

Datum maintenance of the main Egyptian geodetic control networks by utilizing Precise Point Positioning “PPP” technique



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Abstract A geodetic control network is the wire-frame or the skeleton on which continuous and consistent mapping, Geographic Information Systems (GIS), and surveys are based. Traditionally, geodetic control points are established as permanent physical monuments placed in the ground and precisely marked, located, and documented. With the development of satellite surveying methods and their availability and high degree of accuracy, a geodetic control network could be established by using GNSS and referred to an international terrestrial reference frame used as a three-dimensional geocentric reference system for a country. Based on this concept, in 1992, the Egypt Survey Authority (ESA) established two networks, namely High Accuracy Reference Network (HARN) and the National Agricultural Cadastral Network (NACN). To transfer the International Terrestrial Reference Frame to the HARN, the HARN was connected with four IGS stations. The processing results were 1:10,000,000 (Order A) for HARN and 1:1,000,000 (Order B) for NACN relative network accuracy standard between stations defined in ITRF1994 Epoch1996. Since 1996, ESA did not perform any updating or maintaining works for these networks.

To see how non-performing maintenance degrading the values of the HARN and NACN, the available HARN and NACN stations in the Nile Delta were observed. The Processing of the tested part was done by CSRS-PPP Service based on utilizing Precise Point Positioning “PPP” and Trimble Business Center “TBC”. The study shows the feasibility of Precise Point Positioning in updating the absolute positioning of the HARN network and its role in updating the reference frame (ITRF). The study also confirmed the necessity of the absent role of datum maintenance of Egypt networks. © 2016 Production and hosting by Elsevier B.V. on behalf of National Research Institute of Astronomy and Geophysics. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

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1. Introduction

One of the fundamental tasks of geodesy is the building and maintenance of geodetic reference networks. Geodetic networks are comprised of a set of well-defined and monument geodetic markers distributed on Earth's surface. They form the basis for investigations of the shape, dimension and gravity field on the Earth. All these quantities have to be considered as time dependent. Geodetic reference networks also are the basis for all technical and construction works in building as well as the reference frame for monitoring the stability of various large constructions.

The definition and practical realization of geodetic reference networks is changed due to progress in geodetic observation techniques. With the development of satellite surveying methods and their availability and high degree of accuracy, the problem arose, how to use these three-dimensional (3D) observations in their complexity and not to lose or reduce the information about the spatial point positions included in the measurements. When a national coordinate system is established by using high accuracy GPS positioning, a procedure designed for its regular maintenance is also required. It is aimed to ensure the quality and accuracy for the GPS control stations as they might be degraded by any intended or natural effects. If the regular maintenance is not made for those GPS sites, the geocentric reference system based on this fundamental GPS network would be distorted. However, if the maintenance is frequently carried out for those GPS control stations, it would also result in some difficulties for land planning and management as the coordinates of these control stations have to be jointly changed. Therefore, a guideline set up to carry on a stable frequency and consistent quality of maintenance for the GPS control stations in Egypt is particularly required.

Normally, for the maintenance of GPS tracking stations, the accurate coordinates of these GPS tracking stations are determined in the network adjustments integrating with part of the IGS stations whose coordinates are regularly maintained with the realization of the ITRF. When long term coordinate data sets are archived for GPS tracking stations, they can be used to investigate the time evolution. As the coordinates of the first-order GPS control stations are determined by fixing the coordinates of the GPS tracking stations in the network adjustments, the information of time evolution provided by the GPS tracking stations can be used to carry on the maintenance for the first-order GPS control stations (Rabah et al. 2015; Farhan, 2013).

In space geodetic positioning, where the observation techniques provide absolute positions with respect to a consistent terrestrial reference frame, the corresponding precise definition and realization of terrestrial and inertial reference systems are of fundamental importance. Geodetic reference frames are subject to regular maintenance for a number of reasons including the networks "densification (addition of new points)", the correction of survey blunders, unstable or disturbed monumentation, geodynamical effects such as plate tectonics and effects of crustal motion both locally and regionally, and to keep pace with ever increasing accuracy requirements.

In the classical sense, a geodetic datum is a reference surface, generally an ellipsoid of revolution of adopted size and shape, with origin, orientation, and scale defined by a geocentric

terrestrial frame. Once an ellipsoid is selected, coordinates of a point in space can be given in Cartesian or geodetic (curvilinear) coordinates (geodetic longitude, latitude, and ellipsoid height). Two types of geodetic datum can be defined namely a static and kinematic geodetic datum. A static datum is thought of as a traditional geodetic datum where all sites are assumed to have coordinates which are fixed or unchanging with time. This is an incorrect assumption since the surface of the earth is constantly changing because of tectonic motion. Static datum does not incorporate the effects of plate tectonics and deformation events. Coordinates of static datum are fixed at a reference epoch and slowly go out of the date, need to change periodically which is disruptive (Chang and Tseng, 1998).

Datums can either become fully kinematic (dynamic), or semi-kinematic. A deformation model can be adopted to enable ITRF positions to be transformed into a static or semi-kinematic system at the moment of position acquisition so that users do not see coordinate changes due to global plate motions. GNSS devices that use ITRF or closely aligned systems position users in agreement with the underlying kinematic frame; however, in practice there are a number of very significant drawbacks to a kinematic datum. Surveys undertaken at different epochs cannot be combined or integrated unless a deformation model is applied rigorously, or is embedded within the data, and the data are correctly time-tagged. On the other hand, semi-kinematic datum incorporates a deformation model to manage changes (plate tectonics and deformation events). Coordinates are fixed at a reference epoch, so the change to coordinates is minimized. Many countries and regions that straddle major plate boundaries have adopted a semi-kinematic (or semi-dynamic) geodetic datum in order to prevent degradation of the datum as a function of time due to ongoing crustal deformation that is occurring within the country.

High precision GNSS positioning and navigation is very rapidly highlighting the disparity between global kinematic reference frames such as ITRF and WGS84, and traditional static geodetic datum. The disparity is brought about by the increasingly widespread use of PPP and the sensitivity of these techniques to deformation of the Earth due to plate tectonics. In order for precision GNSS techniques to continue to deliver temporally stable coordinates within a localized reference frame.

