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Assessment of Different Approaches of Dynamic/Static Datum Transformation in Egypt using Different Plate Motion Models

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Abstract*: *In this work, one critical geodetic issue in Egypt is discussed. The dynamic nature of the International Terrestrial Reference Frame (ITRF) as a geodetic datum, while the Global Positioning System (GPS) network in Egypt is tied to a static datum (ITRF94 epoch 1996) is considered a very critical geodetic issue. Tying any derived ITRF coordinates to the Egyptian network cannot be directly applied due to the effect of the tectonic motion of the African plate, in addition to the datum definition change from one ITRF realization to another. The simplest solution for this problem is neglecting the effect of the datum definition change and using a Plate Motion Model (PMM) for the backward propagation of coordinates until the specified epoch of the static datum. However, the most opportune solution is applying the 14-parameter datum transformation. Assessment the quality of both solutions based on recent Global Navigation Satellite System (GNSS) observations will be presented in this study. In addition, a new set of 14 parameters is derived to describe the transformation process of the African plate in a better way. Four stations of the Egyptian network were used in the assessment by comparing the transformed coordinates to the known coordinates, tied to ITRF94 epoch 1996. Also, 5 different PMM(s) were used to assess the compatibility of the recent PMM(s) with the actual tectonic plate motion in Egypt. This study shows that using the derived parameters in the 14-parameter transformation model gives the best results among all approaches. In addition, using PMM: APKIM2005D or ITRF2008-PMM as the adopted PMM gave the best results, while using NNR-MORVEL56 and PB2002 gave the worst results. For the horizontal component differences, the 14-parameter transformation model with the derived parameters approach could reach to 1.3cm with Root Mean Square (RMS) 3.1cm in case of using APKIM2005D and 1cm with RMS 2.3cm in case of using ITRF2008-PMM. On the other hand, for the vertical component differences, they ranged from 0.8cm to 10.9cm with RMS 8.6cm. Generally, using the derived parameters in the 14-parameter transformation model adopting APKIM2005D or ITRF2008-PMM as the used PMM can be applied to any recently derived coordinates, tied to the latest ITRF realization, to tie them to the Egyptian static datum.

Index Terms*: *Datum Transformation, Dynamic Datums, GNSS, ITRF, Plate Motion Models, Static Datums.

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I. INTRODUCTION

The GPS network in Egypt comprises the High Accuracy Reference Network (HARN) distributed over the country, in addition to the Notational Agricultural Cadastral Network (NACN) which is the densification of HARN around Nile Valley and the Delta. Thirty stations form the skeleton of HARN with almost 200 km interval, while NACN includes 123 stations with 30-40 km interval. The HARN network was tied to the International GNSS Service (IGS) stations while the NACN network was tied to the HARN network using 12 common stations [1]. These stations were observed to produce 1:10,000,000 (Order A) relative network accuracy standard between the HARN stations and 1:1,000,000 (Order B) between the NACN stations [2].

The Egyptian GPS network adopted ITRF94 epoch 1996 as the reference epoch for the Egyptian datum [1]. As this datum is static, coordinates of stations do not change with time, ignoring both the tectonic motion and the different definition for all the following ITRF realizations. On the other hand, the IGS stations are referenced to the ITRF dynamic datum, where both the tectonic motion and the different definition for all the following ITRF realizations are taken into consideration causing the coordinates of all stations to change continuously. Hence, any tie between the Egyptian network stations and the IGS stations will be inapplicable and unreliable. The latest realization of ITRF(s) is ITRF2014 but data can only be obtained referenced to previous realizations and consequently, ITRF2008 will be used as the latest reference frame for recent observations. This study discusses the different approaches that can be applied to transform any ITRF2008 coordinates at any epoch to their corresponding HARN/NACN coordinates referenced to ITRF94 epoch 1996. Also, the agreement of the transformed coordinates with the HARN/NACN coordinates in the horizontal and vertical positions will be discussed for the different approaches. In addition, the compatibility of five different Plate Motion Models PMM(s) to the actual motion of the African plate in Egypt will be assessed.

II. DATUM TRANSFORMATION

A. Seven-Parameter Transformation

There are a number of mathematical 3D transformations to transform from one coordinate system to another and in this study, where satellite datums are the main concern, the Bursa-Wolf transformation model is suitable for application.

The Bursa-Wolf transformation is a seven-parameter similarity transformation which adopts the cardanian rotation [3]. Mathematically, the model is expressed as:

$$\begin{pmatrix}X_2\\Y_2\\Z_2\end{pmatrix} = (1+\Delta s)\begin{pmatrix}1 & \kappa & -\emptyset\\ -\kappa & 1 & \omega\\ \emptyset & -\omega & 1\end{pmatrix}\begin{pmatrix}X_1\\Y_1\\Z_1\end{pmatrix} + \begin{pmatrix}T_x\\T_y\\T_z\end{pmatrix} \qquad (1)$$

Where

X_1, Y_1 and Z_1 are the coordinates of a point in the first coordinate system.

X_2, Y_2 and Z_2 are the corresponding coordinates in the second coordinate system.

