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Full Length Research Paper

Kinematic GNSS-PPP results from various software packages and raw data configurations

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In this study, kinematic precise point positioning (PPP) was tested. The raw data were taken from permanent stations, two airplane trajectories, a car trajectory and a walking trajectory. International GNSS Service (IGS) final products were used in the post-processing phase. The observations were processed using four different on-line software packages: the Canadian Spatial Reference System On-line Global GPS Processing Service (CSRS-PPP), the GPS Analysis and Position Software (GAPS), the Automatic Precise Positioning Service (APPS) and the Magic Global Navigation Satellite System (MagicGNSS). The results and comparisons are described in detail. The main conclusion is that an accuracy better than 10 cm for the planimetric measurements and better than 20 cm for the altimetric measurements can be achieved using the kinematic PPP method in any of the proposed tests. However, at present, the success of the technique is affected by the software used, and differences at the 0.5 m level can be found for the same specific epoch.

Key words: GNSS, kinematic precise point positioning, PPP software center.

INTRODUCTION

In most commercial and scientific applications of Global Navigation Satellite System (GNSS) kinematic positioning, differential positioning is used with data from a reference station and a rover receiver. However, the main problem with positioning based on double differencing is that the volume of residual errors increases as the distance between the reference and rover receivers increases. One alternative method is precise point positioning (PPP). PPP can provide sub-metre to centimetre positioning accuracy using only one dual-frequency carrier-phase GPS receiver, that is, without the use of base stations, it reduces the cost of the GNSS survey. PPP employs high-resolution carrier phase and pseudorange observations in processing algorithms, in which precise satellite orbits and clock information are used instead of broadcast information. Thus, PPP has the benefit of using the most accurate post-mission or near-real-time information as published by the International GNSS Service (IGS) (Dow et al., 2009; Ray, 2010).

PPP was first developed for use in static applications (for example, Zumberge et al., 1997) and has been studied extensively in recent years (Kouba and Héroux, 2001; Gao and Shen, 2001; Bisnath et al., 2002; Colombo et al., 2004; Chen et al., 2009; Geng et al., 2010; Soycan and Ata, 2011). With the development of final, near-real-time or real-time satellite orbit and clock products, kinematic PPP is being increasingly used in research and survey applications. It is used, for example, in airborne and marine applications, in sparsely populated regions, such as in mountains, prairies or desert regions, and in areas where the GNSS infrastructure is poorly developed, such as in Greenland and North Canada. Examples of these applications can be found in Chen (2004), Héroux et al. (2004) and Jensen and Ovstedal (2008). Some references and results in the field of kinematic PPP are as follows:

In Gao and Shen (2004), tests of kinematic PPP for a vehicle and a helicopter were conducted. The results indicate that positioning information with an accuracy level of 10 cm could be obtained. In Héroux et al. (2004),

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the precise GPS positions of two aircraft GPS antennas were computed using kinematic PPP processing. For the distance between the two antennas (3.804 m), the Root Mean Square (RMS) was below 5 cm and the range was below 25 cm. In Leandro and Santos (2006), GAPS software was used to determine the trajectory of a boat via kinematic PPP. The results include RMS values of 6.5, 5.5 and 13.9 cm for the North, East and up components, respectively. In Ovstedal et al. (2006), the results achieved using kinematic PPP and differential post-processing to track a flight over Fredrikstad in Norway were consistent at a 5 cm level for the horizontal component. In Hu et al. (2008), the IGS station SHAO was evaluated in kinematic mode on days 295, 296 and 297 of the year 2007. The maximum mean differences were 0.6, 3.2 and 4.3 cm for the North, East and up components, respectively. In Jensen and Ovstedal (2008), 24 h of raw data from 14 stations were processed in the kinematic PPP mode using different tropospheric models. In all cases, the standard deviations of the results were 6 to 7 cm for the horizontal components and 13 to 14 cm for the vertical component. In Tsakiri (2008), seven continuous days (24 h, 30 s observation files) of data for 2 IGS stations were processed using kinematic PPP with the CSRS-PPP software. Centimetric standard deviations in both the horizontal and vertical components were obtained. A kinematic vehicle test was also performed that yielded results of 5 to 6 cm for the horizontal component and 13 to 14 cm for the vertical component. In Kjorsvik et al. (2009), the researchers analysed 14 days of continuous observations of a ferry route between Lauvvik and Oanes (Norway) at a 1 Hz observation rate. The comparison of the PPP results with the reference trajectory computed via differential positioning yielded mean error rates of 6.7 and 10.0 cm for the horizontal and vertical components, respectively. Finally, in Landau et al. (2009), one static station was processed using kinematic PPP. Not taking into account the first two hours of convergence time, the RMS values for North, East and up were 4.8, 2.6 and 8.7 cm, respectively. However, few people use kinematic PPP to process GPS data from moving receivers because the quality of the data is extremely vulnerable to signal interruptions. Losing a lock on a GPS satellite signal (or on all GPS signals simultaneously) will require the user to wait for several minutes before attaining sub-decimetric precision because a new ambiguity term will have to be derived from the system of normal equations. In this paper, a case study is conducted to test the effectiveness of kinematic PPP, but the most novel aspect of this study is the comparison of the results obtained using the different available on-line software tools.

METHODOLOGY

In the first test, data from permanent GPS stations were processed in kinematic mode. The results of this test are helpful to evaluate the kinematic PPP model and algorithm because the placement of the receivers should eliminate multipath problems and signal loss. The methodology is as follows: GPS observations from 8 permanent IGS stations (BRST, CONZ, KOUR, MDVJ, MTKA, NANO, REUN and TOW2; Figure 1) were downloaded from the IGS website (URL-1, 2011). The data sets used cover the first four hours of days 33, 211 and 347 of the year 2010, with data recorded at 30 s intervals. The coordinate bias (accuracy) is obtained by comparing the solution for every epoch obtained using the kinematic PPP method with the static PPP solution for the day under consideration.

The second study tested the overall performance of the kinematic PPP method in a kinematic environment. Such data set represent a more realistic scenario than the IGS static data sets because a GPS antenna mounted on a vehicle is strongly susceptible to multipath problems and signal loss due to vehicle dynamics and obstructions in an urban canyon environment. Such signal loss is currently the main problem with kinematic PPP use because the system must be re-initialised to resolve ambiguities.

Two flights over the Valencia region (in the eastern part of Spain), a car trajectory and a walking trajectory are analysed to evaluate the overall performance of kinematic PPP in a kinematic environment; these cases were chosen because they cover the most usual applications of kinematic GNSS. All the Receiver Independent Exchange (RINEX) observation files include phase measurements of the carrier waves for the L1, L2, P1, P2 and C/A pseudo-range codes.