2. Transformation parameters between static and kinematic terrestrial reference systems

Transformations from kinematic ITRF to a static datum are conventionally done by either using the site velocity (measured directly or computed from a plate motion model) to compute the displacement between the reference and current epochs or by a conformal transformation augmented with time dependent parameters to account for rigid plate motion. Rigid Plate movement is conventionally defined by a rotation rate about an Euler Pole Φ , Λ and ω , where Φ and Λ are the latitude and longitude of the pole, and ω is the rate of rotation of the plate around the pole in degrees per million years. Equivalent rotation rates about the Cartesian axes (Ω_X , Ω_Y and Ω_Z) can be computed from the Euler pole definition using Eqs. (1)–(3) (Φ , Λ , and ω) are first converted from decimal degrees to radians:

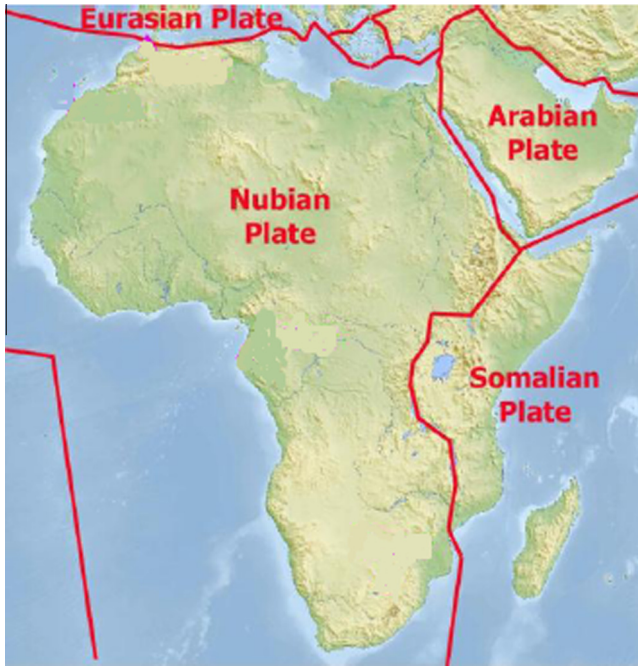


Figure 1 The Africa tectonic plates.

$$\Omega_X = \cos(\Phi) \cos(\Lambda) \omega \quad (1)$$

$$\Omega_Y = \cos(\Phi) \sin(\Lambda) \omega \quad (2)$$

$$\Omega_Z = \sin(\Phi) \omega \quad (3)$$

A site velocity in Cartesian format (X, Y, Z) can be computed for any given location (X, Y, Z in meters) on a rigid plate defined by ($\Omega_X, \Omega_Y, \Omega_Z$) in radians per million years) using:

$$\begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{Z} \end{bmatrix} = \begin{bmatrix} \Omega_Y Z - \Omega_Z Y \\ \Omega_Z X - \Omega_X Z \\ \Omega_X Y - \Omega_Y X \end{bmatrix} \cdot 1\text{E} - 6 \quad (4)$$

By introducing a reference epoch t_0 and an epoch of measurement t (epochs in decimal years), the ITRF coordinates of any point on a rigid plate at a reference epoch (X_0, Y_0, Z_0 in meters) can be computed from the coordinates at epoch t (X_t, Y_t, Z_t in meters) using:

$$\begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix} = \begin{bmatrix} X_t \\ Y_t \\ Z_t \end{bmatrix} + \begin{bmatrix} \Omega_Y Z_t - \Omega_Z Y_t \\ \Omega_Z X_t - \Omega_X Z_t \\ \Omega_X Y_t - \Omega_Y X_t \end{bmatrix} \cdot (t_0 - t) 1\text{E} - 6 \quad (5)$$

For any location on a rigid plate, instantaneous ITRF coordinates can be transformed to a fixed reference epoch using Eqs. (5)–(10) (Stanaway and Roberts, 2009).

$$\begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix} = \begin{bmatrix} T_X \\ T_Y \\ T_Z \end{bmatrix} + S \cdot \begin{bmatrix} X_t \\ Y_t \\ Z_t \end{bmatrix} + \begin{bmatrix} \Omega_Y Z_t - \Omega_Z Y_t \\ \Omega_Z X_t - \Omega_X Z_t \\ \Omega_X Y_t - \Omega_Y X_t \end{bmatrix} \cdot (t_0 - t) / 1,000,000 \quad (6)$$

where

(X_0, Y_0, Z_0): are the ITRF Cartesian coordinates at the reference epoch t_0 (in decimal years),

(X_t, Y_t, Z_t): are instantaneous ITRF Cartesian coordinates at epoch t (epoch in decimal years),

(T_X, T_Y, T_Z): is the translation of the reference frame origin (from ITRF to local system),

($\Omega_X, \Omega_Y, \Omega_Z$): are the Cartesian rigid plate/block rotation parameters in the reference frame,

S : is scale factor (from ITRF to local).

The African continent is broadly divided into two major tectonic plates, see Fig. 1. Most of Africa, west of the East African Rift lies on the Nubian Plate. The Somalian Plate lies on east of the African Rift. A very small section of North Africa along the Maghreb coast in Algeria and Morocco lies on the Eurasian Plate and the Dankalia region of Eritrea lies on the Arabian Plate (Rabah et al. 2015).

Analysis of the ITRF2005 solution (Altamimi et al., 2007; IERS, 2010) indicates that ITRF site velocities for any location within Africa are between 24 and 31 mm/yr due to rigid motion of the African plates over the underlying mantle. These site velocities degrade the accuracy of absolute positions like PPP if the measurement epoch is misinterpreted as a reference epoch for the underlying datum realization in use at the time Eqs. (1)–(3) were used to compute ($\Omega_X, \Omega_Y, \Omega_Z$) for the Nubian Plate using the Euler parameters determined by ITRF2008 PMM “Plate Motion Model” (Altamimi et al., 2012) and Egypt’s Deformation Model (Saleh and Becker, 2013), and the results were depicted in Table 1.

3. Precise Point Positioning technique

PPP has received increased attention in the past several years within the GPS community due to its great operational flexibility and accuracy promise. The major advantages of PPP lie in two aspects: system simplicity at the user’s end and global consistency in terms of positioning accuracy. PPP-based approach significantly reduces the equipment and personnel costs, pre-planning, and logistics compared to conventional GPS network-based approaches. Applying PPP, a single survey team can establish a Continuously Operating Reference Station (CORS) network across a PPP has received increased

Table 1 The Cartesian angular velocity of Nubian Plate.

