been shown to be accurate to two tenths of a nanosecond with respect to the IGS Rapid Products, see Rovira-Garcia et al (2015a). This accuracy is comparable to other ACs in the aforementioned IGS-RTPP.

The impact on the satellite clock accuracy depending on the orbit source has been investigated in Rovira-Garcia et al (2014a). It was shown that slightly more accurate clock corrections were obtained when the Fast-PPP CPF starts from the predicted part of the IGU orbits than when starts from IGS Rapid (IGR) orbits. This was due to the orbit correction module (within the Geodetic Filter shown in Fig. 1.6) being disabled in the second case. Numerically, the satellite clock accuracies with respect to the IGS Rapid Products were 0.17 and 0.20 nanoseconds for IGU and IGR orbits, respectively.

### 2.1.3 Fractional Part of the Ambiguities

Fast-PPP CPF is capable of estimating the satellite fractional part of the ambiguities to enable undifferenced global carrier-phase ambiguity fixing. The results that were presented in Rovira-Garcia et al (2014a) showed:

1. The fractional part of the ambiguities determined in Fast-PPP are slow-varying parameters, and can thus be broadcast to users with large time updates (e.g., every 5 minutes). This requires less bandwidth than the decoupled clock model (Collins et al, 2008) and the integer phase clock model (Laurichesse and Mercier, 2007), that broadcast these fractional parts as additional satellite clocks.
2. The day-to-day discontinuities of the fractional ambiguity on the first $L1$ frequency (i.e., the B1 ambiguity) are typically smaller than a 0.1 cycle (2 centimetres) when IGU orbits are corrected.
3. The consistency of B1 is slightly degraded when the nominal orbit correction implemented in the CPF is disabled. This indicates that

residual orbit errors are transferred to the ambiguity estimation when the IGR orbits are used without any further adjustment.

4. The orbit source does not affect the repeatability of the fractional part of the ambiguity on the Melbourne Wübbena combination, mentioned in Melbourne (1985) and Wübbena (1985). This confirms previous results observed in the literature (Wang and Yang, 2007; Ge et al, 2008).

### 2.1.4 Ionosphere Corrections

The core of the Fast-PPP technique is the real-time determination of the ionospheric delay present in the GNSS signals, i.e., the undifferenced STEC. The present subsection describes some contributions to the Fast-PPP ionospheric model.

A preliminary requirement on the accuracy of the ionospheric corrections can be set at 1 Total Electron Content Unit (TECU), where $1\ TECU = 10^{16}\ e^{-}/m^{2}$ and corresponds to a delay of 16 centimetres at the L1 frequency. Errors in the ionospheric modelling several times larger than $1\ TECU$ would worsen the precise satellite orbits and clocks, typically determined with accuracies at the level of few centimetres.

#### 2.1.4.1 Coverage Extension

One of the major achievements has been the extension of the coverage where the Fast-PPP model provides accurate ionospheric corrections. Partial achievements were presented in Rovira-Garcia et al (2014b), where the Fast-PPP technique was assessed for the first time at the South-East Asia (SEA) region, i.e., in challenging equatorial latitudes.

This SEA area presented Vertical Total Electron Content (VTEC) values 3 to 5 times greater than in mid-latitudes, where previous Fast-PPP experiments were successful, see Juan et al (2012a) and Rovira-Garcia et al (2012). Such a challenging scenario required a number of refinements to consolidate the Fast-PPP algorithms at the CPF level.

The equatorial VTEC gradients, which were also several times larger than in mid-latitudes, required an increase of the process noise added to the covariance matrix after each batch of the ionospheric filter, where the TEC at each IGP is estimated. By adding more noise, the residuals of the ionospheric model were maintained to a similar level than in mid-latitude.

However, augmenting the process noise presents a side effect: the ionospheric corrections lose efficiency in the navigation filter of Fast-PPP users. The reason is that Fast-PPP corrections, including the ionospheric ones, are added as additional equations in the navigation filter normalised by their corrections uncertainties (i.e., the confidence bounds). The greater the standard deviations, the minor the navigation filter takes them into account. In the extreme, infinite values for the ionospheric corrections are equivalent to the ionospheric-free navigation solutions, later described in Section 2.2.2.

Indeed, the trade-off between the formal and actual positioning errors depends on the extent to which the confidence level of the corrections is realistic. This relationship has been carefully studied to obtain the positioning results shown in Rovira-Garcia et al (2015a).

