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EVALUATION OF CODE AND PHASE SOLUTIONS FOR MULTI-REFERENCE BASE STATIONS ON GPS MEASUREMENTS ACCURACY

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Abstract:

The standard scenario of Global Positioning System (GPS) surveying is to use two carrier phase-tracking GPS receivers. The first receiver should be located at a reference station with known coordinates; while the second one is placed at another station whose coordinates need to be determined. The use of two GPS receivers and the relevant software package is costly and time consuming. Hence, it is simply to carry out the conventional Differential Global Positioning System (DGPS) for navigation over a medium scale. The developed approach aimed at providing sufficient accuracy of point coordinates measurements by using a minimum number of reference stations. GPS errors have been modeled and tested over the selected study area. This study compared DGPS against code and phase solutions and discussed pros and cons of single and multi-references on GPS observations. The test results demonstrated that using multi-reference stations are capable of improving the root mean square error (RMS) of the coordinate differences by 11% to 33% in the 3D position accuracy, as opposed for single reference station scenario.

The RMS values can be further improved by 13.5% and 7.94% in plan coordinates and height respectively, when the modeling of atmospheric delay is applied to the differential corrections based on the pseudo-range observations collected from the multi-reference stations. Research outcomes prove that, the multi-reference GPS observations scenario increases performance, efficiency, and flexibility compared to the standard single reference station scenario.

Keywords: Signal Processing, GNSS, Code and Phase solution, PPP, multiple-base Stations.

تقييم حلول الكود والطور في حالة استخدام المحطات الثابتة المرجعية المتعددة على دقة قياسات نظام التموضع العالمي GPS

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الملخص :

يعتبر السيناريو الأمثل لإستخدام نظام تحديد المواقع العالمي (GPS) في القياسات المساحة هو استخدام جهازي استقبال في نفس الوقت لتتبع طور الموجة الحاملة. حيث يحتل جهاز الإستقبال الأول محطة ثابتة مرجعية معلومة الإحداثيات ، بينما يتم وضع جهاز الاستقبال الثاني في المحطة الأخرى المطلوب إيجاد إحداثياتها. ومن ثم فهناك حاجة ضرورية لإستخدام نظام تحديد المواقع العالمي التفاضلي التقليدي (DGPS) للملاحة. يهدف الإسلوب الجديد إلى توفير دقة كافية لقياس إحداثيات النقاط باستخدام أقل عدد ممكن من المحطات الثابتة المرجعية. حيث تم نمذجة وإختبار أخطاء نظام تحديد المواقع العالمي (GPS) في منطقة الدراسة المحددة. قارنت هذه الدراسة نتائج إستخدام DGPS مع حلول الكود والطور وناقشت إيجابيات وسلبيات إستخدام المحطات الثابتة المرجعية الفردية والمتعددة على دقة قياسات GPS. أظهرت نتائج الدراسة أن استخدام المحطات الثابتة المرجعية المتعددة تحسن الخطأ التربيعي المتوسط (RMS) في حساب الإحداثيات بنسبة تتراوح ما بين 11٪ إلى 33٪ في حساب الموضع ثلاثي الأبعاد بالمقارنة بسيناريو إستخدام المحطة الثابتة المرجعية الفردية. كما اثبتت الدراسة أن قيم RMS تحسنت بنسبة 13.5٪ و 7.94٪ في الإحداثيات الأفقية و الرأسية على التوالي وذلك عندما يتم تطبيق نموذج لحساب التأخير بسبب الغلاف الجوي على التصحيحات التفاضلية بناءً على ملاحظات المدى الزائف التي تم جمعها عند إستخدام المحطات الثابتة المرجعية المتعددة. أثبتت نتائج البحث أن سيناريو إستخدام المحطات الثابتة المرجعية المتعددة لأرصاد GPS يزيد من الأداء والكفاءة والمرونة مقارنةً بسيناريو إستخدام محطة ثابتة مرجعية فردية.

1- Introduction:

Global Positioning System (GPS) is a widely used global positioning system, which can be applied to various applications in surveying and navigation. In fact, the accuracy provided by autonomous GPS positioning is not sufficient for geodetic applications (Zarzoura F., 2012). Differential GPS (DGPS) is developed to improve the positioning accuracy for navigation. The basic assumption of the use of DGPS is that GPS error sources, such as orbital errors and atmospheric delay, interconnected substantially.

