Integrity for Advanced Precise Positioning Applications

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BIOGRAPHIES

Miguel M. Romay Merino is the GNSS Business Unit Director at GMV Aerospace and Defence. Miguel leads the GMV Unit that has become one of the strongest groups of GNSS experts thanks to its key involvement in GPS, EGNOS and Galileo. Miguel has been a pioneer in the Galileo Program, collaborating on aspects such as constellation design, precise orbit determination, integrity, performance evaluation, system definition, etc. Miguel is today involved in GMV research activities in the definition of novel GNSS applications and on the design of new generation GNSS. Miguel has been recently elected as the Chairman of the Mission Evolution Advisory Group established by the European Commission.

María D. Láinez Samper is currently coordinating the GMV research activities in the field of Satellite Navigation, and in particular she is coordinating research activities in the field of precise positioning applications. She has also worked in experimentation and verification activities, in the Operational Systems Division, during the preliminary phases of the Galileo Program, and has been the responsible for the clock prediction and navigation message computation modules in the Galileo E-OSPF (Experimental Orbitography and Synchronization Processing Facility).

ABSTRACT

This paper is aimed at laying down a general integrity concept for the PPP solutions, following a practical service oriented approximation. With this we mean that we are going to focus neither on the system integrity nor on the integrity at user level only, but on the most favorable combination of significant indicators we can assess. PPP accuracy performances are about 5 to 10 centimeters after a 15 to 30 minutes convergence period, and our target is being able to ensure protection levels in the 0.5 to 1 meters range. We will use magicPPP, our in-house developed PPP platform, for performing accuracy versus integrity analyses. We will detect and study different failure modes. We will pay particular attention to cases in which the PPP solution exceeds the expected accuracy bounds (in the centimeter magnitude order), and will try to correlate them with indicators either at system or at user levels which can be considered to be significant from the point of view of the integrity.

With these activities we intend to lay down the foundations for an upper-level PPP applicable integrity concept to be refined in subsequent steps, but always closely linked to the final user perspective. There is now a really strong demand for high precision GNSS based applications and services which will keep on increasing in the following years, and our objective is to achieve the challenging task of enabling all these present and future GNSS requested uses, those involving high positioning accuracy, as well as those in which integrity is required.

It is not the objective of this paper to completely define a new integrity algorithm for PPP but to assess the feasibility of such an algorithm and to define the general aspects to be considered. We will try to exploit the strong relationship between high accuracy and integrity trying to take advantages of the fact that PPP algorithms rely on strong physical fundaments.

INTRODUCTION

The use of satellite based navigation systems is nowadays widespread for many different applications, and it will continue growing in the future. Today both GPS and GLONASS are operational GNSS systems, and Compass and Galileo will be deployed in the next years. In parallel, there are systems such as WAAS in the USA, EGNOS in Europe and MSAS in Japan, which provide accuracy and integrity augmentation over the GNSS navigation solutions. The deployment of augmentation systems over new regions, such as GAGAN for India and SDCM over Russia and regional complements such as QZSS in Japan and IRNSS in India is now being promoted. There exists a mass market for single frequency GNSS receivers, which is expected to move towards the dual frequency in the medium term, when access to a second frequency will be affordable. In this context, high precision solutions such as Precise Point Positioning (PPP), as independent services or integrated in the augmentation systems are likely to become popular for ordinary positioning applications. Even if more GNSS constellations are available in the next few years, the associated DOP reduction is not going to be translated into a significant navigation solution improvement. We think that what is going to be really crucial is to have algorithms and infrastructure such as those required for PPP, which can make a revolution in the GNSS positioning field.
The PPP algorithm uses as input code and phase observations from a dual-frequency receiver, and precise satellite orbits and clocks, in order to calculate precise receiver coordinates and clock. The observations coming from all the satellites are processed together in a filter that solves for the different unknowns, namely the receiver coordinates, the receiver clock, the zenith tropospheric delay and the phase ambiguities. Our GNSS team has developed the algorithms and the infrastructure, except for the tracking network, needed for providing a commercial PPP service. All the required components, from the real time orbit and clock products generation, to the PPP filter implementation and the service management, are under our responsibility. As in any positioning navigation system, integrity monitoring, together with accuracy, continuity and availability is important for the PPP technique, and essential for the feasibility of certain critical applications.

Different integrity concepts have been defined for the different satellite navigation solutions. GNSS integrity can be provided both at system and at user level. System integrity is based on the capability of the GNSS to collect and check indicators, in order to warn the user in case some anomaly is detected. The system should be able to alert the user any time the positioning solution is not bounded by the required protection levels. Otherwise, we would say that an integrity failure has occurred, with the associated potential risk of hazardous misleading information transmission to the user. But in many cases, it is not an anomaly in the system what might cause an inaccurate positioning solution, but a local effect in the user environment. In order to cope with these situations, integrity concepts at user level have also been formulated. It is the case of RAIM (receiver autonomous integrity monitoring), which is based on the consistency of the different computed positions with different subsets of redundant satellite measurements, as far as they are available. Besides this, and tightly related to the final application, additional sources of information for complementing the integrity information can be considered, such as consistency checks with non-GNSS measurements, for example. In the end, an optimum combination of all available sources of integrity related information is likely to be the best option to achieve total compliance for the given positioning service integrity requirements.

In this paper we will try to exploit the relationship between high accuracy and integrity with the aim to provide protection levels below a meter with a high degree of availability and integrity. We will first analyze the PPP technique and the current evolutions in the integrity user requirements. The next step will be to launch an extensive experimentation campaign trying to cover a significant number of feared events. Finally we will analyze the results of the experimentation campaign and will outline the main characteristics of a future PPP integrity algorithm. Preliminary performances will be presented and some conclusions for future work will be addressed.