The last improvement of the Fast-PPP ionospheric algorithms was related to the geometry used by the interpolations, which changed from the geographical latitude to the MOdified DIP latitude (MODIP) defined in Rawer (1963). The accuracy of the ionospheric estimates improved by a similar factor than in the results presented by Azpilicueta et al (2006).

#### 2.1.4.2 Ionospheric Accuracy

A devoted methodology to assess the accuracy of ionospheric models used in GNSS has been introduced in Rovira-Garcia et al (2015d). The test is based on actual, unambiguous, unbiased and undifferenced carrier-phase measurements in the geometry-free combination, see Lanyi and Roth (1988). The modelling capabilities of the Fast-PPP CPF at the centimetre-level are key in the procedure to obtain the required reference values.

The assessment overcomes the limitations of evaluations which use the dual-frequency space-borne radar altimeters such as TOPEX/Jason, see the mission description in Fu et al (1994). The new approach overcomes previous assessments with these independent data (e.g. Orús et al, 2003) in terms of:

1. It uses carrier-phase measurements, which present a noise several times fewer, according to Imel (1994).
2. It is not sensitive to the biases of the satellite radar, which are not properly calibrated, see Jee et al (2010).
3. It samples the plasmasphere contribution which can extend up to the Earth radii, see Lee et al (2013).
4. The coverage of the test is global, whereas the sounding of the LEO is restricted around its orbit plane, which is almost fixed in a Local Time (LT) and latitude frame, see González-Casado et al (2015).

The test was applied to the ionospheric models broadcast in real time by GPS and Galileo constellations, which are described in Klobuchar (1987) and in Di Giovanni and Radicella (1990), respectively. The results showed that the errors of the operational models correspond approximately to the 35% of the total slant delay on a global scale.

The ionospheric model used in Satellite Based Augmentation System (SBAS) was also assessed. In particular, the ionospheric corrections computed by the European and American SBASs to GPS: EGNOS and Wide Area Augmentation System (WAAS), respectively. The model is defined in the Minimum Operational Performance Standards (MOPS) by the Radio Technical Commission for Aeronautics (RTCA), see RTCA (2006).

The ionospheric corrections of WAAS and EGNOS have been shown to model the total slant delay with errors of 6% and 9%, respectively. The origin of discrepancy in the accuracy figure has been attributed to the analysed EGNOS service area, which includes lower latitude regions (e.g. the Canary Islands) than WAAS. This additional low-latitude region presents large ionospheric gradients and other irregularities that significantly contributed to the error. In this regard, when both SBASs are compared on the same region, the performance is almost identical.

Different factors were investigated regarding to the accuracy of Global Ionospheric Maps (GIMs) obtained in post-processing from IGS, see Hernández-Pajares et al (2009). It was shown, that the IGS Rapid Product, reproduces the total slant ionospheric delay with an error around 15% of the total slant delay. The effect of the update time was investigated with different GIMs generated by ACs within the IGS, their GIM updated more frequently than two hours decrease the modelling errors to the 12% of the total slant delay.

The Fast-PPP GIM was shown to model the STEC with errors of 5%. The achieved accuracy is compatible with the 1 TECU threshold that was derived from the satellite orbit and clock determinations accuracy. The improvement of the Fast-PPP corrections with respect to the aforementioned models is explained by the following factors:

1. The use of two layers, which improved performance in low-latitude regions. In Rovira-Garcia et al (2015a), the errors of the Fast-PPP model doubled in the equator when the number of layers was reduced to one.
2. Fixing carrier-phase ambiguities, which was shown to be 1.5 TECU (4% of the total slant delay) more accurate than levelling the carrier-phase measurements with code pseudoranges.
3. The use of MODIP-based interpolation, which reduced the error at low latitudes up to the 50% in relation to a latitude-based interpolation.

#### 2.1.4.3 Validation with Independent Measurements

The dual-layer ionospheric modelling performed in the Fast-PPP technique has been assessed with independent measurements from RO of LEO satellites in González-Casado et al (2015). A good agreement has been found between the electron contents inferred from RO measurements and the Fast-PPP model predictions. The analysis has been shown to be consistent with the main ionospheric behaviour (i.e., the anomalies) previously observed in the literature, see Natali and Meza (2011) and references therein.

The presented results showed that the plasmaspheric contribution to the VTEC is significant and even can be the dominant term. The plasmasphere can represent the 80% of the VTEC at night, particularly just before the sunrise, for low and intermediate geomagnetic latitudes. On the contrary, once the ionosphere is fully developed in LTs around noon, a nearly constant ratio of 30% has been observed between the electron content of the plasmasphere and the VTEC.