Theoretically, most GPS errors can be effectively removed or minimized using differential corrections. While the spatial correlation of GPS faults degrades with increasing baseline length, the accuracy of DGPS is primarily dependent on the lengths between the reference and the user stations (Chang C.C., and Lin S.H., 1999).

Wide Area DGPS (WADGPS) concept developed and tested, designed by modeling various GPS errors to reduce space-related errors for DGPS (Kee C., et all, 1991 and Chao C.H., 1996). The benefits of using WADGPS, compared to conventional DGPS, are the reduced number of reference stations, as well as the lower cost associated with operating the system. If the baseline length constraint is the critical factor affecting static or kinematic GPS, then overcoming this limitation through the use of multi-reference receiver techniques can lead to significant improvements in performance. If the "performance improvement" is related to the lower cost of the receiver, the multi-reference receiver network will allow the use of single-frequency GPS receivers instead of the more expensive dual-frequency receivers for static positioning (Chang C.C. and Lin S.H., 1999). However, as a user, implementing data-based GPS positioning technique from multiple reference stations is much more complex than a standard single reference receiver scenario.

Multiple reference station positioning method was first introduced by Raquet J., et al., (1998). The collocation based approach can provide a significant level of improvement over the two single reference station approach to a variety of networks around the world not only in the post-mission phase (Cannon et al., 2001a,b; Fortes et al., 2000a), but also in real-time analysis (Alves et al., 2001). Landau et al., 2002 studied the ability of performing collocation-based multiple reference station positioning; however, results related to this approach did not showed. Zhang, 1999 showed an extension of the previous approach whereby a network of reference stations could predict the effect of the troposphere on a given pair of satellites. An alternative to the collocation-based approach used a simple two-dimensional linear plane model, which could employ three surrounding reference stations (Wanninger L., 1999; Vollath U., et al., 2000).

Multiple reference station positioning is usually described as a three-step process (Odijk D., 2002):

1. Estimate and resolve the ambiguities in the network,
2. Calculate the corrections (error model) for the region, and
3. Transmit the corrections in a receiver-acceptable format.

The estimation and resolution of ambiguities in the network is usually neglected in multiple reference station searches because it can be performed using traditional single reference station methods. There are few publications refer to the modeling of network errors for resolving ambiguities in the network. Wȕbbena et al., (2001a, b) discussed the state space model for estimating ambiguities. This model estimated a variety of parameters including satellite clock, signal delay, satellite orbit, ionospheric delay, tropospheric delay, receiver clock offset, signal delay, multipath, measurement noise, and carrier phase ambiguities. The network ambiguity estimation and resolution performance associated to this model was not discussed.

Alves P.R., (2004) proposed and evaluated two methods of real-time kinematic positioning of the network-dependent carrier phase. These two methods are a correction-based, and a tightly coupled approach. The tightly coupled approach can integrate a reference station with user data in a single solution. Alves P.R., (2004) proved that both methods have better performance compared to the single reference station approach. However, the tightly coupled approach performs slightly better than the correction-based approach in terms of positioning accuracy.

The overall objective of this research is to develop and test a tightly integrated method for multiple reference station positioning. This approach integrates as much information as possible in order to obtain precise positioning of one or more roving receivers in the region of the network.

2- Practical Experiment:

In order to assess the accuracy of using multi-reference base stations on geodesy and survey applications, GPS observations have been collected at nine local reference stations from Egyptian permanent network (EPGN). In this part of EPGN, dual-frequency GPS receivers were used. The network covers an area of approximately 947 km by 484 km in East and North directions. Figure 1 shows the nine GPS stations, while table 1 shows the Cartesian coordinates of these stations. Trimble 5700 and Trimble NETR5 receivers were used to collect the required data. Data related to this study were collected during three days from 12 – 14 October 2019. The base line lengths range from 77 to 1014 km. Measurements were taken by using the static mode. The original data were in receiver independent exchange format with one second sampling rate. An elevation cut-off angle of 13° was used for the collected data. The (SP3) and ionospheric models were imported from IGS.

