# Assessing ITRF Conversion Models for Kinematic GNSS Topographic Mapping in Coastal Areas: A Case Study in Egypt

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## ABSTRACT

Global Navigation Satellite Systems (GNSS) surveying has been extensively performed for a wide range of mapping activities. Precise Point Positioning (PPP) is considered a major approach for collecting and processing 3D GNSS data for static and kinematic applications. Processing PPP data results in 3D coordinates based on the most recent International Terrestrial Reference Frame (ITRF) while a national mapping system might be related to another frame. This study aims to investigate several simple ITRF transformation formulas (between ITRF 2014 and ITRF 1994), within the accuracy limits of kinematic surveying, particularly in coastal areas in Egypt. Twelve coordinate transformation methods, in 3D and 2D scenarios, have been analyzed using about two thousands GNSS points along the Red sea coastlines. Accuracy analysis has been performed for each model trying to figure out the optimal approach to be utilized in topographic mapping projects in Egypt. Results showed that almost all models produced comparable and four transformation models produce standard deviations less than 0.20 m while seven models produced a precision less than 0.10 m. Based on standards of medium-scale topographic maps, it can be concluded that those models might be considered as appropriate models for ITRF conversion in GNSS topographic surveys in Egypt.

**Keywords:** ITRF, GNSS, Coastal Regions, Topographic Maps, Egypt

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## 1. INTRODUCTION

Movement of the tectonic plates causes significant coordinates' changes over time. Such a natural phenomenon is noteworthy in the digital revolution and worldwide use of 3D digital spatial data. On another hand, precise and up-to-date topographic maps constitute a central aspect in integrated coastal planning and management. Kinematic Global Navigation Satellite Systems (GNSS) provide a cost-effective accurate tool for collecting 3D field spatial data needed for topographic mapping. Within GNSS methods, Precise Point Positioning (PPP) has been extensively utilized for positioning in the last couple of decades either in the static or kinematic modes just by using one GNSS receiver. PPP has been employed in several projects including shoreline monitoring (Marques et al., 2019), hydrographic surveys (Abdallah and Schweiger, 2015), deformation monitoring (Zheng et al., 2014)

Recently, online GNSS processing services have been used by several geomatics users worldwide as an easy and quick tool for processing raw GNSS data. Available services include, for examples, the Canadian Spatial Reference System (CSRS) Precise Point Positioning: CSRS-PPP (https://webapp.geod.nrcan.gc.ca/geod/tools-outils/ppp.php), the Australian Online GPS Positioning Service: AUSPOS (http://www.ga.gov.au/scientific-topics/positioning-navigation/geodesy/auspos), and the American Online Positioning User Services: OPUS (https://www.ngs.noaa.gov/OPUS/). Such positioning services generally apply correction models of the satellite orbits errors and the satellite clock errors, as determined by the International GNSS Service: IGS, to increase the accuracy of absolute positioning using a single GNSS receiver. Online GNSS processing services have been utilized extensively in the last decade in numerous surveying and geodetic applications worldwide (e.g. Isioye et al., 2019, Alkan et al., 2016, and Berber et al., 2014). Nationally, such processing services have been investigated and utilized in Egypt (e.g. El Shouny and Miky 2019, and Moamed et al., 2007).

ITRF is the realization of the International Terrestrial Reference System (ITRS) updated periodically since 1992 by the ITRF organization (Altamimi 2016). Transformation parameters between a recent ITRF and its preceding models are determined and published (ITRF 2020). The most recent model is the ITRF 2014. Several studies have investigated the coordinate transformation between different ITRF frames worldwide (e.g. Smith 2020). Nationally, Egypt has established the High-Accuracy Reference Network (HARN) in 1995 as the national GPS-based geodetic datum satisfying the 1: 10,000,000 accuracy standards (ESA 1997). HARN, depicted in Fig. 1, has been developed based on ITRF 1994 (epoch 1996.4992). Consequently, results attained from online GNSS processing services relative to the ITRF 2014 deviate significantly from the corresponding values tied to the HARN network. For instance, Dakhil (2015) has investigated updating the HARN network using PPP technique and found that the coordinates variations between ITRF2008 (epoch 2015) and the