T_x, T_y and T_z denote the translations in the X, Y and Z directions, respectively.

Δs is a scale difference quantity.

ω, $\emptyset$ and κ denote the rotation angles about X, Y and Z axes, respectively.

In order to get the seven transformation parameters between two coordinate systems, three common points, at least, should be available. The availability of more than three common points allows the least squares adjustment to be applied to obtain the transformation parameters. The related part in this study will rely on the combined least squares adjustment at which the coordinates of common points are given an individual weighting unlike the parametric least squares adjustment at which all pairs of common points (coordinate difference) are assumed to have the same variance and therefore the same weight. The equations used for this solution are described in details in [4].

B. 14-Parameter Transformation

The tremendous achievements in the field of determining the geo-center, orientation and scale of the terrestrial reference systems have surpassed the prediction of anyone. One significant improvement is that the change in the seven transformation parameters, discussed in the previous subsection, can now be well estimated. This achievement became possible thanks to the achievements regarding the precise ephemeris determination, precise calibration of the antenna phase center offset, troposheric and ionospheric delay models, etc.

The 14-parameter transformation model uses the 7 transformation parameters and the rate of change of each parameter. The authentic importance of applying the 14-parameter transformation between geocentric datums appears when there is a need to transform coordinates tied to a dynamic datum to the corresponding coordinates tied to a static datum. In other words, its importance appears when there is a need to transform coordinates tied to one ITRF realization at a certain epoch to the corresponding coordinates tied to another ITRF realization at another epoch. In this case, two factors should be taken into consideration. The first is the datum definition (origin, orientation and scale), while the second is the epoch (time) definition which cannot be neglected considering the velocity of any station.

The 14-parameter transformation model is based on transforming coordinates tied to coordinate system (1) at epoch (t_o) to the corresponding coordinates tied to coordinate system (2) at epoch (t), while (t_k) is the epoch at which the seven transformation parameters are determined.

Regarding the relation between the different epochs included in the model, the general case is considering that t_o, t and t_k are not equal. However, a special case may occur when t_o, t and t_k are equal and at this case, the 14-parameter Transformation model changes to the traditional 7-parameter transformation model.

The mathematical derivation of the 14-parameter transformation model is based on the derivative of equation 1 with the help of the position-time kinematic relation expressed mathematically as:

$$\{X(t)\} = \{X(t_o)\} + (t - t_o)\{v(t_o)\} \qquad (2)$$

where

$\{X(t)\}$ is the position vector at epoch t.

$\{X(t_o)\}$ is the position vector at epoch t_o.

$\{v(t_o)\}$ is the velocity vector.

The detailed mathematical derivation can be found in [5] and the final mathematical form of this model can be expressed as:

$$\begin{pmatrix}X(t)\\Y(t)\\Z(t)\end{pmatrix}_2 = \begin{pmatrix}T_x(t_k)\\T_y(t_k)\\T_z(t_k)\end{pmatrix} + (1+\Delta s(t_k))\begin{pmatrix}1 & \kappa(t_k) & -\emptyset(t_k)\\ -\kappa(t_k) & 1 & \omega(t_k)\\ \emptyset(t_k) & -\omega(t_k) & 1\end{pmatrix} * \left[\begin{pmatrix}X(t_o)\\Y(t_o)\\Z(t_o)\end{pmatrix}_1 + (t-t_o)\begin{pmatrix}v_x(t_o)\\v_y(t_o)\\v_z(t_o)\end{pmatrix}_1\right] + (t-t_k) * \left[\begin{pmatrix}\dot{T}_x\\ \dot{T}_y\\ \dot{T}_z\end{pmatrix} + \left[\dot{\Delta s}\begin{pmatrix}1 & \kappa(t_k) & -\emptyset(t_k)\\ -\kappa(t_k) & 1 & \omega(t_k)\\ \emptyset(t_k) & -\omega(t_k) & 1\end{pmatrix} + (1+\Delta s(t_k)) * \begin{pmatrix}0 & \dot{\kappa} & -\dot{\emptyset}\\ -\dot{\kappa} & 0 & \dot{\omega}\\ \dot{\emptyset} & -\dot{\omega} & 0\end{pmatrix}\right] * \left[\begin{pmatrix}X(t_o)\\Y(t_o)\\Z(t_o)\end{pmatrix}_1 + (t_k - t_o)\begin{pmatrix}v_x(t_o)\\v_y(t_o)\\v_z(t_o)\end{pmatrix}_1\right]\right] \qquad (3)$$

where

v_x, v_y and v_z are the station velocities in the X, Y, and Z directions, respectively.

$\dot{T}_x$, $\dot{T}_y$, $\dot{T}_z$, $\dot{\Delta s}$, $\dot{\omega}$, $\dot{\emptyset}$ and $\dot{\kappa}$ are the rates of change of the seven transformation parameters.

