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Increasing PPP Accuracy Using Permanent Stations Corrections

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Abstract: ***One of the main current problems facing Global Positioning System (GPS) is to get the positions with high accuracy and low cost, effort and time. Two techniques are used in GPS positioning, which are the relative and point positioning. In common, the first technique provides the higher accuracy, but with higher cost and effort. Another kind of point positioning is the Precise Point Positioning (PPP) which counts on GNSS precise products. It is adequate for many applications that requires the decimeter level accuracy using one receiver, but requires scientific software or online services for data processing. The main challenge here is to raise the accuracy of PPP to add other applications suited to the gained accuracy.***

The main objective of the current study is to test different mathematical models producing positional corrections to select the best set depending on synchronized data and validate the selected model in synchronized and non-synchronized cases depending on data of two different campaigns. These corrections -produced from permanent stations- are added to the static PPP coordinates of the tested points near the permanent stations to reach the highest possible accuracy depending on GPS single frequency observations using a scientific package. The obtained results offered a synchronized average positional error reaching to 0.074m and RMSE of 0.023m in the first campaign and 0.146m with RMSE of 0.061m in the second campaign. It reaches 0.156m with RMSE of 0.074m in the best non-synchronized case. The user can raise the accuracy of single frequency static PPP when the data of four synchronized permanent stations are available in the same observational time or within 4 days before or after the observational time.

Index Terms: ***GPS, Non-synchronized, Precise Point Positioning (PPP), Single frequency, Synchronized.***

I. INTRODUCTION

The global positioning system (GPS) is rapidly replacing most of traditional surveying techniques due to the flexibility of the system. GPS works 24hours per day under any weather condition. It does not need visibility between observed points [1]. The main idea of positioning using GPS based on the concept of resection which depends on determining four distances from four different satellites of known locations simultaneously by the receiver located on the unknown point [2]. Receivers differ in their expected accuracy and cost depending on different factors like the type of received observations, hardware stability and the ability to measure more than one satellite positioning constellation, etc. [3]. Two scientific types of GPS receivers are valid. The first can only receive code and carrier observations from L_1 [4], while the second can receive the whole components of GPS signal [5]. The last type (dual frequency) produces more accurate positions than the first (single frequency) due to various reasons. One of them is that the dual-frequency users can easily resolve the ionospheric delay problem, which is still needs to be developed for single-frequency users [6]. Although the advantages of the dual type, the single category has the main advantage of low cost.

GPS observables are the resulting ranges from differences of measured time or phase depending on a comparison among received and generated signals. The two categories of observations are the pseudo-range and the carrier phase [7]. The carrier phase accuracy is higher than the pseudo-range. The obtained accuracy can reach centimeters' level using phase data, and few meters in the pseudo-range case [8]. Despite the low accuracy of code measurements, it has two main advantages over the carrier phase, which are the immunity against cycle slips and the no need of ambiguity resolution [9].

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GPS measurements are affected by different errors, which has a bad impact on the positional accuracy. The two basic categories of errors are the systematic and random errors [10].

Point and relative positioning methods are the two techniques which can be used to determine the location of a ground point [7]. The carrier phase relative technique is the most accurate technique which can reach the millimeter level accuracy. Although the advantage of the relative technique, the point positioning technique has many advantages compared to the relative, one of which decreasing the cost and effort, but still has the disadvantage of lower accuracy.

A special case of point positioning is the Precise Point Positioning (PPP) which is available in post processing using pseudo-range and/or carrier phase measurements, precise orbits and precise clocks which is produced by different GNSS organizations and applying different models to reduce the effect of different errors [11]. It must be noted here that PPP requires on-line PPP services or scientific software for data processing [12] which are innovated by different universities, institutes [13].

In the current research, methodology of investigation is presented, the tested mathematical models are discussed, GPS observations are introduced, description of the campaigns are shown, followed by the analysis of the obtained results supported by the statistical analysis, and ending with the associated conclusions.

