

Real-Time Precise Point Positioning (RT-PPP) for Positioning and Mapping



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Abstract Real-Time Precise Point Positioning (RT-PPP) has started to develop among Global Positioning System (GPS) community due to some reasons, such as reference stations are required, very economical and easy to operate from everywhere. By using a dual-frequency receiver with the support from GPS precise products, RT-PPP has proven to give centimetre to decimeter positioning accuracy. Recently, the position can be obtained in real time using the real-time GPS precise products provided by many national geodetic agencies. Current real-time GPS positioning systems also allow accurate positioning by carrier phase-based double differencing approach. However, the limitation of using the differential approach is the process needs simultaneous data collection from common satellites at the reference station and the rover. Directly, the data acquisition process will become more difficult and this will decrease the suitability of this technique in other potential applications. The aim of this research is to analyse the current performance of RT-PPP technique using Hemisphere Atlas for positioning and mapping. This research also assessed the positioning accuracy between RT-PPP and static GPS techniques. Then, the reliability of RT-PPP for cadastral purposes is also evaluated. Methodologically, RT-PPP used Hemisphere Atlas, which is a dual-frequency receiver for position determination by processing raw pseudorange and carrier

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phase observations with the support from precise GPS orbit and clock information. The results of this research show that the coordinate for both positioning and mapping purposes using Hemisphere Atlas are within centimetre-level accuracy, i.e. below 10 cm for positioning and below 30 cm for cadastral purposes. Therefore, this study anticipates that RT-PPP has the potential to offer better operational flexibility that will guide for the full implementation of this technology particularly in surveying and mapping in the future.

Keywords Precise point positioning · Real time · Positioning and mapping Hemisphere atlas

1 Introduction

Nowadays, accessing accurate real-time satellite ephemeris and clock data has begun to receive increased attention among the scientific users of Global Navigation Satellite System (GNSS). The purpose of this improvement is for encouraging real-time-precise point positioning (PPP) solutions. As a result, all issues and development about IGS real-time infrastructure were handled by the IGS Real-Time Working Group (RTWG) [1]. The main advantage of this achievement is, it enables RT-PPP operations. The concept for RT-PPP is to use a single receiver and process raw code and carrier phase measurements. By applying this method, it proposes a backup plan to double differencing approach which is more precise and straightforward as in [2, 3]. RT-PPP is currently used in plate's movement scientific studies, real-time monitoring such as landslide and natural disasters' early warning systems [4]. Even though RT-PPP does not need reference stations but the user must keep in mind that accurate data of the satellite's orbit (ephemeris) and clocks are always required.

Presently, most of the GPS positioning systems only use carrier phase-based double differencing approaches. We cannot deny that this technique is able to provide high accuracy of positioning in real time, but to get this type of accuracy the differential process requires observation of the same GNSS satellites at the reference station (known precise coordinate) and rover stations. The disadvantages are, it will complicate the data collection process and will reduce the potential of this idea in many other practices. Furthermore, establishing a reference station in an area will always increase the expenses in labour and equipment. Besides, the idea of using the differential Real-Time Kinematic (RTK) solutions are restricted by the distance limitation between the base and rover.

Precise Point Positioning (PPP) processing of undifferenced smoothed pseudo-ranges with fixed precise satellite orbits and clocks has been used by Geodetic Survey Division (GSD) since 1992 [5]. By combining precise IGS satellite clocks at 15 min intervals with 30-s recording information from preferred reference stations with constant atomic clocks, 30-s precise satellite clocks are also produced [6]. These products can give metre-level precision that only will satisfy certain users

and only can be used in certain applications. The researches about PPP by using post-processed precise orbit and clock products have been studied in several papers, e.g. [1, 2, 7, 8]. As for current real-time practices only precise post-processed absolute positioning is implemented with the help of global reference stations network and IGS precise products [9].

The aim of this paper is to analyse the current performance of Real-Time Precise Point Positioning (RT-PPP) technique using Hemisphere Atlas for positioning and mapping. The proper place for conducting this research to analyse the positioning is around Universiti Teknologi Malaysia's (UTM) Johor Bahru Campus, particularly in the helipad. Apart from that, this research work was also used to evaluate the reliability of RT-PPP using Hemisphere Atlas for mapping purposes. So, data observation is conducted on the nearby cadastral lot. With its great potential, RT-PPP can replace or as an improvement to geodesy and existing GPS techniques, especially to the Malaysian survey community since it can give a millimetre to centimetre accuracy [10].

1.1 Principle of Carrier Phase-Based Differential Method

The simple basic concept to GPS data processing is to construct new observables by differencing because this way can eliminate or reduce most of the clock biases and the impact of several other measurement biases. The carrier phase-based differential GPS is capable of achieving higher positioning accuracy. The word 'kinematic' is used when the rover is moving from one location to other location. Commonly, the differential processing approach involves the use of at least one stationary reference receiver and at least one stationary or moving receiver, called a rover.

All information and data from reference receiver are transmitted to the roving receiver via communication links such as ground-based radio. The roving receiver will combine this data to form double difference observables and this will cancel the highly correlated errors. It follows the knowledge where the value of the positional error at the reference receiver is knowable when compared to the known value. This process will compute the 3D position vector from the base receiver to the rover. Therefore, the determined position of the rover is dependent upon the accuracy of the coordinates of the reference station and the accuracy of the computed 3D vector. The visualization of the single and double differencing are shown in Fig. 1.