The two flights belong to the Cartographic Institute of Valencia and were located in the Valencia region. The flights were conducted entirely over land on days 185 and 219 of the year 2008 following the path indicated in Figure 2. The altitude of the flights was approximately 5300 m. and the speed of the aircraft was 300 to 330 km/h. The data were recorded at intervals of 0.5 s.

On the 28th of February 2011, GPS data were collected at 5 s intervals for a car trajectory analysis in the Technical University of Valencia surroundings (Figure 3). The streets are wide enough to allow a strong GPS signal.

The final test was conducted on the 18th of February in 2011. In this test, a walking trajectory around the campus of the Technical University of Valencia was analyzed (Figure 4). The data were recorded at 5 s intervals

The methodology used to analyze the kinematic PPP in a kinematic environment was as follows: results obtained using the differential positioning mode were compared with the kinematic PPP solution, yielding the coordinate bias of the kinematic PPP data. In the airplane trajectories, the data from the ALCOY permanent base station, which is part of the permanent GPS network of Valencia (the ERVA network), were used (Figure 2), and the permanent EUREF (the International Association of the Geodesy Reference Frame sub-commission for Europe) site VALE was used for the car and walking trajectories (Figures 3 and 4).

On-line software tools

The second objective of this paper is to evaluate the different on-line software tools used in kinematic PPP post-processing. The four different software packages used in this study are those included in the Precise Point Positioning Software Centre. The PPP Software Centre is a website that was created under the auspices of the Geomatics for Informed Decisions (GEOIDE) Network of Centres of Excellence Project 31 in Canada, Santos et al. (2009). The website has been functioning since May 2009 (URL-2, 2011). The main purpose of this website is to allow access to four different PPP applications via RINEX observation files sent by e-mail. These four different services are as follows:

1. The CSRS-PPP, operated by the Geodetic Survey Division of Natural Resources, Canada (URL-3, 2011), uses the in-house

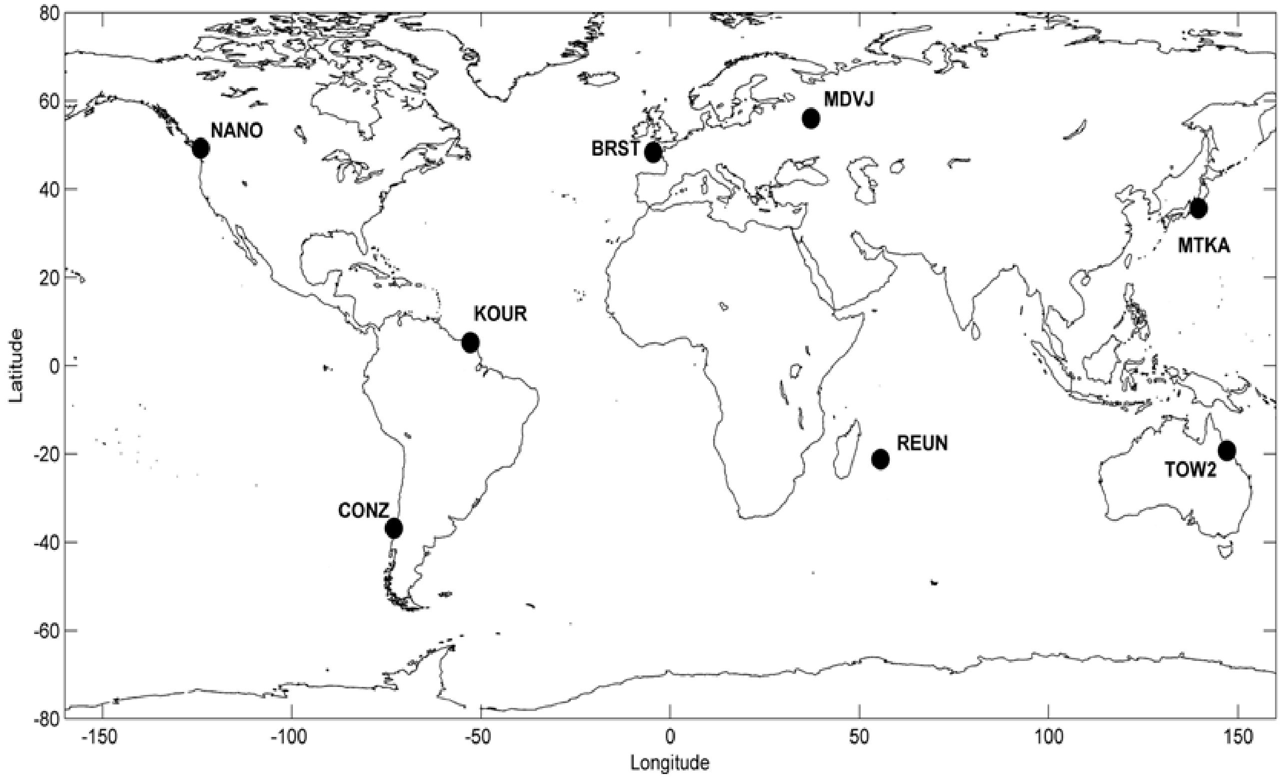

Figure 1. Location of the eight IGS stations used in the study; coastline file from the U.S. National Geophysical Data Center (URL-7, 2010).