ITRF 1994 (epoch 1996.4992) range from 0.34 to 0.37 m in the X coordinates, from -0.08 m to -0.11 m in the Y coordinates, and from -0.07 m to 0.08 m in the Z coordinates. Also, Ahmed and Hassan (2019) have utilized 8 common stations between the HARN network and the Continuously Operating Reference Station (CORS) network in Egypt and found that the average differences between the ITRF1994 and ITRF2008 equal 0.348 m, 0.342 m, and -0.200 m in the N, E, h directions respectively. Concerning such significant differences, Rabah, et al. (2015) have proposed the utilization of a semi-kinematic geodetic datum for Egypt instead of a fixed one to account for the tectonic movements.

Topographic mapping using online GNSS processing services result in 3D coordinates (X,Y,Z) usually based on the ITRF 2014. Such coordinated need to be converted to the local ITRF1994-based reference to be compatible with the Egyptian mapping datum. Additionally, the attained 3D coordinates might be projected to a 2D coordinate system for producing contour maps and Digital Elevation Model (DEM) for coastal management applications. As far as the authors' concern, there is no investigation has been carried out to define a simple relation between both ITRF frames over the HARN network in Egypt. Even though the transformation parameters are published between both frames, their accuracy might differ from one region to another because of the variations of tectonic movements. This paper investigates the reliability of some straightforward 2D and 3D coordinates conversion methods to facilitate kinematic GNSS surveying particularly for medium-scale topographic mapping in coastal areas.

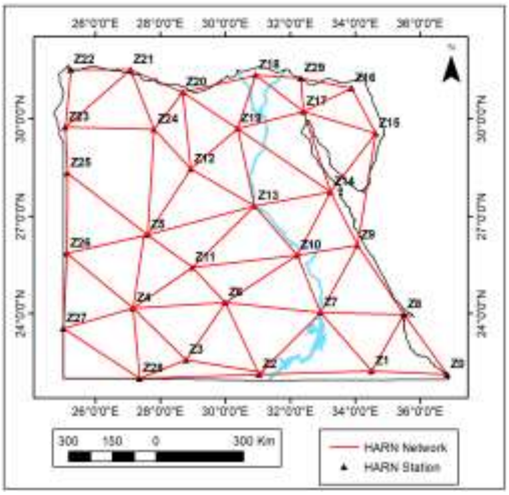

**Fig. 1: The HARN Geodetic Network of Egypt**

## 2. METHODOLOGY

Similarity or Helmert datum transformation process, in 2D or 3D coordinate systems, constitutes a normal task in geodetic and photogrammetric applications. 3D datum transformation models contain, among others, the Bursa- Wolf and the Molodensky-Badekas models. The basic mathematical model can be stated, in a matrix representation, as (e.g. Hofmann-Wellenhof et al, 2008):

$$X_T = c + sRX \tag{1}$$

$$X_T = \begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \end{bmatrix}, \quad X = \begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix}, \quad c = \begin{bmatrix} dX \\ dY \\ dZ \end{bmatrix}, \quad R = \begin{pmatrix} 1 & R_3 & -R_2 \\ -R_3 & 1 & R_1 \\ R_2 & -R_1 & 1 \end{pmatrix} \tag{2}$$

where,
$X_T$ and X are the coordinate vectors for both the transformed and the original 3D coordinate systems respectively, c is the shift vector, s is the scale factor expressed in part-per-million (ppm) units, and R is the 3D rotation matrix containing the three small rotations $R_1$, $R_2$, and $R_3$ about the X, Y, and Z-axis respectively.