1.2 Principle of Real-Time Precise Point Positioning (RT-PPP)

Real-time positioning is very complicated when compared with post-processing operation. The most critical problem that must be taken into concern is only a

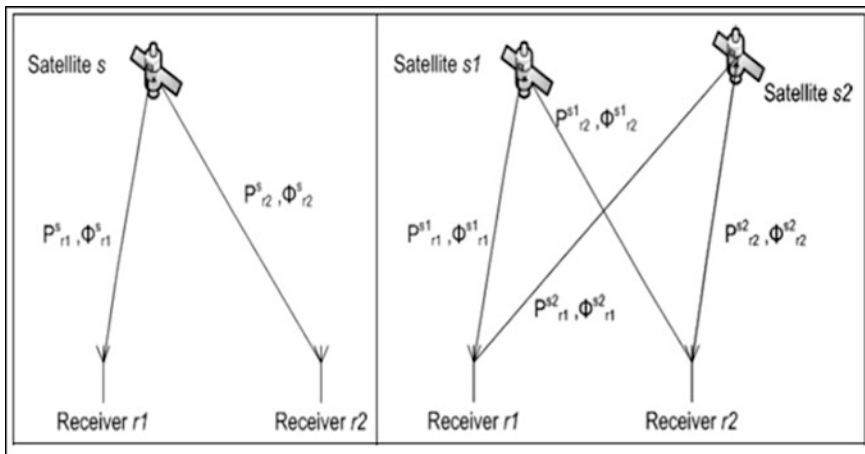


Fig. 1 Visualization of a single (left) and double (right) differencing [11]

wireless communication link is used to transfer the observation data in a short period of time. Generally, the satellite’s position can be determined by using few types of data which are broadcast ephemeris, precise ephemeris and Almanac data [12]. During traditional PPP, only raw pseudorange and carrier phase measurements from the user’s receiver are required.

However, to perform in real time the user’s receiver must have the knowledge of accurate information about the satellite ephemeris and clock corrections. The time delay for the correction to be transferred must be only in few seconds, which is a very short period. On the other hand, the most common disadvantage of traditional absolute positioning by using a single receiver is the need of long convergence time in order to resolve the ambiguity so the positioning given is in centimetre level of accuracy [13].

Recently, with the introduction of a third frequency such as the L5 signal on the GPS constellation and equivalent third frequency on the Galileo constellation, the latency to initialize the ambiguities on a PPP solution has been reduced and now it is comparable to differential positioning techniques [14]. On the other hand, a network of ground reference station facilities is needed to calculate the GPS precise products (satellite’s orbit and clock information). Then, the data analysis process can be done at the master control stations with relevant knowledge and then transmit the correction to users all over the world.

For the past 2 years, the International GNSS Service (IGS) Real-Time Working Group has been investigating the issues associated with real-time CORS infrastructure and data products by running the Pilot Project [15]. During the year 2012, IGS has begun a Real-Time Service (IGS-RTS) for supporting real-time positioning operation. Besides, IGS is also one of the agencies that always provide GPS orbit and clock information in different accuracies and latencies as shown in Table 1.

Table 1 IGS products [16]

Type		Accuracy	Latency	Updates	Sample interval
Broadcast	Orbits	~ 100 cm	Real time	-	daily
	Sat. clocks	~ 5 ns RMS			
		~ 2.5 ns SDev			
Ultra-rapid (predicted half)	Orbits	~ 5 cm	Real time	At 03, 09, 15, 21 UTC	15 min
	Sat. clocks	~ 3 ns RMS			
		~ 1.5 ns SDev			
Ultra-rapid (observed half)	Orbits	~ 3 cm	3–9 h	At 03, 09, 15, 21 UTC	15 min
	Sat. clocks	~ 150 ps RMS			
		~ 50 ps SDev			
Rapid	Orbits	~ 2.5 cm	17– 41 h	At 17 UTC daily	15 min
	Sat. and Stn. clocks	~ 75 ps RMS			5 min
		~ 25 ps SDev			
Final	Orbits	~ 2.5 cm	12– 18 days	Every thursday	15 min
	Sat. and Stn. clocks	~ 75 ps RMS			Sat.: 30 s
		~ 20 ps SDev			Stn.: 5 min

However, several matters must be addressed for the implementation of RT-PPP. The issues that must be taken into consideration are the format of the correction and the mode to transmit the precise orbit and clock information in real time to user’s receiver. The most important condition to encourage the user to use RT-PPP is the real-time PPP algorithms must be implemented inside the GNSS receiver and the proper way to do this is by developing a suitable RTCM standard for receiving and using the GPS precise products for the positioning determination [13].

Even though the “ultra-rapid (predicted)” orbit information by the IGS are available hours in advance to be used by the user in real time, but the predictability of the clock adjustment is really poor. Therefore, to improve the quality of the satellite clock estimation in RT-PPP, the time delay taken in transferring the correction from analysis centre to the user must be shortened. The working concept of RT-PPP using Hemisphere Atlas is illustrated in Fig. 2. The correction transmitted to the user is H10 service level, which can give the position accuracy of 8 and 4 cm of RMS error.