The processing of this data was achieved by using two methods: The first is based on using (HLWN Station) only as a base station; while, the second method suggests the use of three base stations (HLWN, ARSH and ALAM stations).

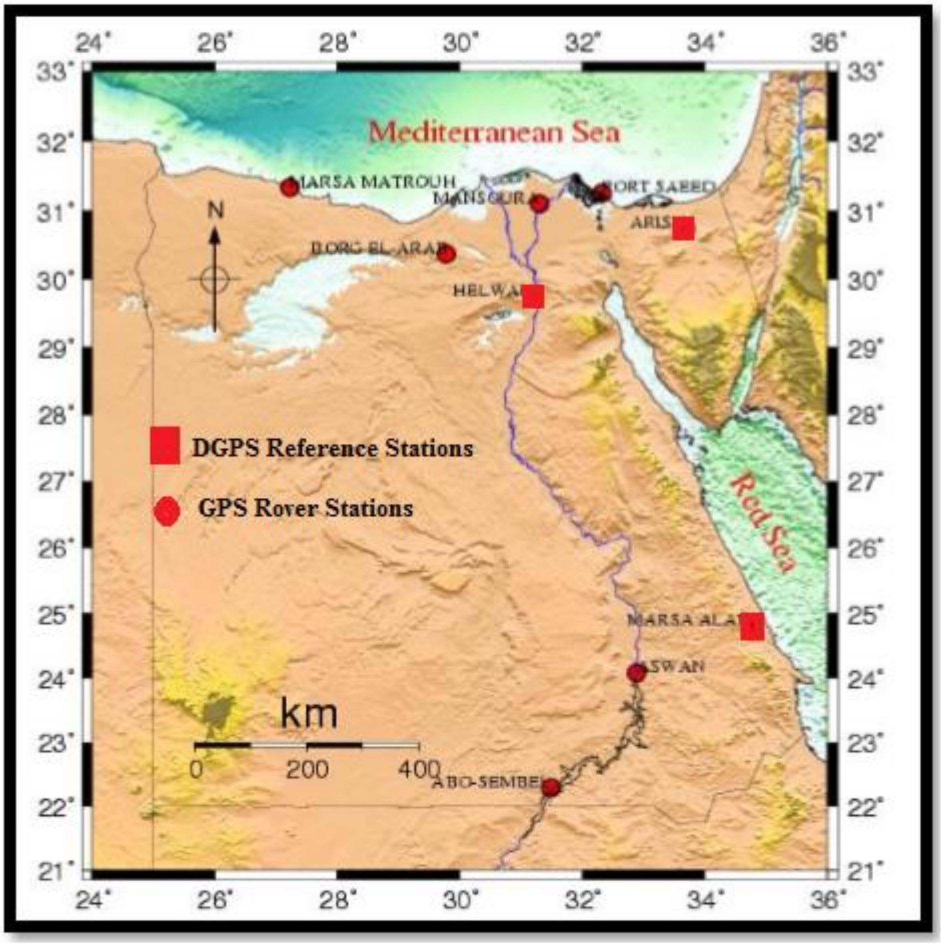

Fig. 1: Location of the used GPS stations.

Table 1: Cartesian coordinates of the GPS sites (Abid M. and Mousa A., 2012).

Stations	Id.	X (m)	Y (m)	Z (m)
Helwan	HLWN	4728141.235	2879662.604	3157147.128
Port Saeed	SAID	4612664.238	2917621.372	3289234.924
Borg Al-Arab	BORG	4765954.319	2704546.167	3252949.162
Al-Arish	ARSH	4551743.574	3026108.353	3276117.453
Aswan	ASWN	4899061.561	3163086.882	2575414.154
Abo-Sembel	ABSM	5024945.154	3084578 .977	2424694 .718
Marsa Alam	ALAM	4742516.385	3305688.980	2685814 .247
Mansoura	MNSR	4671006.228	2845893.571	3269812.079
Marsa Matrouh	MTRH	4847946.893	2494773.302	3298721.224

The atmospheric effects for October 12 to 14 are shown in Table 2. Residual troposphere and orbital errors are 0.1 to 0.16 ppm for all the days and the ionosphere error ranges from 1.4 to 2.2 ppm.