II. METHODOLOGY

The main objective of this research is to statistically analyze the discrepancies in the 3D static PPP GPS coordinates (processed by gLAB 2.2.8 scientific package), which are corrected depending on permanent stations with different mathematical models, using 30seconds single frequency GPS data.

The aim of the first campaign is to choose the best mathematical model used to calculate the corrections from the permanent stations after the static PPP post processing, which are observed with the tested points in the same time. The significance of the second campaign is to validate the gained results from the first campaign in different status, and after that to test the chosen mathematical model depending on non-synchronized data.

III. THE TESTED MATHEMATICAL MODELS

Different mathematical models are used to calculate corrections from permanent stations, which are:

- The arithmetic mean model
- The inverse distance model (1st, 2nd and 3rd orders)
- The polynomial model (1st, 2nd and 3rd orders)
- The XYZ solver model
- The EN solver model

The used equations to calculate the corrections using the arithmetic mean model are:

$$DX_i = S DX_J / n \quad (1)$$

$$DY_i = S DY_J / n \quad (2)$$

$$DZ_i = S DZ_J / n \quad (3)$$

Where:

(DX_i, DY_i, DZ_i): The resulting corrections from the used mathematical model for the tested point (i)

(DX_J, DY_J, DZ_J): The difference between the reference and the static PPP solution for the permanent station (J)

n: Number of used permanent stations

The used equations to calculate the corrections using the inverse distance model are:

$$DX_i = S(DX_J / L_{ij}^m) / S(1 / L_{ij}^m) \quad (4)$$

$$DY_i = S(DY_J / L_{ij}^m) / S(1 / L_{ij}^m) \quad (5)$$

$$DZ_i = S(DZ_J / L_{ij}^m) / S(1 / L_{ij}^m) \quad (6)$$

Where:

L_{ij}^m: The distance between the tested point (i) and the permanent station (J) to the power (m)

The used equations to calculate the corrections using the polynomial model are:

$$DX_i = a_1 X_i^m + b_1 X_i^{m-1} + \ldots\ldots c_1 \quad (7)$$

$$DY_i = a_2 Y_i^m + b_2 Y_i^{m-1} + \ldots\ldots c_2 \quad (8)$$

$$DZ_i = a_3 Z_i^m + b_3 Z_i^{m-1} + \ldots\ldots c_3 \quad (9)$$

Where:

($a_1, b_1, c_1, \ldots\ldots, c_3$): The polynomial parameters

(X_i, Y_i, Z_i): The 3D static PPP coordinates of the tested point (i)

The used equations to calculate the corrections using the XYZ solver model are:

$$DX_i = d_1 X_i + e_1 Y_i + f_1 Z_i + g_1 \quad (10)$$

$$DY_i = d_2 X_i + e_2 Y_i + f_2 Z_i + g_2 \quad (11)$$

$$DZ_i = d_3 X_i + e_3 Y_i + f_3 Z_i + g_3 \quad (12)$$

Where:

($d_1, e_1, f_1, \ldots\ldots, g_3$) are the XYZ solver parameters

The used equations to calculate the corrections using the EN solver model are:

$$DX_i = k_1 E_i + l_1 N_i + m_1 \quad (13)$$

$$DY_i = k_2 E_i + l_2 N_i + m_2 \quad (14)$$

$$DZ_i = k_3 E_i + l_3 N_i + m_3 \quad (15)$$

Where:

($k_1, l_1, m_1, \ldots\ldots, m_3$): The EN solver parameters

(E_i, N_i): The 2D UTM static PPP coordinates of the tested point (i)

The discrepancies of the corrected static PPP Cartesian coordinates from permanent stations can be obtained as:

$$dX_i = |X_{Cppp} - X_{TRef}| \quad (16)$$

$$dY_i = |Y_{Cppp} - Y_{TRef}| \quad (17)$$

$$dZ_i = |Z_{Cppp} - Z_{TRef}| \quad (18)$$

$$dP_i = \sqrt{dX_i^2 + dY_i^2 + dZ_i^2} \quad (19)$$

$$RMSE = \sqrt{\frac{\sum V^2}{r-1}} \quad (20)$$

where;

dX_i: X Tested point discrepancy (Absolute value)

dY_i: Y Tested point discrepancy (Absolute value)

dZ_i: Z Tested point discrepancy (Absolute value)

dP_i: The tested point positional error

(X_{Cppp}, Y_{Cppp}, Z_{Cppp}): The tested point static PPP corrected coordinates

