Enhanced Precise Point Positioning for GNSS Users


Abstract—This paper summarizes the main results obtained during the development of an Enhanced Precise Point Positioning (EPPP) Global Navigation Satellite Systems multi-frequency user algorithm. The main innovations include the application of precise ionospheric corrections to facilitate the resolution of undifferenced carrier phase ambiguities, ambiguity validation, and integrity monitoring. The performance of the EPPP algorithm in terms of accuracy, convergence time, and integrity is demonstrated with actual GPS and simulated Galileo data. This can be achieved with very limited bandwidth requirements for EPPP users (less than 300 b/s for dual-frequency GPS data).

Index Terms—Global Navigation Satellite Systems (GNSS), high precise positioning, integrity monitoring, Precise Point Positioning (PPP), real-time ionospheric corrections.

I. INTRODUCTION

Precise point Positioning is typically considered as the technique that allows a dual-frequency GPS user to determine a position at the decimeter error level (kinematic mode) and centimeter error level (static mode) with a single receiver. This is based on the real-time availability of satellite products (GPS orbits and clocks) that, by using data from a network of permanent GPS receivers and better modeling, are significantly more precise than those computed by the GPS control segment. Another important characteristic of the classical PPP user algorithm is the usage of the ionospheric-free combinations of observables to remove more than 99.9% of the slant ionospheric delay. These main observables, ionospheric-free carrier phases, and code observations for all of the satellites in view must be modeled by the user in a precise way by correcting the dependencies that are relevant at the centimeter level and estimating, in a navigation filter, the remaining relevant unknowns (such as the phase ambiguities and zenith tropospheric delay, together with the 3-D position and receiver clock error).

In this context, recent related developments in the research fields of GPS precise positioning and the modernization of Global Navigation Satellite Systems (GNSS) open the possibility of significantly improving the PPP technique. This paper exploits these developments to propose an Enhanced Precise Point Positioning (EPPP) concept including a user algorithm. Specifically, the paper considers 1) the resolution of undifferenced ambiguities by explicitly accounting for Uncalibrated Hardware Delays, thereby enabling ambiguity fixing [1]–[4]; 2) the feasibility and impact of providing accurate ionospheric delay values as an additional product of the wide area network of permanent receivers, such as the Ranging and Integrity Monitoring Stations (RIMS) of the European EGNOS system, to support High Precise Positioning Services (in a similar way as that in [5], [6]); and 3) the use of the modernized GPS and upcoming Galileo, to not only augment the number of transmitters with the associated redundancy and geometry improvements but also improve the measurement/observable precision, due to the new kind of signals provided over a larger number of frequencies. These new signals have a potentially positive effect of improving the convergence time, position accuracy, integrity, continuity, and availability. Note that recent results ([7]) suggest that it may be feasible to provide reliable integrity monitoring in high-precision GNSS positioning.

The following sections briefly describe the implementation of the suggested improvements, from algorithm specifications to the associated user performance evaluations using actual GPS and simulated Galileo user data.

II. WAYS OF IMPROVING PPP

A. Basic PPP Algorithms

For a given moving receiver “k,” the basic PPP user algorithm consists of the accurate estimation of its position \( \hat{r}_k \) and clock error \( dt_k \) from the accurate predicted GNSS position of each transmitter (satellite) \( \hat{r}_i \) and real-time clock corrections \( dt_i \) for \( i = 1 \ldots N_s \), where \( N_s \) is the number of satellites in view.

This can be performed by means of dual-frequency measurements that allow the removal of the first-order ionospheric delay through the ionospheric-free carrier phase \( L_c \) and code \( P_c \) observables, defined as:

\[
L_c = \frac{f_1^* L_1 - f_2^* L_2}{f_1^2 - f_2^2},
\]

\[
P_c = \frac{f_1^* P_1 - f_2^* P_2}{f_1^2 - f_2^2}.
\]

