Validation of CODE-GIM and Regional Ionosphere Model (RIM) for Single Frequency GNSS PPP Solution using Bernese GNSS software - Case Study: Egyptian Nile Delta

Ashraf ABDALLAH[1,3,*], Tarek AGAG[2], Volker SCHWIEGER[3]

1 Faculty of Engineering, Aswan University, Aswan, Egypt
2 Egyptian Surveying Authority, Giza, Egypt
3 Institute of Engineering Geodesy (IIGS), Stuttgart University, Germany
* Corresponding author

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SUMMARY

Egypt is quickly constructing many infrastructures such as roadways and railways. Further, it is developing new cities like the New Al-Alamin and the New Capital city. GNSS supports the controlling of geodetic networks, developing a local ionospheric model, and estimating the tectonic plate movements. As well, it is needed for infrastructure planning and constructing. Due to the spare coverage of the international GNSS service (IGS) network in North Africa, in January 2012, the Egyptian surveying authority (ESA) established the first permanent Egyptian continuously operating reference stations (CORS) network. This network is covering the Nile valley and its delta. In this study, a developed regional ionosphere model (RIM) is modelled for obtaining a single-frequency precise point positioning (SF-PPP) solution for the Nile delta. The RIM model is developed using 9 stations for six consecutive days 202-207/2019. Bernese GNSS V. 5.2 software has been used for modelling using code phase geometry-free linear combination (P_4). This model has a spatial resolution of $2.5^o \times 5^o$ and a temporal resolution of 2 h. The SF-PPP solution obtained by the developed model is validated by processing five stations and compared with the solution obtained by using the CODE-GIM model. The RIM model showed for SF-PPP solution a mean error of 0.06 m in the east, 0.10 in the north, and 0.30 m in height. In comparison to the CODE-GIM model, this solution is improved by about 60% in, 70%, and 67% in east, north, and height, respectively.

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1. INTRODUCTION

GNSS-Precise Point Positioning (PPP) solution plays a vital alternative to the differential solution to provide a reliable position accuracy, especially in the regions that do not have regional permanent CORS stations. The dual-frequency PPP data is mainly combined to eliminate the first order of ionosphere errors. This combination is called the ionosphere-free linear combination for phase and code observations (Seeber, 2008). One of the greatest challenges for the single-frequency PPP (SF-PPP) technique is the modelling of the ionosphere errors. In context, the ionosphere layer is located about 50 km to 1100 km above the earth, which is ionized with gases as free electrons and ions. This error reaches 1 m – 15 m for mid-latitude to near-equatorial regions (Misra and Enge, 2012). The responsible parameter for the ionospheric delay is the total number of electrons (TEC) that refers to the total electron content along the signal path between the satellite and the receiver. TEC is a function of many variables, which is including the long and short-term changes in solar ionizing flux, magnetic activity, season, time of day, user location, and viewing direction (Klobuchar, 1987).

There are many models to mitigate the ionospheric errors including the Klobuchar model. The parameters of the modeling of the ionosphere are broadcasted to the navigation message for the GPS receivers. The implemented algorithm can reduce ionospheric errors by 50% (Klobuchar, 1987). The International GNSS Services (IGS) provided since 1998 through working group products for vertical total electron content maps (VTEC) that are called final global ionosphere maps (GIM). It provides as well the differential code bias (DCB). These DCB values are derived from the dual-frequency GNSS observation data. The data is available at https://cddis.nasa.gov/archive/gnss/products/ionex/yyyy/ddd. The ionosphere products are provided in IONospheric Exchange (IONEX) format (Schaer et al., 1998). IGS-GIM products contain VTEC values with a spatial resolution of 2.5°×5° in latitude and longitude, respectively. Further, it has a temporal resolution of 2 hours. Hernández-Pajares et al. (2009) reported that the final solution has a latency of approximately 11 days with an accuracy of 2- 8 TECU (1 TECU corresponds to 0.16 m delay on L_1 frequency).

In North Africa including Egypt, the IGS-GIM model has a limitation to obtain a reliable PPP solution for single-frequency users. The IGS stations in Africa have many characteristics. The network is mainly situated in the coastal area with long baselines, which affects the accuracy of the network precision (Walpersdorf et al., 2007). In order to fill this gap, in 2012, the Egyptian Surveying Authority (ESA) established the first permanent Egyptian Continuously Operating Reference Stations (CORS) network. This network is consisting of 40 stations that cover mainly the Nile valley and its Delta (ESA, 2012).

Numerous regional ionosphere models (RIMs) have been introduced to the research community. To study the diurnal, seasonal, and annual TEC variations in India, Bhuyan and Borah (2007) measured VTEC values that were implemented from 16 GPS stations between 2003-2004 and compared with the predicted values by the International Reference Ionosphere (IRI) (Bilitza et al., 1993). Opperman et al. (2007) developed a regional GPS-based near real-time regional ionosphere total electron content (TEC) for South Africa. The model was designed based on 10 GPS-based stations and compared with the Multi-Instrument Data Analysis System (MIDAS) system (Mitchell and Spencer, 2003) and GIM model. Abdelazeem et al. (2017) developed a regional ionospheric model for SF-PPP solution in Europe. 60 IGS and European reference stations (EUREF) were processed using the PPP module in Bernese GNSS V. 5.2 software (Dach et al., 2015) to estimate the VTEC. The model has a spatial and temporal resolution of $1^{o} \times 1^{o}$ and 15 minutes. Three IGS stations were evaluated POTS, IGMI, and ANKR. The results showed an improvement of the RIM model over the IGS-GIM model with 20, 45, and 45% in horizontal, height, and 3D components.