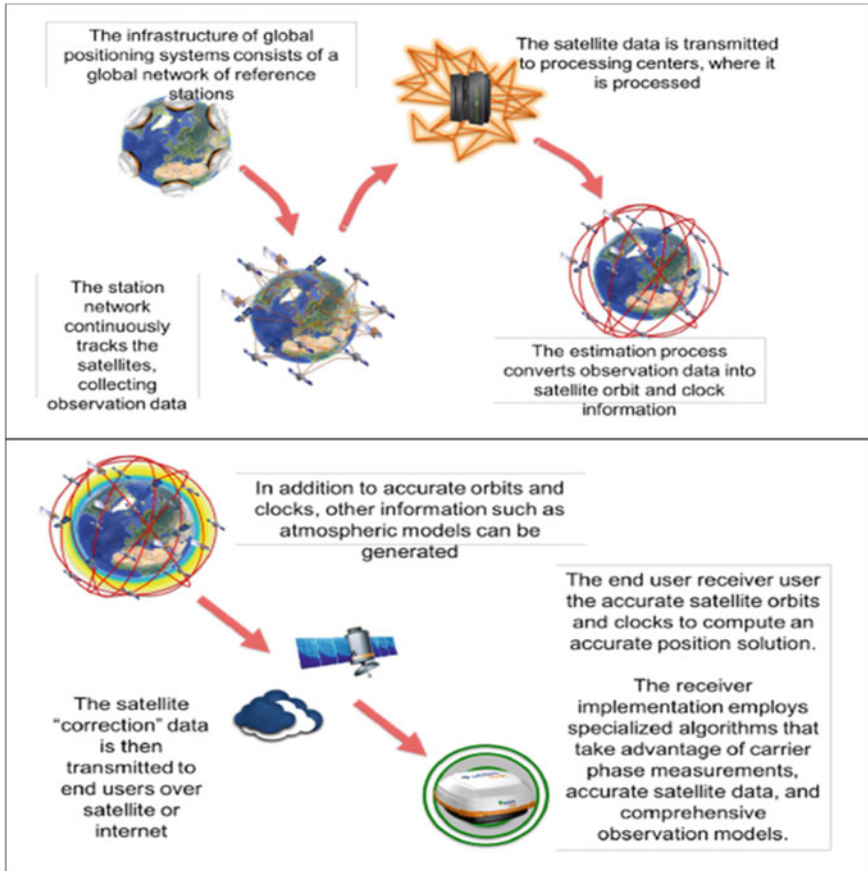


Fig. 2 The global correction services concept of Hemisphere Atlas [17]

2 Research Approach

2.1 Research Area Identification and Data Acquisition

The primary area of interest covers around Universiti Teknologi Malaysia's (UTM) Johor Bahru Campus particularly in the helipad ($1^{\circ} 33' 29.60''N$, $103^{\circ} 38' 13.37''E$) for analysing the positioning. This research is also tested for mapping purposes, so the proper place will be a nearby cadastral lot ($1^{\circ} 29' 59.86''N$, $103^{\circ} 41' 47.03''E$) which is Lot 119,110, Kampung Pasir, Mukim Pulai, Daerah Johor Bahru, Johor. Figure 3 shows the plot of the certified plan (PA 40225) for the study area used for mapping purpose which is in Kampung Pasir.

The coordinate for each boundary stones used in Kampung Pasir cadastral lot is listed in Table 2. All the coordinates are in Cassini–Soldner Geocentric data.

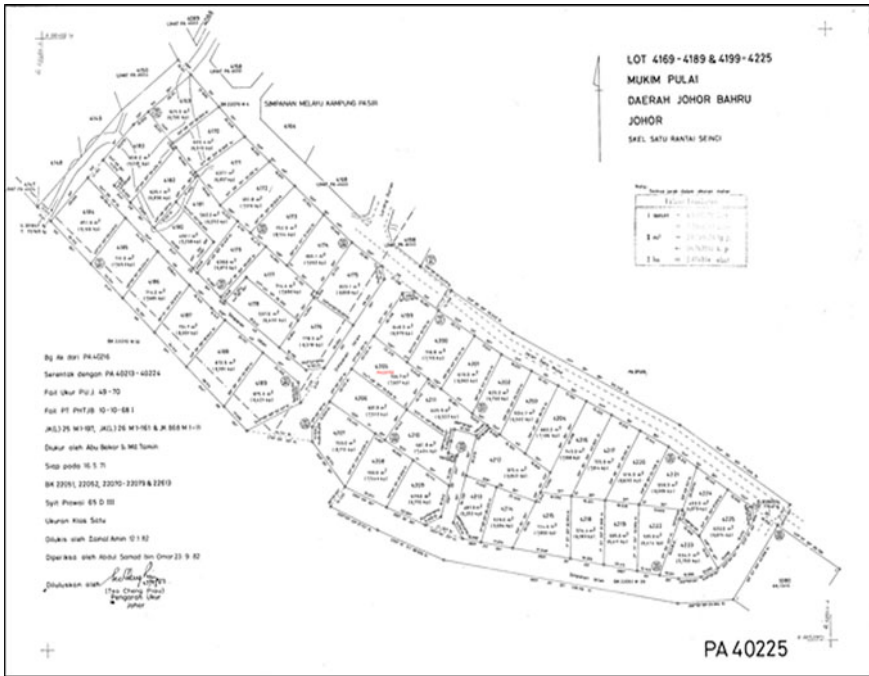


Fig. 3 The certified plan (PA 40225) of study area used for mapping purpose

Table 2 The coordinate of the boundary stones used in Kampung Pasir cadastral lot

Boundary stone	Cassini–Soldner Geocentric Johor	
	Northing (m)	Easting (m)
3	-60,757.255	15,434.181
4	-60,778.149	15,418.435
5	-60,765.888	15,453.547
12	-60,727.827	15,253.414
14	-60,743.953	15,222.431

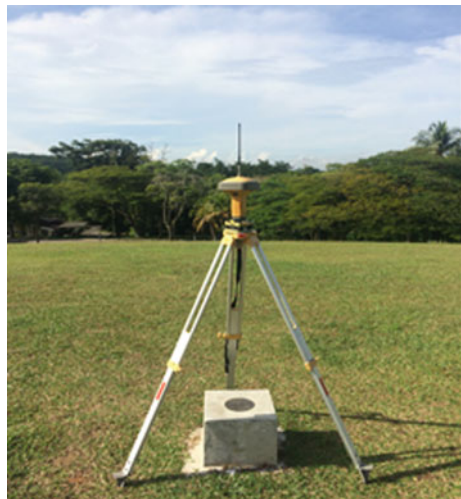
Figure 4 shows the location of the two study areas. The distance between this two study areas is around 9.23 km.

There are two methods used in this positioning data acquisition phase. The first one is by using static GPS technique on the helipad UTM Johor Bahru. The static data is collected for almost 10 h each day for 3 days. Static data is collected for 3 days because to find the differences between the daily solution. The instrument used for this data collection is Topcon GR-5. The coordinate value after the post-processing acted as “ground truth value”. Figure 5 shows the data collection using Topcon GR-5 in UTM helipad. The second method is by using RT-PPP GPS technique. The data is collected in real time by using Hemisphere Atlas instrument.