III. PLATE MOTION

Modeling of the tectonic motion is essential for the derivation of the coordinates of any point located on Earth's crust. Tectonic plates can be treated as rigid caps on the surface of a sphere. The plate motion can be described by its rotation about a virtual axis passing through the center of the sphere (Euler's theorem) [6]. The absolute plate motion is described relative to a fixed reference system that can be chosen to be a rotation-free system coupled with Earth (no-net-rotation condition applied) and it can be described in two ways. The first is by using the latitude and longitude of the Euler's pole and the rate of rotation in degrees/million years.

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The other way is by using the rotation components of the plate about the three Cartesian axes of Earth in radians/million years. The three Cartesian rotation rates can be calculated from the definition of the Euler's pole using the following equations after converting the latitude. And longitude of the Euler's pole and the rate of rotation to radians [7]:

$$\Omega_X = cos(\Phi)\, cos(\Lambda)\, \omega \quad (4)$$
$$\Omega_Y = cos(\Phi)\, sin(\Lambda)\, \omega \quad (5)$$
$$\Omega_Z = sin(\Phi)\, \omega \quad (6)$$

Where

Φ, Λ and ω are the latitude and longitude of the Euler's pole and the rate of rotation, respectively. Ω_X, Ω_Y and Ω_Z are the rotation components of the plate about the three Cartesian axes. A site velocity in the Cartesian form can be calculated for any point located on a rigid plate using:

$$\begin{pmatrix} v_x \\ v_y \\ v_z \end{pmatrix} = \begin{pmatrix} \Omega_Y Z - \Omega_Z Y \\ \Omega_Z X - \Omega_X Z \\ \Omega_X Y - \Omega_Y X \end{pmatrix} . 10^{-6} \quad (7)$$

where

v_x, v_y and v_z are the site velocities in the Cartesian form in meters per year.

X, Y and Z are the Cartesian coordinates of the point in meters.

Ω_X, Ω_Y and Ω_Z are the angular velocities of the plate, where the point is located, in radians per million years.

With the tremendous achievements regarding the space geodetic techniques, a precise estimation of the point velocities was possible. Actual PMM(s) have been estimated by the inversion of these velocities [7].

A number of plate motion models are available to be used in this study but the scope will be focused on the most recently developed tectonic plate motion models; PB2002, APKIM2005, APKIM2005D, ITRF2008-PMM and NNRMORVEL56 [8], [9], [10] and [11]. This study is concerned with the plate Cartesian rotation rates for the African/Nubian plate in order to properly estimate the velocity of any point located on the African plate, in case of APKIM2005, APKIM2005D and PB2002, or on the Nubian plate, in case of NNR-MORVEL56 and ITRF2008-PMM. The plate Cartesian rotation rates for ITRF2008-PMM are published in [10]. For the other models, the latitude and longitude of the Euler's pole and the rate of rotation of the plates are published in [9] and [11] and their plate Cartesian rotation rates can be calculated using Equations 4, 5 and 6. The plate Cartesian rotation rates, in the No-Net Rotation (NNR) frame, for the African / Nubian plate are listed in Table 1.

Table 1. Absolute Plate Cartesian Rotation Rates in (Radians/Million Years) for the African/Nubian Plate According to Different PMM(s)

Model	Plate	Ω_X	Ω_Y	Ω_Z
PB2002	Africa	0.000894	-0.003097	0.003925
APKIM2005	Africa	0.000604	-0.003195	0.003624
APKIM2005D	Africa	0.000566	-0.003055	0.003612
ITRF2008-PMM	Nubia	0.000461	-0.002899	0.003505
NNR-MORVEL56	Nubia	0.001261	-0.003191	0.003768

IV. THE USED HARN/NACN STATIONS

In this study, recent GNSS observations for a number of existing HARN/NACN stations are essential. Observations for 4 stations could be obtained in the form of Receiver Independent Exchange Format (RINEX) data files. Stations OZ88, OZ98, OY11 and OZ92, shown in Figure 1, were occupied using GNSS receivers on 1 January 2015 (epoch 2015), 3 January 2015 (epoch 2015.008), 23 August 2015 (epoch 2015.644) and 9 September 2015 (epoch 2015.69), respectively. Occupation times ranged from 1.5 hours for OY11 to 6.5 hours for OZ92. The obtained RINEX data were processed in the Differential GNSS (DGNSS) processing mode using Trimble Business Center (TBC) software. A number of neighboring IGS stations, shown in Figure 1, participated in this study for this purpose and they are listed in Table 2.

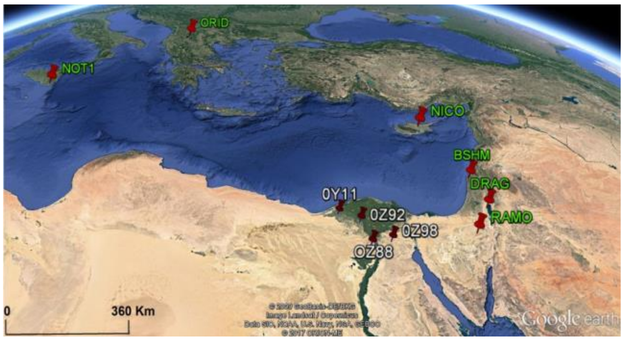

Fig. 1. The HARN/NACN Stations and the IGS Stations Involved in This Study

Table 2. The Chosen IGS Stations to be Involved in the DGNSS Processing

Site	ID
NICOSIA-ATHALASSA	NICO
Noto	NOTl
Ohrid	ORID
Haifa	BSHM
Mitzpe Ramon	RAMO
Metzoki Dragot	DRAG