Deformation model	Absolute pole Cartesian angular velocity for Nubian Plate		
	Ω_X (Rad/Ma)	Ω_Y (Rad/Ma)	Ω_Z (Rad/Ma)
Egypt DM-ITRF2008	0.000820	−0.00286	0.003585
ITRF2008-PMM	0.000461	−0.00290	0.003506

attention in the past several years within the GPS community due to its great operational flexibility and accuracy promise (Elhattab, 2014).

Since PPP is a technique with only one GNSS receiver, no differences between two receivers can be built to eliminate satellite specific errors such as clock and orbital errors. Therefore it is necessary to use the most precise satellite clock corrections and satellite orbits. Relevant products, are available even in real time. Measurements from the IGS global tracking network are processed by the IGS Analysis Centers to provide the highest quality satellite orbit and clock parameters. These parameters are freely available from the Internet and are the basis for PPP development. These IGS products can be applied to significantly reduce the errors in GPS satellite orbits and clocks, which are two of the most significant error sources in GPS positioning. Combining precise satellite positions and clocks with a dual frequency GPS receiver to remove the first order effect of the ionosphere, PPP is able to provide position solutions at centimeter level. Coordinates estimated with PPP will be in the same global reference frame as the satellite orbits. When using orbits from IGS, estimated receiver coordinates are referred to the IGS realization of ITRF. Beyond that the use of the non-integer ionosphere free linear combinations leads to further effects. The combined code and phase noise are amplified compared to the noise of isolated signals. Furthermore, the integer characteristics of the phase ambiguities get lost and ambiguity fixing is prevented, which leads to even longer convergence times. Convergence times are the time spans from start to a stably accurate solution. The convergence time to reach decimeter accuracy is typically about 30 min under normal conditions. To reach centimeter accuracies the PPP processor needs significantly longer (Katrin et al., 2010).

In comparison with common techniques such as DGPS or RTK, the costs are reduced, because no base stations and no simultaneous observations are necessary. On the other hand the necessary models have to be fetched either from globally acting services like IGS (orbits, satellite clocks) or from regional GNSS service providers (atmospheric delays) and standard interfaces (e.g. RTCM) have to be developed to forward this information to the rover. Further problems still to be solved are coordinate convergence periods of up to 2 h as well as ambiguity resolution, which are harmed by non-integer calibration phase biases. These biases vanish only in difference mode and have to be determined a priori.

The major advantages of PPP lie in two aspects: system simplicity at the user's end and global consistency in terms of positioning accuracy. PPP-based approach significantly reduces the equipment and personnel costs, pre-planning, and logistics compared to conventional GPS network-based approaches. Applying PPP, a single survey team can establish a control network across a large area, rather than the complicated logistics and communications needed to organize multiple survey teams to occupy stations simultaneously. It also reduces the needs to analyze the data using scientific software packages, which are not generally too accessible to inexperienced users. PPP also provides a positioning solution in a dynamic, global reference frame such as the International Terrestrial Reference Frame (ITRF) (Altamimi et al., 2012), negating any local distortions associated with differential positioning techniques when local coordinates are used at CORS.

Last decades several PPP post-processing softwares have been developed based on the above observation models. Also

online web services from different organizations such as the Precise Point Positioning Software Center (<http://gge.unb.ca/Resources/PPP/index.htm>) which has been created under the auspices of the Canadian Geomatics for Informed Decisions Network of Centers of Excellence provide users easy access to online PPP services as CSRS-PPP by Natural Resources Canada (NRCan), GPS Analysis and Positioning Software (GAPS) by University of New Brunswick (UNB), Automatic Precise Positioning Service (APPS) by Jet Propulsion Laboratory (JPL), and magic GNSS by GMV (privately owned technological business group).

3.1. Evaluating the PPP solution

The solution of CSRS-PPP SW is now used extensively to provide realizations of ITRF globally with a precision of a few centimeters. Four groups of data from IGS stations, namely MALI (Malindi, Kenya) on the Somalian plate, RABT (Morocco) on the Nubian Plate, RAMON on the Arabian plate and NICO (Nicosia, Cyprus) on the Eurasian plate, distributed over the different sub-plates of Africa and their positioning were computed and published by the IGS data centers at ITRF2008 Epoch2005 and given in Table 2. The data of the four groups of IGS stations were downloaded from <ftp://garner.ucsd.edu/pub/rinex/2015/100/> for Day 100, 2015 and processed using the Precise Point Positioning module of CSRS-PPP. To transfer the IGS published coordinates from Epoch2005, as: $t_0 = 2005$, to the epoch of the PPP solutions, ITRF2008 Epoch2015.274 as t , the following formula (Ray et al., 2006), is used:

$$P(t_0) = P(t) + P^*(t_0 - t) \quad (7)$$

where

$P(t_0)$ = is the positioning at a reference epoch ITRF2008 Epoch2005,

$P(t)$ = is the positioning value at time t , defined by PPP at Epoch2015.274,

P^* = velocity.

The transferred coordinates of the four IGS stations defined in ITRF2008 Epoch2015.274 are tabulated in Table 3 as computed by IGS <http://itrf.ign.fr/>.

To see how the PPP can be used in updating the ITRF of the IGS points, the solution of PPP with the transferred published IGS ITRF2008 at Epoch2015.274 is given in Table 4. The differences between two solutions are computed and outlined in Table 4. As it is shown in the table, the absolute value of the maximum differences does not exceed 17 mm for the Y component of Nico Station, while it does not exceed few mm for the other stations. By comparing the differences of the two solutions for the four IGS stations, one can easily see that, how the PPP is precise in expressing the epochwise solution of the ITRF frame.

Additionally to see for what extent PPP can be an alternative for the differential techniques, seven test points were processed by Trimble Business Center "TBC" Software, the product of Trimble, with considering the PPP solution of Helwan (PHLW) as a reference station for the processing. The results of the processing are demonstrated in Table 5. As it is shown in Table 5, one can easily see the quality of PPP solution compared with the DGPS solution. In spite of the processed baselines exceeding several tens of kilometers to

Table 2 ITRF2008 station position at Epoch2005.0 and velocities.