(1)
In this way, given the moving receiver k, the corresponding system of observation equations can be solved for the set of transmitters in view \( i = 1 \ldots N_s \):

\[
(L_c)_k^i + cdt^i - (\rho_0)_k^i = - (\rho_0)_k^i \cdot [\bar{r}_k - \bar{r}_0,k] + cd t_k + M_k^i
\]

\[
\cdot \delta T_k + (B_c)_k^i + \lambda_n w_k + \varepsilon \tag{2}
\]

\[
(P_c)_k^i + cdt^i - (\rho_0)_k^i = - (\rho_0)_k^i \cdot [\bar{r}_k - \bar{r}_0,k] + cd t_k
\]

\[
+ M_k^i \cdot \delta T_k + \varepsilon' \tag{3}
\]

where \( t \) is the time of reception, \( c \) is the speed of light in vacuum, \( \rho_0 \) is the modeled range considering an initial approximate position \( \bar{r}_{0,k} \) of the receiver \( k \), \( \rho_0 \) is the corresponding unit length vector along the direction pointing the GNSS transmitter \( i \) from its approximate position, \( M \) and \( \delta T \) are, respectively, the tropospheric mapping and residual vertical tropospheric delay (remaining after accounting for the a priori hydrostatic value included in \( \rho_0 \)), and \( w \) is the unmodeled user wind-up (due to the relative transmitter-receiver rotation taken into account in \( \rho_0 \)), where \( \lambda_n = c/(f_1 + f_2) \).

Finally, \( B_c \) is the ionospheric-free carrier phase ambiguity in length units, and \( \varepsilon \) and \( \varepsilon' \) represent, respectively, the phase and pseudorange measurement errors associated with thermal noise and multipath. The transmitter’s wind-up can be easily modeled, and subtracted from the measurements, and the receiver’s windup \( (w_k) \) can also be corrected for receivers with a known attitude (for instance, a fixed site, such as the samples presented in this paper), which can thus be eliminated as unknowns.

At each epoch \( t \), with \( N_s \) satellites in view, the system of \( 2 \times N_s \) equations (for both the ionospheric-free carrier phase and code measurements with \( N_s + 5 \) unknowns (Ns ambiguities + 3 coordinates + 1 receiver clock bias + residual troposphere) can be solved by applying a Kalman filter and the following:

i) The user position and clock \( (\bar{r}_k, dt_k) \) can be treated as white noise.

ii) The residual (“wet”) tropospheric delay can be treated as a random walk process.

iii) The ionospheric free carrier phase ambiguity \( B_c \) is estimated as a random variable (“constant parameter”), with the exception of the occurrence of cycle-slip events. In such a case, \( B_c \) is treated as a white noise process.

The main advantage of the basic PPP approach is its simplicity and the associated low bandwidth message containing precise predicted orbits such as those of IGS and real-time clocks or satellite-clock models (similar to the clock model of the GPS navigation message). However, its main drawback is the large convergence time needed by the user to get a good estimation of \( B_c \), which can last the greater part of 1 h or more before achieving a high accuracy performance at the level of 1–2 decimeters of position accuracy.

To overcome these limitations of the basic PPP approach, the potential improvements of the following new techniques are addressed in this paper.

1) The use of ionospheric corrections computed and broadcast by a dedicated PPP Central Processing Facility (PPP-CPF). See Section II-B for further details.

2) The broadcast of the satellite fractional part of ambiguities (computed at the CPF level), which allows the user to fix the carrier phase ambiguities and improve the positioning solution. See Section II-C for further details.

3) The use of future multiconstellation and multifrequency (more than 2) observables. See Section II-D for further details.

B. Improving the PPP Convergence Time: An Additional Product, the Precise Real-Time Ionospheric Delays

When the convergence time of the basic PPP algorithm could be improved with the availability of precise ionospheric corrections provided by the CPF, in a similar manner as in the WARTK technique (see, for instance, [5] and [6]); this is the reason why this technique can be referred to as fast PPP. Indeed, for (1) and (2), for \( L_w \) and \( P_n \), the user can add the following equations from the Melbourne-Wübbena combination \( L_w - P_n \) and ionospheric phase \( L_I \), which are defined as follows:

\[
L_w = \frac{f_1 L_1 - f_2 L_2}{f_1 - f_2} \tag{4}
\]

