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ARTICLE

REAL TIME PPP APPLIED TO AIRPLANE FLIGTHT TESTS

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Abstract:

The availability in real time of GNSS satellites orbits, clock corrections and code and phase biases provided the possibility of application of Real Time Precise Point Positioning (RTPPP). This paper presents the methodology concerning RTPPP and application to kinematic trajectories of airplane flight tests, but without using the carrier phase bias. So, it is PPP float solution. It requires RT positioning estimation, task that most of time presents certain difficulties due to loss of communication or of satellites during maneuvers of the airplane. However, if the corrections become unavailable for a certain period of time, the system starts using the ultra-rapid IGS orbits. The experiments were accomplished taking into account a case simulating RT and another in fact RT, but storing data and corrections for post processing. The PPP solutions obtained either simulating RT or in RT were compared against the PPP post processed solution that uses the final clock and orbit corrections. Then, statistics were generated to analyze the quality of both results.

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They were applied to kinematic trajectory that on average was 360 km/h, reaching about 600 km/h. The results provided accuracy better than the requisites for such cases which is of about 80 cm in height.

Keywords: Real Time PPP; BNC; Clock Corrections; NTRIP; IGS

1. Introduction

GNSS (Global Navigation Satellite System) is a technology that provided positive impact in the field of positioning and navigation, among others applications. Three main methods of positioning have dominated the literature: precise point positioning (PPP), network RTK (NRTK) and differential GPS (DGPS) (Langley, Teunissen and Montenbruck , 2017).

Concerning PPP, it is an advanced version of the single-point positioning (SPP) technique. Two of the most representative papers on PPP (Héroux and Kouba, 1995; Zumberge et al., 1997) provide the fundamentals and showed the advantages and disadvantageous of the approach and opened the opportunities for the evolution and improvement of the method. The main limitation was the time for ambiguities and parameters convergence. In reality, the estimated ambiguity is a combination of the integer ambiguity, the receiver biases, and the satellite biases. The next advances were about PPP ambiguity resolution (PPP-AR), also called PPP-RTK. As stated by Langley, Teunissen and Montenbruck (2017), PPP–RTK, is a merging of PPP with state-space RTK and can have significant advantages in ambiguity resolution, in convergence time, and in accuracy. Operational systems have been implemented by industry and research organizations. All individual GNSS error components, derived from the RTK monitoring network, are determined and delivered using state-space representation (SSR). These include orbits, clocks, code (pseudorange) and carrier phase biases, ionosphere and troposphere.

Several approaches were proposed which are mainly based in the estimation of the uncalibrated phase delays (UPD) from data of a GNSS network. Linear combinations of wide lane (WL) and narrow line (NL), together with single differences between satellites are the base of the approach (GE et al., 2008; GENG et al., 2009; GENG et al., 2011). Another approach (Collins et al., 2008), was the decoupled clock model. They apply the satellite decoupled clock corrections and estimate the receiver decoupled clock parameters and the undifferenced integer wide-lane and N1 ambiguities can be directly estimated. There is also an integer phase clock model featuring different clock terms for code and phase observations developed by Laurichesse et al. (2008). They utilize the WL satellite bias (WSB) corrections to resolve the integer wide-lane ambiguity, while the integer N1 ambiguity is directly estimated. Shi and Gao (2014) investigated the relationship among those methods and concluded that some practical differences exist among them, but they would provide equivalent results because they have the same degree of freedom (DOF) from the parameter estimation perspective. On the other hand, Khodabandeh and Teunissen (2015) as well as Teunissen and Khodabandeh (2015) stated that these methods differ in the models used, in the corrections applied and/or in the estimation methods employed. Additionally, they state that although some comparative studies between some of these different PPP-RTK methods already exist, they have not been sufficiently conclusive. They state that Shi and Gao (2014), for example, did not identify some of the important differences that exist among the methods. Instead, they concluded that the methods are theoretically equivalent providing analog results. This discovery is also identified in the publications of, for instance, Bisnath and Collins (2012, p. 378), Li et al.

(2013), and Zhang and Li (2013). They showed that there are differences among the methods, at the point that some cannot be accepted as proper PPP-RTK. Stat of art about PPP can be found at Odijk (2017).

Although there are all these advances in the PPP-AR, this paper will be based on the original PPP, where the ambiguities are not fixed as integer and the basic observable is the Ionospheric free (iono-free) and all well-known errors and effects are appropriated treated. But it will be applied for a very challenge application: flight tests scenarios, where the aircraft dynamics are very intense. The required accuracy is provided in Figure 1. From there one can see that when the aircraft is static (0 km/s), and with 150 m/s the required height accuracy is in the level of 20 cm and 1,0 m respectively.

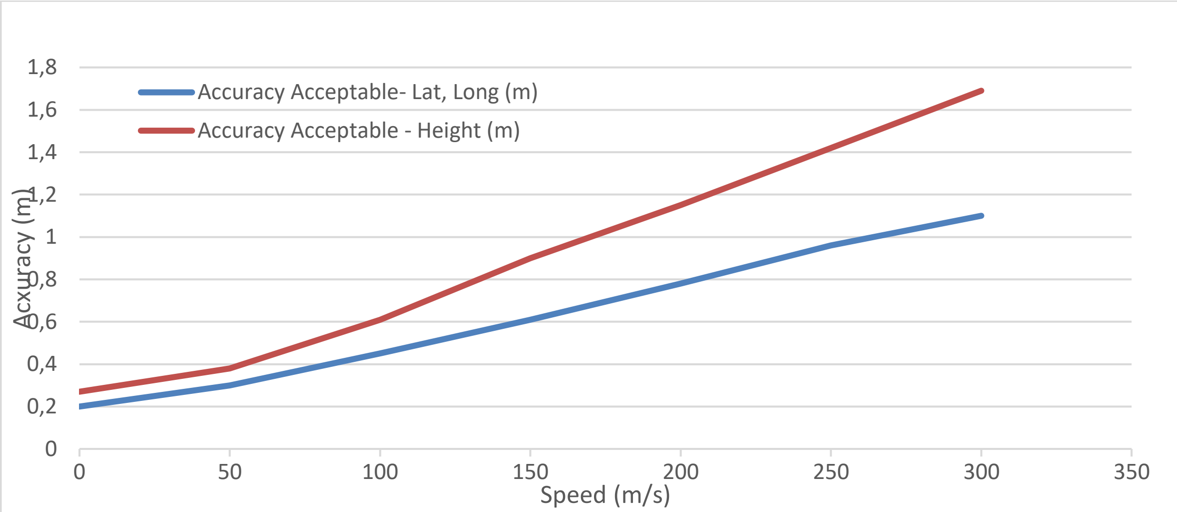


Figure 1: Required accuracy for aircraft flight tests.