For Bursa- Wolf model, the rotations are carried out at the origin of the transformed frame (Fig. 2a). However, Molodensky-Badekas model defines the rotations carried at a specific central point ($X_0$, $Y_0$, $Z_0$) (Fig. 2b). Consequently, the first model has seven unknown parameters and the second model has ten parameters. Assuming small values of the three rotation parameters, both models might be solved in four unknowns (three-shift parameters and a scale factor) and in other cases, three unknowns (shift parameters) could be enough for simplicity.

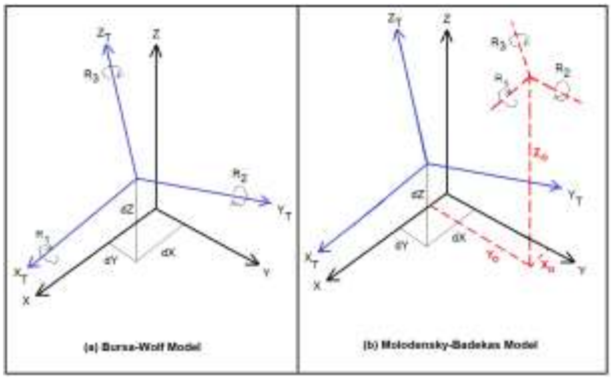

**Fig. 2: 3D Datum Transformation Models**

For the 2D transformation using a planner coordinates systems (UTM for example), the mathematical model could be written as (ibid):

$$X_T = \begin{bmatrix} E_2 \\ N_2 \end{bmatrix}, \quad X = \begin{bmatrix} E_1 \\ N_1 \end{bmatrix}, \quad c = \begin{bmatrix} dE \\ dN \end{bmatrix}, \quad R = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \tag{3}$$

where: α is rotation angle between both 2D coordinate systems.

Equation 3 could be re-written explicitly as:

$$
\begin{aligned}
E_2 &= dE + s\cos\alpha E_1 + s\sin\alpha N_1 \\
Y_2 &= dN + s\sin\alpha E_1 + s\cos\alpha N_1
\end{aligned}
\tag{4}
$$

Equations 3 and 4 would be solved generally in four unknowns and might be solved in just two (shift) parameters for simplicity.

Other unconventional transformation models could integrate 3D and 2D coordinate systems in just one step. For example, the Leica Geomatics Office (LGO 8.4) software performs a direct transformation from X, Y, Z coordinates on the first reference to E, N planner coordinates on the second reference. For instance, it transforms X, Y, Z on ITRF 2014 (epoch 2019.9861) directly to E,N on ITEF 1994 (epoch 1996.4992). That step is called a one-step transformation model and solves for four unknowns: two coordinates of the rotation origin and two datum shift parameters. Additionally, LGO 8.4 performs another transformation process that combines a sequence of 3D Molodensky-Badekas transformation (X, Y, Z transformation between two datums) followed by a 2D transformation solved for the four aforementioned unknowns. Such a process is called the stepwise datum transformation that could be utilized to transforms X, Y, Z on ITRF 2014 (epoch 2019.9861) directly to E,N on ITEF 1994 (epoch 1996.4992). A third transformation process offered in LGO 8.4 is called a two-step transformation, which is similar to the stepwise transformation but using the Buras-Wolf 3D transformation model.

Since the spatial relation between two ITRF frames in a small area could be relatively systematic, the remove-average mathematical model might be applied too. That model is represented by the following two simple equations in 2D:

$$
\begin{aligned}
N_2 &= N_1 - aver_{\Delta N} \\
E_2 &= E_1 - aver_{\Delta E}
\end{aligned}
\tag{5}
$$

where $aver_{\Delta N}$ and $aver_{\Delta E}$ are the averages of N, E coordinates variations between the 2D planner coordinates for both systems respectively. Similarly, equation 5 could be written in 3D coordinates (X, Y, Z) too.