\[
P_n = \frac{f_1 P_1 + f_2 P_2}{f_1 + f_2} \tag{5}
\]

and can be modeled at the time of reception \( t \) for transmitter \( i \) and receiver \( k \) (using the same notation as in (1) and (2)) as follows:

\[
(L_w)_k^i - (P_n)_k^i + \frac{\lambda_m \lambda_n}{\lambda_1 \lambda_2} D^i = (B_w)_k^i - \frac{\lambda_m \lambda_n}{\lambda_1 \lambda_2} D_k \tag{6}
\]

\[
(L_I)_k^i - S_k^i = \frac{\lambda_1 \lambda_2}{\lambda_m \lambda_n} (B_w - B_c)_k^i \tag{7}
\]

where \( S \) is the user slant ionospheric delay computed from the ionospheric model provided by the PPP CPF together with the satellite interfrequency delay code biases, subtracting them for both frequency number 2 and frequency number 1: \( (D)_k^i \equiv (D_2)_k^i - (D_1)_k^i \).

The improvement to the classic PPP proposed in this paper consists of using (2) and (3) (classic PPP equations) with (6) and (7). In this way (from the last two equations, (6) and (7)), the \( B_c \) can be estimated along with the additional parameters \( B_w \) and receiver DCBs \( D_k \), in a geometric and ionospheric-free way. This is possible due to the reduced noise of the \( P_n \) observable, which is several times lower than the noise of \( P_c \). Once we know \( B_w \) very precisely, and considering that the user is receiving precise values of the slant ionospheric delay \( S_k^i \) (at the level of a few centimeters), then the ionospheric-free ambiguity \( B_c \) can be determined very rapidly by means of (7). This strategy can be particularly useful to accelerate the high
accuracy positioning convergence time under the availability of a precise CPF ionospheric model (achievable in the well-covered midlatitude regions, such as Europe, and a network such as the RMSs permanent GNSS receivers) and in the absence of strong code multipath. Notice that there is no need for ambiguity fixing, despite the fact that ambiguity fixing helps to additionally improve performance.

C. Improving the PPP Accuracy: Fixing Carrier Phase Ambiguities

One of the important conditions for GNSS precise positioning, in both postprocessing and real-time conditions, is the integer nature of the double-differenced carrier phase ambiguities, \((B_X)_{i,j}^{X,k}\), expressed in cycles:

\[
(B_X)_{i,j}^{X,k} = \lambda_X (N_X)_{i,j}^{X,k}.
\]

The two pairs of GNSS transmitters and receivers, i, j, k, l, respectively, are involved in the double differences, and \(\lambda_X\) is the wavelength for the corresponding carrier phase at frequency (or combination) \(X\).

With a good enough knowledge of its floated estimation, it can be fixed resulting in further improvement in performance. In this sense, it is easy to show that the condition of the integer double-difference ambiguity is equivalent to express the undifferenced ambiguity in terms of an integer value \((N_X)_{i,j}^{X,k}\) and two “fractional parts,” depending on the GNSS transmitter and GNSS receiver ([1], [8]):

\[
(B_X)_{i,j}^{X,k} = \lambda_X (N_X)_{i,j}^{X,k} + \delta B_{X,i} + \delta B_{X,k}.
\]

where \(\delta B_X\) is the fractional part of the ambiguity, split into a transmitter (i) and receiver (k) term, which are typically stable, at least during times that are significantly larger than the typical correction latencies for the user (see, for instance, Fig. 1 or [1]). The problem in their estimation process for the short wavelength carrier phases (such as L1) is their correlation with the estimation of the clocks.\(^2\) For this reason, some researchers include these fractional terms as parts of the clocks ([2]). However, on the one hand, this redefinition of phase clocks makes them incompatible with the pseudorange clocks, while, on the other hand, the inclusion of the fractional part of the ambiguity into the phase clock impedes the comparison between different computations among analysis centers (so it is still an open issue in the IGS Analysis Centers comparison). It can be shown (see an example in Fig. 1) that its estimation is stable enough in such a way that the CPF can broadcast the fractional terms of the ambiguities, with a refresh time of up to several minutes and a corresponding saving in the CPF for user bandwidth. In such a way, any user can apply the following relationship:

\[
(B_X)_{i,j}^{X,k} - \delta B_{X,i} = \lambda_X (N_X)_{i,j}^{X,k} + \delta B_{X,k}
\]

and consequently, from the single difference between satellites, the exact value of the single differences of \(N_X\) can be known (it must be an integer). Introducing this value as a constraint improves the positioning solution.