Domes	Site	X/VX	Y/VY	Z/VZ	Sigmas		
		m/(m/y)					
35001M002 Rabat	RABT	5255617.683	−631745.687	3546322.552	0.001	0.001	0.001
35001M002		−0.0088	0.0174	0.0142	0.001	0.000	0.0001
33201M001 MALINDI	MALI	4865366.354	4110737.599	−331121.569	0.001	0.001	0.001
33201M001		−0.0172	0.02	0.0167	0.001	0.0001	0.0000
20703S001 Mitz. RAMON	RAMO	4514721.855	3133507.841	3228024.716	0.001	0.001	0.001
20703S001		−0.0205	0.0141	0.0177	0.001	0.0001	0.0001
14302M001 NICOSIA Ath.	NICO	4359415.713	2874117.066	3650777.829	0.001	0.001	0.001
14302M001		−0.0179	0.0116	0.0126	0.001	0.0001	0.0001

Table 3 Data set expressed in ITRF2008 frame station positions at Epoch2015/04/10.

Domes NB	Site name	ID	Soln	X	Y	Z	Sigma x	Sigma y	Sigma z
35001M002	RABAT	RABT	1	5255617.683	−631745.687	3546322.552	0.001	0.001	0.001
33201M001	MALINDI	MALI	1	4865366.177	4110737.805	−331121.398	0.001	0.001	0.001
14302M001	NICOSIA-ATHALASSA	NICO	1	4359415.525	2874117.189	3650777.949	0.001	0.001	0.001
20703S001	Mitzpe Ramon	RAMO	1	4514721.645	3133507.986	3228024.898	0.001	0.001	0.001

Table 4 The updated positioning for four IGS stations defined in ITRF2008 Epoch2015.274 by IGS & PPP.

Sol. type	X	Y	Z
<i>Rabat</i>			
PPP-Solution	5255617.590	−631745.508	3546322.700
IGS-Solution	5255617.593	−631745.508	3546322.698
Differences	−0.003	0.000	0.002
<i>Mali</i>			
PPP-Solution	4865366.174	4110737.798	−331121.393
IGS-Solution	4865366.177	4110737.805	−331121.398
Differences	−0.003	−0.007	0.005
<i>Nico</i>			
PPP-Solution	4359415.522	2874117.172	3650777.950
IGS-Solution	4359415.525	2874117.189	3650777.949
Differences	−0.003	−0.017	0.001
<i>Ramo</i>			
PPP-Solution	4514721.636	3133507.978	3228024.886
IGS-Solution	4514721.641	3133507.982	3228024.891
Differences	−0.005	−0.004	−0.005

120 km, PPP shows good harmony with the DGPS in mm level except the station 0Z20 which has differences of 2.3–3.2 cm that maybe it has the longest baseline as well as it gives the worst accuracy of PPP that is might be due to the surrounding environments around the station.

4. The evaluation study

In 1992, an ESA steering committee developed a plan for the creation of new datum for Egypt, with the following approach (Scott, 1997):

- First, observe approximately 30 stations at approximately 200 km interval, covering all of Egypt, creating a High Accuracy Reference Network (HARN). Both high absolute and relative accuracies are required for these stations.
- Second, establishing the Notational Agricultural Cadastral Network (NACN) relative to these 30 stations, covering the green area of Egypt (Nile Valley and the Delta) at 30–40 km intervals. This station spacing was selected to allow for further densification with single frequency receivers, see Fig. 2.
- Third, densify this network at a station spacing of approximately 5 km for use as cadastral control at the governorate level.
- Finally, replace the existing Egyptian Mercator grid with a new modified UTM coordinate system.

The ITRF1994 was transferred to Egypt's HARN network by connecting it with four IGS stations, namely MATE (Italy), KIT3 (Uzbekistan), HART (South Africa) and MASP in (Canary Island), see Fig. 3. Each HARN's station was observed for six sessions, and every session was 6 h with 30 sec epoch interval. The observation time was planned to produce 1:10,000,000 (Order A) for HARN and 1:1,000,000 (Order B) for NACN relative network accuracy standard between stations. The results of analyzing both of them were defined in ITRF1994 Epoch1996.

To see for what extent can the PPP be an alternative for the differential techniques and its impact on analyzing the geodetic applications that need an ultimate accuracy like the National High Accuracy Reference Networks, a critical example is given to demonstrate this study. The example is concerned with analyzing a part of Egyptian HARN and NACN Networks that is located in and around Nile Delta. The geometric location of this part is illustrated in Fig. 4 and the position of the aforementioned points as given in HARN analysis report (Scott, 1997) is depicted in Table 6. Additionally, this section deals with the computing techniques that are used in transferring the terrestrial frame from epoch to epoch into different frames.

Table 5 The differences between DGPS and PPP solutions for the observed Stations.

St.	DGPS Sol.			PPP Sol.			Differences bet DGPS & PPP		
	X	Y	Z	X	Y	Z	dX	dY	dZ
PHLW	4728141.180	2879662.608	3157147.159	4728141.180	2879662.608	3157147.159	0.000	0.000	0.000
OZ18	4657081.787	2807150.058	3322370.152	4657081.784	2807150.059	3322370.156	0.003	-0.001	-0.004
OZ20	4796793.729	2651830.764	3250924.993	4796793.697	2651830.738	3250924.970	0.032	0.026	0.023
OZ89	4745737.252	2795140.347	3205858.805	4745737.246	2795140.341	3205858.797	0.006	0.006	0.008
OZ94	4739314.560	2828743.551	3186027.207	4739314.553	2828743.544	3186027.199	0.007	0.007	0.008
Burg	4765954.276	2704546.183	3252949.202	4765954.269	2704546.174	3252949.193	0.007	0.009	0.009
O1	4728219.038	2879743.411	3156930.682	4728219.033	2879743.402	3156930.676	0.005	0.009	0.006

Three days campaigns were conducted in June 2015 from 3 to 6, to convert this part of HARN and NACN network in the most recent ITRF available frame at the epoch of observation campaigns, namely ITRF2008 Epoch2015.422. However, we use the aforementioned approach, Eq. (7) in transferring the PPP solution of the specified part of HARN to the ITRF2000 Epoch2000, utilizing the three parameters of Nubian Plate as defined by ITRF2005-PM (Altamimi et al. (2007), Table 1. The results are given in Table 7.