Regarding the local ionospher models developed for Egypt, El Manaily et al. (2018) developed a mathematical local ionospheric model. The model is based on the geometry-free linear combination for pseudo-range (P_4). The model is devolved based on the Egyptian CORS stations that consist of 40 stations that have a baseline of 50 km to 70 km. The determined Egyptian Ionospheric model (EIM) has two hours as temporal resolution and a spatial resolution of 0.5^{o} and 0.5^{o} in longitude and latitude. The study investigated the SF-PPP solution for three stations Aswan, Cairo, and Alexandria using Klobuchar, GIS-GIM, and EIM (Egyptian ionosphere map) model. The study indicated that the root mean square error (RMSE) obtained after a convergence time of 4 hours is in the range of 15 cm, and less than 10 cm in horizontal for GIS-GIM, and EIM models. In height direction, the RMSE reported more than 70 cm for GIM and more than 30 cm for the EIM model. In addition, Sedeek (2021) compared the effect of the ionosphere model on the accuracy of SF-PPP solution using the broadcast parameters of the ionosphere, GIM model from Center for Orbit Determination in Europe (CODE-GIM), and a developed local ionosphere model concerning a spherical harmonic algorithm using Bernese GNSS software. The results proved that the ionosphere corrections enhanced the accuracy of the vertical positions where the absolute vertical error is about 30 cm for local ionosphere maps, 32.3 cm for GIMs, and 57.2 cm for the broadcasted Klobuchar parameter. In addition, the horizontal error varies from 2.7 to 51.8 cm by using LIMs, while changes from 4.5 to 47.2 cm by using GIMs. For further evaluations regarding the ionospheric models over Egypt, see Elghazouly et al. (2022) and Sedeek (2020).

This paper aims to evaluate the accuracy of the SF-PPP solution using the GIM model provided from CODE, and the modeled regional ionospheric model (RIM) for the area of the Nile Delta.

A data set of six consecutive days 202-207/2019 of the ESA-CORS permanent stations were involved in the study. Nine stations were considered for RIM estimation and five stations are used for model validation. Bernese GNSS V. 5.2 software is used to model the regional ionosphere by using a geometry-free linear combination for code observation data (P_4).

2. IONOSPHERE MODELING

The ionosphere layer is located about 50 km to 1100 km above the earth. This layer is ionized with gases as free electrons and ions (Misra and Enge, 2012). The component of ionosphere is based on the single-layer model (SLM). This model considers that all free electrons are concentrated in a shell in height (H) as shown in the following Figure 1. The SLM mapping function (F_I), which is a function of the electron density of the layer (E) is written using equation (1), and (2), where E_v is the vertical TEC. (Dach et al., 2015)

$$F_I(z) = \frac{E}{E_v} = \frac{E}{E\cos(z')} = \frac{1}{\cos(z')} \tag{1}$$

$$\sin(z') = \frac{R}{R+H}\sin(z), \tag{2}$$

where,

$\boldsymbol{R}$	: the mean radius of the Earth,
$\boldsymbol{H}$	: the height of a single layer above the surface of Earth (300-500 km),
$\boldsymbol{z}$	: the satellite zenith distance at the height of station (Receiver on Earth),
$\boldsymbol{z'}$	: the satellite zenith distance of the single-layer ionospheric pierce points (IPP),
$\boldsymbol{\alpha}$	: the geocentric angle (equal $\boldsymbol{z-z'}$).

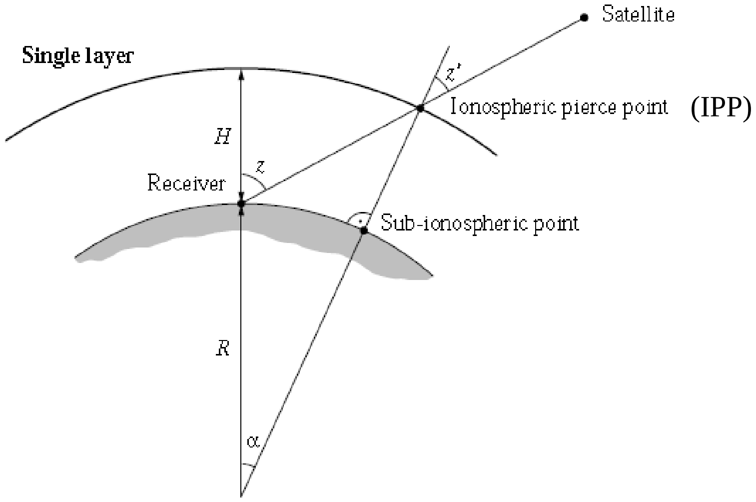

Figure 1: Single-layer model (Dach et al., 2015)