The feasibility and characterization of these approaches, in terms of accuracy and integrity in particular, are shown in the following section.

D. Improving Both Accuracy and Convergence: Multiconstellation and Multifrequency Scenario

One of the bases of the presented method is the fast resolution of \(B_w\) by means of (6). However, although \(P_w\) is less noisy than other combinations and the wide lane combination’s wavelength is quite large (approximately 86 cm for GPS frequencies), several minutes are required to achieve a confident value of \(B_w\) that can fix it. The availability of triple frequency carrier phase measurements offers the advantages of an easier extra-wide lane and a wide lane ambiguity estimation (see, for instance, [5]), which in the case of the availability of precise ionospheric corrections, would contribute significantly to the quick convergence of precise positioning (typically from several minutes with two-frequency GNSS systems to a single-epoch three-frequency GNSS systems).

E. Integrity Monitoring for Precise Positioning

As described earlier, the proposed EPPP user algorithm incorporates the new approach for fixing the zero-differenced ambiguities for increased accuracy and reduces convergence time facilitated by the exploitation of precise ionospheric corrections. Furthermore, an innovative approach to monitor the quality and integrity of the PPP process has been developed. This approach involves the incorporation of ambiguity validation\(^3\) (depending on the PPP mode) into the integrity

\(^2\)If no ionospheric model is considered, i.e., not using Equation (7), the only way to distinguish the fractional part of Be from clocks is by using equation \(P_e\), which is quite noisy and consequently, its weight in the system equations will be small.

\(^3\)One has to take into account that one wrong ambiguity fixing will propagate forward by the Kalman filter, so it is important to detect this wrong fixing as soon as possible.
monitoring process, which also includes Carrier phase Receiver Autonomous Integrity Monitoring (CRAIM) (Fig. 2).

The ambiguity validation method uses the conventional test statistic for ratio testing together with a doubly noncentral F distribution to compute the level of confidence of the ambiguities ([10]). Specifically, this is determined as a function of geometry and the ambiguity residuals from least-squares-based ambiguity resolution algorithms including Least-squares AMBiguity Decorrelation Adjustment (LAMBDA). The technique has the important benefit of facilitating early detection of any potential threat to the position solution originating in the ambiguity space while giving overall protection in the position domain based on the required navigation performance. This integrity monitoring process is particularly important (safety/commercial/liability) for critical mission applications.

III. DATA SETS AND COMPUTATIONS

In line with the main EPPP study goals, the approach adopted to test the EPPP algorithms concentrates a significant part of the effort on the user side. Accordingly, the actual and signal-simulated data used mainly correspond to the user receivers by using different products. However, the different products (e.g., satellite clocks, orbits, and ionospheric corrections) have been generated either from additional permanent stations (in the case of actual GPS data) or by assuming certain characteristic distributions of errors from the true values (in the case of simulated data). A main requirement for the simulated data scenarios is to be as close as possible to the main scenarios with actual data.

A. Generation of Scenarios for Actual GPS Data

For actual GPS data, static receivers are treated as roving users. This constitutes the main test program due to its versatility. Indeed, it has the advantages that 1) a very good reference position for each “rover” can be obtained in postprocess with millimeter/centimeter level accuracy, and 2) there are plenty of such receivers distributed worldwide, for example, in the IGS network. These advantages enable tests to be conducted to quantify the influence of the distribution of satellites in view, the performance with respect to the distance to the nearest CPF receiver, ionospheric conditions, among other potential effects.