Fig. 4 The location of UTM helipad ($1^{\circ} 33' 29.60''N$, $103^{\circ} 38' 13.37''E$) and Kampung Pasir ($1^{\circ} 29' 59.86''N$, $103^{\circ} 41' 47.03''E$)

Fig. 5 The data collection for static mode using Topcon GR-5 in UTM helipad



The GPS observation has been made by 15 epochs on the UTM helipad. The observation is done 15 epochs because to get the average coordinate value. The average coordinate value from real time is compared with the coordinate value that acts as the ground truth value from the static GPS technique. Figure 6 shows the data collection using Hemisphere Atlas for positioning purpose in UTM helipad.

Fig. 6 The data collection for RT-PPP mode using Hemisphere Atlas in UTM helipad



The RT-PPP technique is also tested for mapping purpose. So, data observation is conducted for at least 5 boundary stones on the nearby cadastral lot, Kampung Pasir ($1^{\circ} 29' 59.86''N$, $103^{\circ} 41' 47.03''E$). For mapping purpose, three GPS techniques were used which are fast static (at least 30 min) and network-based RTK (Malaysian Real-Time Kinematic GPS Network) technique using Topcon GR-5 and RT-PPP using Hemisphere Atlas. The RT-PPP observation is made 5 epochs for each boundary stone to get an average value. The fast static technique is used for post-processing PPP. Figure 7 shows the data collection using Topcon GR-5 in Kampung Pasir, while Fig. 8 shows the data collection using Hemisphere Atlas in Kampung Pasir. The coordinate values from both techniques are gone through the

Fig. 7 The data collection for static mode using Topcon GR-5 in UTM helipad



Fig. 8 The data collection for RT-PPP mode using Hemisphere Atlas in Kampung Pasir



transformation approach so that the new coordinate value (Geocentric Cassini–Soldner Johor) can be compared with the boundary stones coordinate value. The coordinate value for the boundary stones can be referred in the certified plan of this lot (PA 40225). By comparing these two values, it is easy to evaluate the reliability of RT-PPP for the cadastral purpose.

2.2 Positioning Data and Processing

During this phase, static data that collected on the helipad for 3 days using Topcon GR-5 undergone post-processing mode by using two different approaches which are by using AUSPOS and Waypoint software. The data that collected using Hemisphere Atlas does not need post-processing because it already gives real-time coordinates. AUSPOS is handled by Geoscience Australia and it is used freely for online GPS data processing. AUSPOS can work with any GPS RINEX data with the support from the network of IGS stations and IGS precise products. The coordinate computation is undertaken using the “Bernese 5.2” GNSS software so the reference frame used is International Terrestrial Reference Frame 2008 (ITRF2008) and double differencing approach is used [18]. The reference stations used for the processing for each day are different with one another and at least 10 reference stations are used for the processing. The result which is the average coordinate from 3 days only can be compared with the coordinate that used ITRF2008 in RT-PPP.

The Waypoint software has two functions, which are GrafNav and GrafNet. GrafNav is a post-processing function that can be used for static and moving GNSS processing. Apart from that, it also can be used with several receiver formats and

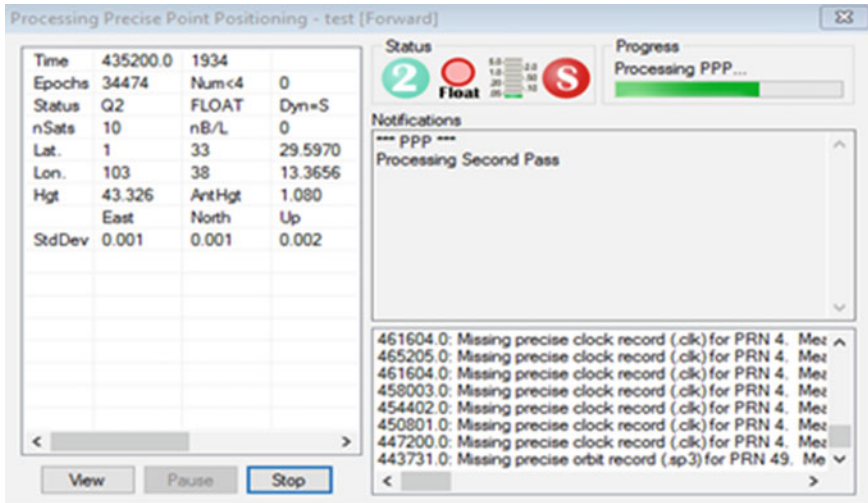


Fig. 9 Waypoint interface

support many types of processing such as PPP and multi-baseline (MB) processing. While GrafNet is largely used for network processing and adjustment. The function that used in Waypoint for this study is GrafNav and the processing method is PPP approach. PPP is an autonomous positioning method, which requires dual-frequency data as well as precise orbit and clock information. Hence, the precise information is downloaded from FTP site cddis.gsfc.nasa.gov. The static data is processed in three different reference frames which are ITRF2000, ITRF2008 and ITRF2014. Figure 9 shows the screenshot of the Waypoint software during the PPP processing.

The coordinate for each different frame is the average value from 3 days of observation. The elevation mask used is 10° and the processing interval is 1 s. Other processing parameters and processing strategies are summarized in Table 3.