Source: Embraer.

In this paper, after this introduction, fundamental of conventional PPP will be presented, followed by a short description of the so called 'RT_PPP' software developed at FCT-UNESP in a doctorate project (Marques, 2012) and posteriorly involved in a Research and Development project supported by Embraer Brazilian company. Following it, the test scenario will be presented together with results and assessments. And finally, some final comments and conclusions will be presented.

2. PPP and Real Time PPP fundamentals

The basic observable involved in the RT-PPP is the Ionospheric free for pseudorange and carrier phase, given by Eq. 01 and 02.

$$PR_{IF_r^s} = \rho_r^s + c\left(dt_r(t_r) - dt_{IF}^s\left(t^t\right)\right) + T_r^s(t_r) + \varepsilon_{PD_r^s} \quad (1)$$

$$\lambda_{IF}\phi_{IF\,r}^{\;\;s} = \rho_r^s + c\left(dt_r\left(t_r\right) - dt_{IF}^s\left(t^t\right)\right) + \lambda_1\tilde{N}_{IF} + T_r^s + \varepsilon_{\phi_r^s} \qquad (2)$$

with:

$\mathbf{PR}_{\mathbf{IF}\mathbf{r}}^{\mathbf{s}}$ and $\lambda_{IF}\phi_{IF\,r}^{\;\;s}$ - the pseudorange and carrier phase ion-free (m) observables;

ρ_r^s - the geometric distance between the satellite at transmit time (t^t) and receiver at reception time (t_r);

$dt_r\left(t_r\right)$ - receiver clock offset from GNSS system time;

$dt_{IF}^s\left(t^t\right)$ - ion-free satellite clock offset from GNSS system time;

$\tilde{N}_{IF}$ - ion-free ambiguity $\tilde{N}_{IF} = N_{IF} + \delta_{IF}$, with δ_{IF} the bias of the ambiguity;

$T_r^s(t_r)$ - is the neutral atmosphere (troposphere) propagation delay;

$\varepsilon_{PD_r^s}$ and $\varepsilon_{\phi_r^s}$ represent unmodeled errors including receiver noise, multipath, and other small effects in the pseudorange and carrier phase respectively.

In the GNSS positioning using code and phase ion-free observables, the first order ionosphere and the so-called Timing Group Delays (TGDs) are cancelled in the combination. The satellite clocks errors (by definition) refer to this combination (Laurichesse, 2008; Sanz Subirana et al., 2013). Therefore, when using the Iono-free observable, only the first order effects are eliminated. The remaining 0.1% of ionospheric refraction affecting the measurements corresponds to only a few centimeters or even less (Marques, Monico and Aquino, 2011), and will not take into account in this application.

Concerning the tropospheric delays, in addition the a-priori model corrections $T_{r,0}^s\left(t_r\right)$, for precise positioning applications it may be necessary to parameterize the residual tropospheric delays

$$T_r^s(t_r) = T_{r,0}^s(t_r) + m_r^s(t_r)T_r^z(t_r) \qquad (3)$$

with m_r^s is a mapping function (Niell for example) and T_r^z is the residual trosposheric delay to be estimated, mainly composed of the wet delay.

As the observation equations is nonlinear with the respect the receiver position, it has to be linearized and approximated values for the coordinates are required. Details of the linearized observation equations and the least square solution can be obtained, for example, in Seeber (2003), Leick (2004), Hofmann-Wellenhof et al. (2008) and Teunissen and Montenbruck (2017).

With the IGS Real Time Pilot Project (IGS-RT) the approach now is available free of charge to the users. IGS-RT provides several products and the corrections to the broadcast ephemeris and clocks are the main one to be used in the development of this work (Elsobeiey and Al-harbi, 2016; IGS, 2018). The main concerns about PPP is related to the time of ambiguity and parameters convergence. Although several developments were presented in the literature on this direction, most of them was for static, static simulating kinematic, slow movement application, but also reaching 130 km/h as in Junbo et al., (2018), or in the post processing mode (Kamil et al. (2018a); Kamil et al. (2018b)). Here it will be presented the case with an aircraft flying at a mean speed of 360 km/h reaching up to approximately 600 km/h and with several maneuvers that is a challenge for real time application. It is related to flight tests of prototype aircrafts. So, our hypothesis is that PPP can be applied for such so dynamic applications and provides the required accuracy (Figure 1). The real time orbit and clocks are corrected using the appropriated IGS product provided by for instance by Bundesamt für Kartographie und Geodäsie (BKG) and Centre National d´études Spatiales (CNES). But the IGU (IGS ultra rapid orbit) is also uploaded to the system to be used if corrections are not available due to sudden communication break resulting in a discontinuity in receiving these products for a period that may extend from a few seconds to minutes. Such kind of approach was also used at some extend by El-Mowafy, Deo and Kubo (2017).

2.1 The in-house RT-PPP software

In order to provide support for the project, a software (denominated 'RT_PPP') that is able to provide RTPPP as well as pos processing capability was developed. It was developed in C++ language and the Kalman Filter is applied for PPP processing together with DIA (Detection Identification and Adaptation) control quality (Teunissen, 1998). The ambiguities are estimated as float solution and the cycle slip detection is carried out based on the wide lane combination involving code and carrier phase as presented by Blewit (1990). When a cycle slip is detected for any satellite, the adopted strategy consists of restarting the phase ambiguity parameter in the processing (Marques, 2012; Marques et al. 2014).