According to Schaer (1999), the SLM mapping function can be converted to a modified SLM (MSLM) by including an additional constant ($\boldsymbol{\alpha}$); equation (2) is expressed by equation (3). The best fit of MSLM is expressed according to Jet Propulsion Laboratory (JPL) extended slab model (ESM) mapping function with $\boldsymbol{H = 506.7\ km}$ and $\boldsymbol{\alpha = 0.9782}$ (when using $\boldsymbol{R = 6371\ km}$, and maximum zenith distance of 80°). This modified mapping function is used in the analysis at CODE using $\boldsymbol{H = 450\ km}$ of the ionospheric pierce points (IPP) (Dach et al., 2015):

$$\sin(z') = \frac{R}{R+H}\sin(\alpha z) \tag{3}$$

To estimate the ionospheric TEC values, a geometry-free linear combination for the un-differenced code ($\boldsymbol{P_4}$) and carrier-phase ($\boldsymbol{\Phi_4}$) observations are used. By applying it, the geometrical term, tropospheric delay, receiver, and satellite clock errors are eliminated. The geometry-free code linear combination contains the ionospheric delay and the differential code bias (DCB) for the receiver and the satellite. On the other side, the geometry-free carrier-phase linear combination contains ionospheric delay and the ambiguity parameters (Dach et al., 2015):

$$P_4 = P_1 - P_2 = +a\left(\frac{1}{f_1^2} - \frac{1}{f_2^2}\right)F_I(z)E(\beta, s) + c(\Delta b^S + \Delta b_R), \tag{4}$$

$$\Phi_4 = \Phi_1 - \Phi_2 = -a\left(\frac{1}{f_1^2} - \frac{1}{f_2^2}\right)F_I(z)E(\beta, s) + (\lambda_1 N_1 - \lambda_2 N_2), \tag{5}$$

where,

$\boldsymbol{a}$: is a constant with $\boldsymbol{a = 4.03 \cdot 10^{17} ms^{-2} VTEC^{-1}}$,
$\boldsymbol{f_1, f_2}$: the associated frequencies for $\boldsymbol{L_1}$ and $\boldsymbol{L_2}$,
$\boldsymbol{F_I(z)}$: the mapping function at the zenith distance ($\boldsymbol{z'}$),
$\boldsymbol{E(\beta, s)}$: the vertical TEC (VTEC) as a function of geographic or geomagnetic latitude ($\boldsymbol{\beta}$) and sun-fixed longitude ($\boldsymbol{s}$) of IPP.
$\Delta \boldsymbol{b^S}$, $\Delta \boldsymbol{b_R}$: the differential code bias (DCB) for satellite and receiver,
$(\boldsymbol{\lambda_1 N_1 - \lambda_2 N_2})$: is a constant bias in meter as an initial phase ambiguity.

The global and regional TEC model is expressed as a function of ($\boldsymbol{E(\beta, s)}$) of a spherical harmonic expansion, which is considered in the solution of Dach et al. (2015). Further information related to the global and the regional modeling is found in Schaer et al. (1996), and Schaer (1999). According to Dach et al. (2015), to estimate such global or regional ionosphere model parameters, smoothed code observation data is applied for zero-difference data (Code observation files). In such a case, the differential code biases (DCB) file for all satellites and receivers is added to the estimation. For double-difference data, smoothed phase observations data is applied and highly recommended for small network sizes.

$$E(\beta, s) = \sum_{n=0}^{n_{max}} \sum_{m=0}^{n} \tilde{P}_n^m(\sin\beta)\left(a_n^m\, cos(ms) + b_n^m\, sin(ms)\right). \tag{6}$$

where,

$\boldsymbol{n_{max}}$: is the maximum degree of the spherical harmonic expansion,

$\widetilde{\boldsymbol{P}}_{\boldsymbol{n}}^{\boldsymbol{m}} = \Lambda(\boldsymbol{n},\boldsymbol{m})\boldsymbol{P}_{\boldsymbol{n}}^{\boldsymbol{m}}$: are the normalized associated Legendre functions of degree $\boldsymbol{n}$ and order $\boldsymbol{m}$, based on normalization function $\Lambda(\boldsymbol{n},\boldsymbol{m})$ and Legendre functions $\boldsymbol{P}_{\boldsymbol{n}}^{\boldsymbol{m}}$,

$\boldsymbol{a}_{\boldsymbol{n}}^{\boldsymbol{m}}$, $\boldsymbol{b}_{\boldsymbol{n}}^{\boldsymbol{m}}$: are the unknown TEC coefficients of the spherical harmonics to be estimated.

3. METHODOLOGY AND SOFTWARE

In order to evaluate the SF-PPP solution by the GIM model and RIM model, a data set of 14 stations are involved in the study of six consecutive days 202-207/2019 of the ESA-CORS permanent stations, see Figure 2. Nine stations have been considered for RIM estimation (square mark) and five stations for validation (triangle mark). The reference solution of the stations was processed based on a network solution according to Abdallah et al. (2021). The processing strategy contianed two steps: first step, six ESA-CORS (ADFO, ALEX, CARO, MOUS, QANT, and SUZE) have been processed with six tied IGS-CORS (YKRO, DYNG, NICO, NKLG, NOT1, and RAMO). The second step, a local constrained network solution has been solved with depending on the previous six ESA-CORS that were solved from the global network.