2.3 Mapping Data and Processing

As already mentioned in research area identification and data acquisition section, the RT-PPP technique using Hemisphere Atlas is also tested for mapping purpose. So, the data is collected using Hemisphere Atlas in Kampung Pasir does not need any post-processing because the coordinate given is already in real-time Cassini–Soldner Johor state data. Besides, the data collected using Topcon GR-5 by applying the network-based RTK (MyRTKnet) technique also does not need post-processing because the coordinate given is already corrected by double differencing approach and the data used is GDM2000. The data collected using the

Table 3 Parameters and strategies used for Waypoint processing

Processing parameters	Processing strategy
Input data	Daily
Process data type	Automatic
Elevation cut off angle	10°
Sampling rate	1 s
Orbits	IGS final orbits (SP3)
Clocks	IGS final clocks
Reference frame	ITRF2000, ITRF2008, ITRF2014
Ionosphere	Ionospheric free (IF) linear combination (L3)
Troposphere	A priori Saastamoinen model
Tropospheric settings	Spectral density (medium)
L1 lock time cutoff	4 s
Time range (GMT)	Process entire time range
Velocity estimation	Doppler
Measurement standard deviations	Code: 7 m Carrier phase: 0.020 m Doppler: 1 m/s
Measurement usage	Enable GLONASS processing

fast-static technique for all boundary stones have undergone post-processing mode using Waypoint. The processing technique used is PPP and the data used is ITRF2000. The elevation mask used is 10° and the processing interval is 1 s. Other processing parameters and strategies are the same as in Table 3. Another data needed for the mapping verification is coordinate from the certified plan (PA 40225). The coordinate is in Cassini–Soldner Geocentric Johor state, which consists of Northing and Easting.

3 Results and Discussion

3.1 Data Verification for Positioning

During this phase, the real-time coordinate from RT-PPP using Hemisphere Atlas is compared with several post-processing approaches to analyse the performance of RT-PPP on the positioning. The coordinate status for RT-PPP is in fixed status for all the positioning. The post-processing coordinate by using AUSPOS is considered as “ground truth value” or data in order to do the comparison because AUSPOS processing strategy is based on double differencing, also normally known as relative positioning. The strategy of this processing is by determining the baseline vectors between two receivers or more but the main condition is the receivers must be observed simultaneously. The accuracy of the double difference technique depends

on the satellite ephemeris accuracy and the baseline length between the base station and rover [19]. Furthermore, AUSPOS is using scientific software, “Bernese 5.2” as the processing engine which can give a high accurate positioning by applying the double differencing approach.

RT-PPP versus AUSPOS. As for the quality control in AUSPOS, there are two outputs that need to be taken into account. The first one is the list and the amount of IGS stations used and the second one is the percentage of the resolved ambiguity. The list and the amount of the IGS stations needed for each day processing are different with one another. Table 4 shows the list of IGS stations used as a reference during the processing for each day. From Table 4, the number of IGS reference stations used for first-day processing is 11 stations, while second- and third-day processing used 14 stations. Table 5 shows the ambiguity resolution percentage results for 3 days. The ambiguity resolution has shown good results as its average is higher than 70%.

The average positioning after post-processing using AUSPOS is shown in Table 6 and the accuracy statistics is given in Fig. 10. The result shows that the precision of both components (horizontal and vertical) is only in millimetre level between the 3 days. The standard deviations of the coordinate (latitude, longitude, and ellipsoidal height) between 3 different days are almost the same which is consistent during that period.

Table 7 shows the positioning of RT-PPP using Hemisphere Atlas for 15 epochs in UTM helipad. The average value is taken in order to do the comparison. The coordinate is in real time and the data used is ITRF2008. The time taken to get the fixed solution is around 10 min. The surrounding of the helipad is an open area, which is free from obstacles that can cause multipath.

The positioning differences between RT-PPP and double difference solutions using AUSPOS are shown in Table 8. The result indicates that accurate positioning has been obtained in real-time using PPP method which is in centimetre level. The differences between the horizontal components are around 11 cm, which is around 7 cm for latitude and around 11 cm for longitude while for vertical is around 17.5 cm.

RT-PPP versus Waypoint. The position from the RT-PPP is also compared with the result from the Waypoint software by using PPP approach. The software used final orbit and clock information to process the data. Different types of data used in the processing but only result from ITRF2008 data can be compared with the position from the RT-PPP. The coordinate status for all the positioning after

Table 4 The list of IGS reference stations used for each day

	Day 1	Day 2	Day 3
Reference stations	BAKO, COCO, DARW, FOMO, HKNP, HYDE, KARR, LHAZ, PIMO, TCMS, XMIS	BAKO, COAL, COCO, DARW, DSMG, FOMO, HKNP, HYDE, IISC, KARR, LHAZ, PIMO, TCMS, XMIS	BAKO, COAL, COCO, DARW, DSMG, FOMO, HKNP, HYDE, IISC, KARR, LHAZ, PIMO, TCMS, XMIS

Table 5 The percentage of the resolved ambiguity for 3 days

Days	Ambiguity resolved		Average (%)
Day 1	BAKO-XMIS	66.6%	72.3
	HKNP-TCMS	82.6%	
	HKNP-LHAZ	40.0%	
	BAKO-HKNP	25.9%	
	KARR-XMIS	83.4%	
	DARW-KARR	81.8%	
	HKNP-PIMO	76.0%	
	FOMO-HKNP	95.5%	
	BAKO-BASE	74.1%	
	HYDE-LHAZ	87.0%	
COCO-XMIS	82.6%		
Day 2	BAKO-XMIS	60.0%	70.7
	HKNP-TCMS	81.8%	
	HKNP-LHAZ	30.0%	
	COCO-XMIS	95.4%	
	COAL-HKNP	86.4%	
	COAL-DSMG	93.8%	
	BAKO-HKNP	19.2%	
	KARR-XMIS	76.0%	
	DARW-KARR	68.0%	
	HKNP-PIMO	78.3%	
	BAKO-BASE	64.0%	
	DSMG-FOMO	93.8%	
	HYDE-LHAZ	72.7%	
	HYDE-IISC	70.0%	
Day 3	HKNP-HYDE	35.3%	72.5
	BAKO-XMIS	57.1%	
	HKNP-TCMS	85.0%	
	COCO-XMIS	85.7%	
	COAL-HKNP	86.4%	
	COAL-DSMG	95.8%	
	BAKO-HKNP	8.0%	
	KARR-XMIS	85.0%	
	DARW-KARR	85.7%	
	HKNP-PIMO	80.0%	
	BAKO-BASE	62.9%	
	DSMG-FOMO	97.7%	
	HYDE-LHAZ	74.1%	
	HYDE-IISC	76.2%	