The RT_PPP software process GPS L1 and L2 code and phase measurements combined into ion-free observable. In case P1 and/or P2 is not available due to receiver configurations or other restrictions, the software is able to detect and use C1 or L2C if available and to apply DCBs (Differential Code Bias) corrections in order to turn those observables compatible with P1 and P2. Concerning the troposphere correction, the Zenith Wet Delay (ZWD) is estimated as random walk process. The Zenith Hydrostatic Delay (ZHD) is obtained from Saastamoinen model together with Vienna Global Pressure and Temperature (GPT) model for each epoch. The Global Mapping Function (GMF) is used to compose the design matrix for troposphere estimation (Boehm, Schuh, 2004). The main implemented mathematical models in the RT_PPP to eliminate or minimize systematic effects in the GPS observable are shown in the Table 1.

Table 1: Mathematical models to account for systematic effects in the RT_PPP software.

Effect	Strategy
Ionosphere – 1st order	Ionosphere free combination
Troposphere	Estimative of ZWD (random walk) with initial values coming from Saastamoinen +GPT model
Ocean Tide Loading and Earth Body Tides	Models proposed by IERS convention
Receiver and Satellite Phase Centre Variation	Absolute Phase Center Variation correction
Precise Orbit and Satellite clock correction	RTIGS or Predicted IGU
Differential Code Bias	Estimated values from CODE
Ambiguities	Float solution
Phase windup	Applied
Relativity correction	Applied

The RT_PP allows accomplishing static and kinematic PPP either in real time or in a post-processed mode. For real time PPP the GNSS observables are retrieved from receiver connected to the internet via NTRIP or computer USB/Serial port. The internet communication was developed based on available source codes from BKG (BKG, 2018). So, the RT_PPP works as client software capable to retrieve GNSS data, orbit and clock correction and to accomplish PPP.

3. Results and Analyses

Two experiments will be presented in the next subsections, being the first one (section 3.1) the kinematic PPP taking into account GPS data collected in a flight test and stored in RINEX file for posterior processing. The second experiment (section 3.2) was accomplished in real time with RT_PPP software installed in a laptop connected to a receiver via serial port and receiving IGS orbits and clocks corrections from internet. For both experiments, the relative positioning and post processed PPP provided reference values to the flight position for accuracy analyses. For relative data processing, the Topcon-Tolls and Trimble Business Center (TBC) commercial software were employed. CSRS (Canadian Geodetic Survey of Natural Resources Canada) PPP (https://webapp.geod.nrcan.gc.ca/geod/tools-outils/ppp.php?locale=en) was used for PPP.

3.1 Kinematic PPP for data collected in the flight test

GPS data were stored during a flight test carried out in 2009-09-01 (DoY 244) referring to the flight number 811. In this experiment, only one dual frequency GPS receiver, located at Embraer airport, collected and stored data that were used in the relative post-processing to generate reference coordinates to compute the flight test PPP accuracy.

Flight 811 started approximately at 13h30min and finished near to 16h30min UTC time and the GPS data were collected with 2 Hz of sample rate. The approximate path of airplane, height and velocity during the flight can be seen in Figure 2

