RESULTS FOR PRECISE GPS TRAJECTOGRAPHY COMPUTATION WITHOUT BASE STATION

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ABSTRACT

The use of differential GPS postprocesing for precise trajectography computation has been widely used since early 90s. Up to recent dates, installation of a GPS receiver in a well known position (base station) has been mandatory. Operating range from this base station varies from 50 km up to 100 km, depending on the accuracy required, which impose single or dual frequency GPS technique.

Nowadays, the huge amount of GPS base stations continuous logging data worldwide have allowed to improve the error models a lot. Using these precise models, it is possible to achieve centimeter accuracy in GPS trajectography by using only one GPS receiver without range to a base station restrictions. This technique is called Precise Point Positioning (PPP).

The performance results for PPP obtained after a real 10 flights campaign will be presented.

Keywords: PPP (Precise Point Positioning), GPS trajectography, centimeter accuracy.

1 INTRODUCTION

The use of differential GPS post-processing for precise trajectography computation has been widely used since early 90s. Differential GPS is based on the spatial and temporary correlation of GPS signal in a specific area. To make use of this correlation, it is mandatory to install a GPS receiver in a well known position (base station). At the beginning, decimeter accuracy within 100 Km range from the base station could be achieved by using code differential techniques. Later, when dual-carrier phase receivers came it was possible to get centimeter accuracies, but only within 50 Km range from the base station.

Nowadays, the huge amount of GPS base stations logging data the whole day has allowed an improvement in the models. Using these models and other precise information, it is possible to achieve centimeter accuracy in GPS trajectography by using only one GPS receiver without range to base station restrictions. This technique is called Precise Point Positioning (PPP).

Section 2 will compare how differential and PPP techniques minimize inherent GPS errors. Besides, it will describe the process and the data needed to compute GPS trajectography using

PPP. **Section** 0 contains means and methodology used to perform the tests and important considerations used during data analysis. **Section** 4 will show results obtained processing static data. Static results simplify the analysis and allow showing some effects of PPP. Solution accuracy and convergence will be analyzed. Moreover, it will be addressed the importance of a good dynamic filter selection. **Section** 0 will describe dynamic PPP results. An analysis of accuracy will be addressed. Two different IGS products will be used to evaluate the impact of their quality in the solution accuracy. Besides, a challenge situation where PPP solution is missed due to GPS satellites obscuration will be analyzed. A possible solution for this environment will be also discussed. **Section 6** includes some real scenarios where Airbus Defence & Space uses PPP.

Conclusions will be summarized in **Section** 7. In terms of performance, a precision of less than 10 cm, 68% of the time will be accredited. Thus, it will be concluded that PPP post-processing is another available tool for flight test trajectography. However, some of the problems and issues inherent to it must be taken into account. PPP turns up to be useful in certain scenarios where using base stations is an economical or technical challenge.

2 COMPUTING GPS TRAJECTOGRAPHY

All GNSS, GPS included, are affected by several errors inherent to the system [1]. Table 1 contains the most significant errors affecting the system in airborne applications, and their impact in the pseudoranges[1] measurements [2]. System accuracy can be improved by minimizing the effect of these errors. In order to achieve centimeter accuracy, two different techniques can be used.

Error source	1σ (probability: 68%)	Error source	1σ (probability: 68%)
Satellite Ephemeris	2.0 m*	**Multipath**	1.0 m*
Satellite Clock	2.0 m*	**Position vertical**	13 m (1σ)
Ionosphere propagation	5.0 m*	**Position horizontal**	10 m (1σ)
Troposphere propagation	0.5 m*	**Impact in distance to satellite*	

Table 1.- Main GPS errors magnitude in pseudorange

2.1 Differential GPS

This technique takes advantage from the spatial and temporary correlation of some errors by taking simultaneous measurements with more than one GPS receiver; usually two. One of the receivers is installed in a place with well-known coordinates (base station). Since most of the effects are common for both receivers, it is possible to compute an accuracy position for the other receiver (rover) [3], [4].