The evaluation strategy is based upon:

1. Evaluating the IGS stations that were used in transferring the ITRF to HARN, by using their published ITRF2008 Epoch2015.422 coordinates values and the related transformation parameter to ITRF1994 Epoch1996 and comparing the transferred values by the reported values of Scott (1997).
2. Transferring the values of HARN and NACN networks that were defined in ITRF2008 Epoch2005 to the original ITRF frame of HARN, namely ITRF1994 Epoch1996 and comparing the resulted values with the original coordinate's values given by Scott (1997). The aforementioned transformation is performed by exploiting the published

14 transformation parameters between different ITRF's Frames by IGS (John and Jim, 2004). However, the transformation process from ITRF2008 Epoch2015.422 to ITRF1994 Epoch1996 will be performed in the following steps:

- a. Transforming the PPP values of HARN and NACN networks defined in ITRF2008 Epoch2015.422 to ITRF2008 Epoch2005 using the published absolute pole Cartesian angular velocity for Nubian Plate, as outlined before.
- b. Transferring the ITRF2008 Epoch2005 to ITRF1994 Epoch2000 using the published parameters in Table 8.
- c. Updating the values specified in Table 8 to be in Epoch1996 instead of Epoch2000.
- d. Compute the differences.

4.1. Evaluating the IGS stations that was used in transferring the ITRF to HARN

Before digging into applying the above procedures, a check for the published transformation parameters is done. This step is

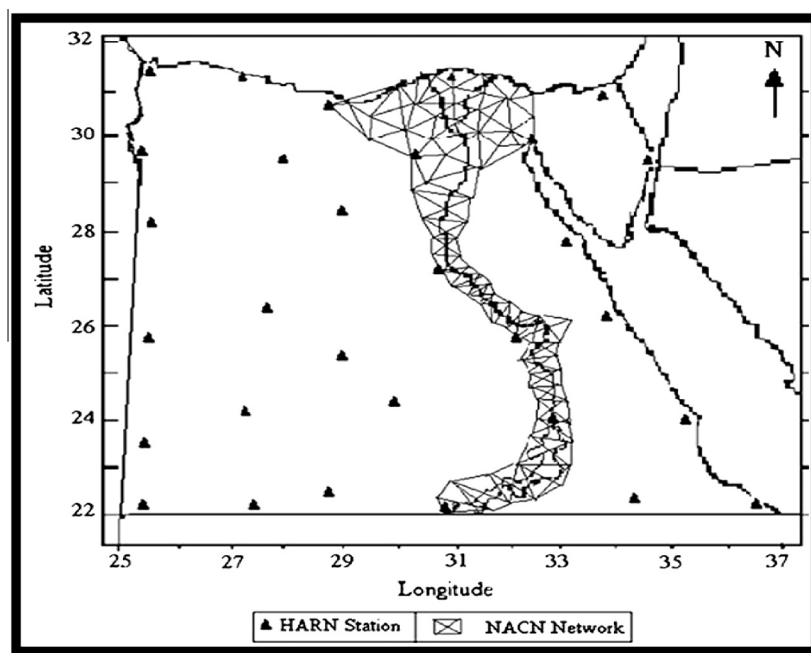
**Figure 2** The HARN and NACN networks.



Figure 3 Connecting parts of Egyptian HARN with four stations of IGS.

so necessary to check the quality of the published data by IGS as well as to see the size of errors embedded in the stations that were used by Scott, 1997 in transferring the ITRF1994 frame to Egypt's HARN, namely MATE (Italy), KIT3 (Uzbekistan), HART (South Africa) and MASP in (Canary Island). Table 9 depicts the coordinates of the four IGS stations defined in ITRF1994 Epoch1996 as given by (Scott, 1997) and the published by IGS in ITRF2008, Epoch2005.

It was stated in http://itrf.ign.fr/rel_trs.php that the standard relation of transformation between two reference systems is an Euclidian similarity of seven parameters: three translation components, one scale factor, and three rotation angles, desig-

nated respectively, $T_1, T_2, T_3, D, R_1, R_2, R_3$, and their first times derivations: $T_1', T_2', T_3', D', R_1', R_2', R_3'$. The transformation of coordinate vector X_1 , expressed in a reference system (1), into a coordinate vector X_2 , expressed in a reference system (2), is given by the following equation:

$$X_2 = X_1 + T + DX_1 + RX_1 \quad (8)$$

With:

$$T = \begin{pmatrix} T_1 \\ T_2 \\ T_3 \end{pmatrix} \quad \text{and} \quad R = \begin{pmatrix} 0 & -R_3 & R_2 \\ R_3 & 0 & -R_1 \\ -R_2 & R_1 & 0 \end{pmatrix}$$

It is assumed that Eq. (8) is linear for sets of station coordinates provided by space geodetic technique (origin difference is about a few hundred meters, and differences in scale and orientation are of 10^{-5} level). Generally, X_1, X_2, T, D, R are function of time. Differentiating Eq. (8) with respect to time gives:

$$\dot{X}_2 = \dot{X}_1 + T' + D'X_1 + DX_1' + R'X_1 + RX_1' \quad (9)$$

D and R are of 10^{-5} level and D^s is about 10 cm per year, the terms DX_1' and RX_1' are negligible which represent about 0.0 mm over years. Therefore, Eq. (9) could be written as:

$$\dot{X}_2 = \dot{X}_1 + T' + D'X_1 + R'X_1 \quad (10)$$

The four stations in Table 7 were transferred from ITRF2008 Epoch2005 to ITRF1994 Epoch2000 using the transformation parameters given in Table 8 and Eq. (8). The results are demonstrated in Table 10. Also the velocities of the specified IGS stations in ITRF1994 are also depicted in Table 10.