The IGS RINEX data files and final orbits files, for the previously mentioned dates, were acquired from the Crustal Dynamics Data Information System (CDDIS) data center. The ITRF2008 coordinates, at the previously mentioned epochs, for the used IGS stations were obtained from the ITRF website [http://itrf.ensg.ign.fr/site_info_and_select/solutions_extraction.php] to be used in the processing as constraints (Fixed coordinates). The processed and adjusted coordinates, tied to ITRF2008 at the epoch of measurements, showed large positional differences with the HARN/NACN coordinates, tied to ITRF94 epoch 1996 and published by the Egyptian Surveying Authority (ESA) after the final adjustment of the network.

V. BACKWARD PROPAGATION USING PMM(S)

The simplest way to transform between coordinates at different epochs is using a PMM which can model the velocity of any point on the surface of Earth.

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The backward propagation of the coordinates of any point, using a PMM, can serve this purpose well. However, the problem in the transformation process is neglecting any effect on the coordinates caused by the change in the datum definition. This problem will affect the transformation quality but based on the fact that the tectonic motion has much larger effect, it may be an acceptable approach. The prime target at this stage is to properly estimate the velocity of the used stations, according to the used PMM(s), using Equation 7. Table 3 shows the calculated velocities in the X, Y and Z directions for the used HARN/NACN stations according to different PMM(s).

Table 3. Calculated Velocities in the X, Y and Z Directions for the used Stations According to Different PMM (s) in (m/Year)

PMM	Station	v_x	v_y	v_z
PB2002	OZ88	-0.0210	0.0158	0.0172
	OZ92	-0.0210	0.0157	0.0171
	OZ98	-0.0212	0.0156	0.0172
	OY11	-0.0208	0.0157	0.0172
APKIM2005	OZ88	-0.0204	0.0153	0.0169
	OZ92	-0.0205	0.0152	0.0168
	OZ98	-0.0207	0.0151	0.0168
	OY11	-0.0203	0.0153	0.0168
APKIM2005D	OZ88	-0.0200	0.0154	0.0161
	OZ92	-0.0200	0.0152	0.0160
	OZ98	-0.0202	0.0152	0.0160
	OY11	-0.0198	0.0153	0.0161
ITRF2008-PMM	OZ88	-0.0192	0.0152	0.0151
	OZ92	-0.0192	0.0151	0.0150
	OZ98	-0.0194	0.0150	0.0150
	OY11	-0.0190	0.0152	0.0150
NNR-MORVEL56	OZ88	-0.0208	0.0139	0.0187
	OZ92	-0.0209	0.0137	0.0186
	OZ98	-0.0211	0.0137	0.0187
	OY11	-0.0207	0.0138	0.0186

Hence, the coordinate change for any station, from the epoch of the static datum (1996) to the epoch of measurements, can be calculated by multiplying the station velocity in (m/year) in the epoch difference in (years). Table 4 shows the resulted coordinate changes according to different PMM(s).

Table 4. Coordinate Changes for the used HARN/NACN Stations from the Epoch of the Static Datum (1996) to the Epoch of Measurements According to Different PMM(s)

Station	PMM	Coordinate Change		
		X (m)	Y (m)	Z (m)
OZ88	PB2002	0.399	-0.300	-0.327
	APKIM2005	0.388	-0.291	-0.321
	APKIM2005D	0.380	-0.293	-0.306
	ITRF2008-PMM	0.365	-0.289	-0.287
	NNR-MORVEL56	0.395	-0.264	-0.355
OZ92	PB2002	0.413	-0.309	-0.337
	APKIM2005	0.404	-0.299	-0.331
	APKIM2005D	0.394	-0.299	-0.315
	ITRF2008-PMM	0.378	-0.297	-0.295
	NNR-MORVEL56	0.412	-0.270	-0.366
OZ98	PB2002	0.403	-0.297	-0.327

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	APKIM2005	0.393	-0.287	-0.319
	APKIM2005D	0.384	-0.289	-0.304
	ITRF2008-PMM	0.369	-0.285	-0.285
	NNR-MORVEL56	0.401	-0.260	-0.355
OY11	PB2002	0.409	-0.308	-0.338
	APKIM2005	0.399	-0.301	-0.330
	APKIM2005D	0.389	-0.301	-0.316
	ITRF2008-PMM	0.373	-0.299	-0.295
	NNR-MORVEL56	0.407	-0.271	-0.365

The resulted coordinate changes should be subtracted from the processed coordinates at the epoch of measurements to get the estimated coordinates at epoch 1996. In order to assess the quality of the backward propagation approach in the horizontal and vertical components, separately, all Cartesian coordinates were transformed to their geodetic coordinates. The difference in the latitude ($\Delta Ø$) and longitude ($\Delta\lambda$) between the propagated coordinates and the HARN/NACN coordinates gives an indication of the quality of transformation in the horizontal component. On the other hand, the difference in the ellipsoidal height (Δh) gives an indication of the quality of transformation in the vertical component. Prior to evaluating the quality in the horizontal component, $\Delta Ø$ and $\Delta\lambda$ should be transformed to the equivalent distances in meters by multiplying their values in the equivalent distance to one arc second which vary from one station to another and can be calculated using the basic rules of geometric geodesy. The resulted equivalent distances to one arc second ranged from 30.792m to 30.796m in the latitude and from 26.579m to 26.844m in the longitude.