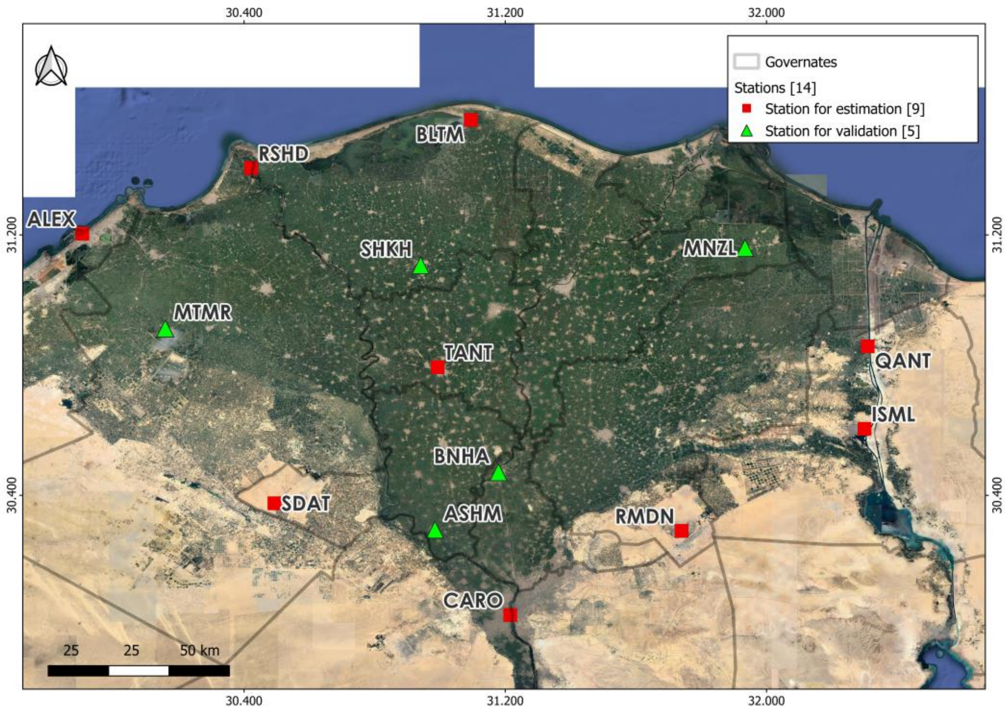

Figure 2: Layout of ESA-CORS stations based on Google Earth platform

Bernese GNSS v. 5.2 software that is developed at the Astronomical Institute of the University of Bern (AIUB), Switzerland is used to model the regional ionosphere and to estimate the SF-PPP solution (Dach et al., 2015). The satellite final orbits ephemeris, clocks with intervals of

30 s., earth rotation parameters, GIM, and differential code biases (DCB) data are downloaded from the CODE FTP server [*http://ftp.aiub.unibe.ch/*], see Figure 3. The antex file for antenna phase center variation (I14.ATX), nutation model, sub-daily pole, and ocean tide coefficients are included in the solution. Figure 3 presents the flowchart for regional ionosphere modeling using Bernese GNSS software. Followings are the modeling procedures according to Dach et al. (2015).

- **Orbit programs**: this package contains of three main programs. The **POLUPD** program is used to convert the earth pole information from International Earth Rotation and Reference Systems Service (IERS) to the internal format for Bernese format. **PRETAB** program provides tabulated satellite orbit data. Further, **ORBGEN** program prepares the standard orbits.
- **RINEX programs**: this package consists of three secondary programs. The first one is called **RNXGRA**, which is used to get a quality check of phase or code data. The second program is the **RNXSMT** program. This program cleans the RINEX phase and code observations from outliers and cycle slips. Finally, the **RXOBV3** program aims to transform the RINEX observation file after smoothing into a binary format.
- **CODSPP program**: this program estimates the receiver clock errors based on the smoothed code combination (P_3) using least square adjustment theory that is inserted to the estimation as a known parameter.
- **GPSEST program**: this program is used to develop the regional ionosphere model. The smoothed zero-difference code observation data is inserted into the ionosphere modeling including the DCB file. Table 1 presents the ionosphere modeling parameters.