The applied methodology is schematically represented in the following figure:

**Figure 1 PPP Integrity Concept, Overall Approach**

**ANALYSIS OF THE PPP TECHNIQUE**

This section provides a brief description of the PPP technique. A deep knowledge of the PPP algorithms is needed for the proper definition of a PPP integrity algorithm. In this section we will briefly describe RTK techniques, the most widely used techniques for precise positioning. We will continue with the definition of the PPP concept. Due to the importance of the accuracy of the PPP products broadcasted to the users some information about the quality of those products and how the products are computed will be presented. And finally the real time PPP service demonstrator used in the field trials will be described.

**Real Time Kinematic**

RTK (Real Time Kinematic) is a differential positioning method, developed in the early 1990’s, based on the use of dual-frequency carrier phase measurements of the GNSS (GPS, GLONASS, QZSS, COMPASS, etc) signals where a base station receiver at a well-known, calibrated location transmits signal corrections in real time to one or several rover receivers. RTK corrections compensate atmospheric delay, orbital and clock errors, etc, increasing positioning accuracy up to the centimeter level.

RTK is a technique employed in applications where precision is mandatory; it is not only used as a precision positioning tool, but also in automatic machine guidance activities such as precision farming. The positioning determination process begins with a preliminary ambiguity resolution. This is a crucial aspect of any kinematic system, particularly in real-time where the velocity of a rover receiver should not degrade either the achievable performance or the system's overall reliability.

The correction data is typically sent via UHF or spread spectrum radios that are built specifically for wireless data.
transfer. The corrections from the base station receiver can be sent to an unlimited number of rovers.

One of the main limiting factors of RTK is the maximum distance, in terms of acceptable performances, between the base station and the rover, so it implies having a rather large density of base stations to ensure a proper coverage in large areas. The variability of both the troposphere and the ionosphere introduces systematic errors which limit this maximum allowable distance for obtaining precise positioning to 10 or 20 km.

In order to tackle this distance problem, the concept of Virtual Reference Station (VRS) was introduced in the year 2000 [1]. VRS allows performing RTK positioning in reference station networks with distances of up to 40 km. The idea is to generate Virtual Reference Stations which simulate a local base station close to the user receiver. Thus, the errors cancel out better than by using a more distant base station. However, even 40 km distance between base stations may still imply a rather large station density for big areas.

**Precise Point Positioning (PPP)**

PPP is a position location process which performs precise position determination using iono-free measurements, obtained from the combination of undifferenced, dual-frequency observations coming from a single GNSS receiver, together with detailed physical models and corrections, and precise GNSS orbit and clock products calculated beforehand. The quality of the reference orbits and clocks used in PPP is critical, as they are both two important error sources in GNSS positioning.

Apart from observations and precise reference products, PPP algorithm also needs several additional corrections which mitigate systematic effects which lead to centimeter variations in the undifferenced code and phase observations, for example phase wind-up corrections, satellite antenna offsets, station displacements due to tides (earth and oceanic), etc.

At a given epoch, and for a given satellite, the simplified observation equations are presented next:

\[
\begin{align*}
I_p &= \rho + c(b_{Rx} - b_{Sat}) + Tr + \epsilon_p \\
I_\phi &= \rho + c(b_{Rx} - b_{Sat}) + Tr + NL + \epsilon_\phi
\end{align*}
\]

Where:
- \(I_p\) is the ionosphere-free combination of L1 and L2 pseudoranges
- \(I_\phi\) is the ionosphere-free combination of L1 and L2 carrier phases
- \(b_{Rx}\) is the receiver clock offset from the reference (GPS) time
- \(b_{Sat}\) is the satellite clock offset from the reference (GPS) time
- \(c\) is the vacuum speed of light
- \(Tr\) is the signal path delay due to the troposphere

\(\lambda\) is the carrier combination wavelength
- \(N\) is the ambiguity of the carrier-phase ionosphere-free combination (it is not an integer number)
- \(\epsilon_p\) and \(\epsilon_\phi\) are the measurement-phase components, including multipath and other effects
- \(\rho\) is the geometrical range between the satellite and the receiver, computed as a function of the satellite \((x_{Sat}, y_{Sat}, z_{Sat})\) and receiver \((x_{Rx}, y_{Rx}, z_{Rx})\) coordinates as:

\[
\rho = \sqrt{(x_{Sat} - x_{Rx})^2 + (y_{Sat} - y_{Rx})^2 + (z_{Sat} - z_{Rx})^2}
\]

The observations coming from all the satellites are processed together in a process that solves for the different unknowns; the receiver coordinates, phase ambiguity terms, the receiver clock offset and the zenith tropospheric delay. Most implementations of PPP algorithms use a sequential filter in which the process noise for the coordinates is adjusted depending on the receiver dynamics, the time evolution of the clock is more or less unconstrained (white noise with a high sigma), and the process noise for the tropospheric delay is adjusted to standard tropospheric activity. In the case of phase ambiguities, they are considered as a constant per pass.

Other implementations feature a batch algorithm instead, and therefore no process noise has to be modeled. In this case, the receiver clock offset is estimated at every measurement epoch, the coordinates are adjusted for the entire observation interval (static mode) or per epoch (kinematic mode), the troposphere is estimated at regular fixed intervals and the ambiguities are also estimated per pass.

Given that PPP is not a differential technique, it cannot resolve integer carrier phase ambiguities (at least, without new enhancements). Hence, it cannot converge to a precise solution in a short time, as other techniques do (RTK, for instance), and requires longer observation times for static positioning. PPP has been normally conceived as a global service, taking into account that the orbit and clock products are themselves global. This assumption can only be considered valid as long as the tracking network used for the computation of the precise products has worldwide coverage.

Under the previous assumption, good visibility of the satellites along all their orbits can be expected, and the accuracy of the orbit and clock estimations does not depend on the receiver location. This approach may lead to some limitations as there are mainly two options in order to fulfill the global coverage:

1. To deploy a global stations tracking network. This may be complex for political and logistic reasons for example, and possibly too expensive to operate for a regional service provider, whose target may not necessarily be to guarantee a global positioning service.
2. To relay on an external precise orbit and clock product provider. This may limit accuracy, real time capabilities and multisystem approaches. For instance, the IGS products (ultra-rapid, rapid, or final) are widely used due to their known high accuracy, however the IGS does not currently provide GLONASS clocks. Furthermore, official IGS products have a latency of several hours, which makes them not valid for real-time PPP.