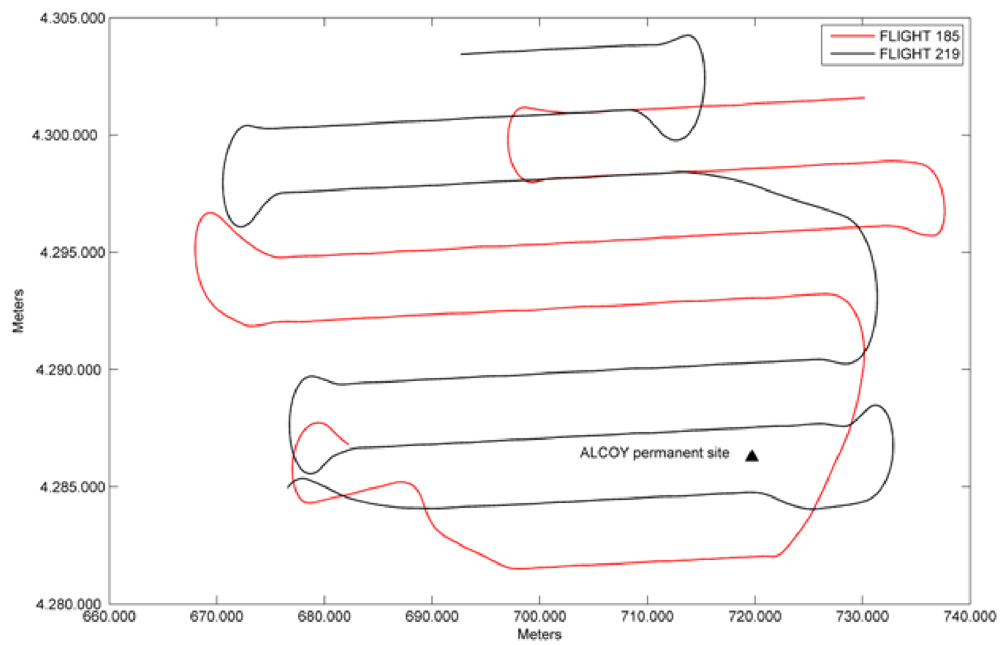

Figure 2. Flights used for the analysis. UTM30N coordinates.

NRCan-PPP software, employing a least-squares batch process (Héroux et al., 1993).

2. The APPS, operated by the Jet Propulsion Laboratory, United States, (URL-4, 2011), uses version 5 of the GIPSY-OASIS

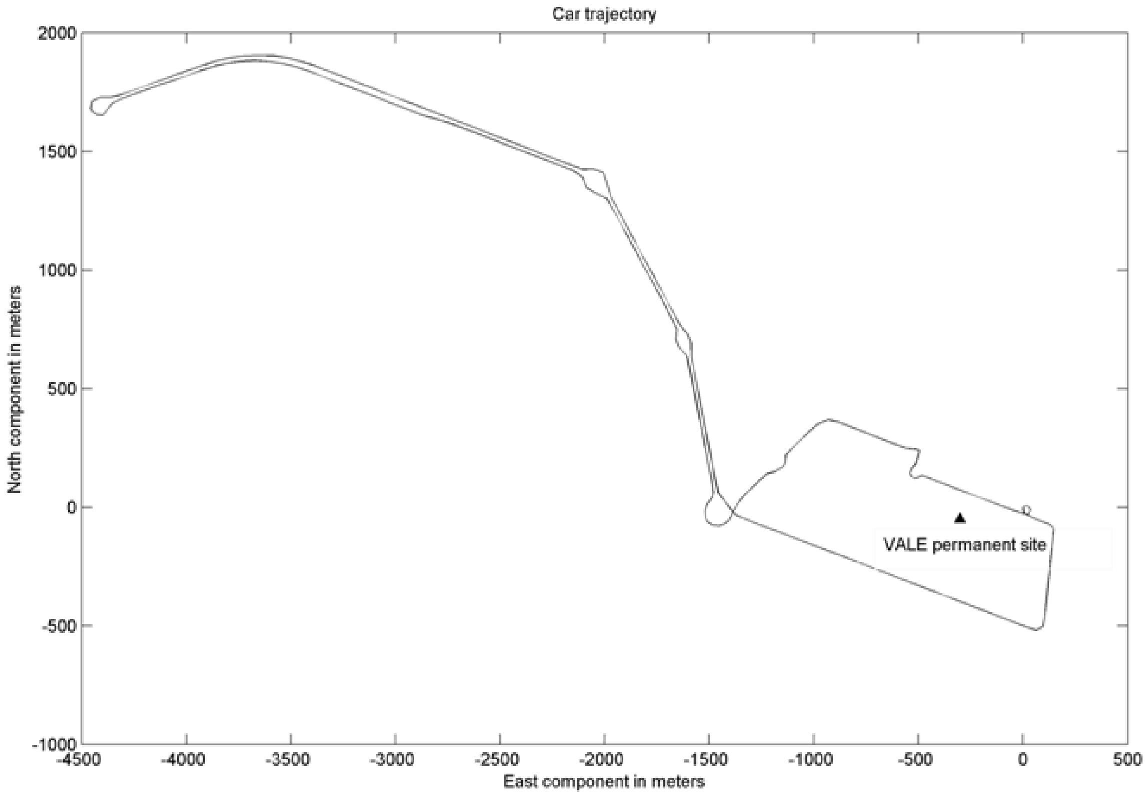

Figure 3. Car trajectory used for the analysis.

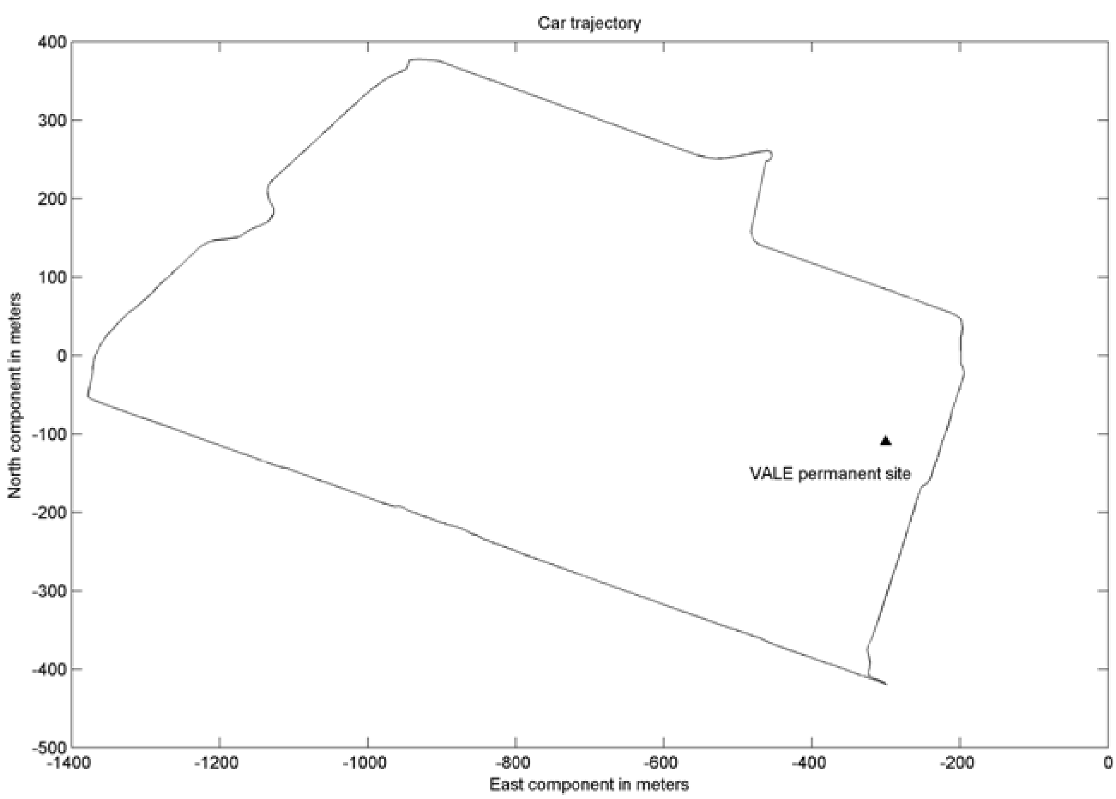

Figure 4. Walking trajectory used for the analysis.

