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Assessment and Testing of GPS Kinematic Surveys using Precise Point Positioning Technique

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Abstract. Precise Point Positioning (PPP) technique, using single GPS receiver, has been used from several years especially in the static applications. Recently, there are many applications that rely on kinematic point positioning where the rover locations is determined using single GPS receiver in addition to the precise GPS satellite orbit and clock corrections that is developed and maintained by International Global Navigation Satellite System Service (IGS). In such environment, the GPS survey discrepancies should be addressed taken into consideration varying system dynamics, modeling algorithms, used software, receiver's types and other factors.

This paper address the accuracy of GPS vehicle trajectory with high frequency data using kinematic point positioning technique and IGS data products. The study involves analyzing the kinematic GPS dual frequency carrier phase and pseudorange measurements utilizing the Real-Time Kinemtic LIB (RTKLIB) software and available data in a post processing mode. The receiver position utilizing point positioning technique has been verified and compared with the post processing relative kinematic trajectory solution. The PPP accuracy results using a low cost receiver were in the level of 10 cm for the horizontal components and 32 cm for the vertical component. The conclusions and further works are also included in the paper.

Key words: GPS kinematic, precise Point positioning**,** IGS precise orbit and clock, RTKLIB, vehicle trajectory

List of Symbols

P_i	the measured pseudorange on L_i (m),
ϕi	the measured carrier phase on Li (m),
ρ	the true geometric range (m),
c	the speed of light,
dt	the receiver clock bias,

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dtrop	the tropospheric delay (m);
f_i	the frequency of Li (m);
Ni	the integer phase ambiguity on Li (cycle);
dm_i	the multipath effect in the measured pseudorange on Li (m);
δmi	the multipath effect in the measured carrier phase on Li (m)
ε	the measurement noise (m).
L_c	ionosphere-free carrier phase biases
"r"	rover,
"b"	base station,
$()^{ij}$	the single-difference between satellites,
$()_{rb}$	the single-difference between receivers,
λ	the carrier wave length,
"B^i_{rb}"	single-difference of carrier-phase ambiguities in cycle.
RTCM	Radio Technical Commission for Maritime Services format.

1. Introduction

Precise Point Positioning (PPP) is a term that related to positioning of a static or moving object using data from only one receiver with precise satellite orbit and clock data [1]. The PPP technique has been gaining more attention in accordance with the continual advancement in obtaining precise satellite orbit data and clock corrections for the GPS satellites that provided by International GNSS Service (IGS) [2]. Intensive research studies were undertaken on static PPP as this mode was the primary task of point positioning technique [3]. The applying of PPP on kinematic mode of operations became an appropriate solution after disabling of clock errors resulting from dithering satellite clocks with a pseudo-random signal, known as Selective Availability, thus enabling the user to obtain accurate interpolated clock estimates at high rates [1]. The kinematic PPP solution, using dual frequency receiver, can provide the user with reliable results over long trajectory distances when compared with differential kinematic solution using two receivers that may suffer from increased and accumulated residuals errors [3].

The PPP single epoch solution is required for many applications such as [1, 3, 4, 5]:

- Remote sensing applications (Photogrammetry, Scanning Radar, Lidar, natural hazard warnings …).
- Marine applications, sparsely regions and isolated areas.
- Geosciences.
- GPS Seismometer.

- GPS Meteorology.
- Precise Orbit Determination of Low Earth Orbit (LEO) Satellite.
- Precise Mobile tracking, vehicular navigation, precise time transfer.

There are many benefits utilizing PPP as follows [4, 6]

- PPP can provide low cost surveys (single receiver instead of more than one),
- PPP can be used anywhere for any mode of operations and not limited with base line length,
- PPP help in understanding of single epoch solution that may improve the modeling of static GPS solution.

PPP can be used in modeling and handling of many GPS errors such as [6]:

- Satellite orbit errors,
- Satellite clock bias,
- Relativistic effects
- Receiver and satellite antenna phase center offsets
- Satellite P1–P2 and P1-C1 differential code biases
- Receiver Differential Code Biases (DCB)
- atmospheric delays (Ionospheric and Tropospheric refraction)
- Phase wind-up
- Solid Earth Tides, Earth orientation parameters and Ocean tide loading.

Table (1) represents a classification of different GNSS observation errors and the various dependency factors that contribute to each error source [7].