In the frame of this paper, and taking advantage of magicGNSS [2] tool, GMV has tackled the previously mentioned limitations by using their own precise GPS and GLONASS orbits and clocks products based on local tracking networks composed of IGS stations.

**Reference Products for PPP**

PPP positioning performances are directly related to the accuracy of the reference GNSS orbit and clock products. Therefore, prior to the performance comparison between PPP and RTK, the process followed for the generation of the precise satellite orbits and clocks used in regional or global PPP will be explained. A complex process as it implies facing the challenge of generating products for a real time PPP service.

For the past years, GMV has been developing an infrastructure for the generation of precise GPS and GLONASS orbits and clocks with very low latency in a first step, and in real time in a second step. A high-level layout of the infrastructure is shown in next figure:

![Figure 2 Product Generation Infrastructure High-level Layout](image)

This process retrieves, from a worldwide station network, via Networked Transport of RTCM via Internet Protocol (NTRIP) (http://igs.bkg.bund.de/ntrip/ntriphomepage), dual-frequency code and phase measurements in real time. Once collected, they are pre-processed also in real time by a Pre-Processing and Validation module (PPV), which then makes iono-free and geometry-free measurements available to the different algorithms.

The reference product generation is based on an Orbit Determination and Time Synchronisation (ODTS) process, which runs every 15 minutes. The ODTS processes 2 days of data in every execution, and provides updated satellite orbits and other estimated parameters (such as phase ambiguities, station tropospheric zenith delays and Earth orientation parameters).

In parallel to the ODTS, another process called RT_CLK estimates the satellite clocks in real time taking as input the pre-processed observations coming from PPV and the outputs from the last ODTS execution. There is a small latency in the delivery of the clock estimate, which is associated to the time that the algorithm waits for the arrival of the measurements from the station through the Internet; typically one or two seconds.

Both GPS and GLONASS satellites are processed together, in order to ensure a consistent solution. It is necessary to estimate an inter-channel bias when processing GLONASS data. This must be done in order to compensate for the different internal delays in the pseudorange measurements through the GLONASS receiver, associated to the different frequencies used by the different satellites. Otherwise the station clock estimate would not be coherent with the pseudoranges. It has been observed that in GPS data this effect is much smaller and therefore negligible; normally it is not necessary to estimate such an inter-channel bias for GPS data.

The real-time orbits and clocks are available as a data stream to real-time processing algorithms (such as real-time PPP), and stored in standard formats (SP3, clock RINEX) to be used as GPS plus GLONASS reference products for magicGNSS PPP service. The products generated this way contribute to the IGS Real Time Pilot Project since 2010, and are also used to feed GMV’s PPP service, part of the web application magicGNSS [3].

The real-time orbit and clock reference products performances versus IGS rapid products can be seen in next figure. It covers the period since mid-2010 till July 2011.

![Figure 3 GMV's Real Time products vs IGS](image)
The clock RMS stays around 0.3 ns and the 15 minute prediction orbit error stays around 6 cm.

As it is also represented in Figure 1, there is also an offline ODTS process running in off-line post-processing mode with a latency of 2 days and specific setup, which allows the generation of more precise products than the real time ones. When available, such products are then used for off-line PPP in replacement of the ones generated previously in real time.

Figure 4 Orbit comparison between IGS products and off-line GPS products for 2011.

Figure 5 Clock comparison between IGS products and off-line GPS products for 2011.

The comparison of the off-line products with the IGS for a typical day is shown in Figure 4 for orbit and in Figure 5 for clocks. In this case the typical orbit performances are around 3cm, and clock accuracy is around 0.2ns.

The network used, which is represented in next figure provides global coverage and some redundancy to cover the relatively frequent (especially from some stations) outages of the real-time data streams. The different colours indicate the number of stations (also called Depth-of-Coverage or DOC) that are tracking a satellite when it is flying over a particular location.

Figure 6 NTRIP Tracking Station Network

Together with the comparison of the off-line reference products with IGS rapid products, their quality is also assured by performing PPP for several IGS stations of known coordinates, over 1 day observation period.

Figure 7 Static PPP Performances vs IGS coordinates

Previous figure shows the positioning performances for 9 IGS stations with respect to the published IGS coordinates. It can be seen that the accuracy of the PPP solution is around 1 cm, both for GPS and GPS/GLONASS. This result illustrates the good quality of the reference products (both for GPS and for GLONASS) as well as the level of performances of the PPP algorithm.

The quality of the PPP real time products are conditioning the accuracy of the final solution and will have a strong impact in the definition of a future integrity algorithm. At GMV a significant effort has been put to ensure a high availability, reliability and quality of the real time products. Several independent machines, sometimes with different configurations and data are running in parallel. The different products go through a complex monitoring process. After that the best product is selected and sent to the final users. The process is schematically represented in the following figure:

Figure 8 magicPPP overview. Product generation

Real Time PPP Service

Based on the high quality of the real time products generated with magicPPP GMV has established a real time PPP service, in a first step to evaluate the concept and to serve as a demonstrator of a new generation high accuracy
positioning service. Although today the service is working in an operational basis and it is widely used.