Table 1. Statistics indicating the mean kinematic PPP bias for the IGS permanent sites. The values are presented in metres.

Software	N		E		Up	
	σ	range	σ	range	σ	range
APPS	0.014	0.133	0.013	0.120	0.043	0.515
GAPS	0.244	1.789	0.225	1.448	1.107	6.655
NRCan	0.052	0.506	0.036	0.301	0.095	0.735
MagicGNSS	0.020	0.173	0.019	0.180	0.062	0.558

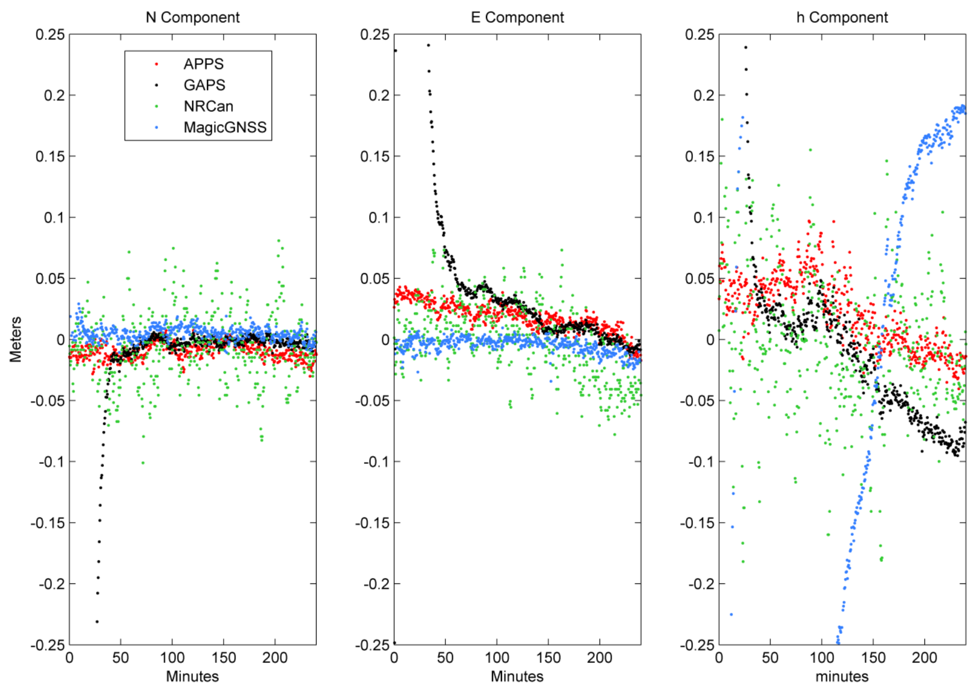

Figure 5a. Kinematic PPP bias for the CONZ site. Day 33 of the year 2010.

software (Zumberge et al., 1997).

3. The GAPS, v5.0 operated by the University of New Brunswick (URL-5, 2011), Canada, uses software that was originally written in MatLab but has been re-designed and re-written in C++ (Leandro et al., 2008).

4. The MagicGNSS, v2.5 operated by GMV Aerospace and Defence (URL-6, 2011), Spain, is based on software developed for GALILEO orbit determination and time synchronisation. A batch least-squares algorithm is used to minimize measurement residuals, and to determine orbits, satellite and station clock offsets, phase ambiguities, tropospheric zenith delays and station coordinates (Píriz et al., 2008).

In Martín et al. (2011), a comparison of these four software tools can be found for a static PPP configuration.

RESULTS

Kinematic solutions at fixed sites

Examples of the obtained bias using the four different software packages can be found in Figures 5a, b and c. Table 1 lists the bias statistics, indicating the mean standard deviation and range (the maximum value minus the minimum value) for the eight permanent stations on the three days under study. Table 2 indicate the mean standard deviation obtained in computing the PPP coordinates, and Table 3 lists the mean RMS post-fit for the code and phase residuals.

Airplane trajectories

Figures 6a and b show the bias (accuracy) for the two flights. Tables 4a and b present the statistics of the bias, indicating the standard deviation and range produced using the GAPS, NRCan and MagicGNSS software.

The APPS software results have a mean bias greater than 2000 m for the planimetric measurements and a mean bias greater than 5000 m for the altimetric