Table (1). Summary of GNSS observation error and its dependency factors (after 7)

Error type				
	Receiver	**Satellite**	**Frequency**	**Obs. Type**
Receiver clock error	Yes			
Sat. clock error		Yes		
Relativity	Yes	Yes		
Troposphere	Yes	Yes		
Ionosphere	Yes	Yes	Yes	Different Sign
Multipath	Yes	Yes	Yes	Yes
Rec. antenna offset	Yes		Yes	

Table (1). Continue

Error type				
	Receiver	**Satellite**	**Frequency**	**Obs. Type**
Multipath	Yes	Yes	Yes	Yes
Rec. antenna offset	Yes		Yes	
Sat. antenna offset		Yes	Yes	
Receiver bias	Yes		Yes	Yes
Satellite bias		Yes	Yes	Yes
Windup	Yes	Yes	Yes	Carrier phase only

The testing of kinematic PPP in various environments using specific instrument and software is very essential to validate the PPP kinematic performance. Such studies are required as the antenna mounted on a vehicle may be affected by signal multipath and vehicle dynamics and expected signal obstruction due to surrounding buildings around the vehicle trajectory in urban or suburban areas [3].

In this paper, the kinematic survey measurements was analyzed using both pseudorange and carrier phase data from a single dual frequency and IGS orbit data and satellite clock corrections using Real-Time Kinemtic LIB (RTKLIB) software [8]. The resulting PPP data will be compared with the truth solution that obtained by computing the reference vehicle trajectory using the relative kinematic mode of operation.

2. Point Positioning Functional Model

Using two-frequency receiver, the PPP traditional mathematical model can be written in the form of ionospheric-free code pseudorange and carrier-phases data as [9, 10]:

$$\mathrm{P_{IF}} = \frac{f_1^2.P_1 - f_2^2.P_2}{f_1^2 - f_2^2} = \rho + \mathrm{cdt} + \mathrm{d_{trop}} + \mathrm{dm_{IF}} + \varepsilon\ (\mathrm{P_{IF}}) \tag{1}$$

$$\phi_{\mathrm{IF}} = \frac{f_1^2.\Phi_1 - f_2^2.\phi_2}{f_1^2 - f_2^2} = \rho + \mathrm{cdt} + \mathrm{dtrop} + \tilde{\mathrm{N}} + \delta \mathrm{m_{IF}} + \varepsilon(\phi_{\mathrm{IF}}) \tag{2}$$

$$\tilde{N} = \frac{cf_1^2.N_1 - cf_2^2.N_2}{f_1^2 - f_2^2} \tag{3}$$

where "P_i" is the measured pseudorange on L_i (m); "ϕ_i" is the measured carrier phase on L_i (m); "ρ" is the true geometric range (m); "c" is the speed of light; "dt" is the receiver clock bias; "$dtrop$" is the tropospheric delay (m); "f_i" is the frequency of Li (m); "N_i" is the integer phase ambiguity on L_i (cycle); "dm_i" is the multipath effect in the measured pseudorange on L_i (m); "δm_i" is the multipath effect in the measured carrier phase on L_i (m) and "ε" is the measurement noise (m). In the previous equations, the satellite orbit and clock errors were cancelled as precise orbit and clock information are used. The multipath errors is present in the equations and need to be reduced using a suitable antenna design to reject many of the multipath errors in areas of significant multipath environment as the case in kinematic vehicle positioning trajectory [10]. Other sources of errors such as satellite code biases and the receiver clock biases can be eliminated through prober combination of differential code biases. The antenna phase center offsets and variations can be corrected using absolute antenna calibration procedure [11]. The ionosphere, carrier phase wind up, solid earth tide and ocean tide corrections models can be applied to reduce its effects [12].

The unknown parameters in kinematic positioning are [7, 13]:

- Receiver position (three variables per station)
- The receiver clock bias *dt* (one variable per station),
- the tropospheric delay *dtrop* (one variable per station),
- The ambiguities *N* (one variable per satellite).

Based on the previous equations the state vector can be estimated using Extended Kalman Filter (EKF) to estimate the rover antenna position and the associated single differenced carrier phase ambiguities [7, 14]. The parameters can be handled in two groups: instantaneous parameters and accumulated parameters (e.g., ambiguities). The nature of system dynamics in kinematic mode of operation can be modeled by adding process noise to parameters and can be treated as random walk or first order Gauss Markov to modify the static positioning model [6, 11, 15]. The solution quality will depend mainly on proper estimate of the ionosphere biases "Lc" [1].