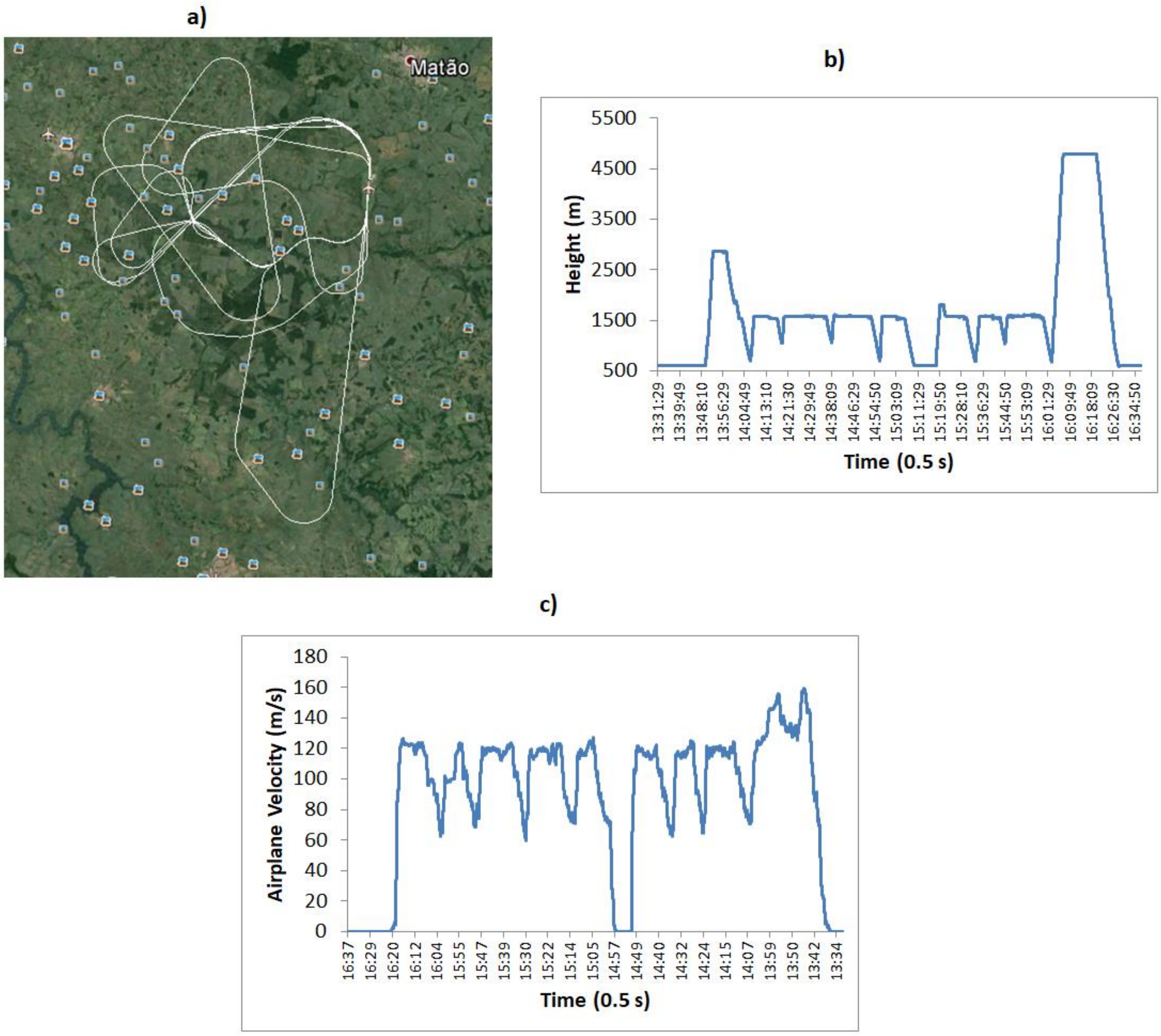


Figure 2: Path of airplane (a), Geometric height (b) and velocity (c) for flight 811.

Source: Google Earth.

The relative GPS data processing was accomplished considering elevation cutoff of 10 degrees and fixed ambiguity resolution was reached for all involved epochs. Time series of precision obtained in the relative positioning are shown in Figure 3 where we can see maximum values reaching near 8 cm, but in general, precisions are better than 5 cm, what can be considered of high quality for airplane kinematic positioning.

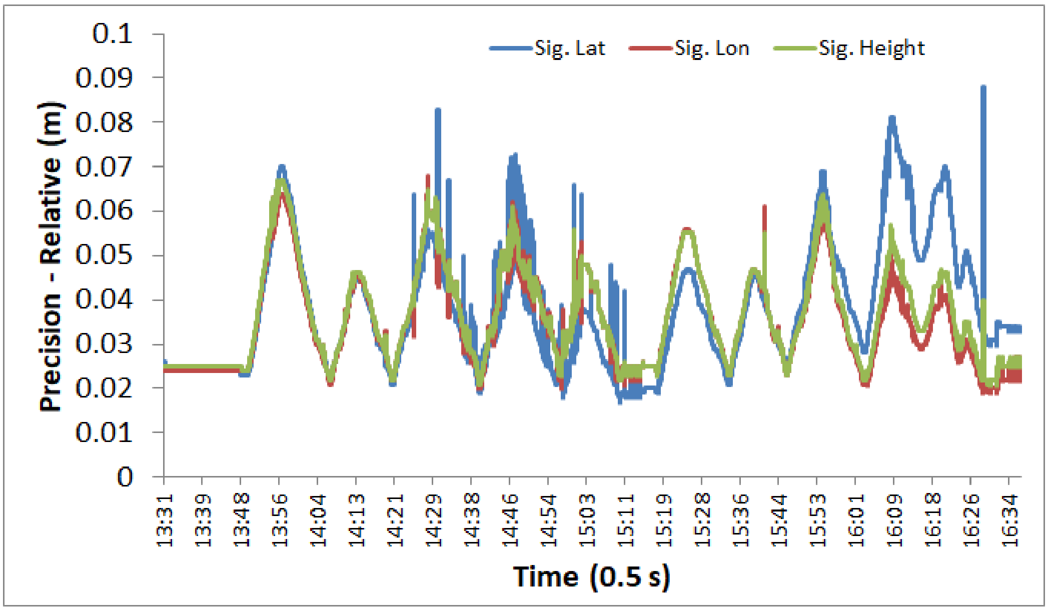


Figure 3: Precision estimated in the relative processing (flight number 811).

The GPS data collected in the flight 811 was processed with RT_PPP software applying clock corrections estimated in real time (clk91 from IGS) and stored aiming post-processing. Satellite positions were interpolated from IGU ephemeris, because of the good quality (Shi, et al., 2017). So, such case is called here as PPP simulating real time. For most of the time, PPP precisions reached the order of 30 cm after the convergence period as can be seen in Figure 4. The errors of PPP simulating real time when comparing with relative positioning are shown in Figure 5 and statistics are presented in Table 2 considering all epochs of data an also only the period after the convergence time, i.e., excluding the initial period required for position precision convergence to a level of 20 cm.

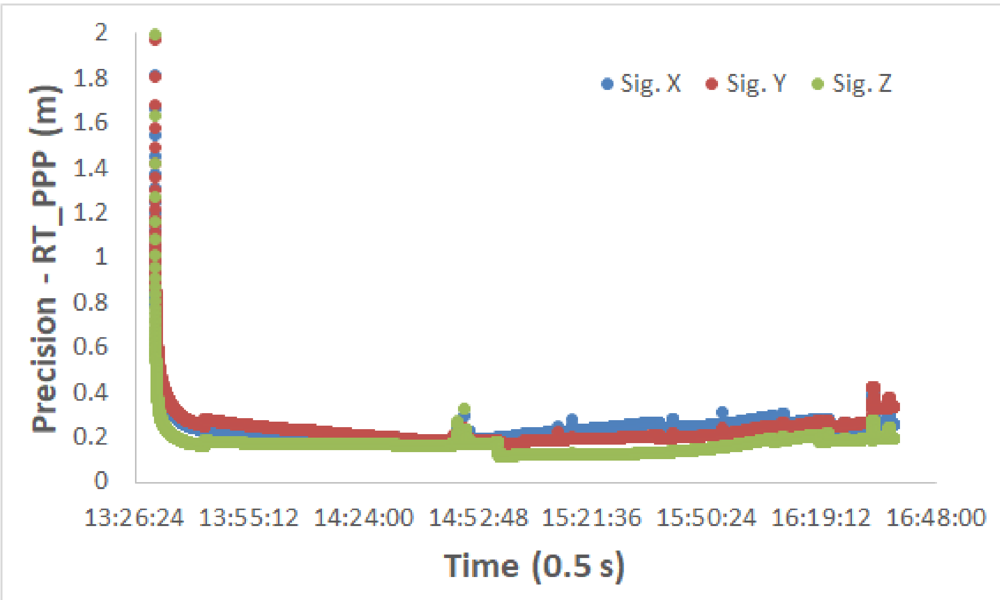


Figure 4: Precision estimated by RT_PPP simulating real time (flight number 811).