In terms of navigation, the coupling between the ionosphere and the plasmasphere evidences the limitations of state-of-the-art models with a single layer at a fixed height. The description of the ionosphere/plasmasphere system with two layers is far from perfect. However, the additional layer of the Fast-PPP model can be understood as having a dynamic effective height, which can trace the vertical structure and evolution of the ionosphere.

### 2.1.5 Satellite Differential Code Bias

The determination of the satellite DCBs is a key factor for single-frequency users applying ionospheric corrections; otherwise, those biases would worsen the positioning accuracy. Moreover, the stability of the DCBs from day to day is an additional indicator of how correctly the ionospheric delay has been determined by means of the ionospheric model. The reason is that DCBs are estimated independently every day at the same time than the ionospheric model.

In this sense, the difference of the Fast-PPP DCBs with respect to the IGS determinations was calculated. The discrepancies have been shown to be at the level of few tenths of a nanosecond, see Rovira-Garcia et al (2015b). Such difference corresponds to the typical level of agreement between different ACs within IGS, as it was previously observed in Hernández-Pajares et al (2009).

A second assessment consisted in the computation of the standard deviation of the DCB estimates. The standard deviation of the Fast-PPP DCBs computed every 5 minutes was 0.10 nanoseconds, while the daily estimation was 0.07 nanoseconds. This result indicates that considering only a daily DCB partially mitigates the ionospheric miss-modelling absorbed in the DCB estimation. This error propagation was sampled in the standard deviation values every 5 minutes.

The Fast-PPP determinations were compared with the daily determinations available at IGS. UPC and European Space Operations Centre (ESOC) presented standard deviations at the level of 0.14 nanoseconds. Fast-PPP DCBs were more stable than those ACs thanks to a more accurate ionospheric modelling. The lowest standard deviation was observed in the Centre for Orbit Determination in Europe (CODE) DCBs, accounting 0.06 nanoseconds. Nevertheless, it must be noticed that CODE DCB produces a three-day solution, which should be smoother than a one-day solution.

## 2.2 Consolidation of the Fast-PPP Navigation

The navigation achieved by the Fast-PPP technique has been consolidated in several aspects, using permanent stations treated as pure kinematic rovers. An example of a sub-network of rover receivers is shown in green dots on the map in Fig. 1.7. The world-wide distribution covers the regions served by the current SBASs and their planned extensions, including equatorial regions. Notice that the distance from each of these rovers to the nearest ionospheric reference station ranges from one to eight hundred kilometres, which is more than one order of magnitude greater than the aforementioned RTK/NRTK baselines.

### 2.2.1 Real-Time Assessment

The Fast-PPP technique was successfully assessed from end to end in strict real-time conditions for the first time in Rovira-Garcia et al (2012). The Fast-PPP CPF calculated the corrections, from actual data gathered in real time, using the streams from the IGS-RTPP through the Networked Transport of RTCM via Internet Protocol (NTRIP). The user navigation was also performed in strict real-time mode.

### 2.2.2 Reference Solutions

The improvement of the Fast-PPP technique has been measured with respect to the single- and dual-frequency ionospheric-free navigation techniques, respectively; the Group and Phase Ionospheric Calibration (GRAPHIC) introduced by Yunck (1993) and the aforementioned PPP, see Section 1.2.2. Notice that the modelling accuracy of GRAPHIC and PPP is at the centimetre level and do not present any bias related to the ionosphere. Therefore, these combinations are adequate to be used as reference solutions to assess the improvement of ionospheric corrections in user positioning.

The drawback of such ionospheric-free solutions (single- and dual-frequency) is that the carrier-phase ambiguities are mainly estimated with the pseudorange measurements. This fact slows the filter convergence to one hour for PPP and few hours for GRAPHIC, to achieve decimetre-level of accuracy.

Ionospheric corrections can be used as additional information to reduce the convergence time of the navigation filter. If the corrections are unbiased, the final solution converges to the ionospheric-free solution, reaching such accuracy several times earlier. On the contrary, if the ionospheric correction presents a bias, it degrades the user solution after the filter has converged. If the biases are smaller than the code noise, biased corrections may marginally improve the navigation solution at the beginning of the convergence period, when the ambiguities are mostly estimated with the noisy pseudo-ranges.