The main motivation for developing the demonstrator and the entire experimentation platform is:

- Evaluate the real-time PPP performances in the field:
  - Realistic scenarios
  - Static and kinematic

- Learn and overcome the challenges associated to the service provision:
  - Communications
  - Reliability

- Learn and overcome the challenges associated to implementing the PPP algorithm in portable devices:
  - CPU and memory load
  - Power consumption

A significant effort has been put in minimizing the latency of the products. Products are generated in almost real time but they have to be transmitted to the final users, latency is introduced in the process and this latency may have a negative influence in the final positioning accuracy. The following figure illustrates the latency introduced in the real time products:

**Figure 9 Real Time Products Latency**

A PPP client software, to be implemented at the user terminal has been developed, the main characteristics of this PPP client software are described below:

- Linux, C++, object-oriented
- Close synergies with product generation algorithms
  - Efficient development
- Dual-frequency code + phase data in RTCM 3 format
- Validated on static and kinematic scenarios
- Robustness against communication outages

The following figure provides an indication about the performances that can be achieved at user application level. It shows the number of satellites in view (considering GLONASS and GPS) and the positioning accuracy in the north, east and height components:

**Figure 10 Positioning performances at user level**

From the previous figure it can be observed that real time positioning accuracies of about 2-3 cm can be achieved in the horizontal component and about 5 cm in the vertical component.

A real time HW demonstrator has been developed, and this demonstrator has been widely used in the integrity trials that will be described in the following sections. It should be noted that the PPP client has been designed to run in any standard platform and many tests have been performed using a standard laptop. The following figure describes the real time PPP demonstrator HW layout:

**Figure 11 Real Time PPP Demonstrator HW Layout**

The PPP user equipment is implementing a standard connectivity and consequently is able to work with any standard geodetic receiver, the main connectivity characteristics are:

- Use RTCM output from geodetic receivers
  - Serial interface
  - Works with virtually all modern equipment
- NMEA output via Bluetooth
  - Can input data to PDAs for professional field use
TcpGPS - Replanteo y Toma de Datos con receptores GNSS - ©  APLITOP

Toma de Datos
La aplicación ofrece numerosas opciones para el replanteo de puntos, carreteras y transversales, estaciones transversales, estaciones a punto, continuo por distancia, tiempo o desnivel, toma de ejes, perfil longitudinal, perfiles y asociarlas a las uniones de puntos basadas en la base de datos de construcción geométrica. En cada punto se puede indicar la altura de antena y el código, y se controla la calidad de la posición obtenida, las desviaciones y los modos de integridad para PPP.

Tambi én existen opciones para replantear mallas rectangulares o por el método del tresbolillo.

**Figure 12 Standardized Connectivity**

The user equipment implements a touch operated user interface for demonstration and to allow the operator to monitor in real time the PPP performances, a typical display of this user interface is illustrated in the figure below:

**Figure 13 Real Time PPP Demonstrator User Interface**

Communications is one of the major limitations of any real time precise positioning application. The magicPPP demonstrator allows testing different communication techniques and some aspects related to the communications having an impact on the final performances. It should be noted that PPP or RTK techniques are based in the transmission of real time information, thus any failure in the transmission of the data will severely impact the final performances. This shall be considered when defining an integrity algorithm.

The PPP data transmission is clearly a major challenge and the main aspects to be considered are:

- **Communications link**
  - Bandwidth
  - Reliability
  - Latency
  - Cost
  - Equipment (modem, antenna, power)

- **Data rate**
  - PPP performances versus communications cost
  - 1-way vs 2-way communications with PPP server

**Figure 14 Communications trade-off**

We have performed some trade-off to evaluate the impact of the PPP transmission data rate and to find the best possible solution. In particular a trade-off between 2-way and 1-way communication has been performed. 2-way communication will allow transmitting corrections only for those satellites in view and consequently will allow a significant reduction in the date rate, but 2-way communications are not feasible on broadcast-like services.

The following table illustrates the bandwidth in bits per second for different scenarios. In all cases corrections to broadcast ephemeris for 56 satellites (GPS & GLONASS) have been considered:

<table>
<thead>
<tr>
<th>Option</th>
<th>Orb rate</th>
<th>Clk rate</th>
<th>1-way</th>
<th>2-way</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-rate</td>
<td>10s</td>
<td>1s</td>
<td>2554</td>
<td>1463</td>
</tr>
<tr>
<td>Low-rate</td>
<td>900s</td>
<td>60s</td>
<td>39</td>
<td>22</td>
</tr>
<tr>
<td>Mid-rate</td>
<td>300s</td>
<td>60s</td>
<td>103</td>
<td>81</td>
</tr>
<tr>
<td>Mid-rate 2</td>
<td>60s</td>
<td>60s</td>
<td>206</td>
<td>134</td>
</tr>
</tbody>
</table>

**Figure 15 Real Time PPP data rate**

From above table it can be seen that the driver for the final bandwidth, and consequently the communication cost and reliability, is the rate for the transmission of the clock and orbit corrections. GMV has a long expertise in the computation of ephemeris and clock products and a lot of effort has been put in optimizing the transmission rate with the aim of increasing the performances of the PPP. Not only performances are enhanced but also the overall communication costs are reduced and the reliability is increased. This certainly will facilitate the concept of integrity for PPP.

The following figure illustrates the PPP real time performances when the orbits and clocks are broadcasted every 300 seconds instead of every 10 seconds (Figure 10):
Figure 16 Positioning performances at user level, corrections broadcasted every 300 seconds

From above figure it can be observed that excellent performances can be achieved broadcasting PPP corrections every five minutes. This clearly reduces communications costs and improves significantly the reliability and robustness of the solutions.

Finally it is important to remark that PPP techniques provide absolute positioning and not relative positioning (as RTK). This has some important advantages but also represents some drawbacks. The main drawback is probably the lack of knowledge of the Terrestrial reference frame in real time. Consequently it would be almost impossible to reduce the current level of accuracy achieved as this would imply a better knowledge of the reference frame in real time.

INTEGRITY DEFINITION

In this section we will outline our view about how a future GNSS system will look like, and we will describe the concept of integrity for PPP that will be later on used in the frame of this paper.