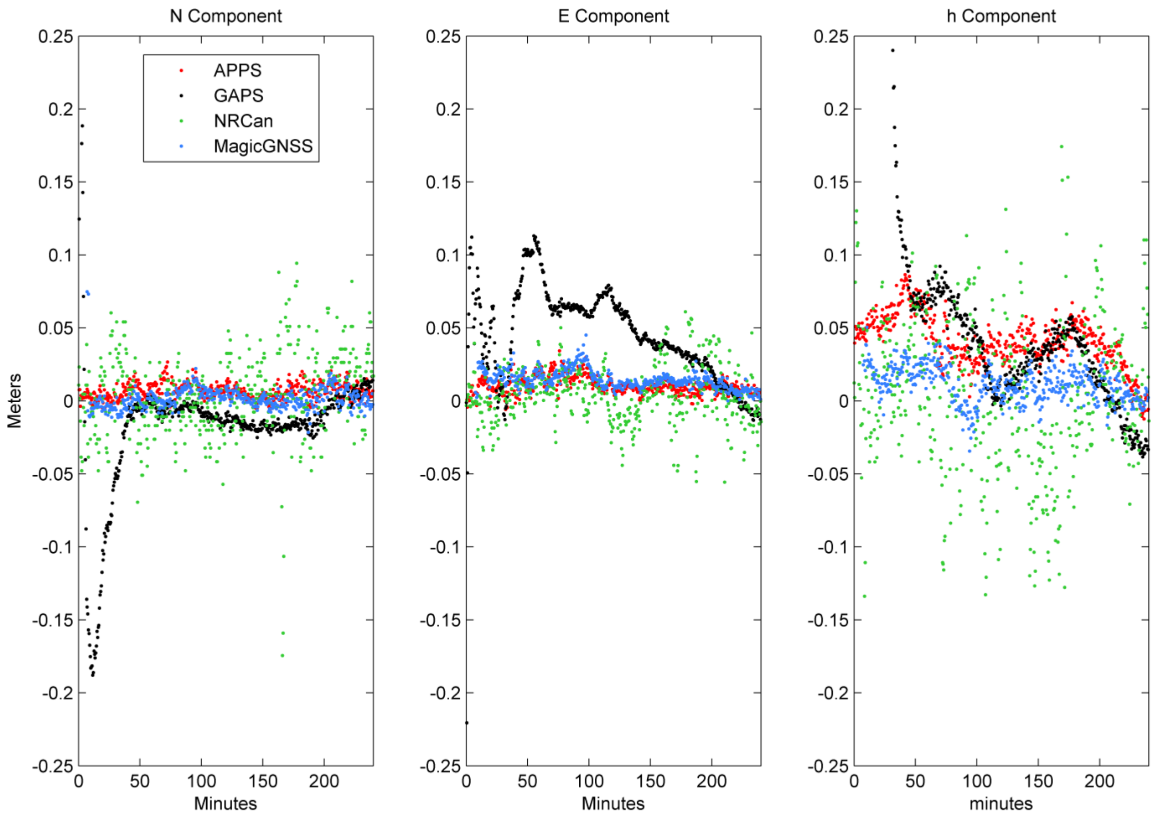

Figure 5b. Kinematic PPP bias for the BRST site. Day 211 of the year 2010.

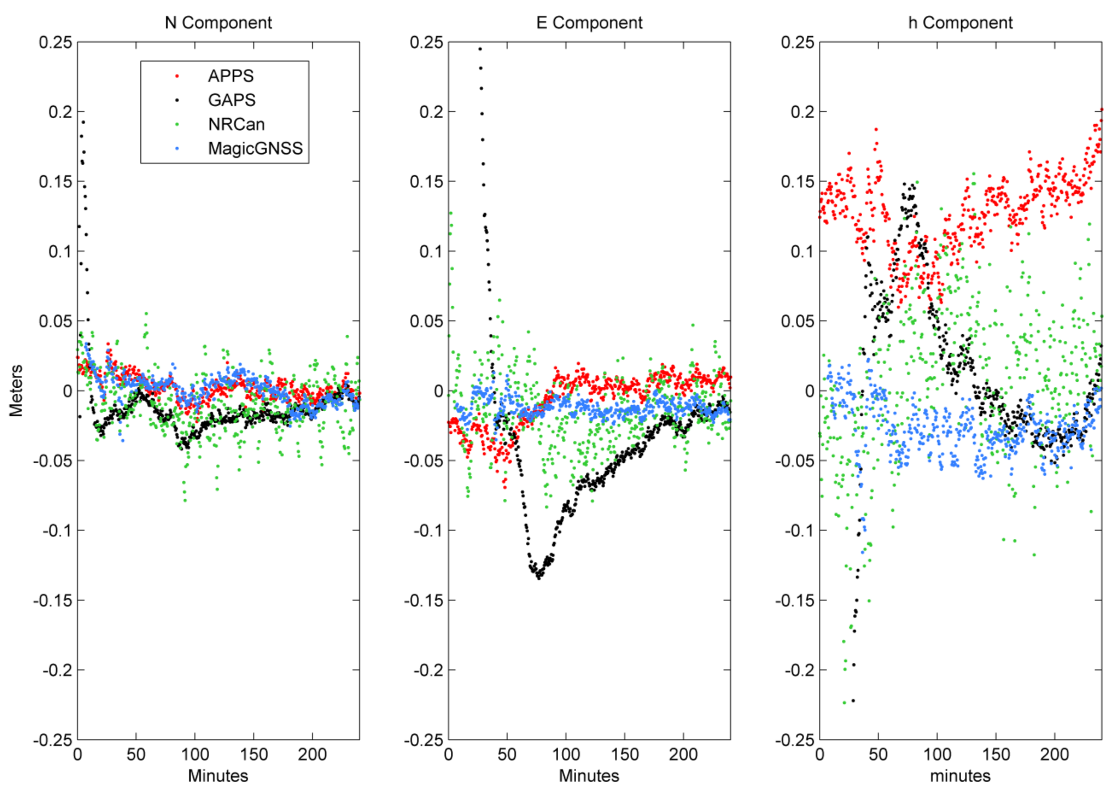

Figure 5c. Kinematic PPP bias for the REUN site. Day 347 of the year 2010.

Table 2. Mean σ for the coordinate computation of the IGS permanent sites. The values are presented in metres.

Software	N	E	Up
APPS	0.013	0.013	0.013
GAPS	0.059	0.059	0.125
NRCan	0.029	0.026	0.061
MagicGNSS	0.026	0.022	0.064

Table 3. The mean RMS post-fit for the code and phase residuals of the IGS permanent sites. The values are presented in metres.

Software	Code	Phase
APPS	0.853	0.005
GAPS	0.861	0.011
NRCan	0.682	0.011
MagicGNSS	0.267	0.004