(X_{Tref}, Y_{Tref}, Z_{Tref}): The reference coordinates of the tested point

RMSE: The Route Means Square Error with residual (v) and number of samples (r)

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IV. DISCERPTION OF USED OBSERVATIONS

The first campaign (Kalabsha campaign) contains 8 stations (KL14, KL53, KL71, KL73, KL52, KL72, KL11 and KL61) located in Kalabsha region, south of Egypt, west of Nasser lake. These stations were observed simultaneously by National Research Institute of Astronomy and Geophysics (NRIAG) on the 27th January, 2012, from 09:00 to the end of the same day. Distances between stations vary from 1.4km to 5.6km (Fig. 1). These stations -with known coordinates referenced to ITRF 2007- are divided into two groups. The first group stations (KL14, KL53, KL71 and KL73) are treated as permanent stations which produce corrections that will be added to the second group coordinates after the static PPP post processing. The other four stations are the tested stations and treated as unknown points.

Fig. 1. Kalabsha campaign stations

The second campaign (USA campaign) contains 6 stations (P690, P693, P695, P696, P697 and P698) downloaded from the National Geodetic Survey CORS network. These 6 stations are located on Mount St. Helens, Skamania country, Washington, in the pacific northwest region of USA as shown in Fig. 2.

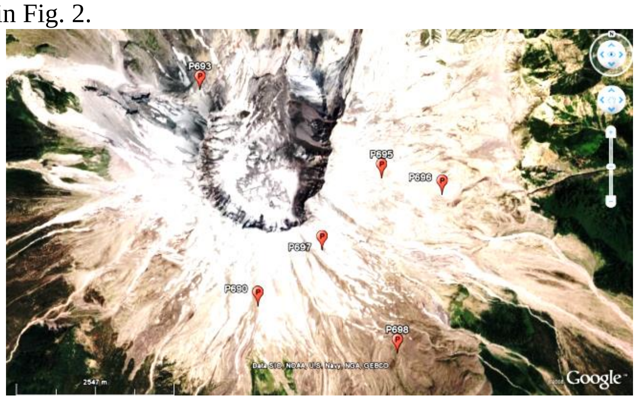

Fig. 2. Second campaign stations

The used data of the second campaign are for the whole days of 1st, 2nd, 3rd, 4th, 5th,6th, 7th, 8th and 9th October, 2015. Distances between stations vary from 1.1km to 5.2km. These stations -referenced to ITRF 2007- are divided into two groups such as the previous campaign. The first group contains (P690, P693, P695 and P696) and the second group stations are (P697 and P698).

V. KALABSHA CAMPAIGN STAGE

The main role of Kalabsha campaign is to select the optimum mathematical model that produces corrections from permanent stations -after the static PPP solution- which will be added to the tested points to enhance their accuracy using the gLAB scientific software. It must be noted here that gLAB package was evaluated for the static PPP processing and its optimum parameters were selected in a previous research [7]. The current campaign data is divided into five sessions, starting at 09:00, 12:00, 15:00, 18:00 and 21:00 respectively. The first step of the Kalabsha campaign is to calculate the static PPP coordinates of the whole stations using the scientific software (gLAB) depending on the selected factors in [7], then calculate the discrepancies of the permanent stations. After that the 3D corrections are calculated from permanent stations depending on the coming mentioned models. These corrections are added to the static PPP coordinates of the tested points and then the discrepancies of the resulting 3D coordinates are obtained. Fig. 3 illustrates the steps of the current campaign to achieve the mentioned goal of Kalabsha campaign.