Although the EPPP Central Processing Facility is not the main focus of this paper, it is vital for actual data scenarios in which the new EPPP approaches are to be studied (as opposed to the classical PPP strategy, in which available IGS PPP products can be used instead). The network of permanent stations for the EPPP CPF for actual data is composed of two distributions: a sparse one (~30 worldwide distributed GNSS receivers) devoted to computing satellite orbit and clock corrections; and another set of stations over Europe to compute more accurate ionospheric corrections. In the context of the ESA-funded project PRTODTS, an assessment of the different components of the corrections/message has been determined in real-time conditions.

The main conclusion of such an assessment, based on actual GNSS data, is that it is possible to achieve for a global service, in real time, satellite orbits, and clocks with an accuracy of few centimeters jointly with the stabilized satellite fractional part of ambiguities (see, for instance, Fig. 1) and, for a regional service, satellite DCBs and range. In this sense, the corrections to be transmitted to the user are as follows.

- Satellite clocks with an update time of few seconds,
- Satellite orbit correction parameters with an update time of few minutes,
- Satellite fractional part of ambiguities with an update time of few minutes,
- Satellite DCBs also with an update time of few minutes,
- and, ionospheric model parameters with an update time of few minutes.

Considering these update times and the required resolution, it can be deduced that the bandwidth requirement is very low: less than 300 b/s for a single constellation GPS single user.

A first example of the feasibility of EPPP based on actual GPS data is shown in Fig. 3, which summarizes the results obtained for users MLVL, EUSK and EIJS (at 252, 170 and 94 km far, respectively, from the nearest reference receiver BRUS). In this example, the full user state was reset every 2 h to better characterize the convergence process, and the position error RMS of the resulting 12 time windows is depicted. The horizontal and vertical errors are shown (left- and right-hand side, respectively) demonstrating the advantage of using precise, real-time ionospheric corrections to speed-up the PPP convergence (Fast PPP). It can be seen that the convergence time (to achieve, for instance, a 10-cm error level) is reduced from about 1 h (without ionospheric corrections) to a few minutes.

B. Generation of Scenarios for Signal-Simulated GNSS Data

As stated earlier, the characterization of the potential improvements in PPP, including a multiconstellation scenario, at the user level is the main purpose of this paper. To do this, a set of signal-simulated scenarios were generated using the hardware setup indicated in Fig. 4. This requires significant
resources particularly due to the fact that the measurements must be taken in “serial” mode (one user at a time) versus the “parallel” mode (all of the users gathering observations from the satellites in view simultaneously) in the actual scenarios.

As shown in Fig. 4, the hardware setup consists of the following.

1) A GNSS signal simulator (SPIRENT), which, from user coordinates and a GNSS constellation, generates a set of GNSS signals able to be gathered by any actual GNSS receiver.

2) A set of actual receivers, which gather in parallel the GNSS signal from the simulator (all corresponding to the same user simulated in the signal simulator). In Fig. 4, the working frequencies of each receiver are depicted. In this way, data from a user but gathered from three different receivers can be acquired.

A static user (NPLD, at 400 km from the nearest reference receiver) has been treated as the roving one. A typical simulation time of 3 h has been used for the rovers (three times the typical convergence time in standard PPP). As in previous simulations performed in the context of other studies (see, for instance, [6]), most of the different conditions (satellite clock and orbits quality, ionospheric and tropospheric delay and multipath) were generated by software, except for thermal noise, which corresponds to the actual data (the observations have been gathered from real receivers). Several scenarios have been simulated, but to focus on the main results, we are going to only present the study with nominal conditions. The nominal scenario consists of adding to the receiver measurements (carrier phase and pseudorange) the following effects: 1) a pseudorange multipath error of few decimeters in the zenith direction and at the meter level at a low elevation (based on actual data), 2) a satellite clock correction with an error of 0.1 ns, 3) from the exact positions of the GNSS satellites, a correction error of 0.05 m in RMS, 4) Ionospheric Correction Error (after ionospheric model correction) from 0.1 to 0.6 TECU (0.016 m to 0.1 m in L1/P1). Most of these error levels were based on the CPF accuracies obtained with real data (see Section III).