The correlations only take place within a delimited area and period of time. Depending on the differential GPS technique used both accuracy and limitations vary. When using code-differential GPS it is easy to achieve decimeter-level accuracies within 100-150 km range from the base station [3], [4]. On the other hand, dual-carrier phase receivers allow centimeter-level accuracies within 50 km from the base station [3][4].

[1] Distance measured to the satellite (different from geometrical distance)

2.2 PPP

It is possible to think about PPP as an extension of the Standard Positioning Service (SPS) used regularly by navigation receivers. The main advantage for PPP is that centimeter-level accuracies can be achieved using only one receiver. It implies that error mitigation strategies used are not the same as in differential GPS.

Beyond the use of only one receiver, PPP also eliminates the need to deal with the different coordinate reference systems and their conversions (i.e.ITRS00, ETRS89, NAD83, ED50, etc…). All PPP positions are directly obtained in WGS84, since there is no reference station.

A filter, adjusted to the expected dynamic of the observations, is used to solve an equation system containing all the unknowns, such as receiver coordinates, tropospheric delay, receiver clock and phase ambiguities [5].

Ionosphere effect is removed in the first-order term by using dual-carrier phase receivers, which allow computation using ionosphere free linear combination [6].

As for differential GPS, multipath can only be reduced by receiver design as the amount of error depends on the location of the antenna and its surroundings.

Satellite ephemeris and clock broadcasted in the navigation message are replaced by precise post-processed orbits and clocks, provided by several scientific services. These services use the huge amount of GPS continuous reference stations over the world to compute accurate information about ephemeris and clocks. The most important service providing these products is the IGS from NASA [7], [8].

	Broadcast (as reference)	**Ultra-rapid (predicted)**	**Ultra-rapid (computed)**	**Rapid (computed)**	**Final (computed)**
Orbits	≈100 cm	≈5 cm	≈3 cm	≈2.5 cm	≈2.5 cm
Clock	≈5ns (±2.5ns)	≈3ns (±1.5ns)	≈150ps (±50ps)	≈75ps (±25ps)	≈75ps (±20ps)
Latency	Real Time	Real Time	3-9 hours	17-41 hours	12-18 days

Table 2.- Orbit & Clock IGS products

As these products are post-processed, a latency time until they are available is mandatory. Accuracy depends on the length of this latency time, as shown in **Table 2**.

Therefore, to compute GPS trajectography using PPP it is necessary to have the airborne GPS observations and the contemporary precise orbits and clocks files.

3 TEST AND METHODOLOGY DESCRIPTION

Two IENA Oberón GPS receivers from Airbus Defence & Space were used to gather 5Hz GPS observations. One installed on ground as base station and the other on board as rover.

Flights were mainly performed within 50 km from the reference station, in order to assure quality dual-carrier differential solutions [3], [4]. Flights valid for analysis were 10 of 11.

The software used to compute all coordinates has been Waypoint Grafnav 8.30 from Novatel, which contains both dual-carrier differential and PPP algorithms.

Dual-carrier differential solutions have been taken as absolute true, being PPP solutions compared to them.

The data gathered by the reference station have been used to analyze static data, avoiding several unknowns associated to movement. Such simplified scenario allows understanding better some PPP characteristics, which improve comprehension of what may be going on during dynamic tests.

For the static tests, the absolute true position taken has been the one differentially computed after 6 hours of continuous observation. A CORS located 14 km away were used as precise reference point. The precise coordinates for the CORS are certified by the Spanish national geodesy agency (IGN). This computed absolute true position has been compared to each epoch[2] processed using PPP following (1),(2) and (3).

$$Diff\_lat_i = Precise\_lat - PPP\_lat_i \quad (1)$$
$$Diff\_lon_i = Precise\_lon - PPP\_lon_i \quad (2)$$
$$Diff\_alt_i = Precise\_alt - PPP\_alt_i \quad (3)$$

$$Diff\_lat_i = Differential\_lat_i - PPP\_lat_i \quad (4)$$
$$Diff\_lon_i = Differential\_lon_i - PPP\_lon_i \quad (5)$$
$$Diff\_alt_i = Differential\_alt_i - PPP\_alt_i \quad (6)$$

For the dynamic tests, all flights have been computed using both dual-carrier differential and PPP. Afterwards, all common epochs (same flight and GPS time) have been compared following equations (4),(5) and (6).