### 2.2.3 User Strategy

An innovative design of the Fast-PPP navigation filter was presented in Rovira-Garcia et al (2015a). The strategy in the filter is to maintain code and carrier-phase measurements separated from externally calculated CPF corrections, included as additional equations with its own confidence bound (the standard deviation or sigma). This is similar to the weighted ionospheric approach described in Teunissen (1997), but in Fast-PPP it is performed in absolute mode (i.e., undifferenced).

There are clear advantages in the Fast-PPP navigation filter strategy of processing the individual measurements, instead of their algebraic combinations, as in the classical PPP. First, high-accuracy navigation is not interrupted due to a loss of one frequency or an individual measurement. This design enhances the robustness of the system in rough environments such as motorways or cities, where the sky visibility is reduced. This flexibility allows the addition of frequencies and measurements without a re-design of the filter equations or processing.

Second, the traceability within the calculation of the PLs is improved, because each correction is added with its own sigma. Adequate PLs are obtained even when the Fast-PPP corrections are degraded, as a result of a network outage, during eclipses or under ionospheric events, among other factors. Notice that the navigation filter mixes different types of data from different sources (i.e., with different quality) based on the standard deviations. As it was shown in Rovira-Garcia et al (2012), great values of sigma associated to an (artificially) erroneous satellite clock correction maintained the navigation accuracy of Fast-PPP users. This was not the case for the classical PPP approach, where satellite clocks are typically assumed to be error-free, or at least, all satellite clocks present the same accuracy.

### 2.2.4 Orbit Corrections Assessment

The impact on the position domain of using Fast-PPP corrections computed from different orbit sources was assessed in Rovira-Garcia et al (2014a). As previously commented in Section 2.1.1, the Fast-PPP CPF can correct the predicted IGU orbits (nominal mode) or start from the post-process IGR Rapid orbits without any further adjustment.

The 3-D positioning error was computed for all rover receivers in single- and dual-frequency navigation modes, using the corrected IGU orbits and the uncorrected IGR orbits. It was shown that both orbit sources provide similar navigation results for the ionosphere-free solutions (GRAPHIC, PPP) and the solutions with ionospheric corrections (Fast-PPP).

### 2.2.5 Accuracy Assessment

The accuracy of the user positioning has been examined using different sources of ionospheric corrections. This is of great interest, because the modelling error of the ionosphere is the largest contribution to the navigation error of single-frequency users (e.g., mass-market receivers), once the satellite orbits and clocks are routinely computed in real-time with few centimetres of error.

In Rovira-Garcia et al (2015f), it was shown that the 3-D positioning error of the single-frequency navigation can range from metre-level when the IGS GIMs are used, to decimetre-level of error when the determinations of EGNOS (regional) are used instead. The Fast-PPP 95% Horizontal Positioning Error (HPE) and Vertical Positioning Error (VPE) were shown respectively 36 and 63 centimetres for single-frequency solutions and the corresponding values for dual-frequency solutions were 11 and 15 centimetres, respectively.

### 2.2.6 Convergence Criteria

The assessment of the reduction of the convergence time in the navigation filter has been conducted as follows. Every 2 hours, the navigation filter of each rover is reset to have 12 windows of independent solutions per day of actual GNSS data collection. Then, the Root Mean Square (RMS) of the HPE and VPE is computed merging all resets.

In order to quantify the reduction in the convergence time, relative to the ionospheric-free dual-frequency PPP solution, the following metric was proposed in Rovira-Garcia et al (2015a):

1. A sigma threshold was set at two times the stationary value of the classical PPP strategy for the horizontal and vertical components respectively.
2. An accuracy threshold was set at three times the final accuracy in each horizontal and vertical component, because the rovers were navigated in kinematic mode.

Under these criteria, a distance from the rover receiver to the nearest reference station of 500 kilometres can be taken as the maximum for which the Fast-PPP ionospheric corrections accelerate the positioning convergence. Numerically, the horizontal component was observed to reduce the convergence time of PPP the most, with a reduction of 40% to 90%. The vertical component was reduced by 20% to 60% for the distance range between 100 and 500 kilometres.

Finally, it was shown that the Fast-PPP navigation error for distances over 800 kilometres or at isolated rovers was never worse than the GRAPHIC and PPP solutions, which were taken as the worst-case reference. This is because the confidence bounds (detailed in the next section) associated to the ionospheric corrections, are realistically determined.

### 2.2.7 Actual vs. Formal Error Assessment

The Stanford plots are used in civil aviation applications to assess how the Signal In Space (SIS) confidence bounds are transferred to the user domain, see Stanford GPS Laboratory (1997).