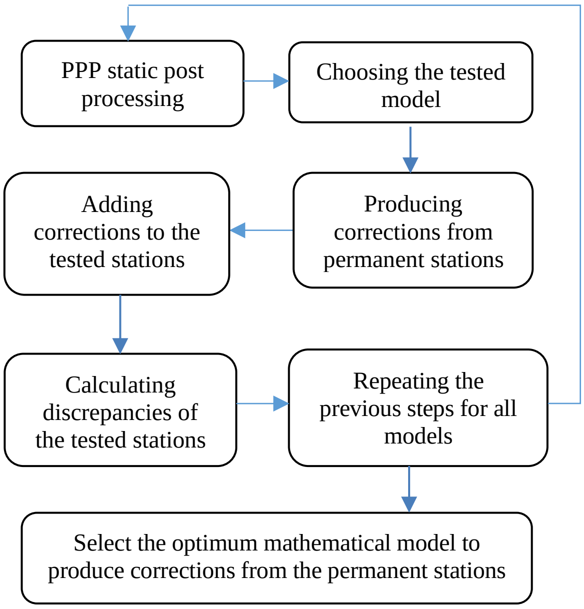

Fig. 3. General steps of Kalabsha campaign

The post processing factors are ESA precise products, UNB-3 and Niell tropospheric model, backward filter solution, solid and wind-up corrections, IGS Ionex correction, 20° mask angle, C/A and L_1 observations for processing, and 3hours session length. Fig. 4 presents the discrepancies of the tested stations resulting from the static PPP post processing.

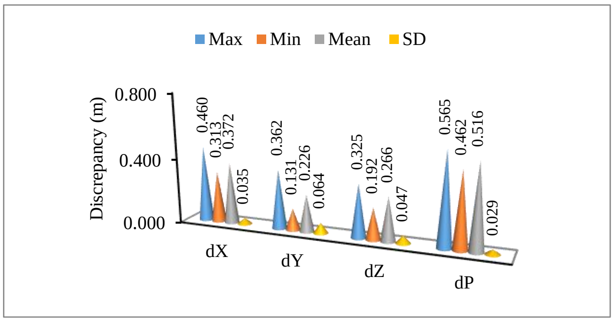

Fig. 4. Discrepancies of Kalabsha tested stations using static PPP post processing

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After the static PPP procedure, the discrepancies of the tested stations using the mentioned models are calculated. Fig. 5 presents the resulted discrepancies from the arithmetic mean mathematical model to calculate the corrections from the permanent stations.

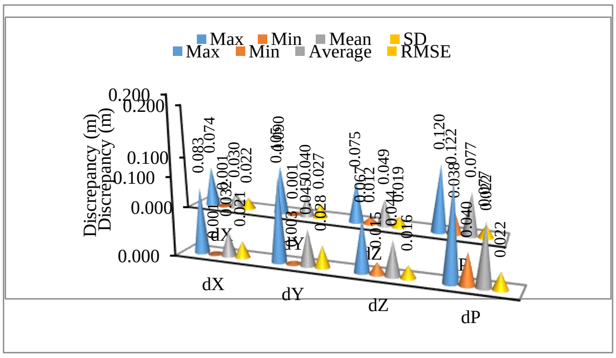

Fig. 5. Tested stations arithmetic mean discrepancies

Referring to Fig.5, the arithmetic mean presents better results with an average positional error of 0.077m and RMSE of 0.022m related to the static PPP solution. Fig. 6, 7 and 8 display the results after using the inverse distance model to three different powers.