Future GNSS Systems

In this paper we are dealing with future integrity algorithms for precise applications, aeronautical and non-aeronautical. Before entering in details it is important to envisage how a future GNSS system will look like [4]. The future user positioning algorithms will be modified to take profit of the new coming GNSS systems and the latest advances in PPP techniques. It seems quite obvious that in some years from now all the GNSS systems will be dual frequency systems. Therefore it can be expected that all user equipment’s, even the mass market ones, will be able to profit from the dual frequency systems. This will allow removing one of the largest errors, the ionospheric propagation. Another significant improvement would be coming from the use of phase instead of pseudorange. Carrier phase measurements are about 100 times less noisy than pseudorange allowing a significant improvement in the positioning accuracy. The main limitation associated to the use of the carrier phase measurements is the need to solve for the ambiguities in real time. Quite a significant progress in this field has been achieved over the last years, GMV is developing a new generation of such algorithms, and the situation will improve over the coming years as more systems and frequencies become available.

Another important topic is the use of PPP like algorithms at user/application level. This is already feasible today but it will be even more evident in the near future. The use of these algorithms allows the removal of the tropospheric effects and to profit from accurate ephemeris and clocks. The availability of regional satellite systems based on geosynchronous orbits will allow the real time transmission of the PPP corrections to users, corrections that could be managed as SBAS corrections are managed today. By doing that it would be possible to obtain reliable centimetric or even millimetric positioning accuracies with mass market equipment’s.

The evolutions of the positioning algorithms are supporting the concept of reducing the total number of satellites, as centimetric accuracies could be obtained with relatively few satellites. The combination of MEO and regional complements based on geosynchronous satellites would be fundamental to support the broadcast of the required navigation information to the users. Other positioning technologies would be used to allow navigation in difficult environments and to ensure continuity and availability.

To conclude we envisage the future as a combination of:

- Only one classical GNSS global system constituted by different contributions from different countries or regions
- A set of regional navigation satellite systems, to improve geometrical configuration and to transmit navigation information or additional services in the region
- A set of SBAS systems, integrated with the satellite regional complements and associated ground segments, to provide regional Safety of Life Services
- Completely new positioning algorithms, benefiting from the availability of dual frequency measurements, phase measurements, and PPP like algorithms at user level
- Additional non satellite-based navigation techniques at user level

GNSS will then be more global, ensuring international cooperation, reducing development and maintenance costs and improving dramatically the performances.

Integrity concept

Users are demanding more and more from a navigation device. Expectations on accuracy, availability, integrity and continuity are higher every day. To satisfy this user expectations we will need to change completely the
positioning algorithms and as already mentioned PPP is probably the best solution. PPP is already providing accuracy with a high level of availability, the question now is to provide integrity on PPP. Other techniques for precise positioning, such as RTK, are unable to provide integrity in most of the situations. In this section we will review the main integrity definitions and we will outline the relationship between accuracy and integrity, more information can be found in [5].

**Integrity** is the measure of the trust that can be placed in the correctness of the information supplied by a navigation system. Integrity includes the ability of the system to provide timely warnings to users when the system should not be used for navigation.

As it has often been cause of confusion, it is worth trying to clarify the distinction between accuracy and integrity:

- From a mathematical point of view, the main difference between them is the point of the tail of the statistical distribution of errors at which to place the cut-off. For instance, civil aviation requirements tend to measure accuracy at the 95% percentile (e.g. "95% of the errors shall be below such and such..."), whereas integrity requirements refer to percentiles that range between 99,999% and 99,9999999% (depending on the particular topic under consideration). The intention behind this is to keep the probability of hazardous situations (that would possibly put at risk human lives) extremely low.
- Another key difference is in the alarms; integrity requirements involve alarms being raised when system's performance is bad enough to become risky, while accuracy requirements do not.
- From a system performance perspective, accuracy is understood as a global system characteristic, whereas integrity is rather intended as real time decision criterion for using or not using the system. For this reason, it has been a common practice to associate integrity with a mechanism, or set of mechanisms (barriers) that is part of the integrity assurance chain but at the same time is completely independent of the other parts of the system for which integrity is to be assured.

This definition of integrity is somewhat vague, and needs further specification. In the case of integrity, this is achieved by means of the concepts of Alert Limit, Integrity Risk, Protection Level and Time to Alert:

**Alert Limit**: The alert limit for a given parameter measurement is the error tolerance not to be exceeded without issuing an alert.

**Time to Alert** (TTA): The maximum allowable time elapsed from the onset of the navigation system being out of tolerance until the equipment enunciates the alert.

**Integrity Risk**: Probability that, at any moment, the position error exceeds the Alert Limit.

**Protection Level**: Statistical bound error computed so as to guarantee that the probability of the absolute position error exceeding said number is smaller than or equal to the target integrity risk.

An integrity failure is an integrity event that lasts for longer than the TTA and with no alarm raised within the TTA. The Stanford diagram actually accounts for integrity events and not for integrity failures (according to the above definitions), but allows distinguishing between two types of integrity events: misleading information (or MI) events and hazardously misleading information (or HMI) events:

- A misleading information event occurs when, being the system declared available, the position error exceeds the protection level but not the alert limit.
- A hazardously misleading information event occurs when, being the system declared available, the position error exceeds the alert limit.

![Figure 17 Stanford diagram](image-url)

**INTEGRITY CONCEPT FOR A PPP ALGORITHM**

In the previous sections we have described the PPP algorithms and the performances in terms of accuracy that can be achieved. We have also reviewed the integrity concept, and we have introduced the concept of integrity for future applications taking into account the evolutions of the navigation systems and applications. In this section we will try to investigate the feasibility of providing integrity to the PPP solutions, and we will outline the
major critical issues associated with the provision of PPP integrity.

As we have already seen there is a strong relationship between integrity and accuracy. In GMV we are used to deal with advanced GNSS applications and when we started to develop the PPP concept we were always having in mind the possibility of implementing integrity. If we are able to compute positions with centimetric accuracy why not to try to provide integrity to those solutions.