To transfer the computed IGS coordinates from Epoch2000, as: $t_0 = 2000$, to the epoch of the HARN solutions, ITRF1994 Epoch1996 as t , Eq. (7) was used. The results of the transformation are given in Table 11. To see the differences between the original coordinate values of the used IGS four stations as given by Scott (1997), defined in ITRF1994 Epoch1996, as outlined in Table 9, the differences between

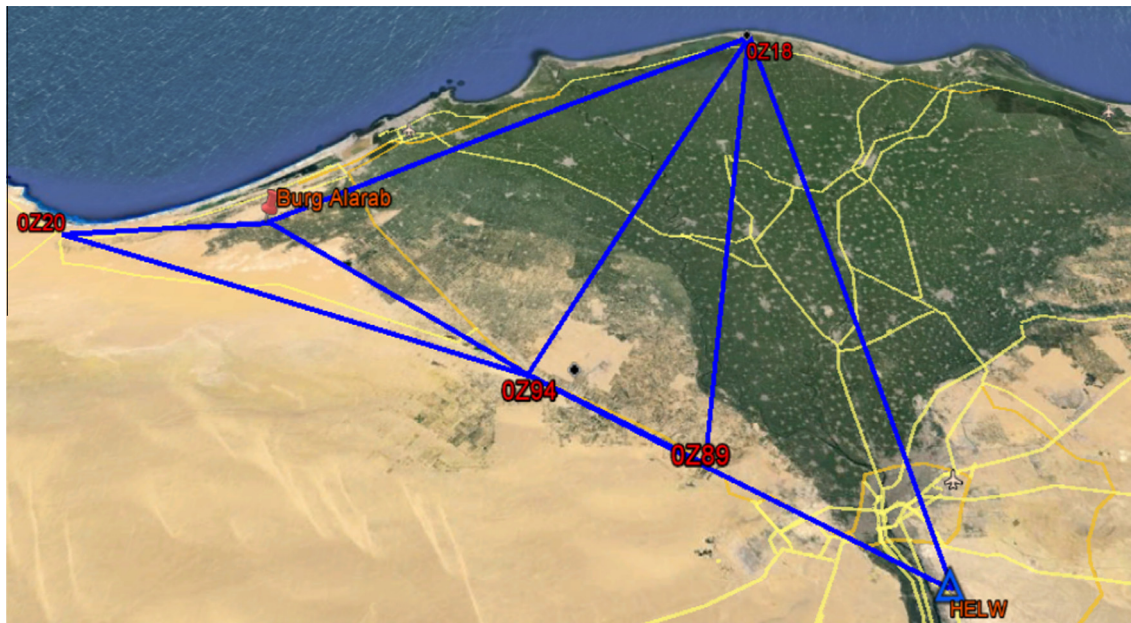


Figure 4 The location of the used part of Egyptian HARN and NACN.

Table 6 The coordinates of chosen points of the HARN and NACN networks.

ITRF1994 Epoch1996 (Scott, 1997)			
Station	X	Y	Z
OZ94	4745737.755	2795140.173	3205858.575
OZ89	4739315.089	2828743.36	3186026.976
OZ18	4657082.606	2807149.887	3322369.803
OZ20	4796794.204	2651830.557	3250924.750

the two ITRFs were computed and are recorded in Table 11. As it is shown in Table 11, in spite of we have already used only in the previous processing the published values and models as specified by IGS, one can see a tolerance ranged between -8.6 cm and 14.6 cm. The reasons behind these differences are mostly due to the limited number of stations, only 13 stations – see Fig. 5, that were used in realizing the ITRF94 that leads to

sub-optimal stations distribution and small discontinuities between IGS realizations of ITRF, as clarified by (Ferland and Kouba, 1996).

4.2. Transferring the solved PPP part of HARN network to the ITRF1994 epoch1996

Firstly, transfer the tested part of HARN and NACN from ITRF2008 epoch2005, specified in Table 5, to HARN ITRF1994 epoch2000, with the aforementioned steps by using Eq. (8) and Table 8. The computation results are given in Table 12.

To transfer the resulted coordinate's values of the tested part of HARN from ITRF1994 Epoch2000 to ITRF1994 Epoch1996, there is a need to define the Nubian Plate Velocity in the same ITRF1994. Eq. (10) can be used in computing the velocities of the Egyptian stations in ITRF1994, provided that the stations velocities should be defined in ITRF2008. This can

Table 7 The part of HARN and NACN network updated in ITRF2000.

St. Id.	PPP results coordinate at Epoch2015.422			Transformed PPP coordinates at ITRF2008 Epoch2005		
	X	Y	Z	X	Y	Z
PHLW	2879662.632	2879662.632	3157147.186	2879662.851	2879662.483	3157147.019
OZ18	4657081.784	2807150.059	3322370.156	4657082.003	2807149.91	3322369.989
OZ20	4796793.697	2651830.738	3250924.970	4796793.916	2651830.589	3250924.803
OZ89	4745737.246	2795140.341	3205858.797	4745737.465	2795140.192	3205858.63
OZ94	4739314.553	2828743.544	3186027.199	4739314.772	2828743.395	3186027.032
Burg	4765954.269	2704546.174	3252949.193	4765954.488	2704546.025	3252949.026
O1	4728219.033	2879743.402	3156930.676	4728219.252	2879743.253	3156930.509

Table 8 Transformation parameters between ITRF2008 Epoch2005 to ITRF1994 Epoch2000.

SOLUTION	T1	T2	T3	D	R1	R1	R1	EPOCH
UNITS.....	mm	mm	mm	Ppb	.001"	.001"	.001"	
RATES	T1'	T2'	T3'	D'	R1'	R2'	R3'	
UNITS.....	mm/y	mm/y	mm/Y	Ppb/Y	.001"/Y	.001"/Y	.001"/Y	
ITRF94	4.8	2.6	-33.2	2.92	0.00	0.00	0.06	2000
rates	0.1	-0.05	-3.2	0.09	0.00	0.00	0.02	

Table 9 The coordinate values of the IGS four stations in ITRF1994, Epoch1996 and the published coordinate values for the nominated IGS stations in ITRF2008 Epoch2005.