Table 6 The average positioning of AUSPOS processing

AUSPOS (ITRF2008)	Latitude	Longitude	Ellipsoidal height
Day 1	+1° 33' 29.59682"	+103° 38' 13.36600"	42.007
Day 2	+1° 33' 29.59685"	+103° 38' 13.36608"	41.993
Day 3	+1° 33' 29.59703"	+103° 38' 13.36603"	42.007
Average	+1° 33' 29.59690"	+103° 38' 13.36604"	42.002

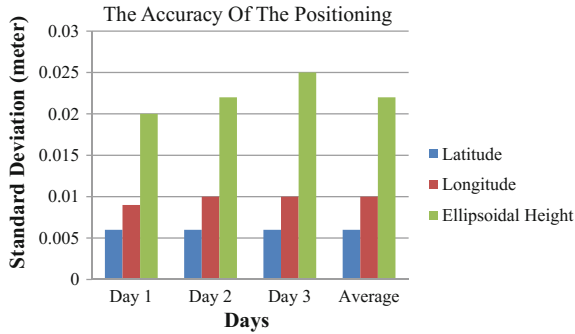


Fig. 10 The accuracy statistics (standard deviation) of the positioning

Table 7 The positioning of RT-PPP using Hemisphere Atlas in ITRF2008 data

No.	Latitude	Longitude	Ellipsoidal height
1	+1° 33' 29.60,140,242"	+103° 38' 13.36163264"	41.7343
2	+1° 33' 29.60115408"	+103° 38' 13.36305742"	41.7406
3	+1° 33' 29.60089396"	+103° 38' 13.36379924"	41.7675
4	+1° 33' 29.59812506"	+103° 38' 13.36562326"	41.8706
5	+1° 33' 29.59709736"	+103° 38' 13.36495736"	41.9275
6	+1° 33' 29.59807062"	+103° 38' 13.36795912"	41.9789
7	+1° 33' 29.59753402"	+103° 38' 13.37043870"	41.9245
8	+1° 33' 29.59722854"	+103° 38' 13.36883296"	41.9015
9	+1° 33' 29.59776478"	+103° 38' 13.36730746"	41.8772
10	+1° 33' 29.59691902"	+103° 38' 13.36502672"	41.8327
11	+1° 33' 29.59660798"	+103° 38' 13.36478150"	41.8175
12	+1° 33' 29.59636030"	+103° 38' 13.36463854"	41.7830
13	+1° 33' 29.59651350"	+103° 38' 13.36543972"	41.8301
14	+1° 33' 29.59652454"	+103° 38' 13.36579574"	41.8501
15	+1° 33' 29.59670158"	+103° 38' 13.36612532"	41.8160
Average	+1° 33' 29.59927"	+103° 38' 13.36569"	41.8270

Table 8 The differences between RT-PPP and AUSPOS positioning

RT-PPP versus AUSPOS	Latitude (m)	Longitude (m)	Ellipsoidal height (m)
Differences	0.0711	-0.0105	-0.1753

processing is a float. The coordinate from ITRF2008 is shown in Table 9 and the accuracy statistics for the position in illustrated in Figs. 11 and 12. The coordinate values for the 3 data are different slightly with one another.

Table 9 The positioning in the ITRF2008 data

Post-process (Waypoint-ITRF2008)	Latitude	Longitude	Ellipsoidal height
Day 1	+1° 33' 29.59712"	+103° 38' 13.36570"	42.239
Day 2	+1° 33' 29.59670"	+103° 38' 13.36670"	42.235
Day 3	+1° 33' 29.59685"	+103° 38' 13.36636"	42.247
Average	+1° 33' 29.59689"	+103° 38' 13.36625"	42.240

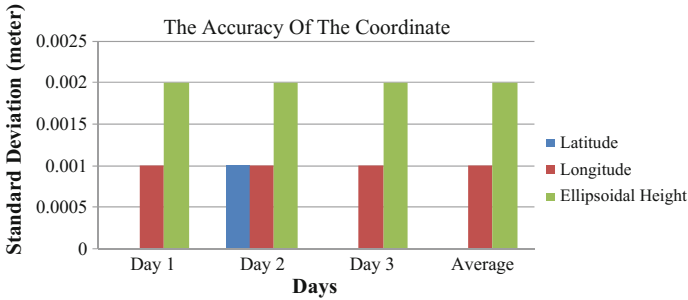


Fig. 11 The accuracy statistics (standard deviation) of the coordinate in the ITRF2008 data

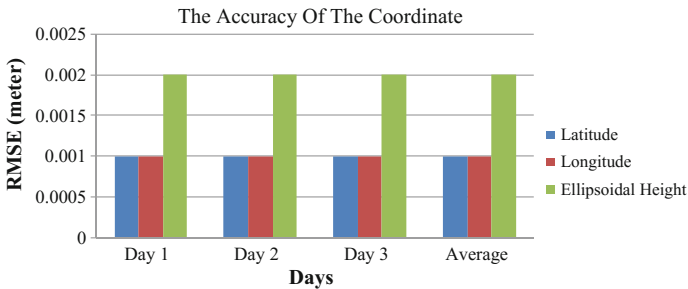


Fig. 12 The accuracy statistics (RMSE) of the coordinate in the ITRF2008 data

Figures 11 and 12 show that the standard deviation and RMS error value for the data is only in millimetre level. It indicates that the precision of the coordinate is having only small differences.