The main advantages of the PPP techniques are that they rely very much on physical laws, and consequently it should be ‘easy’ to detect any anomalous behaviour. We have to keep in mind the following main characteristics:

- The positions and clocks of the satellites are very well known. Orbits with accuracies of about 5 cm or better and clocks with accuracies of about 0.2 ns or better.
- The use of dual frequency measurements allows the removal of the ionospheric delay.
- The tropospheric delay is estimated by the user using the client software implemented in the user equipment. The tropospheric delay is estimated with accuracy better than 2 cm at zenith.
- The phase ambiguity is also computed at user level, and there are different techniques. Some based on integer ambiguity resolutions and others estimating the ambiguity as a real number.
- PPP solutions are based on multi-constellation data. In this case GPS and GLONASS have been used. This improves geometry and allows reducing the convergence period.
- Carrier phase measurements residuals are typically below 1 cm; this facilitates the detection of any anomaly in the position estimation.

Those characteristics mentioned before are clearly indicating the potential of the PPP solutions and seem to indicate the feasibility of an integrity algorithm. But there are other aspects to be considered that may complicate the process:

- The observability of some of the parameters is poor and consequently there are high correlations between some of those parameters.
- The observability can be improved by adding more satellites, increasing the time interval, or adding more physical information to the process.
- The lack of observability implies that a real time precise positioning can only be achieved after some convergence time. Depending on the level of accuracy required this converge time range between 5 to 30 minutes.
- Sensitivity to the quality of the PPP products mainly orbits and clocks. Systematic errors in the products will lead to position errors difficult to be detected.
- The environment, as PPP algorithms need some time to get convergence occultation of satellites (trees or urban environments) may create some problems, and the recovery time maybe large.
- Loss of communications, PPP algorithms are based on the precise knowledge of the orbits and clocks of the GNSS satellites. Communications losses may imply that this information may not arrive with the required accuracy and consequently the PPP solutions will be degraded.

At GMV we have developed our own PPP algorithms based on products generated also at GMV. In this context we have a full control of the process and consequently we can tune the algorithms not only for providing accuracy but also integrity. After this tuning of the algorithms we have performed some trials to investigate the feasibility of providing integrity and to identify the main drivers for a future integrity algorithm. The followed methodology is schematically represented in the following figure.

![Methodology for the PPP Integrity Algorithm Definition](image)

We shall not forget that the integrity concept has to be applied at application level and this is the main reason why we have devoted a lot of effort to analyse the PPP performances in a real application environment before starting with the definition of the algorithm. We have selected the most complex application scenario which is normally a road user. It is expected that for other type of users, such us aeronautical users, the algorithm will behave much better.

We have selected three main scenarios:

1. Static scenario
2. Convergence scenario
3. Dynamic scenario

Those scenarios will now be described. In all cases we have used standard dual frequency geodetic receivers processing data from GPS and GLONASS. The trials started in December 2011; the first trials were used to
improve the PPP algorithm. The PPP algorithm was considered in a stable mode in June 2012 and consequently during July we have performed the trials leading to the first definition of the integrity concept.

**Static scenario**

We have installed a reference station at GMV headquarters in Tres Cantos (Spain). This reference station is installed in the roof of the building and it has been used for tuning the PPP algorithm. The location of this station has been calibrated with accuracy better than 2 cm and consequently will allow us to evaluate the PPP performances. We have accumulated more than six months of operations but for this analysis we have selected four periods, which are described below:

1. Starting on July 9th at noon and lasting for about one and a half day.
2. Starting on July 13th at noon and lasting for about three and a half days.
3. Starting on July 18th at noon and lasting for about one a half day.
4. Starting on July 25th at 08:00 am and lasting for about five days.

Different periods were selected to evaluate the impact of the quality of the products and to identify possible integrity indicators associated to the estimation process. The main purpose of these trials was to investigate the robustness of the solutions over relatively long periods of time. These trials were also aiming to identify possible feared events derived from anomalies in some of the satellites.

**Convergence scenario**

PPP algorithms need some convergence time to provide the best performances. These trials were aiming at investigating if it is possible to provide integrity during the convergence periods in where the accuracy performances deviate significantly from the final ones. For defining the trials we have been analysing the convergence behaviour during several months, both in static and dynamic scenarios. We came to the conclusion that the main driver for the convergence is the satellite geometry. As geometry repeats almost every one day we have defined 35 different trials during July 13th and July 14th. For all cases we have used the static scenario described before launching a PPP every hour for a period of four hours (to ensure that full convergence has been achieved in all cases).

**Dynamic scenario**

Finally a more realistic scenario has been defined, for this scenario we have used a portable geodetic receiver, we have installed the receiver in the roof of a car and we have performed the different trials.

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Figure 19 Dynamic trials setup

In all the cases standard communications using mobile GSM networks have been used. The trajectory has been selected taking into account the following criteria:

- Vicinity of an RTK station for calibration purposes
- Several kilometres near the RTK reference station in a clean environment (good visibility conditions and reliable communications)
- Some parts of the trajectory will go through an urban environment
- The trajectory will cross some rural areas including trees that may block some of the signals
- The trajectory must include some areas with communication losses
- The trajectory must include some areas with variation of altitude to test the tropospheric estimation algorithms

The trajectory selected is represented in the figure below:

Figure 20 Dynamic trials trajectory

The trajectory has been marked with some numbers that try to cover all different conditions.

**Mark 1**: is the closest point to the reference station used for RTK. The reference station that has been used is the one deployed at GMV headquarters described in the static tests. The distance to the reference station is about 5.8 km.

**Mark 2**: is an area of about 8 kilometers with good visibility conditions:
Figure 21 Dynamic trials trajectory, Mark 2

Mark 3: this is an urban environment area, it is not a very aggressive urban environment area but nevertheless it is believed to be quite representative.

Figure 22 Dynamic trials trajectory, Mark 3

Mark 4: this is an area where we cross a relatively deep valley. The altitude variation is about 100 meters in just less than a minute.