In order to obtain a result as close as possible to a real operation scenario, all dynamic data have been included. No filtering of any outranged observation has been performed.

Diff_lat and Diff_lon have been projected to a plain in order to present results in meters instead of grads. Projection was computed following equations described in [9].

4 STATIC RESULTS

The data gathered by the static Airbus Defence & Space reference station during the tests have been used to analyze a simplified scenario without movement. PPP has been computed using final orbit and clock (see Table 2) from IGS and standard GNSS Waypoint profile.

4.1 PPP Performance

Figure 1 contains static data gathered during all the flights. It shows the difference between the precise coordinates and the PPP static data, following the methodology explained in Section 0.

For each flight, differences stay almost constant below 1 centimeter variation. However, there are steps of several centimeters between flights. This is an effect originated by the float solution used in PPP [10][11], in which phase ambiguities cannot be calculated and must be estimated. In each

[2] GPS observation made in a certain GPS time.

initialization this estimation varies slightly, affecting the precision. Nevertheless, note that differences are always inside the centimeter-level (below 10 cm).

4.2 Converged solution

Due to this float solution a convergence time for the final precision was expected [10]. Though, as said in [11], for modern post-processing PPP this effect has been solved. When processing PPP using Waypoint 8.30, converged float solution is provided, so no convergence time has been encountered.

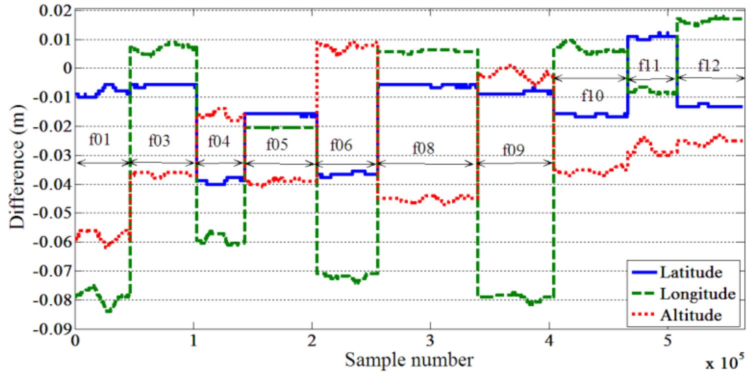

Figure 1.- Precise coordinates minus PPP static

4.3 Appropriate PPP filter selection

Figure 1 has been obtained computing data as what they are: static data. As mentioned in Section 2.2, PPP uses a filter to estimate several unknowns. This filter depends on a right dynamic estimation. Figure 2 shows the same static data processed using dynamic PPP. As it can be observed results are totally different. The signal is much noisier, indicating a higher level of variance in the measurement. Furthermore, the accuracy is worse in the three variables. Especially in altitude, where errors are up to 10 times bigger than in static PPP.

Therefore, it is very important to use a proper dynamic profile in the PPP filter in order to obtain an acceptable level of accuracy when post-processing using PPP.

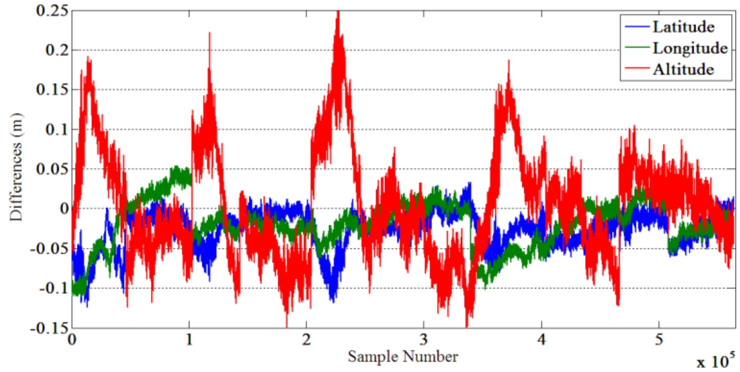

Figure 2.- Precise coordinates minus PPP static processed as dynamic

5 DYNAMIC RESULTS

5.1 PPP Performance

Accuracy may probably be the most important parameter, in order to characterize and determine the situations where PPP is a useful technique. Results in this section have been obtained using Final IGS products (see Section 2.2) and airborne GNSS Waypoint profile.