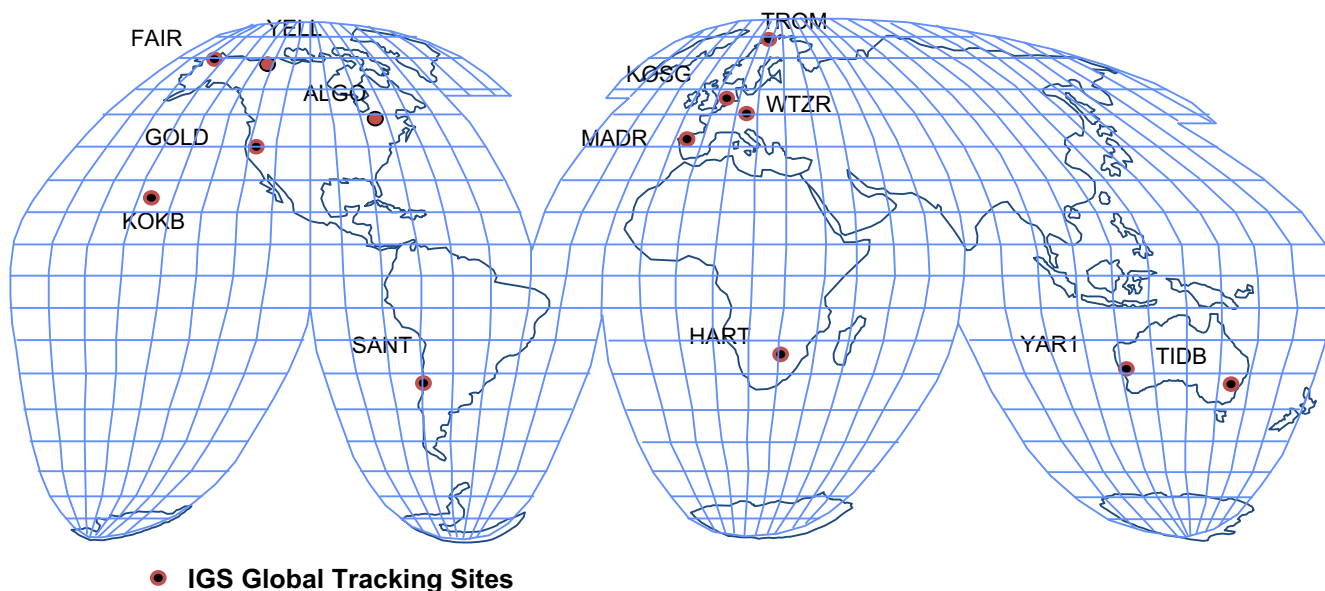
Station	ITRF2008 Epoch2005			ITRF1994 Epoch1996 (as given by Scott (1997))		
MATE	4641949.557	1393045.422	4133287.465	4641949.737	1393045.262	4133287.317
KIT3	1944945.139	4556652.244	4004326.007	1944945.390	4556652.199	4004325.973
HART	5084625.288	2670366.383	-2768494.401	5084625.460	2670366.404	-2768494.470
MAS1	5439192.215	-1522055.484	2953454.847	5439192.277	-1522055.641	2953454.694

Table 10 The transferred coordinate values of the four stations to ITRF1994 Epoch2000.

Station	ITRF1994 Epoch2000			Velocity (m/y)		
MATE	4641949.557	1393045.429	4133287.444	-0.0191	0.0202	0.0121
KIT3	1944945.149	4556652.26	4004325.985	-0.0280	0.0163	0.0064
HART	5084625.308	2670366.394	-2768494.442	-0.0015	0.0164	0.018
MAS1	5439192.236	-1522055.486	2953454.822	0.0001	0.0154	0.0152

Table 11 The differences between the published coordinate values of the four IGS stations and the reported values by Scott (1997) in ITRF1994 Epoch1996.

St. Id	ITRF1994 Epoch1996 transferred from IGS published values in ITRF2008 Epoch2005			ITRF1994 Epoch1996 as reported by Scott (1997)			Differences		
	X	Y	Z	X	Y	Z	dX	dY	dZ
MATE	4641949.633	1393045.348	4133287.396	4641949.737	1393045.262	4133287.317	0.104	-0.086	-0.079
KIT3	1944945.261	4556652.195	4004325.959	1944945.390	4556652.199	4004325.973	0.129	0.004	0.014
HART	5084625.314	2670366.328	-2768494.514	5084625.460	2670366.404	-2768494.470	0.146	0.076	0.044
MAS1	5439192.236	-1522055.548	2953454.761	5439192.277	-1522055.641	2953454.694	0.041	-0.093	-0.067

Station set (13) used for the IGS Realization of ITRF92-93-94**Figure 5** Station set (13) used for IGS realization of ITRF92-93-94.

be performed by applying Eq. (4) and Table 4. The resulted velocities are represented in Table 13. So the HARN stations can be converted to ITRF1994 Epoch1996, by using Eq. (7) and considering Epoch2000 as: $t_0 = 2000$, and Epoch1996 as $t = 1996$. The results are depicted also in Table 13. The differences between the reported part of HARN by Scott (1997) and the computed part based on PPP techniques and the IGS related transformation parameters and velocities defined in ITRF1994 Epoch1996 are displayed in Table 14.

As it is shown in the table, the differences in X-component ranged from 34 to 37 cm, except OZ18 that was partially

destroyed, and Y-component ranged from -8 cm to -11 cm and for Z-component, the differences were ranged between -7 cm and -8 cm, except OZ18. Finally, one can see that size of error budget affects the original processing of Egyptian HARN network which stem from connecting parts of Egyptian HARN with four stations of IGS that were far away from EGYPT, namely HART, KIT3, MAS1 and MAT, forming very long baselines. Also the errors in the definition of ITRF1994 itself were reached 7–14 cm. Additionally, within the plate boundary regions (e.g. in the vicinity of the African Rift and in the northern coastal areas) there will be

Table 12 The Results of Transformation the HARN to ITRF1994 Epoch1997.

St. Id	PPP at ITRF2008 Epoch2005			PPP at ITRF1994 Epoch2000		
	X	Y	Z	X	Y	Z
PHLW	4728141.399	2879662.459	3157146.992	4728141.418	2879662.47	3157146.968
OZ18	4657082.003	2807149.910	3322369.989	4657082.021	2807149.921	3322369.966
OZ20	4796793.916	2651830.589	3250924.803	4796793.935	2651830.599	3250924.779
OZ94	4745737.465	2795140.192	3205858.63	4745737.484	2795140.203	3205858.606
OZ89	4739314.772	2828743.395	3186027.032	4739314.791	2828743.406	3186027.008
Burg	4765954.488	2704546.025	3252949.026	4765954.507	2704546.036	3252949.002
O1	4728219.252	2879743.253	3156930.509	4728219.271	2879743.264	3156930.485

Table 13 The computed velocities and the transferred coordinate values to ITRF1994 Epoch1996 of the specified part of the Egyptian HARN.