Figure 23 Dynamic trials trajectory, Mark 4

Mark 5: this area is characterized for frequent communications losses, some of them lasting more than 3 minutes.

Mark 6: this area is characterized for frequent communications losses, and the presence of trees. It is consequently an area that combines frequent signal losses with the associated cycle slips in the phase measurements with lack or real time PPP corrections due to communication losses.

In all cases, we used RTK to define a reference trajectory. Nevertheless this was not an easy task mainly due to:

- Our RTK solution is based only on GPS, and consequently it does not work properly when the visibility conditions are poor.
- RTK does not work in areas with communication losses lasting more than a few seconds.
- RTK does not provide a good reference when there are significant height variations or when we are far from the reference station. In some parts of the trajectory the distance to the reference station is more than 15 km.

This has forced us to analyze in detail not only the PPP solutions but also the RTK solutions in order to identify when RTK was providing a good solution or not and consequently may be used as a good reference for evaluating the error of the PPP solutions.

Therefore for our integrity analysis we have selected those areas in which RTK was providing a good solution and we have used as the truth the RTK solution. This may be quite pessimistic as RTK is not providing a free of error solution, but it is probably a valid approach for assessing the feasibility of a PPP integrity algorithm.

Trials with this trajectory were performed during a period of more than three months to tune the PPP algorithm, while the test for defining the PPP integrity algorithm were performed during July 13th, July 27th and August 3rd. Different time periods were selected to assess the impact of different meteorological conditions and also the impact of errors in the PPP products.

Integrity indicators and integrity algorithm

After having identified the scenarios and having performed the different trials, the next step is to analyze the results with the aim of identifying a potential PPP integrity algorithm. The analysis of the results is not an easy task, especially for the complexity of the dynamic scenario. We have been looking for anomalous situations and later on each of these situations must be carefully analyzed to find the most suitable algorithm.

As a result of the analysis we have concluded that any PPP integrity algorithm must have to take into account the following factors:

- It is necessary to account for the fact that PPP techniques are providing absolute positioning and not relative positioning. This implies that some errors may be coming from the lack of definition of the terrestrial reference frame.
The indicators coming out from the PPP estimation algorithm implemented at user level must be taken into account. It should be noted that those indicators are based on some hypothesis that may not be correct, and consequently some margins may be added to provide a reliable protection level.

The residuals coming out from the position estimation process, and mainly the phase residuals, are providing a very valuable indicator. This is particularly relevant in urban areas or areas affected by poor visibility conditions. It should be noted that the phase residuals are typically below 1 cm and they will be very sensitive to any positioning error.

The quality of the PPP products, orbits and clocks, must be considered. The PPP service provider must consequently transmit a parameter indicating the quality of the products to be generated. In the case of PPP this is not a complicated task due to the nature of the PPP products to be transmitted.

During convergence periods some additional margins may be added to be able to cope with the strong correlations between the different parameters. This may not be needed if the PPP estimation filter is properly adjusted to cope with these correlations, but as this may be difficult to achieve it is advisable to include this additional margin.

We have tried with the integrity algorithm to cover 100% of the different situations analysed. The complex dynamic scenario is really the driver for the definition of the protection levels. These protection levels may result to be quite pessimistic for static scenarios or for most of the dynamic scenarios. But again the purpose here is to analyse the feasibility and not to find the final algorithm with the best performances.

Finally it is important to recall that a lot of effort has been put in the generation of the PPP products. Those are the key of the process and it is of paramount importance that the PPP service provider implements a lot of internal barriers in the product generation to avoid that wrong products arrive to the final users. At GMV we have put a lot of effort in the reliability of the products, for that we have used our more than 20 years experience in computing precise orbits and clocks for GNSS satellites. To compute a PPP solution may look easy but to do it in real time, operationally and with a high degree of reliability and availability is certainly not.

The system that generates the PPP corrections has a triple redundancy, and there is a continuous monitoring of the quality of the solutions. If any problem is detected this will be transmitted to the user via the quality indicator used to define the protection levels.

**PPP INTEGRITY TRIALS RESULTS**

In this section we will describe the results obtained with the PPP integrity algorithm for the three scenarios described in the previous section.

**Static scenario**

About 940000 epochs in four different time intervals during the month of July 2012 have been processed. Protection levels are computed in the horizontal and vertical directions and the classical Stanford diagrams have been generated.

![Figure 25 PPP integrity algorithm, horizontal component. Stanford diagram](image)

**Figure 24 PPP integrity indicators**

Taking into account the results of the trials, and based on the PPP integrity indicators described before, GMV has developed a preliminary PPP integrity algorithm. This integrity algorithm is not presented here in detail, mainly because the PPP algorithm still need further development, and also because more trials are needed before having full confidence in the algorithm. Nevertheless it is worth to recall again that the main purpose of this paper is to assess the feasibility of a PPP integrity algorithm. If feasible this may constitute a revolution in GNSS as it may be possible to compute positions with centimetric accuracy and with a high level of confidence, opening a new era for the development of advanced applications.
It can be observed that very small protection levels can be found. In the horizontal component a protection level of about 30 cm will ensure 100% nominal operation, while in the vertical component the required protection level to ensure 100% operation will be about 50 cm.

The anomalous points that can be observed correspond to the end of some converge periods and they are not fully representative. They are presented here just to show that even on those conditions there is no risk of integrity failures. It can be observed that the preliminary integrity algorithm seems to provide quite conservative protection levels. As mentioned before the reason is that the algorithm has been designed to cope with the very stringent dynamic scenario.

To illustrate the form of the errors and the protection levels the following figures represent the horizontal and vertical errors and the associated protection levels for one of the four analysed static scenarios:

The temporal evolution of the errors is certainly not erratic, and no significant anomalous behaviours are observed indicating the feasibility of PPP integrity. These figures also illustrate the conservative approach followed for the definition of the PLs. Additional tunings to the integrity algorithm may lead to even lower PLs.