	Epochs Number
Dual-carrier differential	436921
PPP Final	449212
Coincidences	**436200**

Table 3.- Sample size after all flights Final PPP

Dual-carrier post-processing positions are taken as absolute true position and data are analyzed according to methodology in Section 0. After combining data of both techniques coming from all the flights, 436200 samples are suitable to be compared, as they were taken in the same GPS epoch.

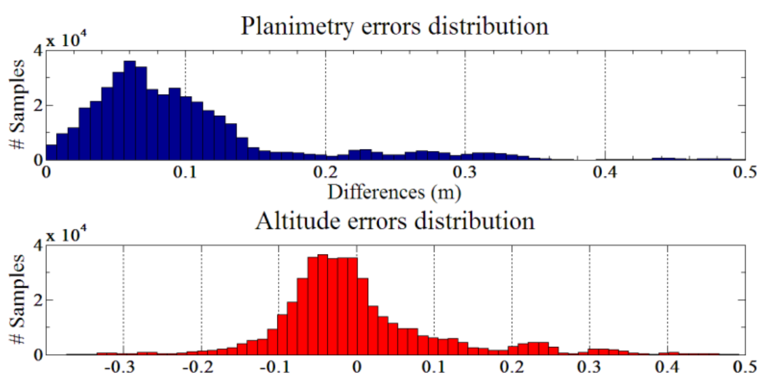

Figure 3.- Differential minus Final PPP

Figure 3 shows the histograms (100 bins) both for planimetry and altitude errors. Planimetry is obtained following (7). Assuming a gaussian distribution for the errors, some statistical data for the accuracy can be extracted, as shown in Table 4.

$$\text{planimetry} = \sqrt[2]{\text{Diff lat}^2_{i(\text{meters})} + \text{Diff lon}^2_{i(\text{meters})}} \qquad (7)$$

In general, PPP solution agrees with differential, as 68% of the samples are below 10 centimeters error. Being more ambitious, almost all samples (99,7%) lies below 30 centimeters error. Nevertheless, 3σ includes positions computed in challenge situations similar to the one described in Section 5.3.

5.2 PPP performance using Rapid vs. Final IGS data

As mentioned in Section 2.2, precise orbits and clocks files are key when computing PPP. It was also said that there are files of different quality, depending on the time elapsed from data gathering to the processing date.

Looking at Table 2, it seems there are not big differences in quality between rapid and final products. They only differ in the dispersion of the clock drift in an amount of 5 ps. However, rapid files are available several days before. If position accuracy penalty is not too big, it could be interesting to use rapid files in an operational scenario.

	Planimetry (m)		**Altitude (m)**	
	PPP Final	PPP Rapid	PPP Final	PPP Rapid
Mean (Accuracy)	0.08	0.26	0.00	0.08
Deviation 1σ (Precision) (68% samples inside)	0.07	0.24	0.10	0.29
Deviation 3σ (Precision) (99,7% samples inside)	0.22	0.74	0.32	0.87

Table 4.- Accuracy statistics for PPP dynamic errors

The same methodology as in Section 5.1 has been followed, in order to get similar results and compare them. Results are shown in Table 4 and Figure 4.

	Epochs Number
Dual-carrier differential	436921
PPP Rapid	449210
Coincidences	**436198**

Table 5.- Sample size after all flights Rapid PPP

As expected, sample size is almost the same for Final and Rapid PPP, as obtaining a solution mainly depends on satellites in view.