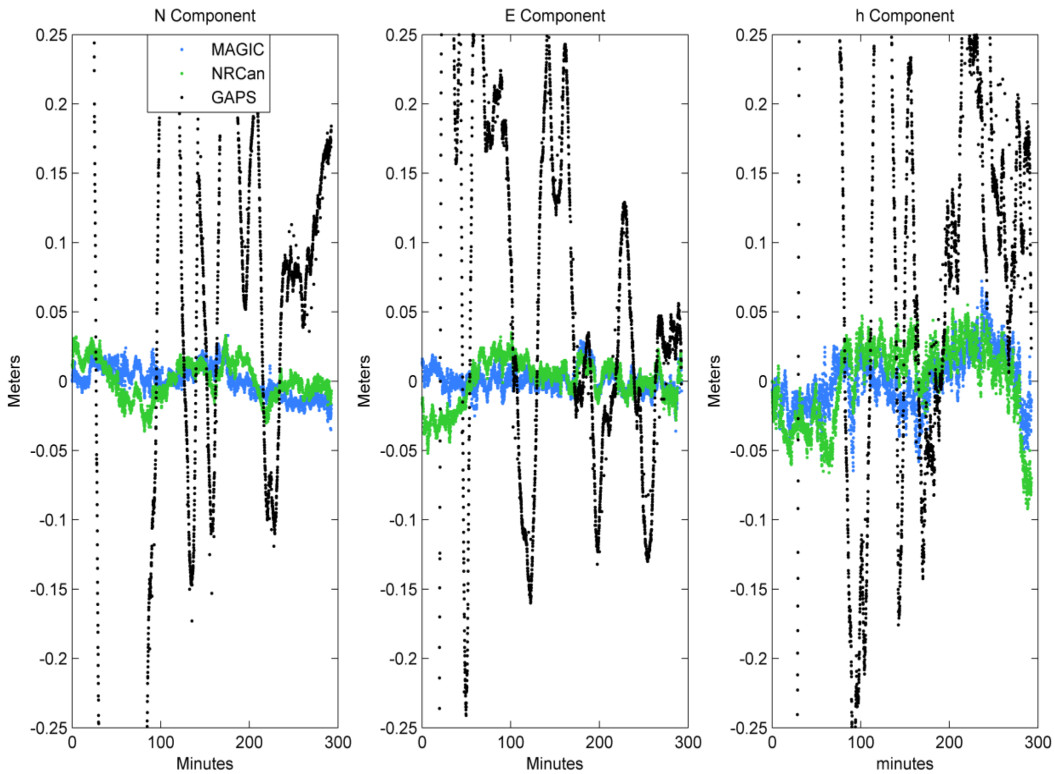

Figure 6a. Kinematic PPP bias for flight 185.

measurements for flight 185. Because of this and because there are no results for 75% of the raw data for flight 219, we decided not to include these results in our analysis. Table 5 lists the mean standard deviations obtained in computing the PPP coordinates and Table 6 present the mean RMS post-fit for the code and phase residuals.

Car trajectory

Figure 7 show the bias for the car trajectory. Table 7 presents the bias statistics, indicating the standard deviation and range produced using the GAPS, NRCan and MagicGNSS software. Because the APPS mean bias is more than 200 m for the planimetric measurements

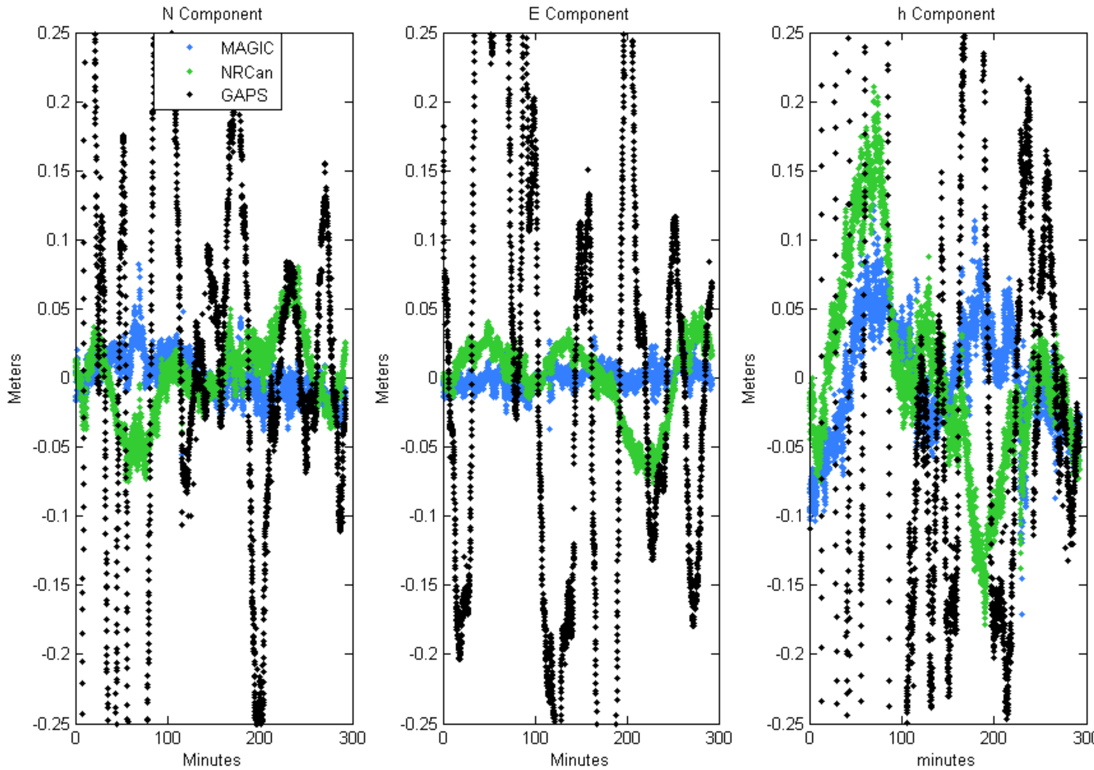

Figure 6b. Kinematic PPP bias for flight 219.

Table 4a. The mean Kinematic PPP bias for flight 185. The values are presented in metres.

Software	N		E		Up	
	σ	range	σ	range	σ	range
GAPS	0.337	2.368	0.477	2.827	0.989	8.389
NRCan	0.015	0.087	0.013	0.069	0.029	0.147
MagicGNSS	0.008	0.065	0.011	0.068	0.021	0.137

Table 4b. The mean kinematic PPP bias for flight 195. The values are presented in metres.

Software	N		E		Up	
	σ	range	σ	range	σ	range
GAPS	0.273	2.058	0.243	1.274	0.513	3.527
NRCan	0.028	0.155	0.028	0.127	0.073	0.389
MagicGNSS	0.015	0.137	0.007	0.067	0.041	0.301

and more than 1000 m for the altimetric measurements, we decided not to include these results. The statistics were performed over all the epoch solutions, that is, no filtering was used to remove the PPP results affected by multipath effects, which present a higher bias.

Table 8 lists the mean value of the standard deviations obtained in computing the PPP coordinates, and Table 9 presents the mean RMS post-fit for the code and phase residuals.

Walking trajectory

Because of the very high degree of bias affecting the coordinate comparisons, the APPS results again could not be used. Thus, Figure 8 presents the bias produced using the GAPS, NRCan and MagicGNSS software only. As observed, this is the test that produced the most significant multipath effects and loss of GPS signals; 10% and 30% of the code or phase observations were not

Table 5. The mean σ value for the flights coordinate computation. The values are presented in metres.

Software	N	E	Up
GAPS	0.035	0.039	0.070
NRCan	0.028	0.024	0.059
MagicGNSS	0.019	0.012	0.035

Table 6. The mean RMS post-fit for the code and phase residuals for the flights. The values are presented in metres.