IV. EPPP ACCURACY, PROTECTION LEVELS, AND CONVERGENCE TIME

In the following subsections, an assessment of the user EPPP results is presented in two scenarios: with and without resetting the user navigation filter. The resetting of the navigation filter states will provide us with a characterization of the position convergence time.

A. Navigation Filter Results Under the Signal-Simulated Scenario

This scenario has been run without resetting the user states (i.e., its navigation filter) and only for GPS data (Fig. 5). The positioning results show very good performance, confirming the suitability of undifferenced PPP ambiguity fixing, in addition to the expected accuracy and convergence time.
results. In particular, it is worth mentioning that the fundamental role of the accurate real-time ionospheric correction is confirmed, which allows for a very fast convergence (one order of magnitude faster), with a final accuracy that is only slightly better than that from not using such corrections (at the centimeter error level). The corresponding analysis of the dual-constellation and three-frequency measurements is presented in Fig. 6.

Taking into account Figs. 5 and 6, the most relevant issue for accuracy and convergence time is the availability of the ionospheric corrections (this is reconfirmed in the next section).

i) Without ionospheric corrections when using only GPS data, the convergence takes about 2000 s, but using both constellations, the convergence is shortened by up to 900 s. These results are independent of whether the ambiguities are fixed.

ii) With ionospheric corrections, the convergence takes a few minutes with only GPS data (300 s are needed to fix $B_w$), while when using three frequencies, the convergence is nearly instantaneous.

iii) Without taking into account the ionospheric corrections, the final accuracy of all of the cases is at the centimeter level, but this accuracy is achieved faster with multiconstellation rather than single constellation data.

B. Real-Time Positioning Results Resetting the Whole User State Each 900 S

To better characterize the convergence time, the user navigation states were reset (to simulate a receiver cold start) every 900 s. Moreover, the different variants considered in the previous sections of this paper (multiconstellation GPS + Galileo versus single GPS constellation, dual-frequency versus three-frequencies, simple ambiguity fixing versus LAMBDA ambiguity fixing) were taken into account.

In Fig. 7, the detailed 3-D positioning error in terms of the actual time is shown, showing clearly the resetting and that the required convergence time under a single dual-frequency constellation is shorter with ionospheric corrections. Among other interesting features, it can be seen that the LAMBDA method fails to fix some ambiguities during some periods when no ionospheric corrections are used. The worst LAMBDA results obtained during some resetting periods when ionospheric corrections were used are related to poorer geometry (higher DOP) when this technique was applied. This is directly related to the LAMBDA implementation in this paper, in which this technique has been applied outside of the navigation filter, for the satellites in view with their wide lane ambiguities initially fixed.

Finally, to summarize the performance of each processing mode, the 11 time windows (resetting every 900 s for 3 h) are shown together through its 3-D positioning RMS (see Fig. 8). In this figure, the benefits of using the three PPP improvements proposed in this paper (i.e., ambiguity fixing, multiconstellation and ionospheric corrections; see Section II) are clearly seen. The following conclusions can be extracted:

1) Better performance is achieved when the three improvements proposed in this paper are simultaneously used.
2) The main factor in the convergence time is the usage of ionospheric corrections. However, if the ambiguities are not fixed, the ionospheric model error limits the accuracy at the end of the convergence period (yellow points in Fig. 8).
3) The use of the ionospheric correction allows achieving the required accuracy to be able to fix the carrier phase ambiguities. Otherwise, without ionospheric corrections, the minimum accuracy needed to fix ambiguities in the 900-s windows cannot be achieved.

C. EPPP Integrity: First Glance

Integrity is the ability of a positioning service to protect against hazardous anomalies. For instance, the positioning service must guarantee that the probability of positioning errors greater than a certain value (protection levels) is small and acceptable (i.e., $10^{-7}$). In this sense, the service provider must transmit not only the corrections but also their confidence levels. Using this information, the user receiver computes its
position and the corresponding protection levels. Accordingly, integrity is a critical part of positioning, and the improvement of any solution must take into account the achieved protection level.

In this section, it is shown that the protection levels (computed from the message) always protect the positioning errors, and in the next section, the other user level other integrity algorithms are presented.