Fig. 6. Tested stations inverse distance to the 1st power discrepancies

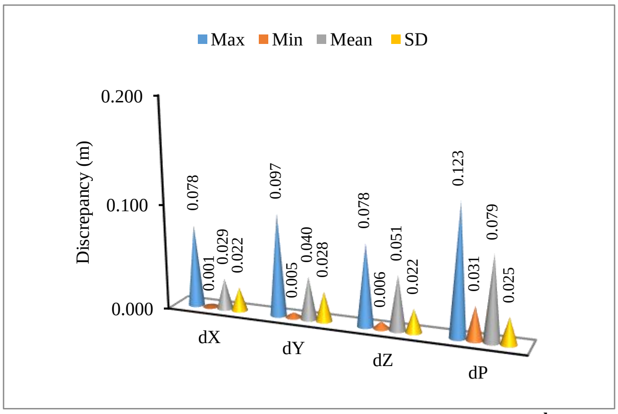

Fig. 7. Tested stations inverse distance to the 2nd power discrepancies

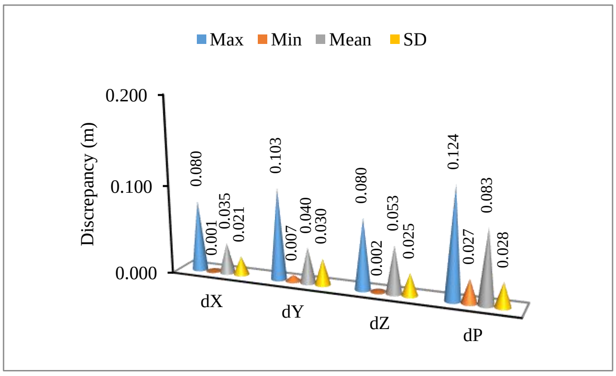

Fig. 8. Tested stations inverse distance to the 3rd power discrepancies

Depending on the three previous figures, the inverse distance gives the optimum results when using the 1st order model. It produces an average positional error of 0.077m and 0.022m RMSE.

The next tested mathematical model is the polynomial using the 1st, 2nd and 3rd orders to calculate the corrections. Fig. 9, 10 and 11 display the discrepancies of the mentioned mathematical models with different orders.

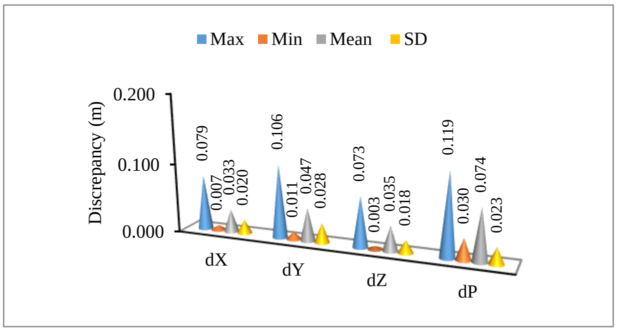

Fig. 9. Tested stations 1st order polynomial discrepancies

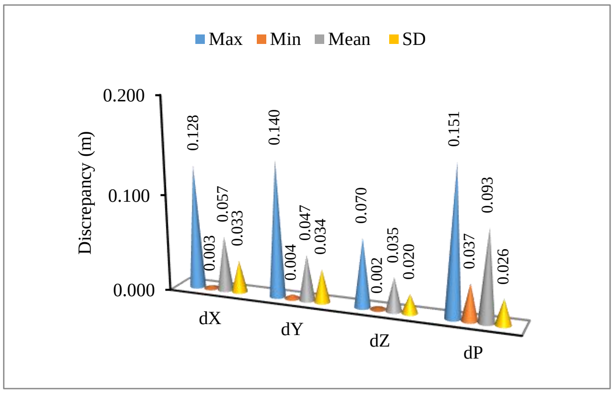

Fig. 10. Tested stations 2nd order polynomial discrepancies

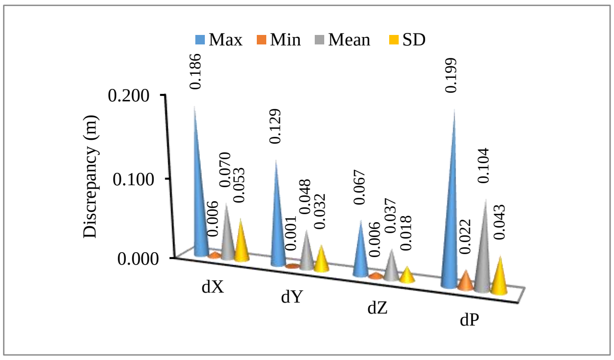

Fig. 11. Tested stations 3rd order polynomial discrepancies

Referring to the three previous figures, the polynomial mathematical model gives the best results when using the 1st order model. In this case, the mentioned model produces the minimum average positional error of 0.074m and 0.023m RMSE. Fig. 12 presents the resulting discrepancies of the tested four stations using the XYZ solver mathematical model.