The Horizontal Protection Level (HPL) and Vertical Protection Level (VPL) are computed as $HPL = 6.00\sigma_H$ and $VPL = 5.33\sigma_V$, where $\sigma_H$ and $\sigma_V$ are the formal errors computed by the navigation filter. The values of $6.00$ and $5.33$ are the K-factors associated with probabilities of the Misleading Information (MI) of $2 \cdot 10^{-9}$ and $10^{-7}$, see Appendix J of RTCA (2006).

We have used this metric to assess the internal consistency of the parametrization assumed in the Fast-PPP navigation. As it has been already commented, the navigation filter mixes different types of data from different sources (i.e., with different quality) based on the standard deviations. In this sense, the ratio among the actual errors (HPE and VPE) and the corresponding PL is determined by the correctness of the hypotheses assumed.

The previously stated Fast-PPP accuracy figures were achieved with safe margins with respect to the HPL and VPL. Numerically, 95% HPL and VPL were respectively 2.08 and 3.34 metres for single-frequency solutions and the corresponding values for dual-frequency solutions were 57 and 87 centimetres.

Chapter 3

# Quality Indexes

This chapter is aimed at providing evidence of the quality of the research developed in the context of my Ph.D. study. The work supporting this thesis has been presented to a number of international conferences and peer-reviewed journals, where experts have provided valuable comments that have improved the quality and clarity of the research. The list of papers and conference proceedings can be found in Section 3.1 and Section 3.3, respectively.

The research has achieved a scientific relevance and a noticeable impact in the field of the satellite navigation. In this regard, Section 3.2 presents two different international recognitions that have been awarded by the European Institution "European Geosciences Union" and the American Institution "The Satellite Division of the Institute of Navigation".

## 3.1 Peer-reviewed Journals

Table 3.1 shows the publications realized in peer-reviewed journals indexed in the Journal Citation Reports (JCR). The importance of each journal where the research has been published is proven in Table 3.2, by means of presenting the latest Impact Factor (IF) and quartile available at the time of writing this dissertation, according to Thomson Reuters (2015). Because such indicators can vary significantly from year to year, it is also displayed the IF and quartile based on the last 5 years, except for the journal of the Institute of Navigation which was added to JCR in 2014.

Table 3.1: Articles published in peer-reviewed journals.

| Journal Name | | Publication Title |
|---|---|---|
| **Short** | **Complete** | |
| IEEE TGRS | IEEE Transactions on in Geoscience and Remote Sensing | A Real-time Worldwide Ionospheric Model for Single and Multi-frequency Precise Navigation |
| JGR | Journal of Geophysical Research | Ionospheric and plasmaspheric electron contents inferred from radio occultations and global ionospheric maps |
| JOGE | Journal of Geodesy | Accuracy of Ionospheric Models used in GNSS and SBAS: Methodology and Analysis |
| Navigation | Navigation, Journal of the Institute of Navigation | Fast Precise Point Positioning: A System to Provide Corrections for Single and Multi-frequency Navigation |

Table 3.2: Journal information and ranking in its category based on the IF. Source: Thomson Reuters (2015).

| Journal | ISSN | Impact Factor | | Quartile | | | |
|---|---|---|---|---|---|---|---|
| | | 2014 | 5 Years | 2014 | | 5 Years | |
| IEEE TGRS | 0196-2892 | 3.514 | 4.112 | 2/28 | Q1 | 5/24 | Q1 |
| JGR | 0148-0227 | 3.426 | 3.667 | 19/179 | Q1 | 26/175 | Q1 |
| JOGE | 0949-7714 | 2.699 | 3.329 | 23/79 | Q2 | 19/79 | Q1 |
| Navigation | 0028-1522 | 0.562 | n/a | 17/30 | Q3 | n/a | |

## 3.2 Awards

**Name of the award:** Outstanding Student Poster (OSP) Awards 2014
**Institution:** European Geosciences Union, Geodesy Division
**Congress:** EGU General Assembly 2014
**Reference:** Rovira-Garcia A, Juan M, Sanz J (2014b) Fast-PPP assessment in European and equatorial region near the solar cycle maximum. In: Proceedings of the European Geosciences Union General Assembly 2014: Geophysical Research Abstracts Vol. 16, Vienna, Austria, URL https://static2.egu.eu/media/awards/union-osp-award/2014/adria_rovira-garcia.pdf