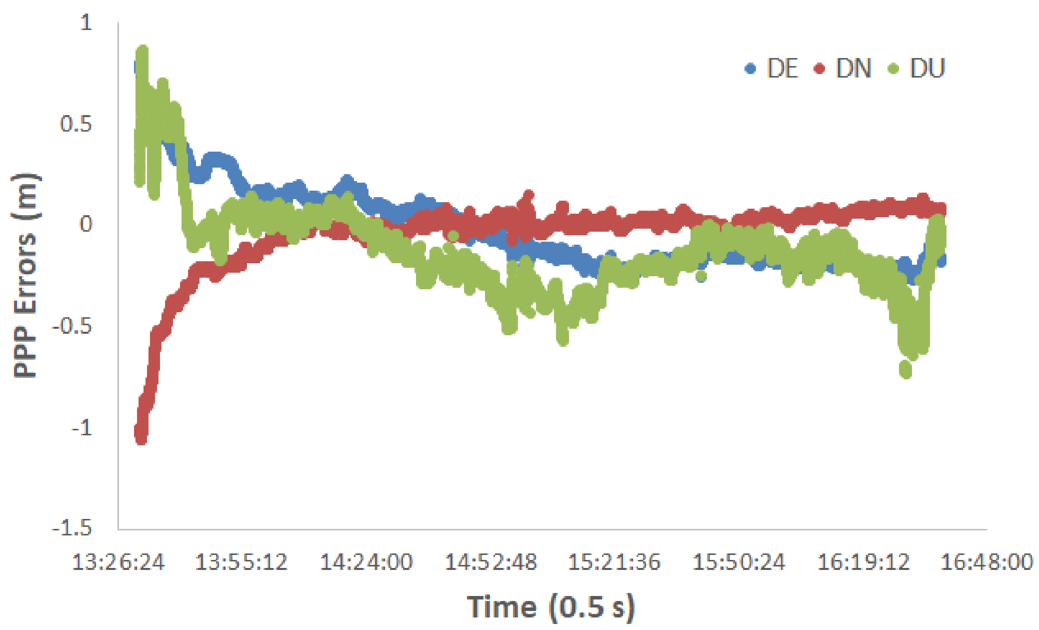


Figure 5: PPP (simulating real time) errors when comparing with relative positioning.

Table 2: Statistics for PPP simulating real time.

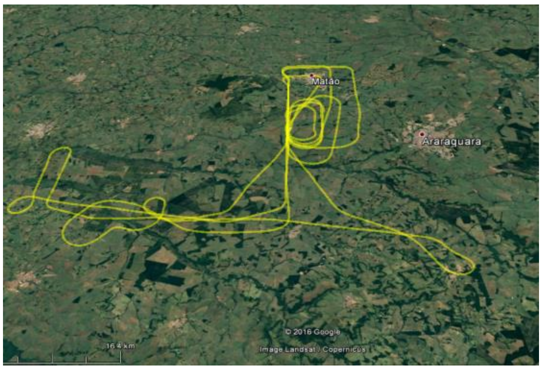
Considering convergence time period					
Statistics (m)	DE	DN	DU	2D Error	3D Error
Mean Error	-0.019	-0.039	-0.124	0.204	0.307
Standard Deviation	0.203	0.161	0.216	0.166	0.193
RMS	0.204	0.166	0.250	0.263	0.363
Not considering convergence time period					
Statistics (m)	DE	DN	DU	2D Error	3D Error
Mean Error	-0.047	-0.004	-0.150	0.153	0.248
Standard Deviation	0.149	0.055	0.144	0.063	0.094
RMS	0.156	0.055	0.208	0.165	0.266

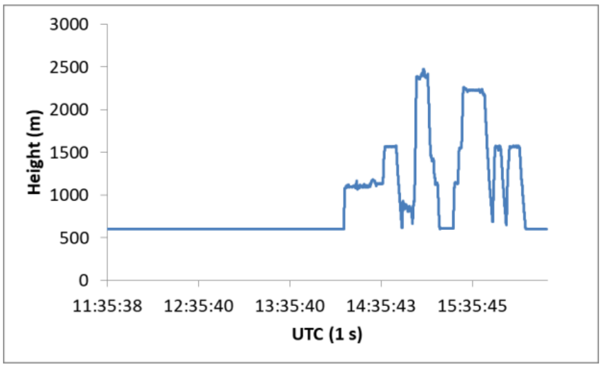
From Figure 5 we can see that PPP errors reach maximum values of the order of 50 cm and most of values reached the order of 30 cm after the convergence period. Considering all involved epochs, the horizontal RMS (2D) reached values of 0.263 m and the 3D RMS reached 0.363 m (see Table 2). Taking into account only the period after convergence period, the 2D and 3D maximum errors reached, respectively 0.165 m and 0.266 m. As IGU orbits are likely of not being completely compatible with the clock corrections provide by IGS, one can expect that such values can be improved at some extend if the compatible corrections for the satellite positions are applied.

3.2 Real time PPP for flight test

The flight test 454 was realized on 2017-06-01 (DOY 152) using a Legacy airplane. The computer with the RT-PPP system was connected to a dual frequency receiver (ProPak V3 Novatel) available in the airplane via serial cable to receive the receiver data (RTCM messages 1004). There was also internet available in the airplane which also allows for uploading the most recent IGU ephemerides and to get the real time IGS products (orbit and clock corrections from CLK 91) together with real time broadcast from mountpoint RTCM3EPH. The flight started around 11h35min and finished at 16h24min UTC. The aircraft took off around 14h11min, so, with a lot of time for ambiguity convergence. Figure 6 provide a general idea of the path of the flight, height and the velocity during it.