Table 2: RMS error of the L_1 ionosphere, residual troposphere and orbital errors on 12th, 13th and 14th October 2019.

	L_1 Ionosphere	Residual troposphere and Orbit
October 12	1.6 ppm	0.0.16 ppm
October 13	1.4 ppm	0.15 ppm
October 14	2.2 ppm	0.10 ppm

The Bernese V.5 software was used for the analysis of the data. The software is particularly well suited for the rapid processing of small size single and dual frequency surveys, permanent network processing, ambiguity resolution on long baselines, ionosphere and troposphere modeling, clock estimation and time transfer, combination of different receiver types, simulation studies, orbit determination and estimation of Earth rotation parameters and the generation of free network solutions (Chris R., et al., 2000).

3- Results and Discussions:

The basic conventional DGPS is that the data used to obtain the differential corrections are collected and computed at only one reference station, and then the differential corrections are sent to the local user stations in order to improve the positioning accuracy by mainly reducing the error of selective availability (SA). The DGPS network, composed of at least three reference stations, which can be used to obtain one set of differential corrections, computed by the weighted mean of the range corrections from different reference stations. Then this set of differential corrections is provided to the regional user stations to reduce the space-related errors and to effectively expand the working area to a medium scale of range for DGPS. The results and analysis of observations are presented in the following subsections:

3.1- Results based on the type of solution:

To achieve the main objective of the current study, the collected data is processed twice using the Bernese V.5 processing software, according to the previously mentioned procedures. The first run is performed using Code only approach while the second run is carried out using

Code-Phase approach. In each run, the first process utilizes the main default solution, while in the following processes the type of solution is replaced only, with fixing all other processing parameters. The differences between the coordinates of rover stations in each run of Code and Code-Phase solutions in 72 hours and their known coordinates are presented in table (3).

Table 3: Differences of coordinates computed using Code solution and Code-Phase solution, and their known coordinates.

Station	Code solution			Code-Phase solution		
	Δ N, cm	ΔE, cm	ΔH, cm	Δ N, cm	ΔE, cm	ΔH, cm
SAID	21.8	28.2	32.6	1.8	3.2	4.2
BORG	23.4	25.8	30.2	1.4	3.6	5.1
ASWN	32.6	34.6	40.0	2.6	4.2	6.0
ABSM	-52.4	-52.4	-58.2	-2.4	-3.4	-4.2
MNSR	30.6	32.8	37.4	2.4	3.8	5.2
MTRH	-48.2	-46.4	-52.1	-2.2	-2.6	-3.8
Mean value	**1.3**	**3.8**	**5.0**	**0.6**	**1.5**	**2.1**
RMS	**36.72**	**37.93**	**42.96**	**2.17**	**3.56**	**4.80**

Results of table 3 showed that the differences between the code-phase solution values and the known values (as in table 1) lie between -3.4 cm and 4.2 cm in east component with mean value of 1.5 cm and RMS of 3.56 cm, -2.4 cm to 2.6 cm in north component with mean value of 0.6 cm and RMS of 2.17 cm and ranging from -4.2 to 6.0 cm in height component with mean value 2.1 cm and RMS 4.8 cm.

The differences between the code solutions values and the known values are ranging between -52.4 cm and 34.6 cm in east component and from -52.4 cm to 32.6 cm on north component and in height component ranging from -58.2 to 40.0 cm. RMS values in case of Code solutions only arrived to 37.93, 36.72 and 42.96 cm in east, north and height components, respectively.

The accuracy of the code solution is greatly degraded due to GPS biases compared to the phase solution. Moreover, the code-phase solution is the most available system, which represents the adopted value for studying the accuracy of the solution. For these reasons, the code-phase solution is considered as the only reference for the GPS's solution in the current study.

3.2- Results based on single and multi-reference stations:

Instead of using single reference station, the DGPS network, consisting of three reference stations, was also tested for the medium-range DGPS. When using multi-reference stations; final differential corrections were calculated for each satellite with band corrections received from three different reference stations. In order to realize the accuracy of DGPS, improved by using multi-reference stations, the results tested for the user stations were included in Table 4.

Table 4: RMS positioning errors for single and multiple reference stations measurements.