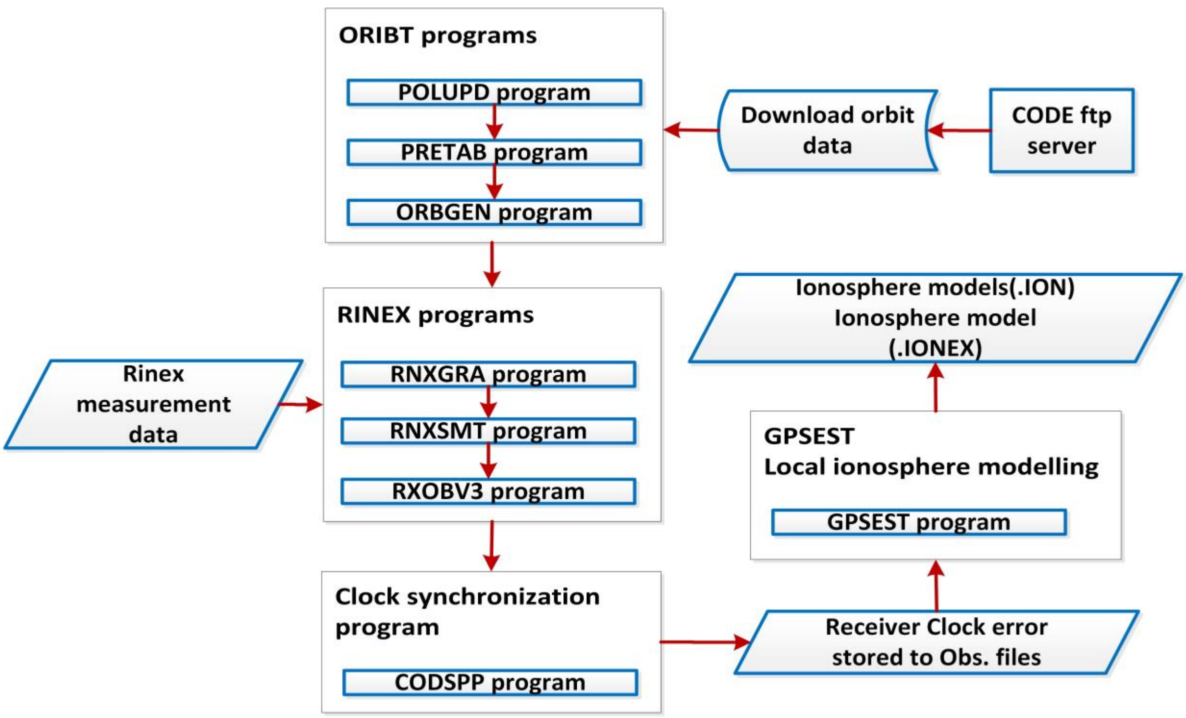

Figure 3: Flowchart of regional ionosphere modeling

Table 1: Parameters for RIM modeling using Bernese GNSS software

Parameter	Value
Satellite system	GPS & GLONASS
Differential level	Zero-difference
Frequency	P_4
Elevation angle	10°
Sampling interval	30 s
Temporal resolution	2 h
Max. degree of spherical harmonics (n_{max})	6
Max. order of spherical harmonics (m_{max})	6
Height of single layer (H)	450 km
Reference frame definition	geomagnetic
Latitude of the geomagnetic pole	79°
Longitude of the geomagnetic pole	-71°
Ionosphere grid (*Lat.*×*Long.*)	2.5°×5°

As seen in Figure 4, after estimating the regional ionosphere model for the study area, the SF-PPP solution is obtained by the Bernese processing engine (BPE-PPP) twice, one time using the GIM model and on the othertime using the RIM model. The general flowchart of the evaluation strategy is presented in Figure 4. The evaluation strategy is based on error calculation (δ) between the reference network solution and SF-PPP solution in East, North, and height directions. Furthermore, the mean (μ) and the RMS values are estimated in addition to the standard deviation (SD) that refers to deviation relative to the mean values.