The motivation of this point of study was to check whether the very first results of integrity in the positioning domain could be obtained for EPPP from the simulated data sets. To do this, the same protection levels used in the more extended integrity study recently performed for the WARTK high precise positioning technique (MRS project; see, for instance, [7]) have been used. Indeed, the vertical protection level (VPL) and horizontal protection level (HPL) are defined as

\[ VPL = 5.33 \times k \times VSigma \]
\[ HPL = 6.2 \times k \times HSigma, \]

where VSigma and HSigma are the corresponding vertical and horizontal standard deviation estimated in the filter, and k is a factor to guarantee the proper overbounding of the protection levels with respect to the actual errors. The nominal scenario adopted in this point, to have some minimal statistics, was to reset (every 900 s) the user navigation filter under a low multipath using single constellation (GPS) data for the roving user NPLD (see Fig. 7 for the reference result).

It can be seen in Figs. 9 and 10 that the integrity is always maintained (actual errors lower than protection levels), even during the first steps of convergence, after each reset every 900 s. In particular, it can be seen that the integrity margin (protection levels minus actual errors) is high for dual constellation (Fig. 9) and even higher when the ambiguities are fixed thanks to the real-time ionospheric corrections (Fig. 10).

V. EPPP INTEGRITY: SENSITIVITY TO ERRORS AND FAILURES

For EPPP, there are two main sources of potential failures: the errors in the measurements of a PPP user and those in the messages provided to the user. The scenarios simulated to measure the performance of the EPPP integrity algorithms were based on the manifestation of potential failures at the user side irrespective of source. In this case, the simulated scenarios reflect all known classes of failure modes both at system and user levels (i.e., both measurement and message errors/failures are included).

The approach to quality and integrity mentoring developed for EPPP involves three stages. First, outlier detection is applied at the ionospheric slant delay interpolation stage in order to detect anomalous values, second, ambiguity validation (i.e.,
ambiguity domain integrity monitoring) is carried out using the proposed approach that employs a doubly noncentral F distribution based test and finally, the CRAIM method is employed in the position domain. The technique has the important benefit of facilitating early detection of any potential threat to the position solution, originating in the slant ionospheric delays and the ambiguity space, while at the same time giving overall protection in the position domain based on the required navigation performance. Since the occurrence of failures (depending on source) should in fact affect the user’s computation of the slant delays and resolution of ambiguities, the corresponding integrity monitoring algorithms are designed to offer maximum protection from their effects before they propagate to the position domain. Therefore, the first two stages of integrity monitoring justify the assumption of single failure in the specification and testing of the position domain algorithm (i.e., CRAIM). Clearly, further work is required to confirm the validity of this assumption for specific PPP applications.

This study has analyzed the sensitivity of the approach to the integrity monitoring proposed for EPPP, including those of HPL determination and ambiguity validation to ionosphere errors. Although several types of failures were simulated and successfully treated by the integrity algorithm, this paper focuses on the integrity results related to the ionospheric corrections.

The following abbreviations are used to represent various scenarios: G denotes GPS data only; X denotes GPS and Galileo data; ni denotes Ionospheric corrections not considered; I denotes Ionospheric corrections applied and fw denotes Wide lane ambiguities are constrained and N1 ambiguities fixed with LAMBDA.

### A. Sensitivity of HPL to Ionosphere Errors

Figs. 11 and 12 show the sensitivity of HPL to the ionospheric error corrections from the CPF. The absolute values of ionospheric correction error range from 0.01 to 6.7 cm with a mean of 1.4 cm. It can be seen from Fig. 11 that the HPLs for the two cases (with and without ionospheric error corrections) are always larger than the corresponding horizontal position errors (HPEs) during the positioning period. This shows that the HPLs overbound the HPEs. Furthermore, as expected, the HPL for the case without ionospheric error corrections is consistently higher than in the case with ionospheric corrections. Both findings provide a level of confidence in the algorithm for the computation of the HPL.