As shown in Table 10, centimetre accurate positioning results have been achieved. The key to achieving this level of accuracy is by using real-time precise orbit and clock products in the RT-PPP. The differences between RT-PPP and Waypoint post-processing is only in centimeter level for both horizontal and vertical. The latitude difference is around 7 cm and for longitude is around 17 cm.

Table 10 The positioning differences between RT-PPP and Waypoint

RT-PPP versus Waypoint	Latitude (<i>m</i>)	Longitude (<i>m</i>)	Ellipsoidal height (<i>m</i>)
Differences	0.0714	-0.0168	-0.4133

Table 11 The positioning in the ITRF2000 data

Post-process (Waypoint-ITRF2000)	Latitude	Longitude	Ellipsoidal height
Day 1	+1° 33' 29.59578"	+103° 38' 13.36570"	42.256
Day 2	+1° 33' 29.59536"	+103° 38' 13.36670"	42.251
Day 3	+1° 33' 29.59550"	+103° 38' 13.36637"	42.263
Average	+1° 33' 29.59550"	+103° 38' 13.36626"	42.257

Table 12 The positioning in the ITRF2014 data

Post-process (Waypoint-ITRF2014)	Latitude	Longitude	Ellipsoidal height
Day 1	+1° 33' 29.59707"	+103° 38' 13.36576"	42.237
Day 2	+1° 33' 29.59664"	+103° 38' 13.36676"	42.232
Day 3	+1° 33' 29.59679"	+103° 38' 13.36642"	42.244
Average	+1° 33' 29.59683"	+103° 38' 13.36631"	42.238

However, the ellipsoidal height for the two approaches is slightly higher than a horizontal component which is 41 cm.

Table 11 shows the coordinate values using ITRF2000 and Table 12 shows the coordinate values using ITRF2014. In order to do the comparison between different reference frames, the average value is taken. Besides, the precision of the positioning for ITRF2000 and ITRF2014 are also in millimetre level.

The differences of the positioning between three different reference frames which are ITRF2000, ITRF2008 and ITRF2014 using Waypoint is illustrated in Table 13. The table indicates that the differences between the horizontal components are only in centimetre level. The biggest differences that can be seen are in latitude component for ITRF2000 which is around 42 cm compared with ITRF2008 and around 40 cm compared with ITRF2014. Besides, the differences for longitude component are only in cm level and the biggest differences are in ITRF2014 which

Table 13 The differences of positioning between three different frames

Post-process (Waypoint)	Latitude	Longitude	Ellipsoidal height
ITRF2000	+1° 33' 29.59550"	+103° 38' 13.36626"	42.257
ITRF2008	+1° 33' 29.59689"	+103° 38' 13.36625"	42.257
ITRF2014	+1° 33' 29.59683"	+103° 38' 13.36631"	42.257

Table 14 The positioning differences between AUSPOS and Waypoint

AUSPOS versus Waypoint	Latitude (m)	Longitude (m)	Ellipsoidal height (m)
Differences	0.0003	-0.0063	-0.2380

is 2 cm compared with ITRF2000 and ITRF2008. As for ellipsoidal height, the value remains constant for three reference frames which are 42.257 m.

AUSPOS versus Waypoint. The results from two post-processing mode are also compared to see the differences. As mentioned earlier in positioning data and processing section, AUSPOS is using double differencing approach, while Waypoint is using the PPP method. So, the positioning from AUSPOS is more accurate than the Waypoint result. The differences are shown in Table 14 which indicates that latitude and longitude differences are only in millimetre level while ellipsoidal height differences are around 23.8 cm. By processing the data with accurate information about the satellite orbit and clock, high accuracy of positioning always can be achieved.

3.2 Data Verification for Mapping

This research is also to analyse the performance of RT-PPP using Hemisphere Atlas on cadastral purpose. The mapping projection used for real-time data collection is Cassini–Soldner Geocentric (Johor) which only consists of Northing and Easting. The coordinate is compared with other results from different techniques to find the differences. The real-time coordinate is collected for 5 boundary stones which are boundary stones 3, 4, 5, 12 and 14. Some of the boundary stone is under the house roof (boundary stone 12) or near to the fence or tree (boundary stones 3 and 4). So, the coordinate is in autonomous or float status. The RT-PPP coordinate for boundary stone 3 is in autonomous, boundary stones 4 and 12 are in float status and boundary stones 5 and 12 are in fixed status.

RT-PPP versus Waypoint. The RT-PPP coordinates that are taken for each boundary stone are shown in Table 15. The coordinate is only in 2D which consists of Northing and Easting. Boundary stones are located in a different location so the

Table 15 The coordinate of the boundary stones using RT-PPP

Boundary stone	Coordinate status	Cassini–Soldner Geocentric (Johor)	
		Northing (m)	Easting (m)
3	Autonomous	-60,757.1983	15,434.3748
4	Float	-60,778.5130	15,418.1127
5	Fixed	-60,766.1231	15,453.3525
12	Float	-60,728.5327	15,251.7930
14	Fixed	-60,744.0074	15,222.7516

Table 16 The coordinate of boundary stones using Waypoint post-processing

Boundary stone	Coordinate status	Waypoint (ITRF2000)	
		Northing (m)	Easting (m)
3	Float	-60,757.470	15,434.650
4	Float	-60,778.369	15,418.773
5	Float	-60,766.095	15,454.015
12	Float	-60,728.241	15,254.028
14	Float	-60,744.100	15,223.002

Table 17 The coordinate differences between RT-PPP and Waypoint

Boundary stone	RT-PPP versus Waypoint (m)		RMSD (m)	
	Northing	Easting	Northing	Easting
3	0.272	-0.275	0.144	0.450
4	-0.144	-0.660		
5	-0.028	-0.662		
12	-0.292	-2.235		
14	0.093	-0.250		

real-time coordinate taken are in different status depends on the condition of the location.