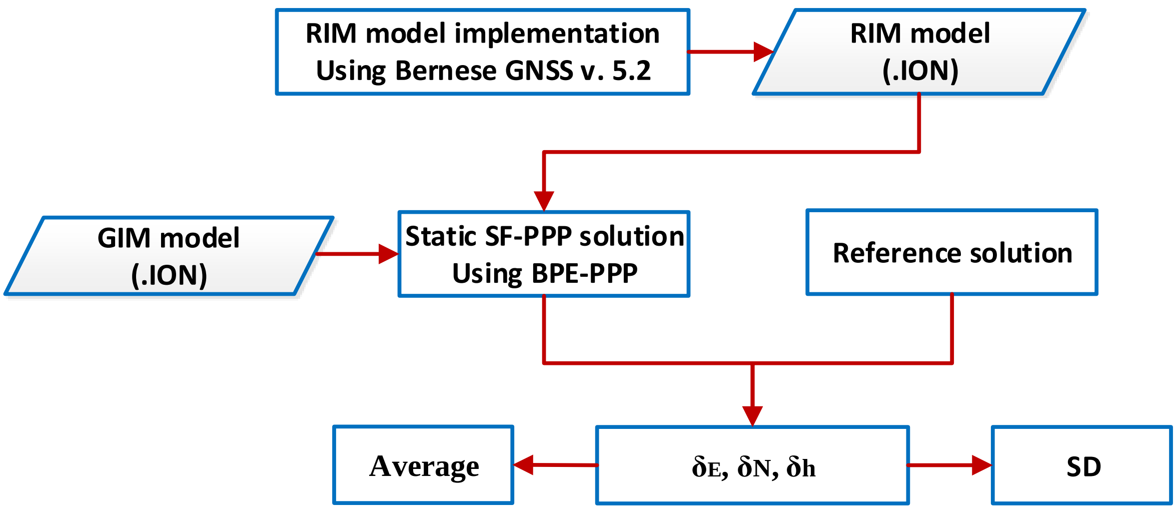

Figure 4: Flowchart of evaluation procedure

4. RESULTS AND ANALYSIS

To evaluate the effect of the ionosphere models on the SF-PPP solution, the errors in East, North, and height are shown in Figure 5 for the GIM model and in Figure 6 for the regional ionosphere model. Regarding the GIM model, In north direction, the results show an error range of 0.26 – 0.43m (average= 0.35 m) for all observation days. For the east direction, the accuracy reports however a better solution than the north direction. The solution delivers an error range of 0.02 – 0.29 m (average= 0.14 m) for all days, but it can be seen that the results obtained from day 202 is the best and day 203 is the worst. The height component is the most sensitive error regarding the SF-PPP solution. It provides an error range of 0.68 – 1.04 m with an average value of 0.88 m. In general, the results that are delivered seem to be hemogenious for all days.

The results of this study indicate that the SF-PPP solution using the RIM model shows in the east direction an error range of 0 – 0.24 m ($E_{average}$ = 0.06 m) for all days. In addition, stations ASHM, BNHA, MTMR, and SHKH from day 202 shows the highest errors in the east direction. Regarding the north direction, the results provide an error range of 0.02 – 0.17 m with an average ($N_{average}$ = 0.10 m). From the data in Figure (6), the results indicate for height direction an error range of 0.14 – 0.41 ($H_{average}$ = 0.30 m). In general, the results are homogeneous and refer that the developed regional model is very effective for SF-PPP solution.