St. Id	Velocities at ITRF1994 (m/y)			PPP at ITRF1994 Epoch1996		
	VX	VY	VZ	X	Y	Z
PHLW	-0.0187	0.0149	0.0121	4728141.343	2879662.53	3157147.016
OZ18	-0.0190	0.0146	0.0119	4657081.945	2807149.979	3322370.013
OZ20	-0.0182	0.0151	0.0122	4796793.862	2651830.66	3250924.828
OZ94	-0.0186	0.0150	0.0121	4745737.409	2795140.263	3205858.655
OZ89	-0.0187	0.0149	0.0121	4739314.716	2828743.466	3186027.057
Burg	-0.0184	0.0150	0.0122	4765954.433	2704546.096	3252949.051
O1	-0.0187	0.0149	0.0121	4728219.196	2879743.324	3156930.533

Table 14 The difference between the computed PPP HARN transferred to ITRF1994 Epoch1996 and the given values at the same epoch as computed by Scott (1997).

St. Id	PPP Sol transferred to ITRF1994 Epoch1996			ITRF1994 Epoch1996 (Scott, 1997)			Differences		
	X	Y	Z	X	Y	Z	dX	dY	dZ
OZ18	4657081.945	2807149.979	3322370.013	4657082.606	2807149.887	3322369.803	0.6606	-0.0923	-0.2101
OZ20	4796793.862	2651830.66	3250924.828	4796794.204	2651830.557	3250924.75	0.3421	-0.1029	-0.0782
OZ94	4745737.409	2795140.263	3205858.655	4745737.755	2795140.173	3205858.575	0.3458	-0.0897	-0.0797
OZ89	4739314.716	2828743.466	3186027.057	4739315.089	2828743.36	3186026.976	0.3731	-0.1058	-0.0806

inter-seismic deformation of up to a 3–4 mm/year which will not be modeled using a rigid plate transformation model (Stanaway and Roberts, 2009).

5. Conclusions

To evaluate the performance of the PPP processing engine, several PPP tests on several African IGS station were performed to transfer them to ITRF2005 Epoch2000 using three parameters kinematic rigid plate model and comprising the results of the IGS stations published IERS values in the same Epoch. The differences were just a few centimeters. The results confirm the usability of PPP with the kinematic rigid plate model in updating the frame.

The difference between the computed coordinates and the given original values computed by Scott (1997), in X -component ranged from 34 to 37 cm, and Y -component ranged from -8 to -11 cm and Z -component, and the differences were ranged between -7 and -8 cm. As a closing conclusion for the overall results, one can say that PPP is the most feasible factor in performing datum maintenance by time and cost. The Egyptian HARN and NACN Networks need to update their frame, to be the most recent one either by PPP or by traditional approach.

References

- Altamimi, Z., Collileux, J., Legrand, J., Garayt, B., Boucher, C., 2007. ITRF2005: a new release of the international terrestrial reference frame based on time series of station positions and earth orientation parameters. *J. Geophys. Res.* 112, B09401. <http://dx.doi.org/10.1029/2007JB004949>.
- Altamimi, Z., Métivier, L., Collileux, X., 2012. ITRF2008 plate motion model. *J. Geophys. Res.* 117, B07402. <http://dx.doi.org/10.1029/2011JB008930>.
- Chang, C., Tseng, L., 1998. A Geocentric Reference System in Taiwan. In: *Surv. Rev.*, Department of Surveying and Mapping Engineering Chung Cheng Institute of Technology, Taiwan, ROC.
- Elhattab, A., 2014. Assessment of PPP for establishment of CORS network for municipal surveying in Middle East. *Surv. Rev.* 46 (335), 97–103. <http://dx.doi.org/10.1179/1752270613Y.0000000064>.
- Farhan, M., 2013. Evaluation of GPS Long Baseline Algorithms and Its Implication on New Egyptian Geodetic Control Network. Ph. D. thesis. Faculty of Engineering, Banah University..
- Ferland, R., Kouba, J., 1996. IGS ITRF Realization and Transformations. Geodetic Survey Division Natural Resources Canada (NRCan), Ottawa K1A 0E9, Canada.
- IERS, 2010. <http://itrf.ensg.ign.fr/ITRF_solutions/2005/doc/ITRF2005_GPS.SSC.txt> (accessed on 11th November, 2010).
- John, D., Jim, 2004. International Terrestrial Reference Frame (ITRF) to GDA94 Coordinate Transformations. Minerals and Geohazards Division, Geosciences Australia, version 01.03.2004.
- Katrin, H., Florian, H., Christoph, A., Ana, K., Robert, W., Philipp, B., 2010. PPP: Precise Point Positioning – Constraints and Opportunities, Facing the Challenges – Building the Capacity Sydney, Australia, 11–16 April 2010.
- Rabah, M., Abd-Elsattar, A., Hamed, M., 2015. Towards a semi kinematic datum for Egypt. *Positioning* 2015 (6), 49–60. <http://dx.doi.org/10.4236/pos.2015.63006> (published online August 2015 in SciRes. <<http://www.scirp.org/journal/pos>>, <<http://www.scirp.org/Journal/PaperInformation.aspx?>>).
- Ray, J., Dong, D., Altamimi, Z., 2006. IGS reference frames: status and future improvements. *GPS Solut.* 8 (4), 251–266. <http://dx.doi.org/10.1007/s10291-004-0110-x>.
- Saleh, M., Becker, M., 2013. A new velocity field from the analysis of the Egyptian Permanent GPS Network (EPGN). *Arab. J. Geosci.* <http://dx.doi.org/10.1007/s12517-013-1132-x>.
- Scott, M., 1997. Results of Final Adjustment of New National Geodetic Network. Geodetic Advisor for the Egyptian Survey Authority.
- Stanaway, R., Roberts, C., 2009. A simplified parameter transformation model from ITRF2005 to any static geocentric datum (e.g. GDA94). In: *Proceedings from International Global Navigation Satellite Systems Society IGNSS Symposium 2009*, 1–3 December, Surfers Paradise, Qld, Australia.