Finally, the following equation can be applied to get the difference in the horizontal component:

$$\Delta HZ \simeq \sqrt{\Delta Ø^2 + \Delta\lambda^{\,2}} \quad (8)$$

where

ΔHZ is the difference in the horizontal component in meters.
$\Delta Ø$ is the difference in latitude in meters.
$\Delta\lambda$ is the difference in longitude in meters.

Table 5 shows the final results of ΔHZ and Δh, in addition to the positional difference (ΔP) according to different PMM(s).

TABLE 5. Differences between the Propagated Coordinates and the HARN/NACN Coordinates According to Different PMM(S)

Station	PMM	ΔHZ (m)	Δh (m)	ΔP (m)
OZ88	PB2002	0.04	-0.128	0.134
	APKIM2005	0.025	-0.129	0.132
	APKIM2005D	0.022	-0.129	0.130
	ITRF2008-PMM	0.031	-0.129	0.132
	NNR-MORVEL56	0.048	-0.129	0.138
OZ92	PB2002	0.048	-0.033	0.058
	APKIM2005	0.033	-0.032	0.046
	APKIM2005D	0.027	-0.032	0.042
	ITRF2008-PMM	0.035	-0.032	0.048
	NNR-MORVEL56	0.053	-0.032	0.062
OZ98	PB2002	0.048	-0.105	0.115
	APKIM2005	0.034	-0.103	0.109
	APKIM2005D	0.036	-0.103	0.109
	ITRF2008-PMM	0.045	-0.103	0.112
	NNR-MORVEL56	0.043	-0.103	0.112
OY11	PB2002	0.086	-0.132	0.158
	APKIM2005	0.073	-0.133	0.151
	APKIM2005D	0.065	-0.133	0.148
	ITRF2008-PMM	0.059	-0.133	0.146
	NNR-MORVEL56	0.078	-0.132	0.153

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VI. DERIVING A NEW SET OF 14 TRANSFORMATION PARAMETERS

Applying the 14-parameter datum transformation is the most opportune approach in dynamic/static datum transformation. There are sets of published transformation parameters to transform any coordinates tied to recent ITRF realizations at any epoch to the corresponding coordinates tied to the previous realizations at any epoch. These parameters were derived considering ITRF stations located on different tectonic plates. This study is concerned with the HARN/NACN stations located on the African/Nubian plate and consequently, the used strategy adopts a preliminary Analysis based on considering only the ITRF stations located on the African/Nubian plate which can describe the Transformation process in a better way than considering Also the stations located on other plates. Generally, having more available stations to derive any set of transformation parameters gives the opportunity to obtain higher quality and

accuracy. Unfortunately, only eight stations can serve the strategy in this study.

These stations have available observations for the concerned period (from 1996 to 2017) and they are all tied to both ITRF94 and ITRF2008. The site name and country for these eight stations are listed in Table 6, while their distribution on the plate is shown in Figure 2.

Table 6. ITRF Stations used in Deriving the Set of Parameters

Site name	Country
Arlit	Niger
Arta Geophysical Observatory DJIBOUTI	Djibouti
Dakar	Senegal
Hartebeesthoek	South Africa
Hartebeesthoek	South Africa
HELWAN	Egypt
LIBREVILLE	Gabon
Sutherland	South Africa

Fig. 2. ITRF Stations used in Deriving the set of Parameters

The coordinates of the concerned ITRF stations, tied to ITRF94 epoch 1996, with their uncertainties (standard deviations) could be obtained from the ITRF website [http://itrf.ensg.ign.fr/site_info_and_select/solutions_extraction.php]. Also, the coordinates, tied to ITRF2008, with their uncertainties were obtained at epochs 1996, 1997, 1998, ..., 2017. At first, the seven transformation parameters from ITRF2008 epoch (t_k) to ITRF94 epoch 1996 were computed 22 times for (t_k = 1996, 1997, 1998, ……, 2017) using a MATLAB script which uses the Bursa-Wolf model with combined least squares adjustment to derive the transformation parameters. The relations between the seven transformation parameters and time were plotted as shown in Figures 3 to 9.