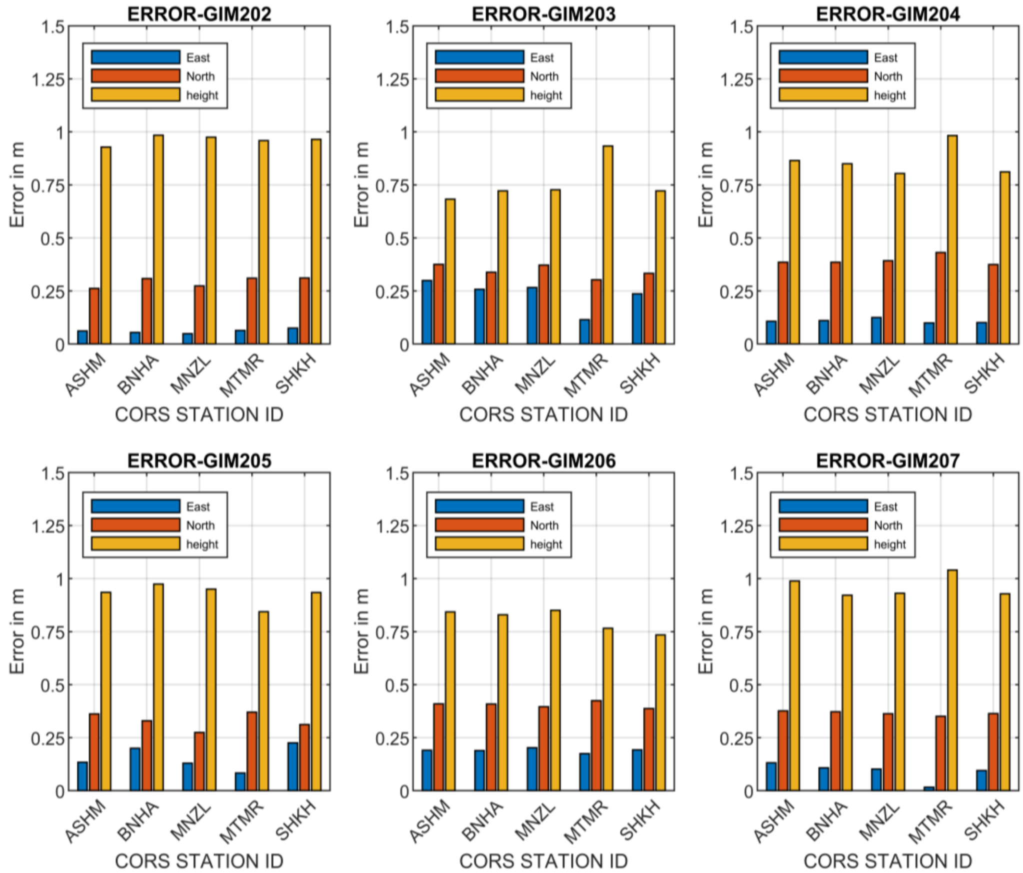

Figure 5: SF-PPP errors using CODE-GIM model

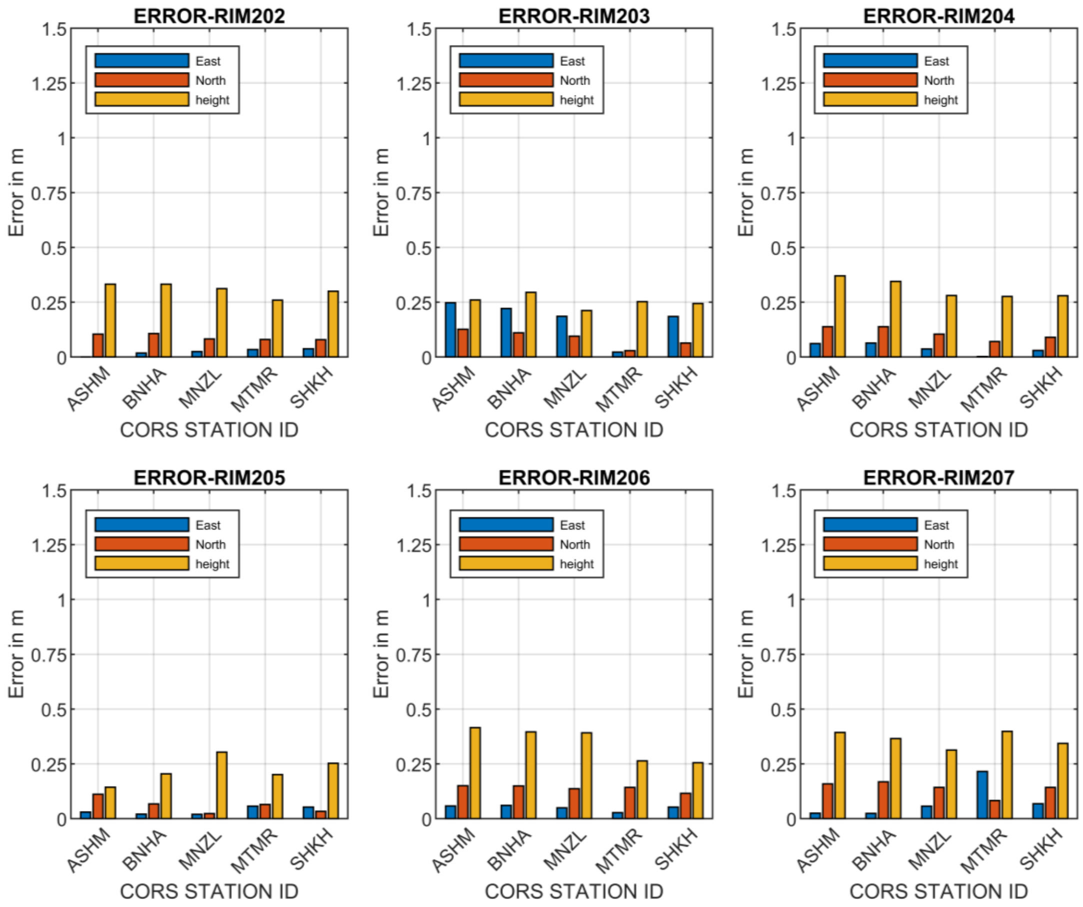

Figure 6: SF-PPP errors using RIM model

Further statistical analysis is concluded in Table 2. This table presents maximum, minimum, average, and sd values for each station. Regarding the SF-PPP accuracy obtained by using the CODE-GIM model, station ASHM, BNHA, MNZL, and SHKH show an average error of 0.15 m (*SD*= 0.08 m) in the east, while equals to 0.09 m for MTMR station. In north direction, all stations deliver an average error of 0.35 m (*SD* = 0.03- 0.05 m). In addition, the solution gets an average error of 0.85- 0.92 m (*SD* = 0.10 m) in height. Overall, the SF-PPP solution that is obtained by using CODE-GIM shows an average 2D accuracy of 0.38 m and height of 0.88. Further it delivers an average 3D error of less than 1 m.

As to be illustrated in Table 2, the estimated accuracy of the SF-PPP solution using the modelled RIM model shows an average error for all stations of 0.06- 0.07 m (*SD* = 0.06- 0.07 m) in the east direction. For north, the solution displays an approximate average error of 0.1 m (*SD* = 0.03- 0.04 m). Based on the results presented in this table, the height average error shows approximately 0.3 m (*SD* = 0.05- 0.10 m). Generally, the SF-PPP solution using RIM model shows an average 2D accuracy of 0.13 m and height of 0.30 m. In addition, the solution provides an average 3D accuracy of 0.33 m. Overall, these results indicate that the solution obtained by using the RIM model is better than the one from the CODE-GIM model. The solution is improved by 60%, 70%, and 67% in east, north, and height, respectively. This shows the benefit of using a regional rather than a global ionosphere model.