(a) (b)





(c)

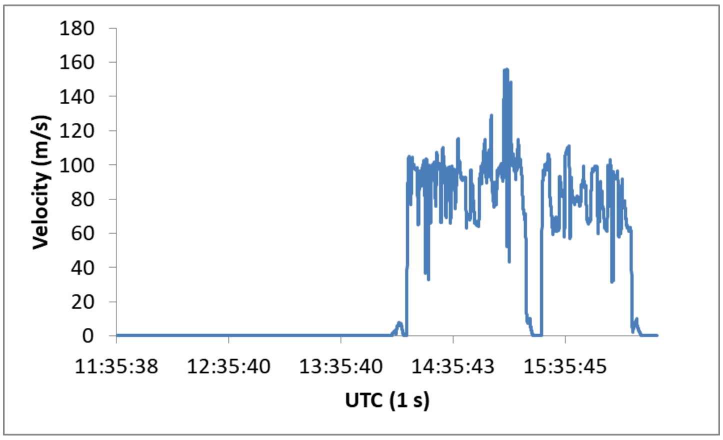


Figure 6: Path of airplane (a), Geometric height (b) and velocity (c) for flight 454.

Source: Google Earth.

From Figure 6 one can see that the flight was very dynamic, going up and down and with several turn around and the velocity that on average was 100 m/s reached the level of about 160 m/s (~600 km/h). Figure 7 shows the time series of the level of precision. As one can see, after 30 min the level of precision was better than 10 cm for each component, attending the requirement showed at Figure 1. The peaks that can be observed in Figure 7 are related with internet loss or maneuver of the aircraft.

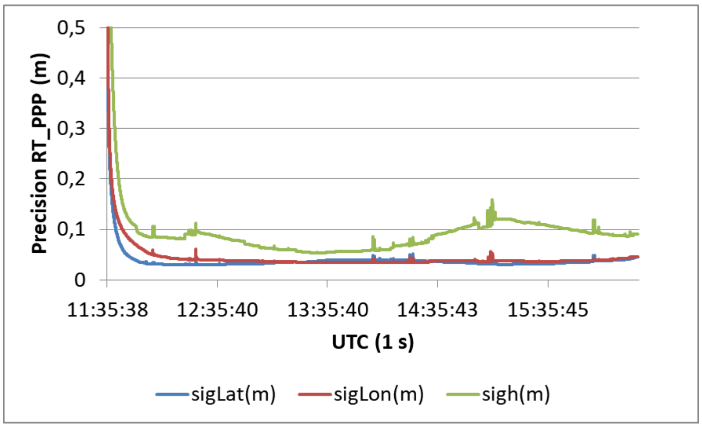


Figure 7: Real time coordinates components precision.

In order to have a robust reference to assess the quality of the positioning not only in terms of precision, but also biases with relation to a reference, two main processing scenarios were made available; the post-processing PPP using an independent software (CSRS PPP) and the relative positioning, which used several base stations in the vicinity of the flight path, using the TBC software from Trimble. The precision of both and the discrepancies between them are shown in Figure 8.

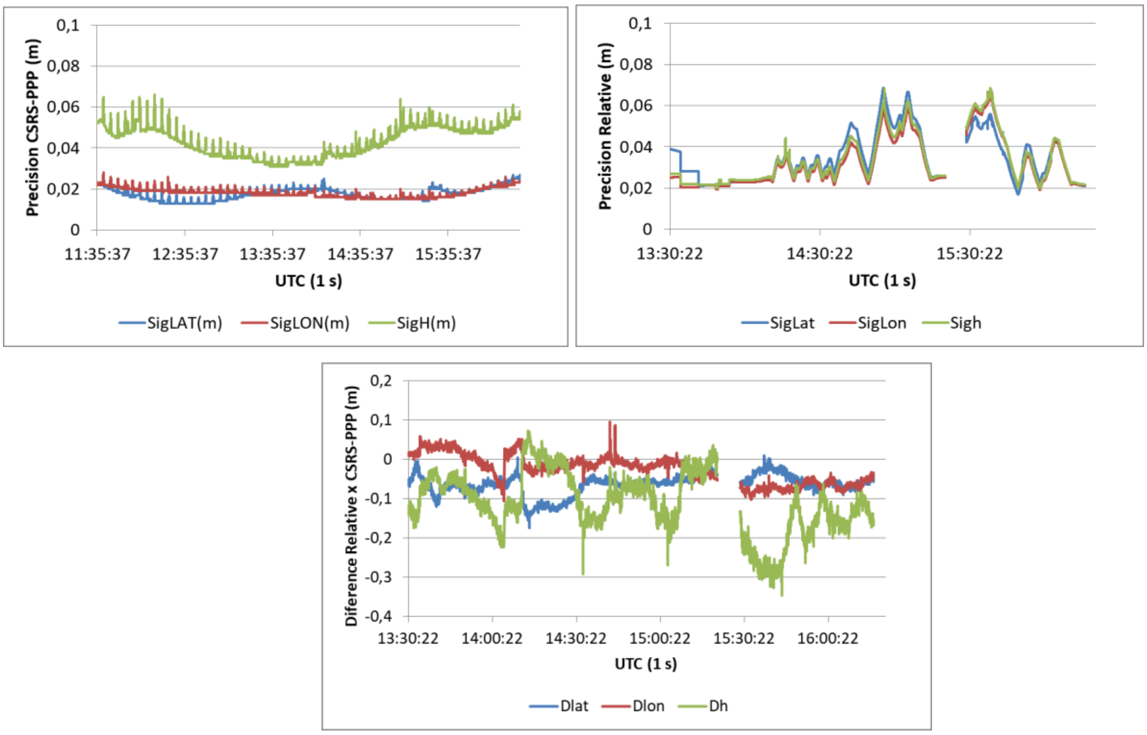


Figure 8: Precision of CSRS from NRCAN (a), Relative Positioning (b) and discrepancies between them (c).

Taking into account the precision of the two references solutions, they provided formal precision quite better than 8 cm for most of the time, even for the h component. So, in the next step the CSRS PPP solution was compared with the relative positioning, which are based on different approaches. The maximum difference was of about 30 cm for h component for the case in which the velocity was of about 600 km/h. Therefore, such references provided quite good reliability to assess the quality of the RT_PPP.