In order to gain more confidence in the sensitivity of the HPL to ionospheric residual errors, the ratio of the effect of this error in the position domain, i.e., the HPE to the HPL is plotted in Fig. 12 for the two cases (i.e., with and without ionospheric error corrections). The results show that for both sets the ratios are always below 1 confirming the observation made on overbounding above. Furthermore, as expected, the HPE/HPL ratio for the case with ionospheric error corrections is significantly smaller (after convergence and wide lane ambiguity fixing) than the case without ionospheric corrections, further demonstrating that the HPL algorithm is sensitive to the effect of ionospheric errors and wide lane ambiguity fixing.

### B. Sensitivity of Ambiguity Validation to Ionosphere Errors

Figs. 13 and 14 each show the ratio of residuals from the best and second best sets of ambiguities, the number of ambiguities, and the confidence level of the best set of ambiguities for the scenarios with and without ionosphere corrections. The key parameter for ambiguity validation—the confidence level—is calculated by using a doubly noncentral F distributions as explained earlier. The wide lane ambiguities are constrained while the N1 ambiguities are fixed with LAMBDA.
From the results in the figures above, it can be seen that the impact of the ionospheric error corrections is a higher confidence level in the ambiguities, compared to the case without ionospheric error corrections.

C. Sensitivity of Test Statistics to Failure

In order to analyze the impact of failure on integrity monitoring in the ambiguity and position domain, the following errors were simulated and injected to specific measurements separately:

1) A bias of one cycle is added to the L1 carrier phase measurements from one (random) satellite. The bias is added to the measurements after preprocessing starting from the first epoch to the end. This should enable the capability for ambiguity resolution to be tested.

2) A bias of half a cycle is added to the L1 carrier phase measurement from one (random) satellite. The bias is added to the measurements after preprocessing starting from the first epoch to the end. This represents a potential worst case for ambiguity validation. Therefore, this should enable the capability for ambiguity validation to be tested.

3) Slowly growing error is added in the L1 carrier phase measurements of a specific satellite. The quantity of the drift applied to the measurements accumulates to one wavelength in about 300 s. The drift starts at 100th epoch and ends at 700th. This should enable the capability for early detection algorithms to be tested.

4) Large error—in January 2004, there was a significant clock failure on SVN23. The average clock acceleration was estimated at $1.88 \times 10^{-11}$ s/s². This is applied to P1 measurements of one satellite, starting from the 100th epoch to the 700th. This should confirm the capability for integrity algorithms to deal with gross errors.

5) Critical error—The critical bias in any measurement results in the test statistic being very close to the threshold, thus presenting a challenge for failure detection.

VI. Conclusion

In this paper, detailed results on enhanced precise point positioning strategies have been presented, centering on the extensive signal simulations of GPS and Galileo observations incorporating realistic user errors that affect PPP performance (code multipath, real-time orbits, clocks, and ionospheric corrections). This paper includes the identified EPPP modes (PPP classical approach, adding undifferenced ambiguity fixing and using precise ionospheric corrections) and different related aspects (multiconstellation versus single constellation, LAMBDA ambiguity fixing method, etc.).

The main conclusions can be summarized in terms of demonstrating the central role of the precise ionospheric corrections to provide a centimeter-error-level accuracy with very small convergence times, in both the single-constellation/dual-frequency scenario and the dual-constellation/three-frequencies scenario.

The advantage of undifferenced ambiguity fixing has been confirmed in line with insights of previous authors ([1]–[3]). The availability of precise ionospheric corrections is also important to guarantee the right carrier phase ambiguity fixing. Additionally, it has been confirmed that resetting the user filter every 900 s, the positioning protection levels always overbound the actual positioning errors. The overbounding becomes particularly large when dual-constellation, three-frequency measurements, and precise ionospheric corrections are used.

Finally, it has been shown that the integrity monitoring algorithms developed (including ambiguity validation) are very sensitive to failures, including ionospheric residual errors. This should facilitate the use of PPP to support critical mission applications. Regarding ambiguity validation, the method developed based on doubly noncentral F-distributions is capable of generating reliably the confidence level of the resolved ambiguities at every epoch. The application of good quality ionospheric error corrections has been demonstrated to be crucial to the confidence level associated with ambiguity resolution.
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Authors photographs and biographies not available at the time of publication.