**Convergence scenario**

The performances of the PPP integrity algorithm have been tested during the convergence period. During these periods PPP solutions are not as accurate as during nominal operations but it is important to know if it is possible to provide integrity during those periods. The algorithm has been tested over a significant number of convergence periods, and has been adjusted to provide integrity. The following figures represent the results for the convergence scenario described in previous section. For all the analysed cases we got 100% nominal operations, this means that no integrity failure has been detected. The following figures represent the RMS of the errors and PLs obtained in all cases and epochs in the horizontal and vertical components.

From the above figures it can be observed that the integrity algorithm works during converge periods and no integrity failures are detected. Convergence is normally faster in the vertical component than in the horizontal
Convergence is normally quite fast and typically after 10 minutes positioning performances are better than 20 cm.

Following figures are presenting the worst case found during all convergence periods analysed:

![Figure 31 PPP integrity algorithm, horizontal component. Convergence period, worst case](image)

![Figure 32 PPP integrity algorithm, vertical component. Convergence period, worst case](image)

It can be seen that the integrity algorithm is able to protect the users also in the worst convergence cases.

**Dynamic scenario**

Till now we have seen that the PPP integrity algorithm is able to provide 100% nominal operation in static and convergence conditions, this means that no integrity failures have been detected. Now we will analyse a more complex dynamic case, the scenario has been described in the previous section and here the results will be analysed for each of the parts of the trajectory identified form mark 1 to mark 6.

**Mark 1 and Mark 2**

This section correspond to a relatively open sky environment with a RTK reference station in the vicinity and no communication losses, some communication losses were forced to test the performance of the algorithm under these conditions. The following figures are showing the errors and the obtained PLs in the horizontal and vertical component for this part of the trajectory.

![Figure 33 PPP integrity algorithm, horizontal component. Dynamic scenario mark 1&2](image)

![Figure 34 PPP integrity algorithm, vertical component. Dynamic scenario mark 1&2](image)

From previous figures it can be observed that the PPP integrity algorithm is able to work in 100% of the cases and no integrity failures are detected. It should be noted that the real errors are computed as the difference between the RTK and the PPP solutions and that RTK is certainly not free of errors, consequently results are believed to be conservative. PLs obtained are in the range of 0.5 meters which is quite remarkable considering that we are providing 100% availability of integrity.

Two peaks in the PLs can be observed around the time intervals (2700-3000) and (3300-3600). Around those points communication losses were forced to test the performances of the algorithm under these severe conditions. It can be seen that despite of the fact that we lose communications for periods lasting about 10 minutes PPP performances were not degraded and the PLs increased significantly to cope with this contingency.

The mark 1 area, the one closest to the RTK reference station, is the one around the two peaks, between 2400 and 3600, and corresponds to a static scenario. It is important to notice that no significant difference in performances, both in terms of integrity and accuracy, can be observed for dynamic and static cases. In fact this is something that we have confirmed during all the trials. The main difference is not coming from the fact that we are moving, but from the environment conditions, signal blockage (buildings or trees), multipath, communication losses, etc.
Mark 3

This section corresponds to an urban environment without significant communication losses. This is a quite complex scenario, with continuous changes in geometry, blocking of signals, multipath, etc. We shall consider that RTK does not work well in these conditions and consequently the horizontal and vertical errors may be quite pessimistic. The following figures are showing the errors and the obtained PLs in the horizontal and vertical component for this part of the trajectory.

From previous figures it can be seen that even in such a difficult environment the PPP integrity algorithm is able to provide excellent performances, again no integrity failures have been detected. Previous figures are just showing an example of an urban trajectory of about 10 minutes, but much more tests have been performed and no integrity failures were detected in any of them.

Some of the strange behaviours observed, like the one around the time interval 100 to 250, are due to bad performances of RTK, and they are not due to bad performances of the PPP algorithm. It can be seen that in most of the cases horizontal PLs below 0.5 meters and vertical PLs below 1 meter can be obtained. The cases in where PLs are high correspond normally to cases with a very bad geometry or with anomalous measurements, mainly due to multipath.

Mark 4

In this part of the trajectory we close a deep valley with significant height variation and frequent losses of communications. In fact these communications losses are the reason for not having a reference trajectory based on RTK, as no RTK solution was possible. As we have seen before, the PPP algorithm does not seem to work worse in dynamic conditions, so to evaluate this part of the trajectory we will mainly look at the errors at the entrance of the valley and the errors at the exit of the valley. Results are presented in the following figures:

Again it can be observed that PLs are adapting quite well to the situation, PLs are growing when there are communication losses or when there are anomalous measurements, like those around point 340 in where we are going through an area densely populated by trees.

Mark 5 and Mark 6

This is an area characterised by frequent communication losses and presence of trees on both sides of the road. Trees are leading to frequent signal losses and cycle slips in the carrier phase measurements and it is quite interesting to evaluate PPP performances under this scenario. Results are presented in the following figures:
CONCLUSIONS

A state of the art PPP algorithm has been developed at GMV. This covers not only the algorithm at user level but also all the generation of the PPP products in real time. A significant effort has been put in the reliability and robustness of the PPP products.

Real time positioning accuracies of about 2-3 cm can be achieved in the horizontal component and about 5 cm in the vertical component. The robustness of the products and the high accuracy of the solutions motivated us to investigate on integrity algorithms for PPP. A significant number of experimentation campaigns were performed to adjust the PPP algorithm and after that some integrity indicators were identified. With these indicators we developed an integrity algorithm and we tested the feasibility in some difficult scenarios.

The main conclusion is that the integrity algorithm has been able to cover all possible situations and no integrity failures have been observed. Very low PLs can be obtained, around 30 cm in horizontal component and around 50 cm for the vertical component.

In the near future using dual frequency measurements, more than one GNSS constellation and PPP algorithms at user level, it will be possible to provide integrity to very accurate positioning solutions, opening a new field for GNSS applications.

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