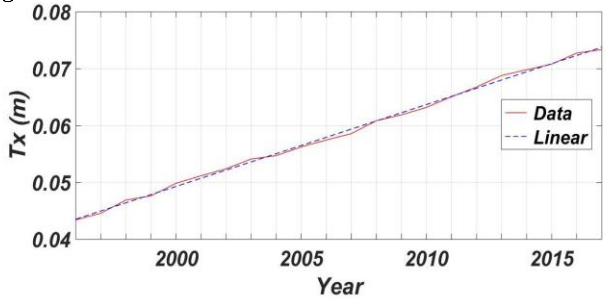

Fig. 3. Change of T_x over Time and the best Fitting Linear Attitude

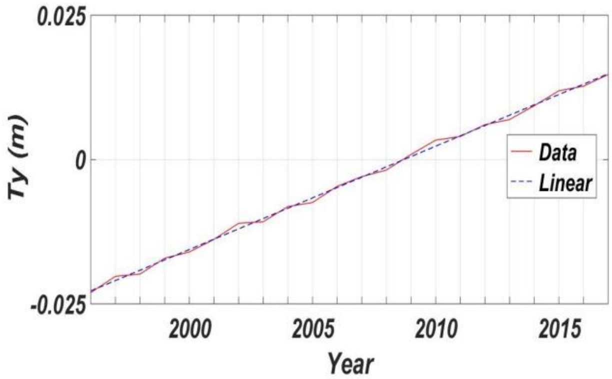

Fig. 4. Change of T_y Over Time and the Best Fitting Linear Attitude

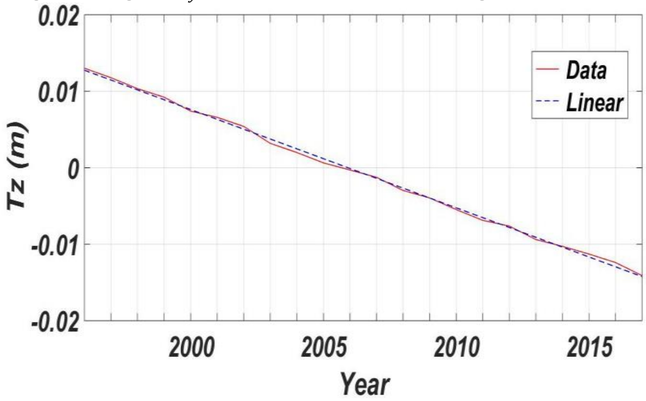

Fig. 5. Change of T_z Over Time and the best Fitting Linear Attitude

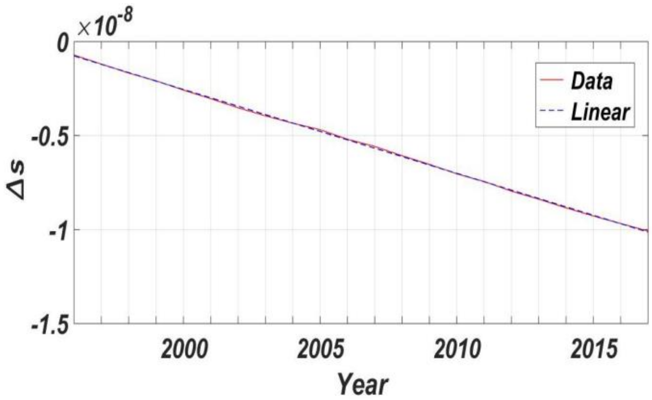

Fig. 6. Change of Δs Over Time and the best Fitting Linear Attitude

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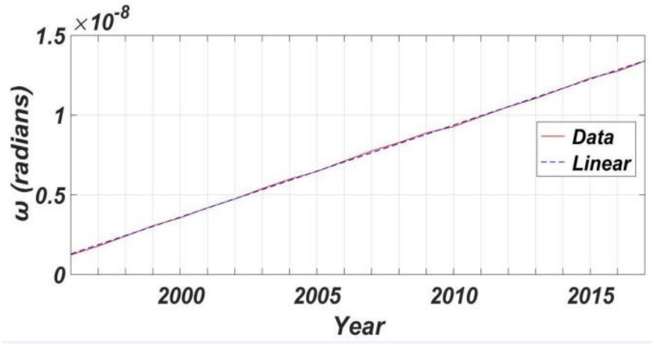