Day		North (cm)	East (cm)	Height (cm)	3D (cm)
Oct. 12	Single RS	2.2	4.6	5.8	7.7
	Multiple RS	1.7	2.8	4.0	5.2
	Improvement	24 %	40 %	31 %	33 %
Oct. 14	Single RS	2.0	2.8	6.5	7.3
	Multiple RS	1.50	3.0	4.7	5.8
	Improvement	25 %	-6 %	27 %	21 %
Oct. 15	Single RS	1.8	3.4	4.9	6.3
	Multiple RS	1.7	2.1	4.9	5.6
	Improvement	6 %	39 %	1 %	11 %

Table 4 shows that the RMS positioning errors for the north, east, elevation and 3D components. When applying the network corrections, relative to a single baseline approach using the closest network reference station, 11 to 33% of the improvement in 3D position accuracy was obtained. In general, there is improvement in all cases when corrections are applied, but the reduction in RMS errors for 3D position ranges from 0.7 cm to 2.5 cm. The results indicate that the use of a network of reference stations improves the performance of the single baseline approach.

3.3- Results based on applying atmospheric models:

It has been mentioned that the space-related errors, such as the atmospheric delay, are primarily increased with the baseline length between the reference and user stations. In order to investigate the effectiveness of applying atmospheric corrections to the medium-range DGPS network, the results tested by modeling ionospheric and tropospheric delay errors were presented in table 5 and table 6 for horizontal and vertical RMS coordinate differences, respectively.

Table 5: Horizontal RMS coordinates differences for Atmospheric Modeling (cm).

Stations	None	Correction Models applied			
		Ionospheric model		Ionospheric and tropospheric models	
	RMS	RMS	Improvement (%)	RMS	Improvement (%)
SAID	2.5	2.4	4	2.2	12
BORG	3.1	2.9	6.50	2.6	16.13
ASWN	3.7	3.5	5.40	3.3	10.81
ABSM	4.7	4.5	4.26	4.3	8.51
MNSR	3.6	3.3	8.33	3.0	16.67
MTRH	4.5	4.1	8.89	3.8	15.56
Mean value	3.7	3.45	6.23	3.2	13.5

Table 6: Vertical RMS Coordinate Differences for Atmospheric Modeling (cm).

Stations	None	Correction Models applied			
		Ionospheric model		Ionospheric and tropospheric models	
	RMS	RMS	Improvement (%)	RMS	Improvement (%)
SAID	1.9	1.85	2.63	1.7	10.53
BORG	2.0	2.0	0	1.9	5
ASWN	3.0	2.95	1.67	2.8	6.67
ABSM	4.1	3.95	3.66	3.7	9.75
MNSR	2.8	2.75	1.79	2.6	7.14
MTRH	3.5	3.35	4.28	3.2	8.57
Mean value	2.88	2.81	2.34	2.65	7.94

Table (5) and (6) proved that the RMS values can be further improved by modeling atmospheric delay errors, compared with those based on simply using multi-reference stations. When ionospheric delay model is applied to the differential range corrections, the average RMS values of coordinate differences can be reduced by 6.23% and 2.34% in plan coordinates and height, respectively. The average RMS coordinate differences obtained by applying both ionospheric and tropospheric delay models can be totally improved by 13.50% in horizontal coordinates and 7.94% in vertical coordinate. A level of up to 17% in plan coordinates and 11%

in height can be found from RMS coordinate variations implemented by atmospheric delay modeling.

3.4- Results based on base line lengths:

To discuss the relationship between the lengths and accuracies of the results implemented by DGPS, the user stations shown in table 7 are listed with the baseline lengths. The accuracy index shown for the horizontal and vertical components is the RMS values based on the coordinate differences between the DGPS results using single reference station and those pre-defined coordinates..

Table 7: DGPS results using HLWN as the reference station.

Station	Base line length (km)	RMS (cm)	
		Horizontal	Vertical
MNSR	130.760	3.40	3.2
SAID	179.508	4.1	3.5
BORG	203.159	4.8	3.7
ARSH	258.295	4.4	5.0
MTRH	427.243	6.8	4.8
ALAM	635.500	10.2	5.8
ASWN	669.295	10.6	6.2
ABSM	816.437	11.8	7.9

It is also evidence to demonstrate that the positioning accuracy of DGPS using a single reference station is closely related to the baseline lengths between the reference and the user stations. For the lengths between 130 km and 816 km approximately, the variations of RMS coordinate differences are ranging from 3.4 cm to 11.8 cm in plan coordinates and from 3.2 cm to 7.9 cm in height.