It worth mentioning that all the previous transformation models have been investigated herein, in terms of both precision and accuracy, for the sake of choosing an optimal simple datum transformation model that facilitates the GNSS-based topographic mapping for coastal management in Egypt.

## 3. AVAILABLE DATA

The dataset utilized in the current study has been extracted from the ongoing research project conducted by the Survey Research Institute (SRI) for GNSS mapping of coastlines of the Red Sea from Suez to the Egypt-Sudan borders. Data include 1850 points being surveyed, on

December 2019, by kinematic GNSS in four lines extending about 19 kilometers in length, with approximately a point every ten meters (Fig. 3).

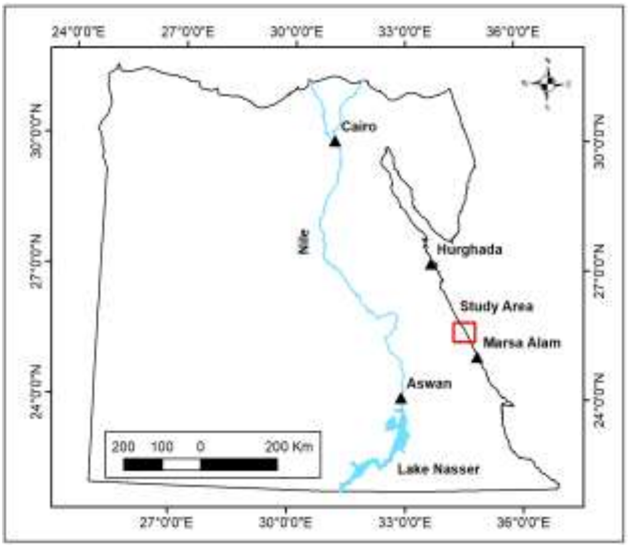

**Fig. 3: The Study Area**

## 4. RESULTS AND DISCUSSIONS

The utilized GNSS kinematic surveys have been tied, in a static session, to the HARN national GPS network and the Trimble Business Center (TBC) v. 4.1 software has been utilized for data processing. Consequently, the computed coordinates of the kinematic points are referenced to the ITRF 1994 (epoch 1996.4992) frame. On the other hand, the raw GNSS kinematic datasets have been uploaded to the CSRC-PPP website and their ITRF 2014 (epoch 2019.9861) coordinates have been obtained. The coordinates discrepancies between ITRF 2014 (epoch 2019.9861) and ITRF 1994 (epoch 1996.4992) have been computed and their statistical summary is presented in Table. 1. From this table, it can be recognized that the coordinates' variations between the two frames are in the order of half a meter in both 2D and 3D coordinates. Moreover, it can be seen that the range of horizontal coordinates variations vary from 0.08 to 0.15 m over the study area. That implies that the remove-average mathematical model (Eq. 5) could be utilized as a simple datum transformation model. Furthermore, it can be recognized that the resultant 2D vector of horizontal coordinates variations (on UTM), due to tectonic movements, equals 0.708 m in magnitude and its azimuth is N 51$^{o}$ E. Such findings extremely necessitate datum transformation in GNSS mapping when utilizing the online GNSS processing survives.

**Table 1: Coordinates Variations between ITRF 2014 (epoch 2019.9861) and ITRF 1994 (epoch 1996.4992) in Egypt (m)**

| Coordinates Variations (ITRF 2014 - ITRF 1994) | Minimum | Maximum | Average | Standard Deviation |
|---|---|---|---|---|
| dE (UTM) | 0.455 | 0.611 | 0.553 | ± 0.016 |
| dN (UTM) | 0.402 | 0.483 | 0.442 | ± 0.012 |
| | | | | |
| dX | -1.043 | -0.463 | -0.740 | ± 0.130 |
| dY | -0.47 | 0.367 | 0.415 | ± 0.096 |
| dZ | 0.014 | 0.462 | 0.238 | ± 0.086 |

Next, the aforementioned mathematical models have been applied to come up with transformation models between ITRF 2014 (epoch 2019.9861) and ITRF 1994 (epoch 1996.4992). So, the LGO 8.4 software has been used in determining similarity transformation equations in both 3D and 2D systems. Tables 2 and 3 presents the accomplished results.