Fig. 7. Change of ω Over Time and the Best Fitting Linear Attitude

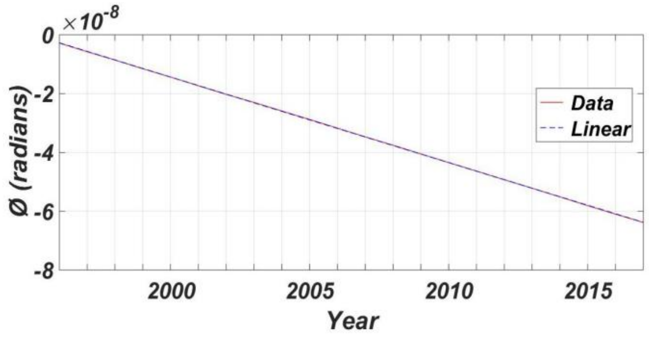

Fig. 8. Change of Ø Over Time and the best Fitting Linear Attitude

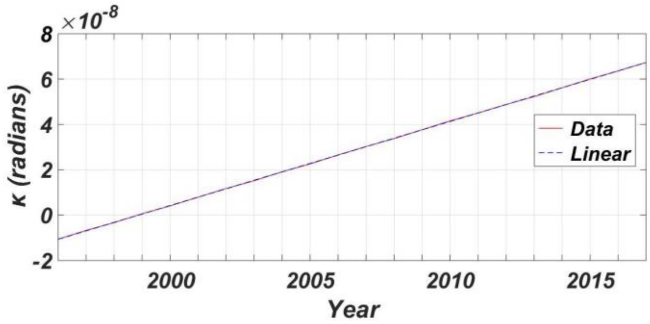

Fig. 9. Change of κ Over Time and the best Fitting Linear Attitude

All relations showed an attitude which is very close to be linear. The best fitting linear equation ($y = ax + b$) for each relation was concluded using MATLAB where (y) represents the parameter, (x) is the epoch (time) and (a) is the rate of change of the parameter. From the linear equations, the rate of change for each parameter could be determined. Epoch 2011 was chosen to be the initial epoch (t_k) in the model as it has, generally, the minimum residuals to the best fitting linear relations. Hence, the required set of parameters needed to apply the model is complete and listed in Table 7.

TABLE 7. Derived Transformation Parameters from ITRF2008 to ITRF94 at t_k = 2011

Parameter	Value	Parameter	Value
T_x (m)	0.0650680	$\dot{T}_x$ (m/y)	0.0014402
T_y (m)	0.0040002	$\dot{T}_y$ (m/y)	0.00179
T_z (m)	-0.0068786	$\dot{T}_z$ (m/y)	-0.0012849
Δs	-7.43965 $* 10^{-9}$	$\Delta\dot{s}$ (y^{-1})	-4.4627 $* 10^{-10}$
ω (rad.)	9.91322 $* 10^{-9}$	$\dot{\omega}$ (rad./y)	5.7749 $* 10^{-10}$
Ø (rad.)	-4.63484 $* 10^{-8}$	$\dot{Ø}$ (rad./y)	-2.9075 $* 10^{-9}$
κ (rad.)	4.50444 $* 10^{-8}$	$\dot{\kappa}$ (rad./y)	3.7117 $* 10^{-9}$

Equation 3 was applied to the processed coordinates. The resulted transformed coordinates were compared to the HARN/NACN coordinates and the differences in the horizontal and vertical components could be determined and the results are shown in Table 8.

TABLE 8. Differences Between the Transformed Coordinates, using the Derived 14 Transformation Parameters, and the HARN/NACN Coordinates According to Different PMM(s)

Station	PMM	ΔHZ (m)	Δh (m)	ΔP (m)
OZ88	PB2002	0.042	-0.105	0.113
	APKIM2005	0.031	-0.106	0.111
	APKIM2005D	0.013	-0.105	0.106
	ITRF2008-PMM	0.012	-0.105	0.106
	NNR-MORVEL56	0.071	-0.106	0.127
OZ92	PB2002	0.048	-0.009	0.049
	APKIM2005	0.035	-0.009	0.036
	APKIM2005D	0.017	-0.008	0.019
	ITRF2008-PMM	0.010	-0.009	0.013
	NNR-MORVEL56	0.074	-0.009	0.074
OZ98	PB2002	0.042	-0.081	0.091
	APKIM2005	0.027	-0.080	0.085
	APKIM2005D	0.016	-0.081	0.082
	ITRF2008-PMM	0.019	-0.080	0.082
	NNR-MORVEL56	0.062	-0.080	0.101
OY11	PB2002	0.083	-0.109	0.137
	APKIM2005	0.068	-0.108	0.128
	APKIM2005D	0.056	-0.109	0.122
	ITRF2008-PMM	0.039	-0.108	0.115
	NNR-MORVEL56	0.089	-0.108	0.140

Already, there are sets of transformation parameters, published on the ITRF website [http://itrf.ensg.ign.fr/trans_para.php] and the concerned parameters in this study transforms ITRF2008 coordinates to ITRF94 coordinates. These parameters were derived at epoch (t_k) 2000. To avoid any confusion about the quality of the derived parameters compared to the published parameters, the same analysis is performed for the published parameters in case of using ITRF2008-PMM as it is the adopted PMM in ITRF solutions. Table 9 shows the differences at this case.

TABLE 9. Differences Between the Transformed Coordinates, using the Published 14 Transformation Parameters, and the HARN/NACN Coordinates According to ITRF2008-PMM

Station	ΔHZ (m)	Δh (m)	ΔP (m)
OZ88	0.011	-0.117	0.117
OZ92	0.018	-0.022	0.028
OZ98	0.027	-0.092	0.096
OY11	0.053	-0.122	0.132

VII. ANALYSIS OF RESULTS

At this stage, results of the different approaches are analyzed. A common behavior between all approaches is that station OY11 gives the worst results among all stations and the reason behind that is mainly due to be the short occupation time for this station (only 1.5 hours).