Figure 9 shows a report generated by the RT-PPP system. It is possible to observe the instants that the internet fail and so, there were no corrections available from IGS mount point (clk 91). At such time, it starts to use IGU ephemerides (Using IGU) instead of broadcasted ephemeris with IGS corrections (BRDC+Corr). See two examples below highlighted by the blue lines, showing the case of loss of connection and the reconnection.

h:m:s	SecOfWeek	TypeOfSolu	X(m)	sigx(m)	Y(m)	sigy(m)	Z(m)	sigz(m)
...								
15:04:33.00	399873.000	BRDC+Corr	3911074.230	0.073	-4443231.551	0.091	-2373778.135	0.056
15:04:34.00	399874.000	BRDC+Corr	3910955.586	0.073	-4443283.627	0.091	-2373850.949	0.056
15:04:35.00	399875.000	BRDC+Corr	3910839.583	0.073	-4443324.015	0.092	-2373939.090	0.056
15:04:37.00	399877.000	UsingIGU	3910620.350	0.090	-4443379.036	0.111	-2374148.505	0.065
15:04:38.00	399878.000	UsingIGU	3910517.697	0.082	-4443400.127	0.102	-2374264.791	0.060
15:04:39.00	399879.000	UsingIGU	3910418.103	0.079	-4443420.136	0.098	-2374384.680	0.059
...								
15:05:30.00	399930.000	UsingIGU	3905689.101	0.067	-4446545.560	0.088	-2376293.542	0.047
15:05:31.00	399931.000	UsingIGU	3905645.338	0.067	-4446631.622	0.088	-2376206.998	0.047
15:05:32.00	399932.000	UsingIGU	3905604.213	0.067	-4446716.146	0.088	-2376117.519	0.047
15:05:34.00	399934.000	BRDC+Corr	3905532.380	0.097	-4446882.216	0.122	-2375930.988	0.072
15:05:35.00	399935.000	BRDC+Corr	3905501.022	0.088	-4446962.643	0.114	-2375833.451	0.063

Figure 9: Report of RT-PPP showing internet loss of connection.

In order to see the effects of using IGU instead of the IGS clk91 corrections for the satellite positions and clocks, Figures 10 and 11 show the discrepancies of the satellite positions and clock obtained from IGU against the real time (BRDC+ Corr). As one can observe, the discrepancies for position can reach at maximum 10 cm, but for clock it reaches the level of 80 cm (Figure 11). Therefore, once we have loss of connection, the positions may be affected due to these effects.

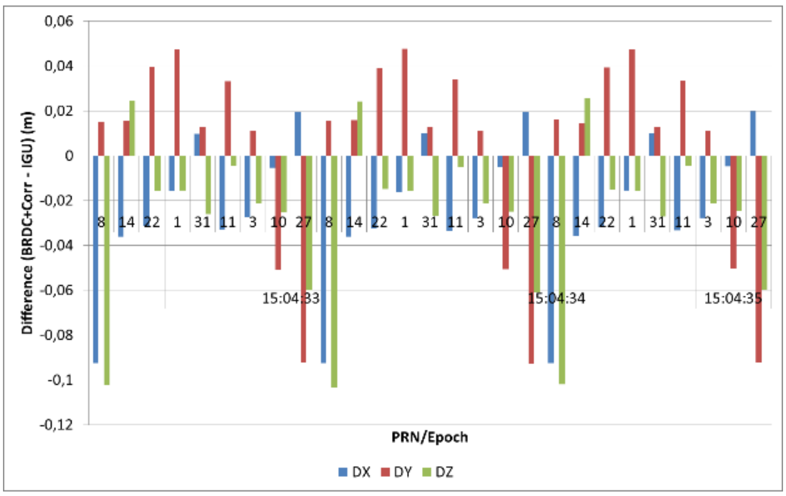


Figure 10: Discrepancies for satellite positions from IGU and broadcasted with corrections (BRDC+Corr).

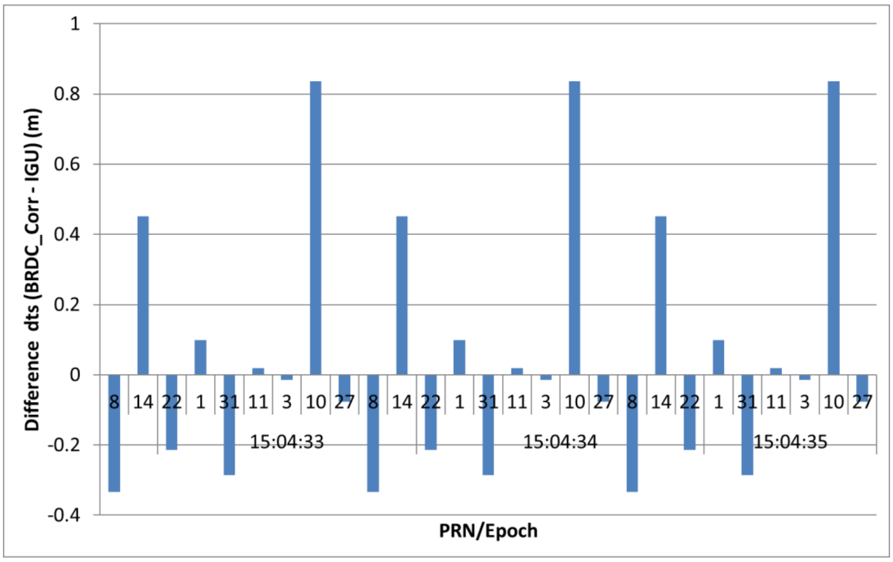


Figure 11: Discrepancies for satellite clocks from IGU and broadcasted with corrections (BRDC+Corr).

The discrepancies of the RT_PPP solution against the one from CRCS PPP are shown in the Figure 12.