**Name of the award:** Best Presentation Award
**Institution:** Institute of Navigation
**Congress:** 27th International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS+ 2014)
**Reference:** Rovira-Garcia A, Juan M, Sanz J (2014a) A Real-time World-wide Ionospheric Model for Single and Multi-frequency Precise Navigation. In: Proceedings of ION GNSS+ 2014, Tampa, Florida (USA), pp 2533–2543, URL http://www.ion.org/publications/abstract.cfm?jp=p&articleID=12446

## 3.3 Conference Proceedings

1. Rovira-Garcia A, Juan M, Sanz J, González-Casado G, Ibáñez Segura D, Romero-Sánchez (2015f) Assessment of Ionospheric Models for GNSS During a Year of Solar Maximum. In: Proceedings of ION GNSS+ 2015, Tampa, Florida (USA), pp 3833–3840, URL http://www.ion.org/publications/abstract.cfm?jp=p&articleID=13088
2. González-Casado, G and Juan, J M and Sanz, J and Rovira-Garcia, A and Aragon-Angel, A (2015) Ionospheric and Plasmaspheric contribution to the Total Electron Content Inferred from Ground Data and Radio-Occultation-Derived Electron Density. In: Proceedings of ION GNSS+ 2015, Tampa, Florida (USA), pp 3459–3468, URL http://www.ion.org/publications/abstract.cfm?jp=p&articleID=13105
3. Rovira-Garcia A, Juan J, Sanz J, Gonzalez-Casado G, Ibáñez Segura D (2015c) A Methodology to Assess Ionospheric Models for GNSS. In: Proceedings of the European Geosciences Union General Assembly 2015 Geophysical Research Abstracts Vol. 17, Vienna, Austria, URL http://meetingorganizer.copernicus.org/EGU2015/EGU2015-1015.pdf

4. Rovira-Garcia A, Juan J, Sanz J, González-Casado G, Ibáñez Segura D (2015e) Assessment of Ionospheric Models Tailored for Navigation. In: SBAS Ionospheric Working Group Meeting 22, Trieste, Italy

5. Juan M, Sanz J, González-Casado G, Rovira-Garcia A, Ibáñez Segura D, Orús-Pérez R, Prieto-Cerdeira R, Schlueter S (2014) Accurate reference ionospheric model for testing GNSS ionospheric correction in EGNOS and Galileo. In: Proceedings of the 7th ESA Workshop on Satellite Navigation Technologies: Era of Galileo IOV (NAVITEC 2014), ESA/ESTEC, Noordwijk, The Netherlands

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Chapter 4

# Conclusions and Future Research

The present chapter brings together the conclusions achieved in this dissertation. In addition, future research directions for the development of the Fast-PPP technique are suggested, based on the outcomes of this doctorate thesis.

## 4.1 Conclusions

The conclusions are aligned with the aim of this dissertation: to assess and to consolidate the Fast-PPP technique, and can be summarised as follows:

**Assessment:** The accuracy of the Fast-PPP satellite orbit and clock corrections has been assessed with respect to the standard precise products from the IGS, with accuracies of few centimetres and two tenths of a nanosecond. The Fast-PPP determinations of the satellite DCB have been compared with respect to different ACs, with average standard deviation of 0.10 (5 minutes) and 0.07 nanoseconds (daily). The fractional part of the ambiguities have been assesed comparing independent estimations in consecutive days, being found that the day-to-day discontinuities are smaller than 0.1 cycle (2 centimetres). Finally, the Fast-PPP ionospheric modelling has been shown to be accurate to 1 Total Electron Content Unit, (i.e., $16.24$ centimetres in the L1 frequency) with a new methodology based on the carrier-phase ambiguity fixing performed in the Fast-PPP CPF.

**Consolidation:** The implementation of the ionospheric model has been extended from a regional scale to a global scale. The two-layer modelling has been validated with independent measurements from RO of LEO satellites. A new strategy has been designed for the Fast-PPP user navigation filter, considering single- and multi-frequency capabilities. The CPF and the navigation module have been assessed in strict real-time conditions.

It has been showed critical to correctly weight the different corrections within the navigation filter. In this sense, the user module has been optimised to use the confidence bound of the corrections computed by the Fast-PPP CPF. The actual positioning errors present short convergence times and great consistency with respect to the formal errors, as demonstrated using similar figures of merit used in civil aviation, as the Stanford plots.

Numerically, the Fast-PPP 95% HPE and VPE were shown respectively 36 and 63 centimetres for single-frequency solutions and the corresponding values for dual-frequency solutions were 11 and 15 centimetres, respectively. Fast-PPP accuracies presented safe margins with respect to the 95% HPL and VPL, which were respectively 2.08 and 3.34 metres for single-frequency solutions and the corresponding values for dual-frequency solutions were 57 and 87 centimetres.