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By analyzing the differences in the vertical component in Table 8, in case of using the 14-parameter transformation model with the derived parameters, they ranged from 0.8cm to 10.9cm with mean value 7.6cm and RMS 8.6cm. On the other hand, the differences in the vertical component in Table 9, in case of using the 14-parameter transformation model with the published parameters, they ranged from 2.2cm to 12.2cm with mean value 8.8cm and RMS 9.7cm. In addition, propagating the coordinates using PMM(s) obtained differences in the vertical component, in Table 5, ranging from 3.2cm to 13.3cm with mean value 9.9cm and RMS 10.7cm. Only station OZ92 achieved a very high quality in the vertical component with 0.8cm difference in case of using the 14-parameter transformation model with the derived parameters. The reason for that is the long occupation time for OZ92 (6.5 hours). For the other stations, the resulted differences in the vertical component are large compared to the differences in the horizontal component. The reason for that is the long baselines formed between the HARN/NACN stations and the used IGS stations, while the occupation time was not long enough to give better vertical precision except for station OZ92. Regarding the resulted differences in the horizontal component, the difference by propagating the processed coordinates back to epoch 1996 using a PMM could reach to 2.2cm with RMS 4.1cm in case of using APKIM2005D. In addition, the difference by using the 14-parameter model with the derived parameters could reach to 1.3cm with RMS 3.1cm in case of using APKIM2005D and 1cm with RMS 2.3cm in case of using ITRF2008-PMM. The statistics of the resulted differences in the horizontal component obtained for these two approaches are expressed in Figures 10 and 11.

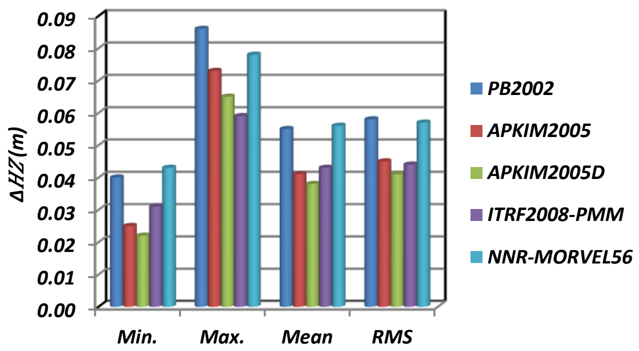

Fig. 10. Statistics of the Resulted Differences in the Horizontal Component in case of using the first Approach: Propagating the Coordinates Back using the Different PMM(s)

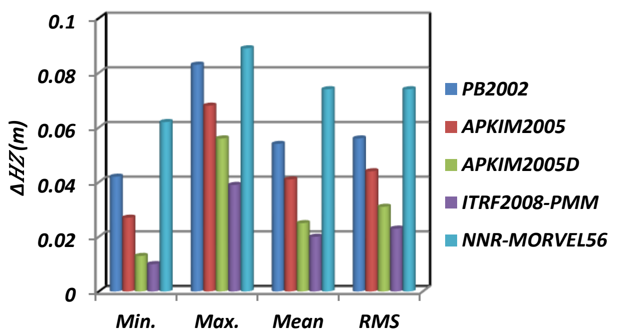

Fig. 11. Statistics of the Resulted Differences in the Horizontal Component in case of using the 14-Parameter Transformation Model with the Derived Parameters for the Different PMM(s)

Using the 14-parameter model with the published parameters and ITRF2008-PMM obtained differences in the horizontal position varying from 1.1cm to 5.3cm with mean value 2.7cm and RMS 3.2cm. This numerical analysis concludes that the 14-parameter model, using the derived parameters, gave the best results compared to the other approaches. Despite the few number of available ITRF stations on the African/Nubian plate, this approach proved better quality. Besides, if more than eight stations were available, the transformation process on the African/Nubian plate would be described in a better way. Regarding the evaluation of the compatibility of the recent PMM(s) with the actual tectonic plate motion in Egypt, APKIM2005D and ITRF2008-PMM gave the best results compared to the other PMM(s). On the other hand, NNRMORVEL56 and PB2002 gave the worst results.

VIII. CONCLUSION

The quality of different approaches for dynamic/static datum transformation in Egypt. Is assessed. Different recently developed PMM(s) were used to assess the compatibility of each PMM with the actual tectonic plate motion in Egypt. Fourteen parameters were derived to be used in the 14- parameter transformation model to describe the transformation process on the African/Nubian plate in a better way. The results showed that:

- Using the 14-parameter transformation model with the derived parameters gives the best results in the differences in the horizontal and vertical components.
- For the horizontal component differences, the 14-parameter model with the derived parameters could reach to 1.3cm with RMS 3.1cm in case of using APKIM2005D and 1cm with RMS 2.3cm in case of using ITRF2008-PMM.
- For the vertical component differences in case of using the 14-parameter model with the derived parameters, they ranged from 0.8cm to 10.9cm with RMS 8.6cm.
- The station occupation time using GNSS receivers had a significant effect on the transformation quality.
- APKIM2005D and ITRF2008-PMM gave the best results compared to the other PMM(s), while NNR-MORVEL56 and PB2002 gave the worst results in the transformation process.

Generally, using the derived parameters in the 14-parameter transformation model adopting APKIM2005D or ITRF2008-PMM as the used PMM can be applied to any recently derived coordinates, tied to the latest ITRF realization, to tie them to the Egyptian static datum.

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