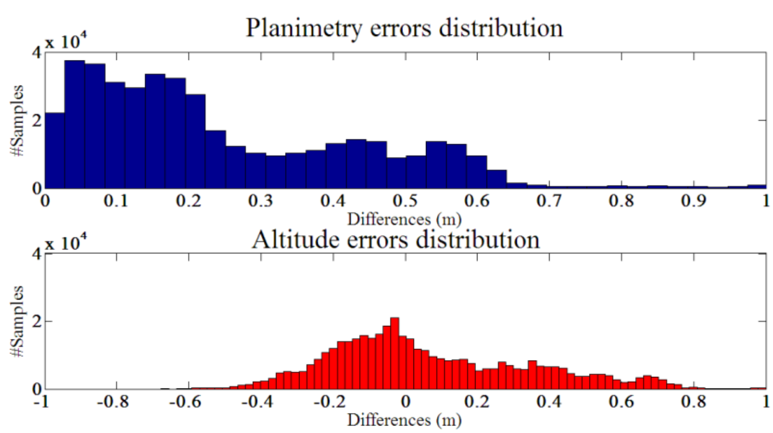

Figure 4.- Differential minus Rapid PPP

Comparing Figure 4 and Figure 3, it is easy to observe that the precision (differences dispersion) degrades a lot when rapid IGS products are used to compute PPP trajectography. Although rapid and final products slightly differ in the clock accuracy, this error source has enough weight (see Table 1) to penalize the accuracy a lot.

Quantitative results are shown in Table 4. It can be seen that the accuracy (differences mean) and precision (differences dispersion) is 3 times worse with Rapid PPP than with Final PPP. In fact, Rapid PPP numbers are similar to those obtained with code-differential GPS.

A compromise solution, depending on the trajectography requirements, must be taken if Rapid PPP is going to be used. In some cases results response time is more important and a sub-meter position is enough. Nevertheless, using Final IGS products is advisable.

5.3 PPP inicialization after satellite losses

As it has been seen in Section 4.1 the initialization of PPP affects the accuracy. On the other side, PPP needs at least 5 satellites in both GPS frequencies to get a solution, while differential do not. During aircraft turns it is fairly normal to lose some satellites. This section analyzes what happens after one of these satellite losses. In Figure 5 it can be seen the event analyzed, where PPP solution has been lost for 8 seconds, due to satellite looses. It can be observed a jump in the error after recovering PPP solution (Figure 6).

In the present-day this solution loss occurs very often during aircraft's turns when using only the GPS constellation. The addition of GLONASS constellation would improve the number of satellites, providing a more reliable solution. Waypoint 8.40 already includes this feature, which could be very useful.

In the future, it is expected a minor incidence of satellite losses, as more satellites will be available with the GALILEO constellation if it is finally fully deployed in 2020 [12].

On the other hand, many of the losses occur because of the L2 GPS signal, which is quite weak in non cryptographic receivers used for flight test. New modernized satellite signals used in GPS modernization [13] and GALILEO [14] will be stronger and easier to follow. These more reliable signals are expected to minor the incidence of satellite losses.