Software	Code	Phase
GAPS	0.681	0.028
NRCan	0.51	0.005
MagicGNSS	0.33	0.005

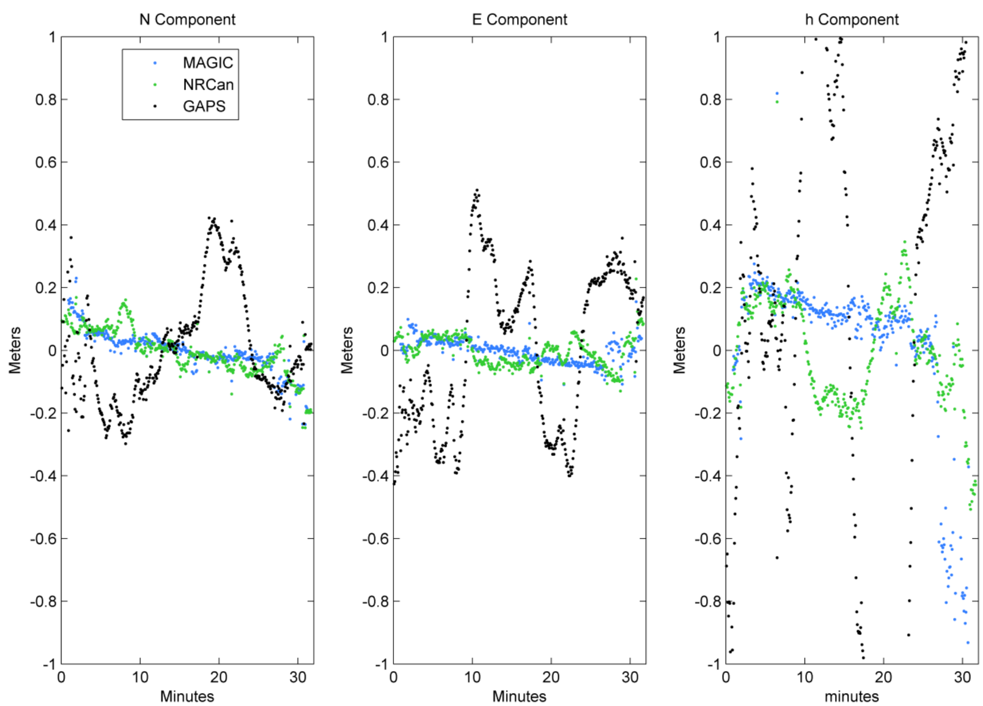

Figure 7. Kinematic PPP bias for the car trajectory.

processed by the NRCan and MagicGNSS software, respectively. Most issues arose in the final part of the trajectory (in exactly the same zone in which the multipath effects occurred in the car trajectory because of building obstructions -NE area in Figures 3 and 4-). For that portion of the trajectory, continuous jumps in the solutions can be found. Table 10 presents the bias statistics, indicating the standard deviation and range obtained using the GAPS, NRCan and MagicGNSS software.

As in the car trajectory, the statistics were performed over all the epoch solutions, that is, no filtering was used to remove the PPP results affected by multipath effects. Table 11 shows the mean value of the standard deviations obtained in computing the PPP coordinates, and Table 12 presents the mean RMS post-fit for the code and phase residuals.

DISCUSSION

The bias statistic result of the kinematic solution at fixed

Table 7. The mean kinematic PPP bias for the car trajectory. The values are presented in metres.

Software	N		E		Up	
	σ	range	σ	range	σ	range
GAPS	0.267	2.182	0.191	1.678	1.002	3.895
NRCan	0.085	1.514	0.095	1.416	0.174	1.299
MagicGNSS	0.082	1.480	0.089	1.366	0.331	2.603

Table 8. The mean σ value for the coordinate computation for the car trajectory. The values are presented in metres.

Software	N	E	Up
GAPS	0.116	0.157	0.408
NRCan	0.033	0.034	0.109
MagicGNSS	0.026	0.024	0.081

Table 9. The mean RMS post-fit for the code and phase residuals for the car trajectory. The values are presented in metres.

Software	Code	Phase
GAPS	1.032	0.016
NRCan	1.06	0.008
MagicGNSS	0.25	0.006

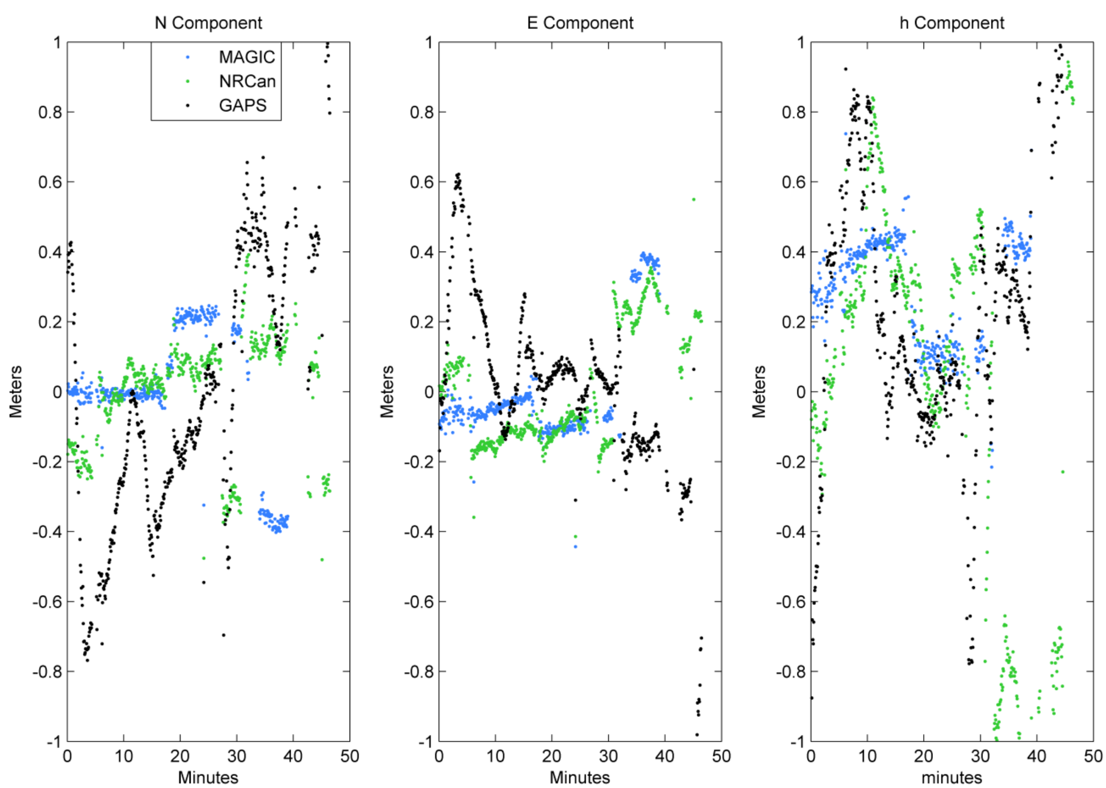

Figure 8. Kinematic PPP bias for the walking trajectory.