More investigation was conducted to realize the relationship between DGPS accuracy and baseline length. Further tests are performed using the ARSH station as a reference station and in another round using ALAM as a reference station. In each round, the coordinates of the other stations are determined and compared with their known coordinates. The results show that different levels of positioning accuracy are appeared if single reference station located at different locations is used in the conventional DGPS. As seen from the case for the user station at BORG, whose baseline lengths are 203 km to HLWN station, 387 km to ARSH station and

827 km to ALAM station, the RMS values are significantly varied from 4.8 cm to 12.3 cm in horizontal coordinate differences and from 3.7 cm to 8.2 cm in vertical coordinate differences, based on different sites of single reference station used for DGPS.

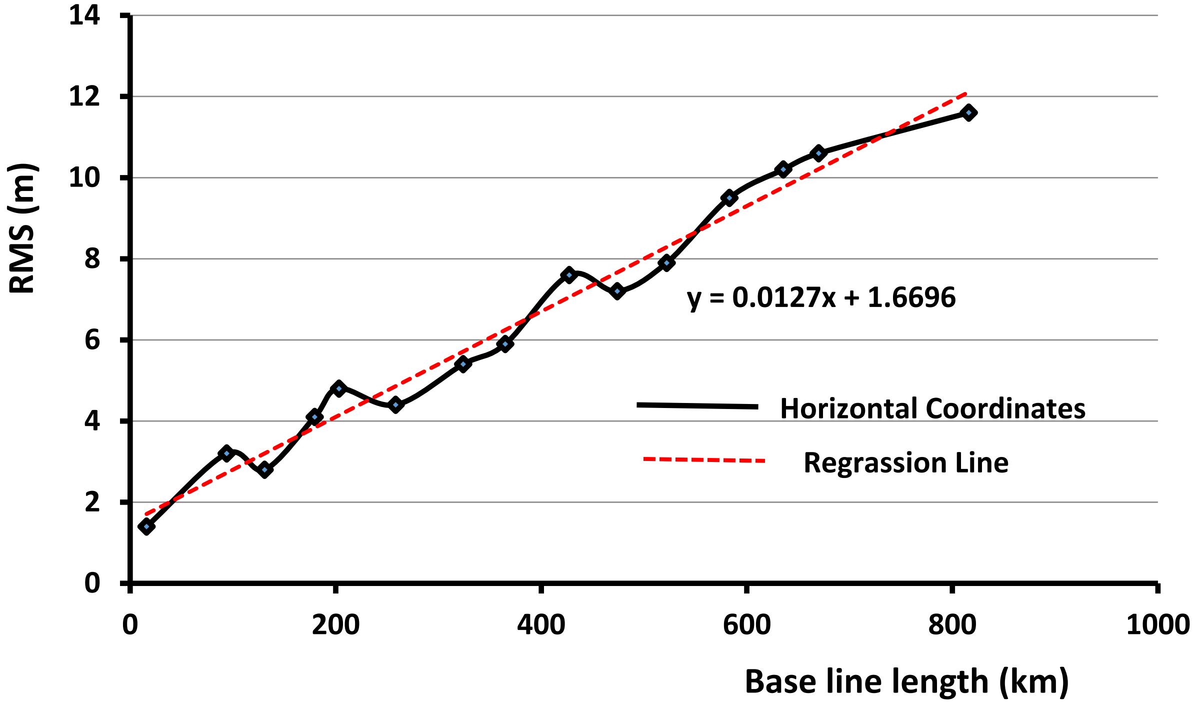

Fig. 2: Relation between horizontal accuracies and baseline lengths.