Two criteria have been defined in order to assess the reduction of convergence of Fast-PPP, based on the accuracy and sigma of the navigation solution. Fast-PPP ionospheric corrections accelerate the positioning convergence up to a maximum distance of 500 kilometres to the nearest reference station. Numerically, for the distance range between 100 and 500 kilometres, the convergence time of the horizontal component was reduced from 40% to 90% and the vertical component was reduced by 20% to 60%. Rovers located at more than 800 kilometres never worse the ionosphere-free solutions, thanks to the confidence bounds of the ionospheric corrections.

## 4.2 Future Research

Currently, real-time streams of the International GNSS Service are available for geodesy (e.g., the Centre National d'Études Spatiales, including the fractional part of the ambiguities) and ionosphere (e.g. European Space Operations Centre), but no centre provides a jointly processed product. As it has been already explained, the major advantage of Fast-PPP is that it transfers the accuracy of geodesy estimates to the ionospheric determinations.

The Technology Readiness Level of the Fast-PPP would be greatly risen by disseminating the corrections (geodesy and ionosphere, DCBs and fractional part of ambiguities) via Internet, prior to its satellite-based broadcasting. The availability of the Internet-based Fast-PPP service would enable transferring the decimetre-level of accuracy within a few minutes of the Fast-PPP technique to single-frequency mass-market receivers, in operational environments.

Moreover, the broadcasting of the fractional part of the ambiguities would enable global ambiguity-fixing capability for PPP users (i.e. professional). This high-accuracy service is considered an important target by the current evolution plans of Galileo and EGNOS. As it was previously mentioned, the long convergence times are limiting PPP in many applications (e.g., precision agriculture).

Chapter 5

# Publications

The present chapters brings together the publications realized in the context of my Ph.D. study. Section 5.1 provides the required thematic unity which interconnects the different manuscripts of the dissertation. Section 3.1 and Section 5.3 provide the complete bibliographic information of the peer-reviewed journal articles and book chapters, respectively. A copy of the original manuscripts is appended right after.

## 5.1 Thematic Justification

The GNSS data sets involve a number of standards, which are reviewed in Rovira-Garcia (2013a). From these data sets, the user position can be estimated following a modelling stage and filtering. An implementation of the algorithms needed to complete such GNSS data processing are explained in Rovira-Garcia (2013b). Especial attention is given to the cycle-slip detection, because it is required in positioning techniques that use the carrier-phase measurements to achieve high-accuracy navigation.

An example of such high-accuracy navigation technique is the Fast-PPP. The core part of the technique is the ionospheric model, which was extended for first time to low-latitude regions in Rovira-Garcia et al (2015a), together with a new design for the user filter. The ionospheric model has been validated with independent measurements from RO of LEO satellites in González-Casado et al (2015), where a good agreement has been shown between the electron contents inferred from ROs and the Fast-PPP model predictions.

Because it is crucial to characterize the accuracy of ionospheric models tailored for GNSS applications, a methodology was developed and assessed in Rovira-Garcia et al (2015d). Finally, a further assessment of the Fast-PPP technique at both the CPF and the user domain is presented in Rovira-Garcia et al (2015b).

## 5.2 Articles in Peer-reviewed Journals

1. Rovira-Garcia A, Juan J, Sanz J, González-Casado G (2015a) A Worldwide Ionospheric Model for Fast Precise Point Positioning. Geoscience and Remote Sensing, IEEE Transactions on 53(8):4596–4604, doi: 10.1109/TGRS.2015.2402598, URL http://ieeexplore.ieee.org/xpl/articleDetails.jsp? arnumber=7053952

2. González-Casado G, Juan JM, Sanz J, Rovira-Garcia A, Aragon-Angel A (2015) Ionospheric and plasmaspheric electron contents inferred from radio occultations and global ionospheric maps. Journal of Geophysical Research: Space Physics 120(7):5983–5997, doi: 10.1002/2014JA020807, URL http://dx.doi.org/10.1002/2014JA020807

3. Rovira-Garcia A, Juan J, Sanz J, González-Casado G, Ibáñez Segura D (2015d) Accuracy of Ionospheric Models used in GNSS and SBAS: Methodology and Analysis. Journal of Geodesy pp 1–12, doi: 10.1007/s00190-015-0868-3, URL http://dx.doi.org/10.1007/s00190-015-0868-3