Table 10. The mean kinematic PPP bias for the walking trajectory. The values are presented in metres.

Software	N		E		Up	
	σ	range	σ	range	σ	range
GAPS	0.250	1.195	0.180	0.932	0.365	2.325
NRCan	0.106	0.685	0.079	0.548	0.255	1.705
MagicGNSS	0.105	0.57	0.044	0.487	0.156	1.431

Table 11. The mean σ value for the coordinate computation for the walking trajectory. The values are presented in metres.

Software	N	E	Up
GAPS	0.261	0.211	0.462
NRCan	0.087	0.079	0.161
MagicGNSS	0.023	0.020	0.067

Table 12. The mean RMS post-fit for the code and phase residuals for the walking trajectory. The values are presented in metres.

Software	Code	Phase
GAPS	1.495	0.014
NRCan	1.620	0.007
MagicGNSS	0.390	0.006

sites and the mean standard deviation obtained in computing the PPP coordinates according to Tables 1 and 2, respectively, indicate that the APPS software performs the best, followed by the MagicGNSS software. The NRCan Software presents small differences with respect to the MagicGNSS software in terms of the bias deviation shown in Table 1, and finally, the GAPS software is less stable than the other software. The best results in the mean RMS post-fit code and phase residuals according to Table 3 are produced by the MagicGNSS software. Finally, it should be noted that only 1, 0, 884 and 194 code or phase observations have not been processed using the APPS, GAPS, NRCan and MagicGNSS software, respectively. Considering all of the solutions at play (the number of satellites ranged from 5 to 9, and the data spanned 4 h on each of the three days at 30 s intervals at the 8 sites), these results are good and indicate the effectiveness of using kinematic PPP processing data from permanent sites, as expected. Therefore, the capabilities of kinematic PPP can be observed in the best possible scenario.

The kinematic solution in a kinematic environment can be analysed only for GAPS, NRCan and MagicGNSS software because of the the bad behaviour of the APPS software in the kinematic environment. Determining the reasons for this very high bias in the results is beyond the scope of this case study.

As shown in Tables 4a and b, the MagicGNSS software presents the best performance with regard to the three components for the airplane trajectories: the standard deviation of the bias is at the centimetric level for the planimetric measurements and is less than 5 cm for the altimetric measurements for the two flights. NRCan produces similar results for flight 185, but its figures for flight 219 are somewhat higher (less that 3 cm for the planimetric measurements and less that 8 cm for the altimetric measurements). For flight 185, the GAPS software produces a mean bias greater than 0.3 and 0.9 m for the planimetric and altimetric measurements, respectively; the corresponding results for flight 219 are greater than 0.2 and 0.5 m, respectively. Finally, Table 5 (mean standard deviations obtained in computing the PPP coordinates) and Table 6 (mean RMS post-fit for the code and phase residuals) indicate that the MagicGNSS software produces superior results, followed by the NRCan software.

The results for the car trajectory indicate the good planimetric bias produced by the NRCan and MagicGNSS software: the standard deviation of the bias is less that 10 cm. The standard deviation of the altimetric

Table 13. Summary of the mean σ of the kinematic PPP bias for the kinematic trajectories. The values are presented in metres.

Software	Flight 185			Flight 195			Car trajectory			Walking trajectory		
	N	E	Up	N	E	Up	N	E	Up	N	E	Up
GAPS	0.337	0.477	0.989	0.273	0.243	0.513	0.267	0.191	1.002	0.250	0.180	0.365
NRCan	0.015	0.013	0.029	0.028	0.028	0.073	0.085	0.095	0.174	0.106	0.079	0.255
MagicGNSS	0.008	0.011	0.021	0.015	0.007	0.041	0.082	0.089	0.331	0.105	0.044	0.156

measurements produced by the NRCan software is less than 20 cm, and the inferior results produced by the MagicGNSS software are a result of the multipath effects that developed in the last part of the test (Figure 7) because of building obstructions on the university campus. Table 8 (mean standard deviations obtained in computing the PPP coordinates) and Table 9 (mean RMS post-fit for the code and phase residuals) indicate that the MagicGNSS performs the best, followed by the NRCan software.

Finally, the results for the walking trajectory show the good performance of the NRCan software and, particularly, the MagicGNSS software; the former produced standard deviations of 10 cm for the planimetric measurements and of 25 cm for the altimetric measurements, whereas the latter produced standard deviations of 10 cm for the planimetric measurements and of 15 cm for the altimetric measurements. Again, Table 11 (mean standard deviations obtained in computing the PPP coordinates) and Table 12 (mean RMS post-fit for the code and phase residuals) indicate that the MagicGNSS software produces superior results, followed by the NRCan software. The walking trajectory produced the most significant multipath effects and the greatest loss of GPS signals, as observed in Figure 8 and Table 12, where the mean RMS post-fit for the code and phase residuals were higher than those of the other tests. If we centre the attention on the results produced by the kinematic environment, which is the usual use for the kinematic mode, the MagicGNSS is the most favourable software in this case study, followed by the NRCan software. Table 13 summarises the standard deviation of the bias for the two flights, the car and the walking trajectory, which will help to explain the above software results. The efficiency of both software packages depends on multipath effects and signal loss: the airplane trajectories present the most favourable results in terms of bias, mean standard deviation in the computing PPP coordinates and mean RMS post-fit residuals, and the results becomes worse in the car and walking trajectories, where signal loss occurs.

Conclusions

This paper presented a case study of kinematic PPP accuracy using different raw data configurations and different on-line post-processing software. The results show that kinematic PPP can achieve an accuracy level better than 10 cm with regard to planimetric measurements and an accuracy level better than 20 cm with regard to the altimetric measurements in any of the proposed tests. The MagicGSS produces the most favourable results, followed by the NRCan software; the APPS software only produces good post-processing results for permanent stations, and the GAPS software produces larger biases than the NRCan and MagicGNSS software in any of the performed tests. The strong dependence of the results on the software is problematic; a difference of 0.5 m can be found for the same epoch when the NRCan and MagicGNSS software results are compared. Obviously, we assume that the NRCan and MagicGNSS software packages use different processes to produce their results, but a difference of 0.5 m appears to be very large. Finally, as has been previously noted by other authors, multipath errors and interruptions in signal tracking significantly influence the accuracy of the kinematic PPP.

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