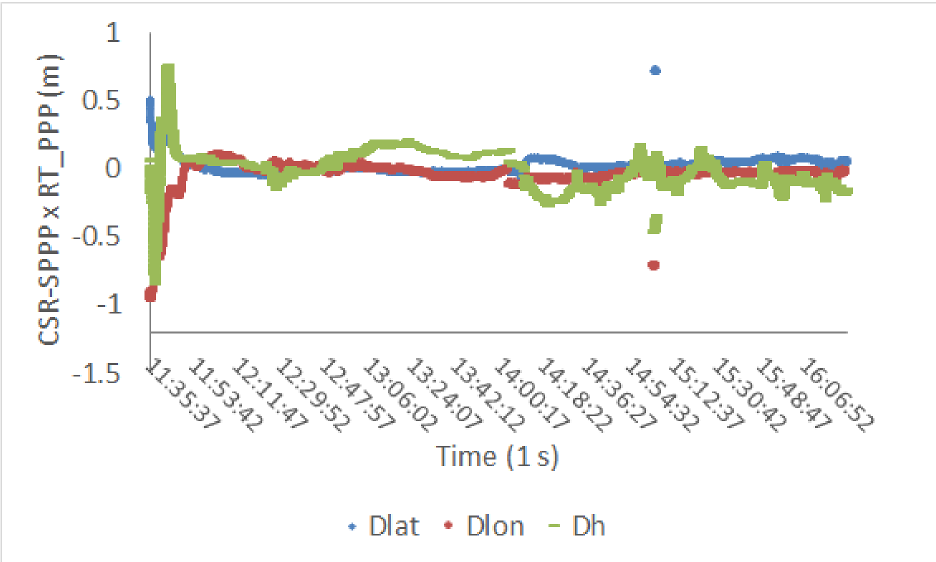


Figure 12: Discrepancies of RT-PPP against the CSCR PPP post processed.

From Figure 12 one can observe the required time for the convergence, about 30 min, as expected. One can also identify few peaks after convergence. They correspond to the instants that occurred loss of connections and errors of the order of about 50 cm or more were obtained. Thanks to the IGU orbits uploaded in the beginning of the experiment, otherwise it would be quite worse.

Next, once all corrections were available, the collected data were post processed using RT_PPP. The discrepancies are shown in Figure 13. One can observe that the results are quite good. After the convergence, only few peaks are observed, but they are quite small.

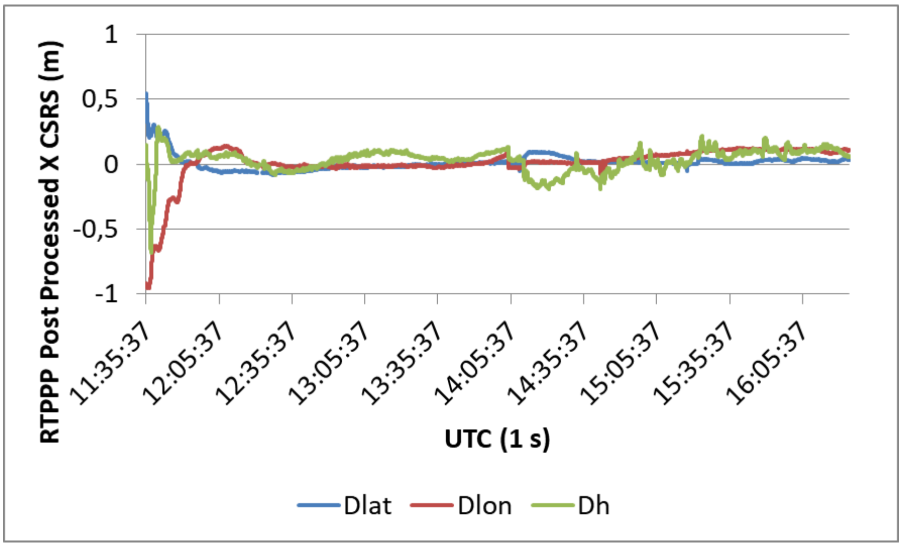


Figure 13: Discrepancies of RT-PPP pos processed against the CSRS solution.

Finally, in order to provide a general idea, Tables 3 and 4 provide the final statistics of these results, RT_PPP and post processed. It is possible to observe that the post processed solution is better than the real time one, as expected. It is due to the fact of the loss of internet connection during the flight, otherwise, the results probably would be quite more compatible.

Table 3: Quality information of the RT-PPP solution.

Statistics	Dlat (m)	Dlong (m)	Dh (m)
Mean Error	0,009	-0.161	-0,182
SD	0,076	0,233	0,452
RMS	0,077	0,283	0,487
Abs Max error	0,800	1,000	0,500

Table 4: Quality information of the post processed solution.

Statistics	Dlat (m)	Dlong m)	Dh (m)
Mean Error	0,024	-0.015	0,045
SD	0,098	0,235	0,168
RMS	0,101	0,236	0,174
Abs Max error	0,400	0,250	0,200

From Tables 03 and 04 one can observe that the maximum RT error reduced from 100 cm to 25 cm in the Longitude. On average, in RT the RMS reached at maximum 49 cm in the height and was reduced to 17 in the post processing. The worse result was for Longitude. Considering the specification at Figure 1, it is clear that real time PPP without internet loss can provide the required accuracy for such kind of application.

4. Final Comments and Conclusions

A system that provide RT_PPP was developed, which use IGS RT products. It is also able to process GPS data in a post-processing mode. Two main tests were carried out. One, flight 811, simulating RT kinematic in which IGU orbits and clk91 were used. The obtained accuracy was in the level of 50 cm. A second test, a real time one, flight 454, using IGS corrections (clk91) for broadcasted ephemerides (position and clock). The worst result was in the level of 1m for the aircraft at 600 km/h. And it was due to the problem of internet connection. The average accuracy was in the level of 20-30 cm for all components. Therefore, even for such a challenge situation, the RTPPP proofed to be useful for such applications. Thanks to IGS products. As a future development, a full GNSS system is expected to be implemented, starting with Galileo, together with ambiguity resolution.

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Author’s contribution

Definition of research topic (Monico, Wentz and Marques); Algorithms implementation (Marques, Oyama and Queiroz); Literature review (Monico and Marques); Definition of methodological procedures (Monico, Marques, Souza and Wentz); Air flight test and GPS data collection (Souza, Oyama, Tsuchiya and Marques); Data processing (Marques, Tsuchiya and Monico); Analysis and interpretation of results (Marques and Monico); Manuscript writing (Monico and Marques).

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