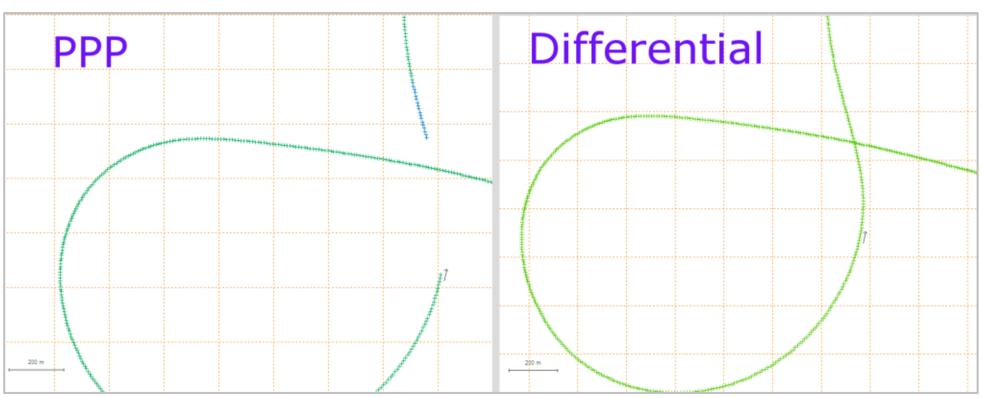

Figure 5.- PPP vs. Differential trajectography

In the meanwhile, using the data and tools available, an action has been taken in order to minimize the accuracy step, in case it occurs near a region of interest during the flight. PPP algorithm has been manually forced to initialize again after losing the satellites. A reduction in the planimetry and altitude differences can be seen in Figure 6, which means that this is a feasible solution to fix losses in regions of special interest of the trajectography.

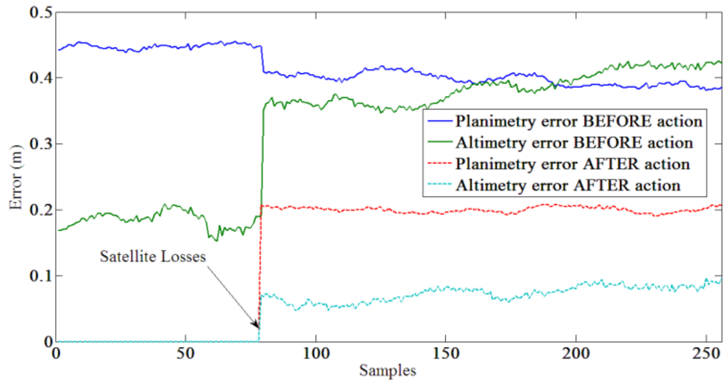

Figure 6.- Differential minus PPP before and after action.

6 AIRBUS DEFENCE & SPACE TYPICAL PPP SCENARIOS

A test requiring precise trajectography over the sea represents a technical challenged scenario, as base stations can only be installed hundreds kilometers away. Thus, dual-carrier differential performance is quite poor, due to its dependency on the distance to the GPS base station. In such scenario, PPP turned up to be a perfect technical solution, according to experience.

Another scenario is a test implying a continuous trajectography for long distances over the land. It requires the use of several base stations, which usually represents a logistical and economical problem. Airbus Defence & Space uses PPP in order to save time and money in such scenario.

7 CONCLUSIONS

After all the results shown in this document, it is concluded that PPP post-processing is another available tool for flight test trajectography, which can be very useful in certain scenarios where using a base station is an economical or technical challenge (see Section 6).

Accuracy when using Final PPP is in the centimeter-level, both for planimetry and altitude. Precision (accuracy dispersion) is below 10 cm more than 68% of the time (see Section 5.1).

Main disadvantage of the technique is that precise results using final IGS products cannot be delivered until around two weeks after the date of the test.

Trying to avoid this latency time, PPP computation using rapid IGS products were studied. Regrettably, accuracy does not achieve the levels required in most flight tests (30 cm - 68% time). Anyway, it may be taken into account for some tests, as the results are obtained several days before PPP with final IGS products (see Section 5.2). Problems and issues inherent to the technology cannot be neglected when using it.

Selecting the appropriate dynamic model (static, ground, airborne, etc…) in the algorithm is important in order to achieve an accurate solution when using PPP (see Section 4.3)

Satellite obscuration during dynamic tests has an impact in the accuracy, due to the PPP inherent initialization dispersion (see Section 4.1). It is expected a reduction in satellite losses by future improved GNSS constellations. Nevertheless, a solution method in the meanwhile is proposed (see Section 5.3).

Finally, big convergence times until full accuracy achievement where not found with the Waypoint software used.

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9 ACRONYMS

CORS	Continuous Operating Reference Station
ED50	European Datum 1950
ETRS89	European Terrestial Reference System 1989
GNSS	Global Navigation Satellite System
IENA	Instrumentation d'Essais des Nouveaux Avions
IGN	Instituto Geográfico Nacional (Spain)
IGS	International GNSS Service
ITRS00	International Terrestial Reference System 2000
RGF93	Réseau Géodésique Français 1993