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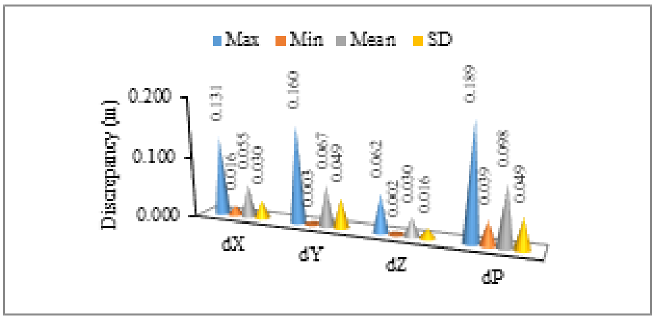

Fig. 12. Tested stations XYZ solver discrepancies

The previous figure shows that the XYZ solver corrections produces better results referring to the static PPP case with an average positional error of 0.098m and 0.049m RMSE. The last tested model in Kalabsha campaign is the EN solver. Fig. 13 mentions the enhancement of results when using the EN solver model for corrections. The current model reduces the average positional error to 0.079m with RMSE of 0.026m.

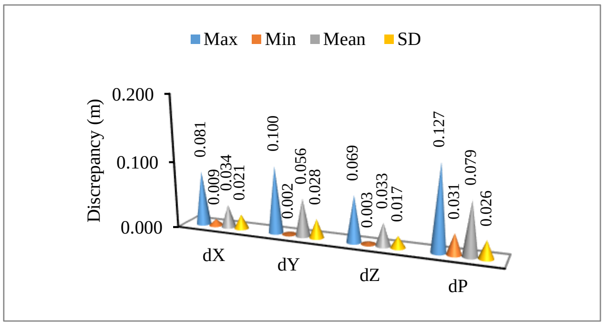

Fig. 13. The EN solver discrepancies

Regarding Kalabsha campaign, it is very clear that the tested mathematical models enhance the resulting discrepancies after adding their corrections. They produce almost similar results, but the 1st order polynomial model is chosen as the optimum with minimum average positional error of 0.074m and RMSE equals 0.023m. Fig. 14 shows the good effect of the synchronized 1st polynomial corrections on the resulting discrepancies when compared to the static PPP post processing case.

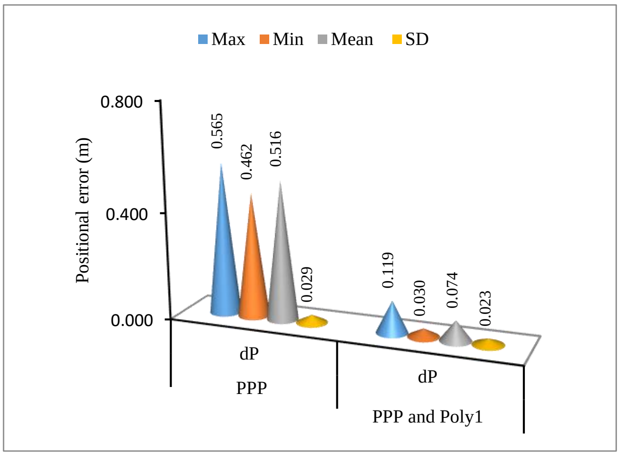

Fig. 14. The effect of the 1st polynomial synchronized corrections on the static PPP solution

VI. USA CAMPAIGN

In order to validate the selected mathematical model in Kalabsha campaign, it is necessary to apply it on the other campaign (USA campaign) in different conditions. The main goal here is to validate the 1st polynomial model, which is selected from Kalabsha campaign as the optimum model to produce corrections from synchronized permanent stations.