The problem of fixing ambiguities is more significant in kinematic mode of operation than that of the static solution. This criterion was investigated before [4] for obtaining kinematic solution of IGS station and found that fixing ambiguities minimize slope effects that appeared due to float solutions. The accuracy of horizontal components was seemed to be affected by satellite geometry while the up component was affected receiver clock error and troposphere errors [4].

Another issue that may affect the PPP solution is the compatibility of the adopted solution with the IGS global solution and conventions. Therefore similarities in IGS station solutions, antenna offsets, IERS (International Earth Rotation Reference) convention, ITRF (International Terrestrial Reference Frame) used version, etc should be adopted [2].

As the PPP kinematic solution will be compared with the relative kinematic data that was collected for RTK (Real Time Kinematic) test, and then the traditional double differencing technique neglecting satellite, receiver and atmospheric errors can be written as [14]:

$$\phi^{ij}_{\mathrm{lrb}} = \rho^{ij}_{rb} + \lambda(\mathrm{B}^{\mathrm{i}}_{\mathrm{rB}} - \mathrm{B}^{\mathrm{j}}_{\mathrm{rb}}) + \varepsilon_{\phi} \tag{4}$$

$$P^{ij}_{\mathrm{lrb}} = \rho^{ij}_{rb} + \varepsilon_{P} \tag{5}$$

Where r refers to rover, *b* means base station, $()^{ij}$ is the single-difference between satellite, $()_{rb}$ refer to single-difference between receivers, λ is the carrier wave length, B^{i}_{rb} is single-difference of carrier-phase ambiguities (cycle).

Many tests were undertaking on kinematic PPP. The accuracy of vehicle survey that was undertaken in Springbank, Alberta was in the level of 10cm using P3 software (developed by the University of Calgary [10]. The accuracy results were in the level of 5 to 6 cm for the horizontal component and 13 to 14 cm for the vertical component as obtained outside Stavanger, Norway [16]. Another study investigated the accuracy of kinematic GPS that obtained by various softwares by comparing the survey results with a reference trajectory obtained by relative kinematic positioning technique. The results were as shown in Table (2) [3]. The analysis showed that the Natural Resource Canada (NRCan) and Magic Global Navigation Satellite System (MagicGNSS) software produce reliable results as the resulting errors were less than 10cm for horizontal component while the vertical component were 17cm and 33 cm using the two mentioned software respectively. The third software, GPS Analysis and Positioning (GAPS) Software , produce less reliable results as presented in Table (2) [3].

Table (2). The mean kinematic PPP bias (σ in meters) for the car trajectory (After 3)

Software	N(m)	E(m)	Up(m)
GAPS	0.267	0.191	1.002
NRCan	0.085	0.095	0.174
MagicGNSS	0.082	0.089	0.331

3. Data Analysis and Results

The analyzed data was for a site located in Nirasaki area, Japan (site at 35º 48′ 42″ N, 138º27′9″E). The test data are based on previously collected data [8]. This data was provided mainly with the RTKLIB software to test the software validity in the RTK environment. The data were collected on 15 may, 2009 utilizing a dual frequency receiver (NovAtel OEM3 with NovAtel GPS-702-GG antenna) as a rover that mounted on a car and the GPS were recorded with an observation interval of 0.05 seconds. The base station was a Virtual Reference Station (VRS) that offers a RTK data corrections in Radio Technical Commission for Maritime Services (RTCM) format and was used to obtain the vehicle trajectory truth in a post processing mode. The number of the available satellites was not less than 4 satellites all over the test and equal to 6 satellites or more in 97.7% of the experiment time. In case of the number of the available GPS satellites is less than4, tracking capabilities of other satellite systems such as GLONASS or GALILEO will be helpful. The stand-alone rover trajectory was computed using the RTKLIB software version 2.4.2 [17] and compared with the truth solution that obtained using the relative kinematic mode of operation of the vehicle trajectory with the base station. The distance between the initial survey station and the rover receiver did not exceed 1.2km. The kinematic solution was considered to be initiated and locked after about 1.2 second. For the PPP solution, the required precise orbits and satellite clock corrections data were downloaded from the IGS site [18]. The solution was based on correcting the measurements for ionosphere, troposphere, earth tide and satellite and receiver antenna errors.

The PPP kinematic rover coordinates in terms of longitude, latitude and ellipsoidal heights were calculated using RTKLIB, and the results were transformed into UTM coordinates using a spread sheet [19] and compared with the computed reference relative kinematic vehicle trajectory. Both vehicle trajectories wither that obtained by PPP and by the relative kinematic solution are represented as shown in Figure (1). Enlarged views of both PPP and relative kinematic solutions are shown in Figure (2) at selected locations.