The GPS data is also collected in fast-static technique using Topcon GR-5. The data is processed using Waypoint in ITRF2000 data. The ambiguity status for all coordinates is float. The coordinate for each boundary stone is shown in Table 16.

The differences between the RT-PPP and Waypoint coordinate for all the boundary stones are only in centimetre level and the result is illustrated in Table 17. The smallest differences that can be achieved are around 3 cm for Northing on boundary stone 5 and around 25 cm for Easting on boundary stone 14. The coordinate status for both these boundary stones is fixed. The significant difference that can be seen is for Easting coordinate on boundary stone 12 which is around 2 m. The difference is so big because the boundary stone is located under the house roof. Moreover, the coordinate that collected is in float status. The table also shows the value for RMS deviation is around 14 cm for Northing which is smaller compared with Easting that shows around 45 cm. The RMS deviation is only in cm level because the difference for Easting component for boundary stone 12 is excluded for the RMS deviation calculation because of the float status and big differences with RT-PPP coordinate.

RT-PPP versus Network-Based RTK (MyRTKnet). The RT-PPP is also compared with the coordinate from network-based RTK (MyRTKnet), which uses GDM2000 as data. The MyRTKnet coordinate for each boundary stones is taken for 3 epochs so the coordinate given in Table 18 is the average value. The number of epochs for each coordinate is the average from 30 readings. Only one boundary stone gives a float status coordinate which is from boundary stone 12.

Table 18 The average coordinate readings using network-based RTK (MyRTKnet)

Boundary stone	Coordinate status	MyRTKnet (GDM2000)	
		Northing (m)	Easting (m)
3	Fixed	-60,757.317	15,434.258
4	Fixed	-60,778.217	15,418.508
5	Fixed	-60,765.945	15,453.648
12	Float	-60,726.348	15,254.409
14	Fixed	-60,743.942	15,222.455

Table 19 The coordinate differences between the RT-PPP and network-based RTK (MyRTKnet)

Boundary stone	RT-PPP versus MyRTKnet (m)		RMSD (m)	
	Northing	Easting	Northing	Easting
3	0.118	0.117	0.186	0.294
4	-0.296	-0.395		
5	-0.178	-0.295		
12	-2.184	-2.616		
14	-0.066	0.296		

The coordinate differences between the RT-PPP and network-based RTK (MyRTKnet) technique for most of the boundary stones are only in centimetre level and the differences are shown in Table 19. The most significant difference that can be seen for Northing and Easting components are on boundary stone 12 which is around 2 m for each of them. The difference is so big because the boundary stone is located under house roof. Moreover, the coordinate that collected is in float status. The smallest differences that can be achieved are around 7 cm for Northing on boundary stone 14 and around 12 cm for Easting on boundary stone 3. The constant differences for both Northing and Eating are for boundary stone 3 which are around 12 cm. Besides, the result also shows the RMS deviation for both Northing and Easting is below 30 cm. The RMS deviation for Northing is 19 cm which is smaller than Easting that shows around 30 cm. The differences for boundary stone 12 are excluded during the RMS deviation computation due to float solution.

RT-PPP versus Cassini–Soldner Geocentric (Johor). The coordinate for 5 of the boundary stones used are taken from certified plan (PA 40225). All the coordinates for each boundary stones are in Cassini–Soldner Geocentric of Johor state and the coordinate is shown in Table 20.

As can be seen, the differences between the RT-PPP and Cassini–Soldner Geocentric coordinate for most of the boundary stones are only in centimetre level and the differences are shown in Table 21. The big differences between both of them are for boundary 12 which give 71 cm for Northing and 1.6 m for Easting. The difference is so big because the coordinate collected is in float status. The smallest differences that can be achieved are around 6 cm for Northing on boundary

Table 20 The coordinate of each boundary stones from PA 40225

Boundary stone	Cassini–Soldner Geocentric (Johor)	
	Northing (m)	Easting (m)
3	-60,757.255	15,434.181
4	-60,778.149	15,418.435
5	-60,765.888	15,453.547
12	-60,727.827	15,253.414
14	-60,743.953	15,222.431

Table 21 The coordinate differences between RT-PPP and Cassini–Soldner Geocentric (Johor)

Boundary stone	RT-PPP versus Cassini–Soldner Geocentric Johor (m)		RMSD (m)	
	Northing	Easting	Northing	Easting
3	0.057	0.194	0.197	0.238
4	-0.364	-0.322		
5	-0.235	-0.194		
12	-0.706	-1.621		
14	-0.054	0.321		

stone 3 and 14 and around 20 cm for Easting on boundary stone 3 and 5. The table also indicates that the RMS deviation for Northing is around 20 cm and for Easting is 24 cm. The differences on boundary stone 12 for Northing component is around 71 cm and for Easting component is around 1.6 m so the RMS deviation is calculated by excluding the differences.

4 Conclusion

The performance of Real-Time Precise Point Positioning (RT-PPP) has been assessed by using Hemisphere Atlas under different dynamic environments. The results describe that Hemisphere Atlas can achieve centimetre accuracy for positioning by using precise orbit and clock information, which is an alternative way to traditional double differencing positioning. Apart from that, the results also indicate that the Hemisphere Atlas also can be used for mapping purpose because the coordinate accuracy is at centimetre level only. But the accuracy of the coordinate using RT-PPP for both positioning and mapping are influenced by the condition of the surrounding environment.

The results and analysis shown in this research prove the capacity of RT-PPP using Hemisphere Atlas for both positioning and mapping purpose. The main benefit of the RT-PPP approach is there are no differential approaches applied, so the need of local base stations are not required and this method can be used

anywhere on earth such as in urban or rural areas which have sparse GPS network [20]. Besides, this method will give greater operational flexibility in the future because it can reduce the cost of equipment and labours for maintaining the GPS base stations.

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