4. Rovira-Garcia A, Juan J, Sanz J, González-Casado G (2015b) Fast Precise Point Positioning: A System to Provide Corrections for Single and Multi-frequency Navigation. Navigation-Journal of the Institute of Navigation, submitted Dec 2014, revised Aug 2015

## 5.3 Book Chapters

1. Rovira-Garcia A (2013a) Session 2.2. GNSS standard file format. In: J Sanz, J Juan, M Hernández-Pajares, ESA Communications (ed) GNSS Data Processing Fundamentals, Algorithms and Laboratory Exercises, Vol. II: Laboratory Exercises (ESA TM-23/2), ISBN: 978-92-9221-886-7, ISSN: 1013-7076, Noordwijk, the Netherlands, pp 39–52

2. Rovira-Garcia A (2013b) Session A.1. Examples of GNSS Elemental Routines. In: J Sanz, J Juan, M Hernández-Pajares, ESA Communications (ed) GNSS Data Processing Fundamentals, Algorithms and Laboratory Exercises, Vol. II: Laboratory Exercises (ESA TM-23/2), ISBN: 978-92-9221-886-7, ISSN: 1013-7076, Noordwijk, the Netherlands, pp 265–291

**ATTENTION ¡**

Pages 31 to 126 of the thesis, containing the texts mentioned above, should be consulted on the web pages of the respective publishers.

# List of Acronyms

| | |
|---|---|
| **AATR** | Along Arc TEC Rate |
| **AC** | Analysis Centre |
| **CODE** | Centre for Orbit Determination in Europe |
| **CNES** | Centre National d'Études Spatiales |
| **CORS** | Continuously Operating Reference Station |
| **CPF** | Central Processing Facility |
| **DCB** | Differential Code Bias |
| **DD** | Double Difference |
| **EGNOS** | European Geostationary Navigation Overlay System |
| **ESA** | European Space Agency |
| **ESOC** | European Space Operations Centre |
| **Fast-PPP** | Fast Precise Point Positioning |
| **FUGRO** | FUGRO Intersite B.V. |
| **gAGE** | group of Astronomy and GEomatics |
| **GIM** | Global Ionospheric Map |
| **GNSS** | Global Navigation Satellite System |
| **GPS** | Global Positioning System |
| **GRAPHIC** | Group and Phase Ionospheric Calibration |
| **HPE** | Horizontal Positioning Error |
| **HPL** | Horizontal Protection Level |

| | |
|---|---|
| **HPPS** | High-Precision Positioning Service |
| **IAR** | Integer Ambiguity Resolution |
| **ICAO** | International Civil Aviation Organization |
| **IF** | Impact Factor |
| **IGP** | Ionospheric Grid Point |
| **IGS** | International GNSS Service |
| **IGS-RTPP** | IGS Real-Time Pilot Project |
| **IGU** | IGS Ultra-Rapid |
| **IGR** | IGS Rapid |
| **JCR** | Journal Citation Reports |
| **LAMBDA** | Least-squares AMBiguity Decorrelation Adjustment |
| **LEO** | Low Earth Orbit |
| **LT** | Local Time |
| **MI** | Misleading Information |
| **MODIP** | MOdified DIP latitude |
| **MOPS** | Minimum Operational Performance Standards |
| **NPI** | Networking/Partnering Initiative |
| **NRTK** | Network RTK |
| **NTRIP** | Networked Transport of RTCM via Internet Protocol |
| **PL** | Protection Level |
| **PPP** | Precise Point Positioning |
| **RIMS** | Ranging and Integrity Monitoring Stations |
| **RMS** | Root Mean Square |
| **RO** | Radio Occultation |
| **RTCA** | Radio Technical Commission for Aeronautics |
| **RTCM** | Radio Technical Commission for Maritime Services |
| **RTK** | Real Time Kinematics |

**S/A** Selective Availability

**SBAS** Satellite Based Augmentation System

**SD** Single Difference

**SEA** South-East Asia

**SIS** Signal In Space

**STEC** Slant Total Electron Content

**TEC** Total Electron Content

**TECU** Total Electron Content Unit

**TRL** Technology Readiness Level

**UHF** Ultra High Frequency

**UPC** Technical University of Catalonia

**VHF** Very High Frequency

**VPE** Vertical Positioning Error

**VPL** Vertical Protection Level

**VRS** Virtual Reference Station

**VTEC** Vertical Total Electron Content

**WAAS** Wide Area Augmentation System

**WARTK** Wide-Area Real-Time Kinematics

**ZTD** Zenith Tropospheric Delay

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