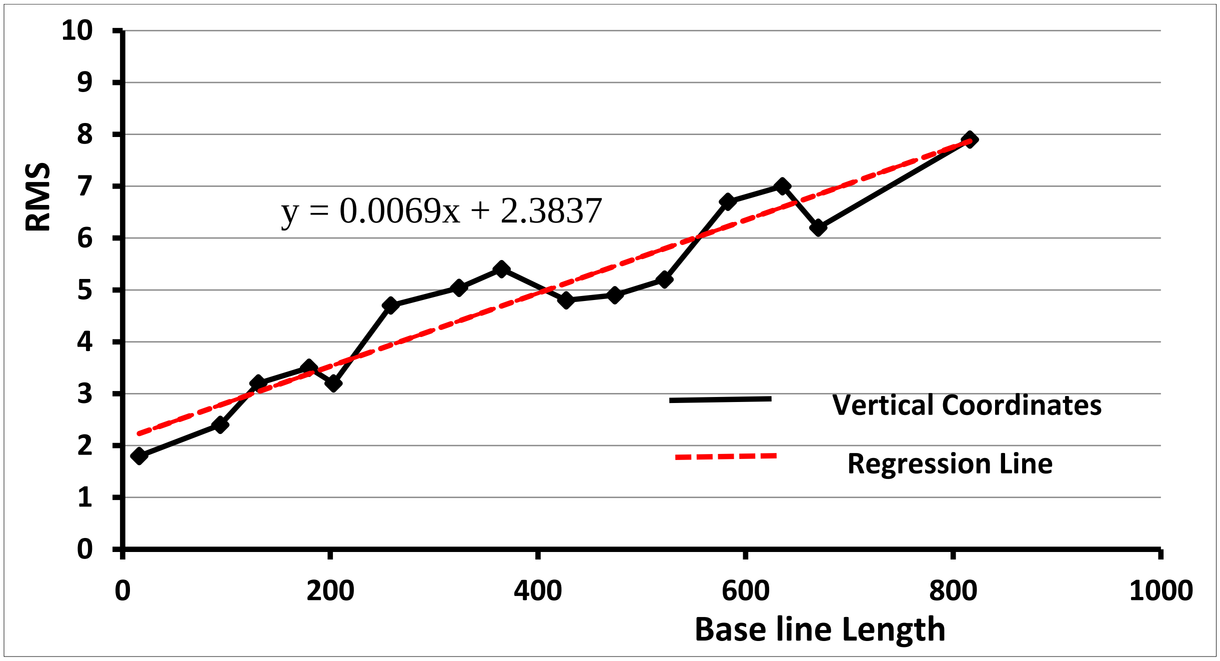

Fig. 3: Relation between vertical accuracies and baseline lengths.

The variations of RMS coordinate differences are plotted with different lengths of baseline, and shown in Figure 2 and Figure 3 for horizontal and vertical coordinates, respectively.

The degree of correlation between the RMS coordinate differences and the baseline lengths was also estimated by using a linear regression model for both horizontal and vertical components. The regression models, tested with the values of RMS in cm and baseline length (***S***) in km, are listed as follows:

Horizontal coordinates	RMS = 1.67 + 0.0127 ***S***	***r*** = 0.962
Vertical coordinates	RMS = 2.38 + 0.0069 ***S***	***r*** = 0.876

The correlation coefficients (*r*) for horizontal and vertical components are greater than 0.7, which means a higher level of correlation between the DGPS accuracy and baseline length. These regression models can also be provided to simply estimate the accuracy of conventional DGPS using single reference station around the Egypt area.

4- Conclusions:

Conclusions can be drawn on the study of the multiple reference stations as follows:

1. The results show that the multi-reference station positioning technique can be used to improve the static and kinematic positioning performance.

2- Our developed approach enhances the accuracy of the 3D position accuracy by 11 to 33%, when the network corrections are applied. The multi-reference GPS observation increased performance, efficiency and flexibility compared to the standard single reference station scenario.

3- The average RMSE in the northern coordinates arrived to 36.72 cm with the use of phase solution only while no more than 2.17 cm with the use of code-phase solution. Moreover, the average RMSE for the eastern coordinates have been improved by almost 90% when a DGPS network composed of three reference stations was used.

4- The effectiveness of applying atmospheric delay to the differential corrections, based on the modeling of ionospheric and tropospheric errors, has been assured by the apparent improvements in both plane coordinates and height by 14% and 6%, respectively. The variations of RMSE in plane coordinates were significantly correlated to the baseline length between the reference and user stations.

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