Table 2: Summary of SF-PPP solution for CODE-GIM and RIM models

ID	ASHM$_{GIM}$			BNHA$_{GIM}$			MNZL$_{GIM}$			MTMR$_{GIM}$			SHKH$_{GIM}$		
	E	**N**	**h**	**E**	**N**	**h**	**E**	**N**	**h**	**E**	**N**	**h**	**E**	**N**	**h**
min	0.06	0.26	0.68	0.05	0.30	0.72	0.05	0.27	0.73	0.02	0.30	0.77	0.07	0.31	0.72
max	0.29	0.40	0.98	0.25	0.40	0.98	0.26	0.39	0.97	0.17	0.43	1.04	0.24	0.39	0.96
Avg.	0.15	0.36	0.87	0.15	0.35	0.88	0.14	0.34	0.87	0.09	0.36	0.92	0.15	0.35	0.85
SD	0.08	0.05	0.10	0.07	0.04	0.10	0.08	0.05	0.10	0.05	0.05	0.10	0.07	0.03	0.10
ID	**ASHM$_{RIM}$**			**BNHA$_{RIM}$**			**MNZL$_{RIM}$**			**MTMR$_{RIM}$**			**SHKH$_{RIM}$**		
	E	**N**	**h**	**E**	**N**	**h**	**E**	**N**	**h**	**E**	**N**	**h**	**E**	**N**	**h**
min	0.00	0.10	0.14	0.02	0.07	0.20	0.02	0.02	0.21	0.00	0.03	0.20	0.03	0.03	0.24
max	0.25	0.16	0.42	0.22	0.17	0.40	0.19	0.14	0.39	0.22	0.14	0.40	0.18	0.14	0.34
Avg.	0.07	0.13	0.32	0.07	0.12	0.32	0.06	0.10	0.30	0.06	0.08	0.28	0.07	0.09	0.28
SD	0.08	0.02	0.10	0.08	0.04	0.07	0.06	0.04	0.06	0.07	0.04	0.07	0.06	0.04	0.05

5. CONCLUSION

This paper investigates the SF-PPP solution using the CODE-GIM model and a developed RIM model for the Egyptian Nile Delta. The regional model is designed using six sequences days with a spatial resolution of 2.5º×5º and a temporal resolution of 2 h. The RIM model was estimated by using nine ESA-CORS stations. Further, Bernese GNSS V. 5.2 software has been used for the modelling using code phase geometry-free linear combination (P_4) and for the SF-PPP estimation. For validation, five stations were used for delivering the SF-PPP solution with a convergence time of 24 h. The results showed that the accuracy obtained by the RIM model has provided approximately a mean error of 0.06 m, 0.10 m, and 0.30 m in east, north, and height, respectively. In comparison to the CODE-GIM model, the SF-PPP solution has improved by the RIM model by about 60% in the east, 70% in the north, and 67% in height. What is now needed is an a cross-national study involving the whole ESA-CORS stations for shorter convergence times to be applicable in surveying applications and for cost-efectivnesse purposes. In additioin, the study is requied to study the effect of the various diurnal periods.

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BIOGRAPHICAL NOTES

Dr. –Ing. **Ashraf Abdallah**

1998 – 2003 Studies of Civil Engineering in Aswan (University of Aswan, Egypt)
2005 – 2009 Research associate in Civil Engineering in Aswan (University of Aswan, Egypt)
2009 Master of Science (University of Aswan, Egypt)
2009 – 2011 Assistant lecturer in Civil Engineering in Aswan (University of Aswan, Egypt)
2012 – 2016 Ph. D. student at the Institute of Engineering Geodesy, University of Stuttgart
2016 Assistant Professor at the Faculty of Engineering, Aswan University, Egypt.
2021 Post-doc researcher at Institute of Engineering Geodesy, University of Stuttgart.

Eng: **Tarek AGAG**

1983 – 1988 B.SC in Civil Engineering (Project: Surveying) (University of Aswan, Egypt).
1990 – 1998 Aswan cadastral Inspectorate, Egyptian Survey Authority.
1995 – 1996 Preliminary Master in Surveying (University of Aswan, Egypt).
1998 – 1999 German project leader (cadastral project) Egyptian Survey Authority.
1999 – 2000 Professional Master Degree in Geoinformation Science and Earth Observation ITC Enschede Netherlands.
2001 – 2004 Aswan cadastral Inspector, Egyptian Survey Authority.
2005 – 2007 Cadastral manager for upper Egypt, Egyptian Survey Authority.

2007 – 2010 Giza Provincial manager, Egyptian Survey Authority.
2011 – 2012 Cairo Provincial manager, Egyptian Survey Authority.
2013 – 2020 General manager for Geodesy, Egyptian Survey Authority.
2016 Member of un-ggim arab region.
2017 Member of subcommittee for Geodesy in un-ggim arab region.
2020 Chief of Mapping Sector, Egyptian Survey Authority.

Prof. Dr.-Ing. habil. Dr. h.c. **Volker Schwieger**

1983 – 1989 Studies of Geodesy in Hannover.
1989 Dipl.-Ing. Geodesy (University of Hannover).
1998 Dr.-Ing. Geodesy (University of Hannover).
2004 Habilitation (University of Stuttgart).
2010 Professor and Head of Institute of Engineering Geodesy, University of Stuttgart.
2015 - 2018 Chair of FIG Commission 5 ‘Positioning and Measurement’.
2016 - 2021 Dean of Faculty of Aerospace Engineering and Geodesy, University of Stuttgart.
2019 Dr. h.c. at Technival University of Civil Engineering, Bucharest, Romania

CONTACTS

Dr. –Ing. Ashraf Abdallah

Faculty of Engineering, Aswan University, Egypt.
81542 Aswan, Egypt
Email: ashraf.abdallah@aswu.edu.eg

Institute of Engineering Geodesy (IIGS), Stuttgart University, Germany.
Geschwister-Scholl-Str. 24D, 70174 Stuttgart, Germnay.
Email: ashraf.abdallah@iigs.uni-stuttgart.de
Website: https://www.iigs.uni-stuttgart.de/team/Abdallah/.