The position errors are adjusted using the coordinate components average errors to handle the systematic variations between the RTK solutions that were based on instantaneous corrections determined with the VRS station and the PPP solution. Also, last epoch solution was omitted as an erroneous fix appeared similar to that happen in a previous test [20]. The results are shown in Figure (3) and the errors statistics are presented in Table (3). The PPP kinematic solution is characterized by sudden variations that may be due to cycle slips and multipath errors as shown in Figure (3). The positions variations seemed to be high as the vehicle travelled to the south direction when compared with vehicle was heading to the north as shown in Figure (2). The accuracy results were in the level of 10 cm for the horizont1al component and 32 cm for the vertical component as presented in Table (3). These results confirm with the results reviewed in the literature. The results were affected by used software, receiver type and site environment. Besides, the results were affected by unknown antenna offset.

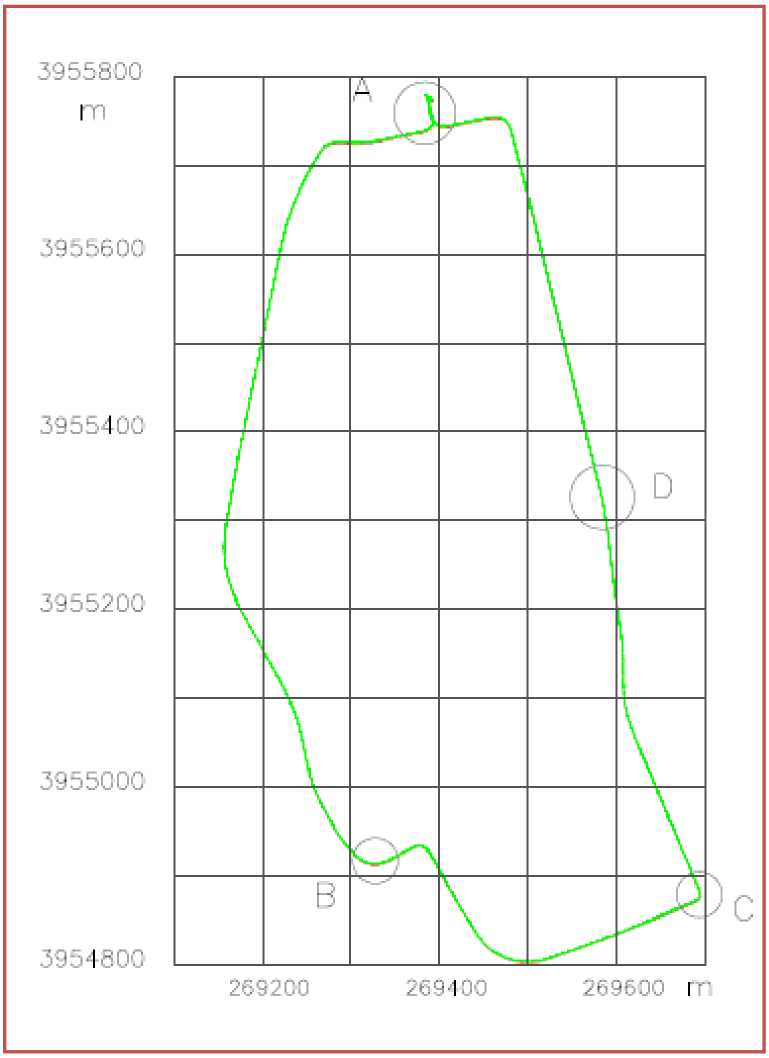

Fig. (1). The vehicle Trajectory obtained by the PPP solution.