**Table 2: 3D Transformation Models between ITRF 2014 (epoch 2019.9861) and ITRF 1994 (epoch 1996.4992) in Egypt**

| Model No. | Model | No. of Parameters | Results |
|---|---|---|---|
| 1 | Bursa-Wolf | 3 | dX = 0.740 ± 0.003 m<br>dY = -0.170 ± 0.003 m<br>dZ = -0.238 ± 0.003 m |
| 2 | | 4 | dX = 3.502 ± 1.467 m<br>dY = 1.733 ± 0.011 m<br>dZ = 1.362 ± 0.850 m<br>s = -0.582 ± 0.310 ppm |
| 3 | | 7 | dX = -3.561 ± 8.458 m<br>dY = 95.957 ± 7.880 m<br>dZ = -98.511 ± 5.265 m<br>$R_1$= -3.016 ± 0.035 "<br>$R_2$ = 2.270 ± 0.245 "<br>$R_3$ = 2.355 ± 0.329 "<br>S = -0.583 ± 0.121 ppm |
| 4 | Molodensky-Badekas | 6 | $X_o$ = 4736812.545 m<br>$Y_o$ = 3264642.161 m<br>$Z_o$ = 2744958.911 m<br>dX = 0.740 ± 0.003 m<br>dY = -0.170 ± 0.003 m<br>dZ = -0.238 ± 0.003 m |
| 5 | | 7 | $X_o$, $Y_o$, $Z_o$, dX, dY, and dZ as above,<br>s = -0.583 ± 0.310 ppm |
| 6 | | 10 | $X_o$, $Y_o$, $Z_o$, dX, dY, dZ, and s as above,<br>$R_1$= -3.016 ± 0.035 "<br>$R_2$ = 2.270 ± 0.245 "<br>$R_3$ = 2.355 ± 0.329 " |

**Table 3: 2D Transformation Models between ITRF 2014 (epoch 2019.9861) and ITRF 1994 (epoch 1996.4992) in Egypt**

| Model No. | Model | No. of Parameters | Results |
|---|---|---|---|
| 7 | Classical 2D<br>(E,N to E,N) | 4 | $X_o$ = 658074.948 m<br>$Y_o$ = 2838742.895 m<br>dE = -0.553 ± 0.0003 m<br>dN = -0.442 ± 0.0003 m |
| 8 | | 6 | $X_o$, $Y_o$, dE, and dN as above,<br>$\alpha$ = -0.092 ± 0.008 "<br>s = -0.654 ± 0.039 ppm |
| 9 | Two Steps<br>(X,Y,Z to E,N) | 9 | Bursa-Wolf 3D parameters:<br>dX = 121.200 m, dY = -98.240 m, dZ = 10.800 m, $R_3$ = 0.544", s = -0.226 ppm<br>Plus grid Transformation:<br>dE = 10.854 ± 0.001 m. dN = 164.147 ± 0.001 m, $X_o$ = 2838731.603 m, $Y_0$ = 657910.248 m |
| 10 | Stepwise<br>(X,Y,Z to E,N) | 12 | Molodensky-Badekas 3D parameters:<br>dX = 0.473 ± 0.0006 m, dY = -0.354 ± 0.0006 m, dZ = -0.393 ± 0.0006 m, $X_o$ = 4736812.54 m, $Y_0$ = 3264642.161 m, $Z_0$ = 2744958.911m<br>Plus grid Transformation:<br>dE = 0.000 m. dN = 0.000 m, $X_o$ = 658074.948 m, $Y_0$ = 2838742.895 m, $\alpha$ = -0.081 ± 0.016 ", s = -0.634 ± 0.079 ppm |
| 11 | Removing Average | 2 | $aver_{\Delta N}$ = 0.442 m<br>$aver_{\Delta E}$ = 0.553 m |