The data of the current campaign is divided into 16 sessions with 3hours length for each, in the two days of the 4th and 6th October, 2015. Each day contains 8 sessions. The first session started at 00:00 on the 4th October, 2015 and the last session started at 21:00 on the 6th October, 2015. Fig. 15 presents the discrepancies when using static PPP processing for the mentioned observations using gLAB only.

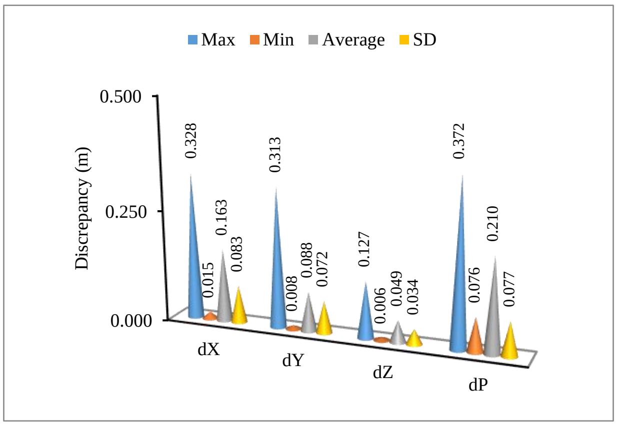

Fig. 15. Discrepancies of USA tested stations using static PPP post processing

Based on Fig. 15, the average positional error reaches the value of 0.210m with RMSE of 0.077m before using the 1st polynomial corrections. Fig. 16 represents the discrepancies when using the 1st polynomial model to produce corrections from the permanent stations.

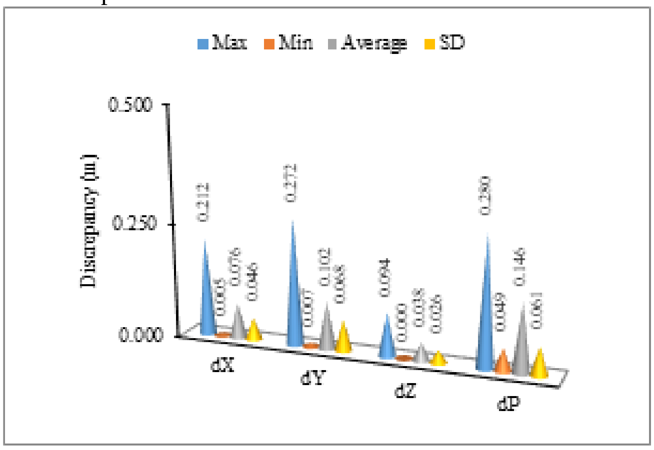

Fig. 16. Tested stations 1st order polynomial discrepancies using USA data

Referring to Fig. 15 and 16, the average positional error is reduced from 0.210m with 0.077m RMSE before using the synchronized 1st polynomial corrections to 0.146m and RMSE of 0.061m after the usage of the mentioned model.

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VII. APPLICATION OF THE SELECTED MODEL USING NON-SYNCHRONIZED DATA

The main goal of the current stage is to test the achievable accuracy that can be obtained when using data of the tested stations which is not synchronized with the data of permanent stations using the mentioned optimum model.

The chosen permanent and tested stations are those of the synchronized USA campaign. The data of the tested points is for the whole days of the 1st, 2nd, 3rd, 4th,6th, 7th, 8th and 9th October, 2015. Each day is divided into 8 sessions with 3hours length. The data of the permanent stations is for the whole day of the 5th October, 2015. This day is divided into 8 sessions with 3hours length too. The corrections are calculated depending on the same 3hours of the tested stations but on the 5th October, 2015 only.

Fig. 17, 18, 19 and 20 show the resulting discrepancies of the tested stations when using the non-synchronized corrections.