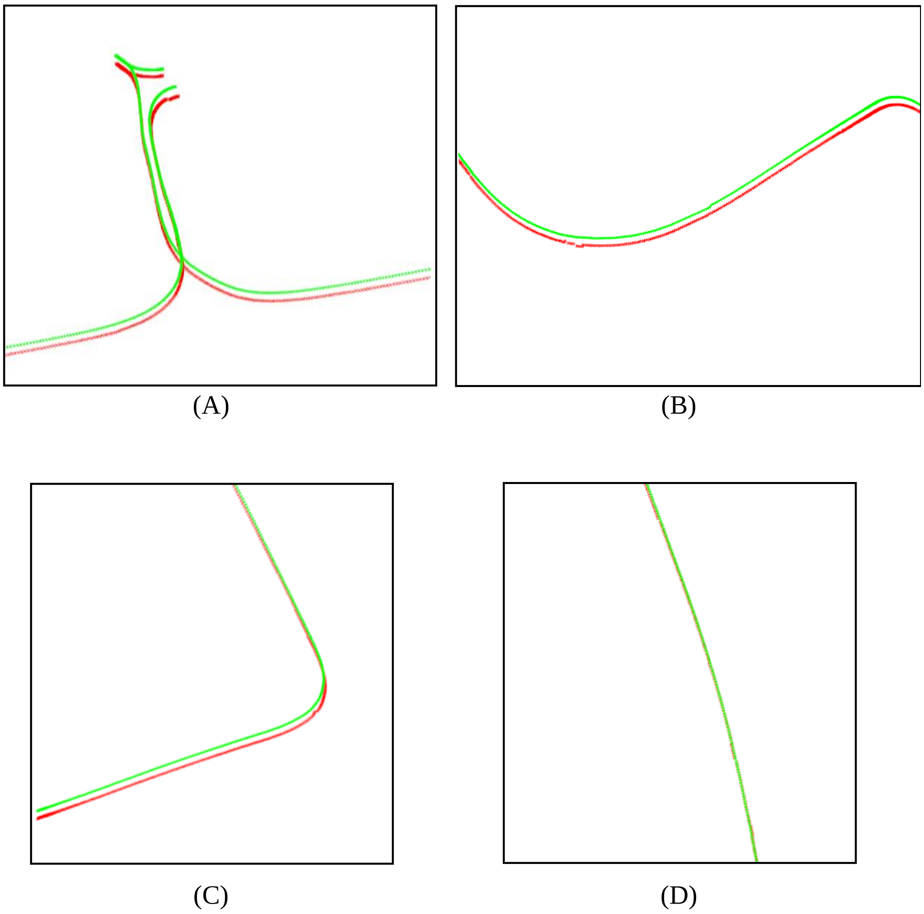

Fig. (2). Enlarged views of both PPP and relative kinematic solutions at selected locations (red : PPP solution , green : relative kinematic solution)

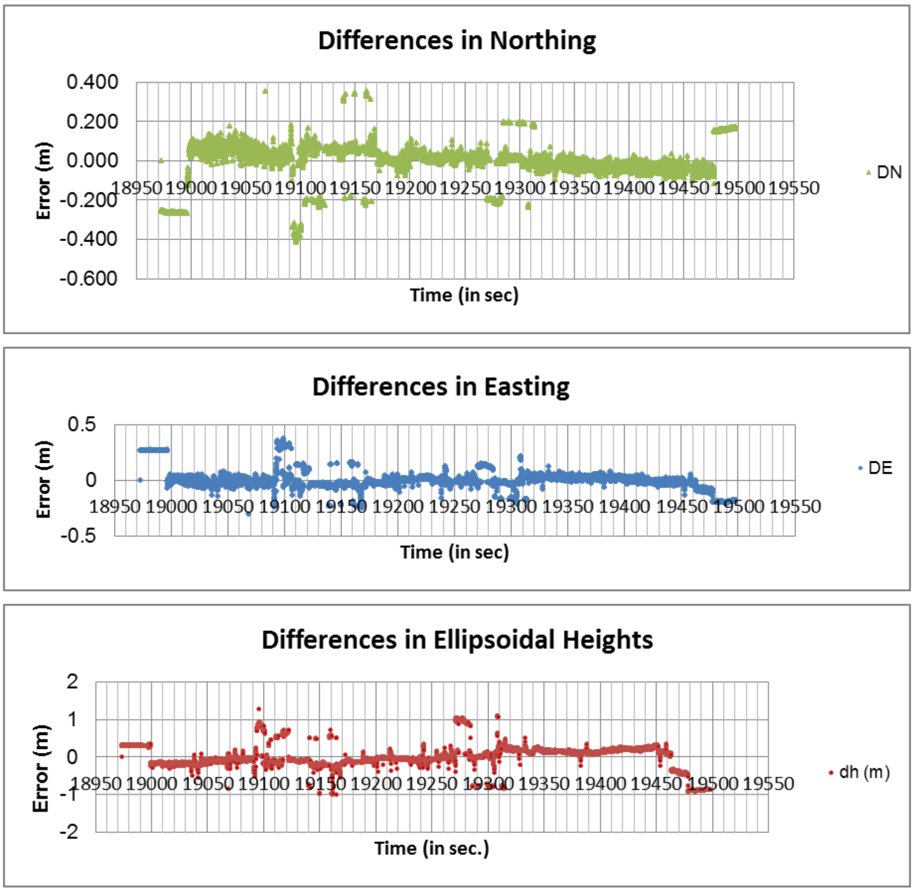

Fig. (3). Difference between Point positioning solution and RTK solutions

Table. (3). Position Accuracy of GPS PPP Kinematic Solution

In meter	DN (m)	DE (m)	DH (m)	3D (m)
Min. error	-0.4138	-0.3100	-1.0057	0.0058
Max. Error	0.3518	0.3745	1.2713	1.3495
STDV	0.0998	0.0903	0.3226	