Precision analysis of the residuals, as expressed by their standard deviations, has been carried out for the utilized transformation models between ITRF 2014 (epoch 2019.9861) and ITRF 1994 (epoch 1996.4992) in Egypt. Table 4 presents the statistical characteristics of the attained results over the 1850 GNSS kinematic points. It can be noticed, from that table, that almost all models produce comparable results. Additionally, four transformation models (no. 3, 6, 10, and 11) produce standard deviations less than 0.20 m. Also, seven models (no. 3, 6, 7, 8, 9, 10, and 11) produce a precision less than 0.10 m. It is known that standards of medium-scale topographic maps and DEM development match a ten-centimeters tolerance in the horizontal coordinates. Then, it can be concluded that those models might be considered as appropriate models for ITRF conversion in GNSS topographic surveys in Egypt. From a precision point of view, either the Bursa-Wolf or the Molodensky-Badekas models with 7 and

10 parameters respectively (models no. 3 and 6) could be considered the optimum transformation model for 3D coordinates with a precision level less than 0.10 m. Also, the classical 2D transformation and removing average models are the best methods for planner coordinates transformation with a precision level of less than 0.05 m.

**Table 4: Precision Analysis of Utilized Transformation Models (m)**

| Model No. | Minimum Residuals | Maximum Residuals | Average of Residuals | Overall Standard Deviation of Residuals |
|---|---|---|---|---|
| 1 | -0.302 | 0.277 | 0.0001 | 0.183 |
| 2 | -0.302 | 0.278 | 0.0001 | 0.183 |
| 3 | -0.151 | 0.188 | 0.0000 | 0.071 |
| 4 | -0.302 | 0.277 | 0.0001 | 0.183 |
| 5 | -0.302 | 0.278 | -0.0001 | 0.183 |
| 6 | -0.151 | 0.188 | 0.0000 | 0.071 |
| 7 | -0.098 | 0.058 | 0.0000 | 0.020 |
| 8 | -0.098 | 0.058 | 0.0000 | 0.019 |
| 9 | -0.167 | 0.122 | 0.0000 | 0.074 |
| 10 | -0.120 | 0.087 | 0.0000 | 0.047 |
| 11 | -0.099 | 0.057 | 0.0000 | 0.020 |

## 5. CONCLUSIONS

Nowadays, the world witness a revolution in collecting, processing, and utilization of 3D spatial data. Precise 3D (and also 4D) coordinates play a major role in geomatics applications, particularly with the widespread of GNSS utilization. In this regard, the coordinates changes due to tectonic movements are noteworthy and should be considered in topographic mapping.

It is a matter of reality that 3D coordinates obtained from on-line GNSS processing services are based on the most recent ITRF while a national mapping system might be related to another frame. Hence, this study has investigated several simple ITRF transformation formulas (between ITRF 2014 and ITRF 1994), within the accuracy limits of kinematic surveying, particularly in coastal areas in Egypt. Twelve coordinate transformation methods have been analyzed using about two thousands GNSS points along the Red sea coastlines.

Accomplished results showed that almost all models produced comparable and four transformation models produce standard deviations less than 0.20 m while seven models produced a precision less than 0.10 m. Based on standards of medium-scale topographic maps, it can be concluded that those models might be considered as appropriate models for ITRF conversion in GNSS topographic surveys in Egypt. From a precision point of view, either the Bursa-Wolf or the Molodensky-Badekas models with 7 and 10 parameters respectively could be considered the optimum transformation model for 3D coordinates with a precision level less than 0.10 m. Also, the classical 2D transformation and removing average models are the best methods for planner coordinates transformation with a precision level of less than 0.05 m. Since Egypt is entirely located within the Nubian tectonic plate, the attained ITRF transformation models are recommended to be utilized in all topographic mapping projects in the country.

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