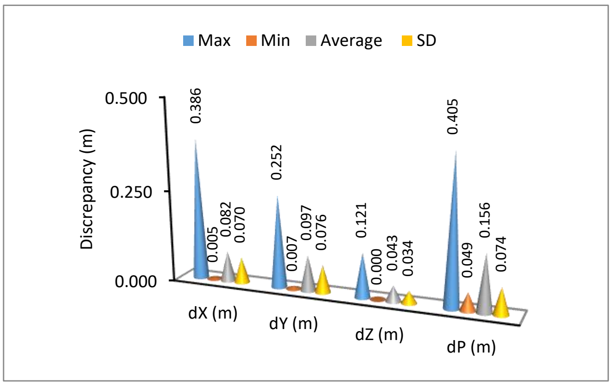

Fig. 17. Tested stations 1st order polynomial discrepancies one day before and after permanent stations observations

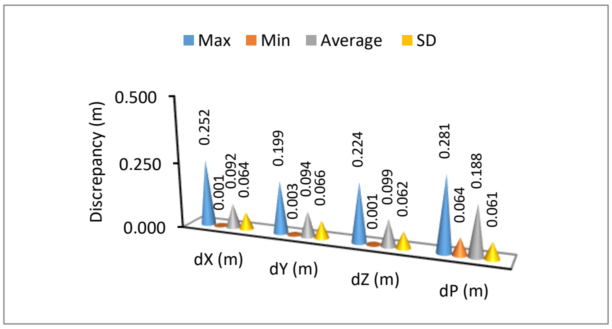

Fig. 18. Tested stations 1st order polynomial discrepancies two days before and after permanent stations observations

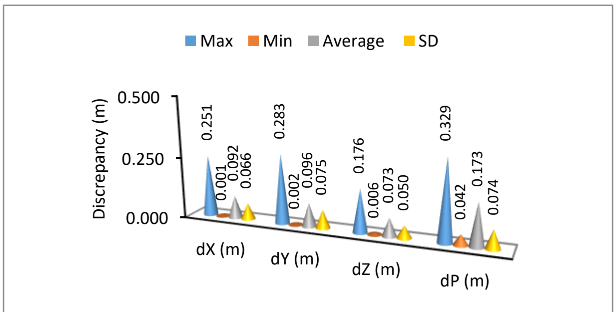

Fig. 19. Tested stations 1st order polynomial discrepancies three days before and after permanent stations observations

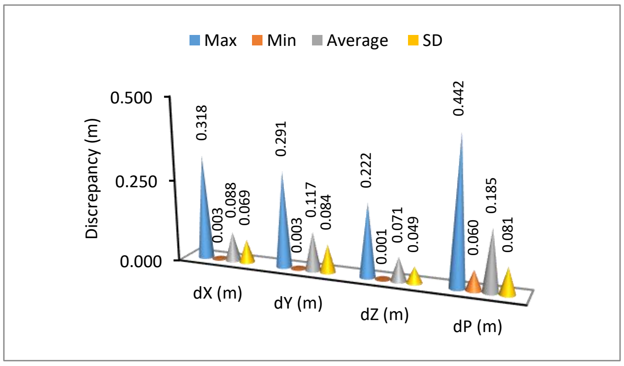

Fig. 20. Tested stations 1st order polynomial discrepancies four days before and after permanent stations observations

Fig. 17, 18, 19 and 20 show that the three cases produce better results than the static PPP, but still the synchronized results are the best.

VIII. CONCLUSION

Depending on the previous results, many important conclusions can be extracted:

- The tested mathematical models produce nearly similar results when using the synchronized corrections, and the 1st polynomial is selected as the optimum.
- When using gLAB software for processing, the 1st polynomial corrections produce better results in the synchronized case related to the only static PPP solution.
- The 1st polynomial model produces better results when using gLAB in non-synchronized case related to the only static PPP gLAB processing.
- The 1st polynomial model produces better results when using gLAB in the synchronized case related to the case of non-synchronized corrections.
- The 1st polynomial model can be generalized to produce corrections using single frequency GPS data and gLAB package.
- The user can raise the accuracy of single frequency static PPP when the data of four synchronized permanent stations are available in the same observational time or within four days before or after the time of observation.
- The non-synchronized case has the advantage of increasing PPP positioning using corrections from permanent stations and avoids the restrictions of the relative technique.

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