Another comparison was made using a reference trajectory that estimated using a DGPS solution using the nearest IGS station located at Usuda Deep Space Tracking Station (USUD station at location 36.133116N,138.362049E) that located at a distance about 47km from the vehicle trajectory. Large discrepancies were found between the relative kinematic solution using the VRS corrections and the kinematic relative positioning using the (USUD) station. These discrepancies may be due to the modeling nature of the RTKLIB software that considers the baseline length of the RTK solution is short and the same receiver type was used. Also the differences may be due to the large distance between the (USUD) station and the vehicle trajectory.

While the reference truth data provide a precise relative trajectory solution, the ground truth data should be clear enough to handle the analysis of the PPP kinematic solution. Besides, the data should be ready to be converted to any data format and should be associated with all required information such the antenna type data and the relevant test data.

4. Conclusions and Future Works

The kinematic GPS positioning utilizing the PPP technique using IGS products was addressed in terms of observation equations, GPS error sources, the unknown parameters and fixing ambiguities status. Results from a vehicle trajectory data using RTKLIB software showed that the discrepancies between PPP solution and a truth survey estimated by relative kinematic technique were in the level of 10 cm for the horizontal components and 32 cm for the vertical component. The accuracy results depend mainly on the receiver type, site environment, software used and system dynamics. The adopted methodology ensures handling of the variations of the PPP solution data with the reference data to isolate the systematic variations. Also the adopted approach is used to analyze a low cost dual frequency receiver and the results can be compared with other kinematic surveys that were undertaken using other well known receiver's types and different software.

It is recommended to repeat such tests utilizing a reference trajectory that obtained from relative kinematic technique with a well known base station such as IGS stations using various frequencies combinations (L1, L2 and L5). The ultra-rapid data products should be analyzed to investigate the kinematic solution in real time or near real time status. Also the test should include a receiver with known absolute antenna offset if unknown receiver offset is assumed to be tested. Besides, further analysis for the multipath effects on kinematic positioning should be addressed.

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التقييم الديناميكي والاختبارات للمسح الكينماتيكي باستخدام جي بي اس بتقنية تحديد المواقع المطلق الدقيق

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ملخص البحث. ان تقنية تحديد الموقع المطلق الدقيق (PPP)، باستخدام جهاز استقبال اشارات GPS واحد، قد استخدم منذ عدة سنوات وخاصة في التطبيقات الاستاتيكية. في الوقت الحالي ، فأن الكثير من التطبيقات تعتمد علي تحديد الموقع المطلق الكينماتيكي حيث يتم تحديد موقع الراصد المتحرك باستخدام جهاز واحد بالإضافة الي معلومات مدارات الاقمار الصناعية وتصحيحات الوقت من موقع IGS . وفي مثل هذه الاجواء فأن الاختلافات المتوقعة يجب ان تدرس في ضوء العناصر المختلفة مثل ديناميكية الحركة للراصد، البرنامج المستخدم للحسابات ، نوع جهاز المستقبل ، الخ.

وتتضمن الدراسة تحليل اشارات GPS والمحمول علي عربة متحركة وتشمل قياسات اشباه المسافات والطور الموجي باستخدام موجات ثنائية التردد باستخدام تقنية تحديد الموقع المطلق الدقيق وقياسات IGS وتم استخدام برنامج (RTKLIB) وبيانات التجربة لإجراء معالجة البيانات في مرحلة لاحقة للقياسات. وقد تم ايجاد الفروقات بين مواقع الراصد المحسوب بتقنية PPP وايضا المواقع المرجعية المحسوبة بتقنية (Post processing Relative positioning). وقد وجدت دقة تحديد الفروقات في حدود ١٠سم للمركبات الافقية ، ٣٣ سم للمركبة الرأسية باستخدام جهاز المستقبل المذكور . وقد تم ذكر استنتاجات البحث ومقترحات الاعمال المستقبلية.

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