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3D Modelling of Earth Kinematics in Palestine for GNSS and Geodetic Time-Dependent Positioning

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Abstract**: The use of GNSS technologies for precise point positioning enabled the calculations for single-point observations or relative positioning of long baselines. The GNSS absolute and relative positioning techniques can be implemented between points within different tectonic plates, while the classical surveying methods start from local reference/triangulation points to near points within a few kilometers. The definition of the kinematic models of the earth has become an important role in GNSS measurements techniques and networks adjustment methods based on international terrestrial reference frames (ITRF), where the reference points can be located in different continents and tectonic plates. Thus, the position calculations in the ITRF systems are time-dependent. To satisfy the requirements of land and cadastral surveying, the bidirectional transformation between classical geodetic networks and GNSS global, regional and local networks is nowadays a primary requirement in modern geodesy. While the classical networks were defined locally assuming a static earth system, the ITRF coordinates by GNSS techniques are defined globally and directly affected by earth kinematics including plate tectonics and local crustal movements. However, Palestine has a special kinematic situation because it is located at the border between two plates; Nubia/Sinai plate and the Arabia plate along the Jordan valley line. Thus, the result is unsteady surface kinematics all over the country, which has a longitudinal shape parallel to the Jordan valley rift. Using the IGS/EUREF stations and GNSS stations data that are freely available on the internet, varying positional velocities were calculated in both magnitude and direction using years of daily available GNSS raw observations. The GNSS precise observation techniques have proven that the points of the classical networks were subjected to a kinematic situation over the years. Therefore, the Palestinian geodetic network has to be revised for kinematic effects for the integration with the modern GNSS positioning. In this work, the effect of surface movements is included in the calculations between the different ITRF coordinate systems and the classical geodetic network of Palestine. To achieve the required transformations between ITRF and the classical network, a velocities model was established and tested utilizing GIS raster interpolation. The accuracy of the modeled velocities could support 1cm in static or real-time GNSS positioning. This made it possible for the integration between geodetic measurements between different time epochs.

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I. INTRODUCTION

At the beginning of the 1920s, the project of establishing the geodetic triangulation network of Palestine was started by the Survey of Palestine to be used for the cadastral surveying, planning and mapping issues in Palestine. By 1935, the major parts of the geodetic network was completed for both observations and calculations of geographic and plane coordinate of the measured points. The network consisted of roughly 100-second order (major points), marked by letter M, and more than 14000 points of the third and fourth-order triangulation network and traversing points, see figure (1).

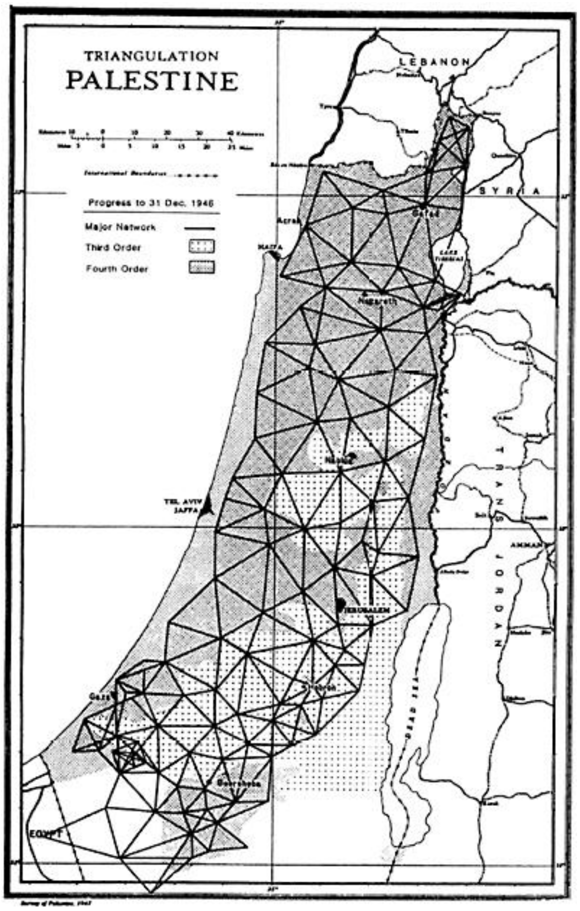

Figure (1): The network of geodetic points in Palestine. [3]

The field tests by Survey of Palestine and the Egyptian surveyors invited during the British mandate have shown that the accuracy of the network is first/second-order degree. This network has defined the coordinate system for Palestine. However, the network consisted of the coordinates in a two dimensional projected system (Easting, Northing) [1]. But the heights were missing or calculated by trigonometric leveling with an accuracy level required for distance reductions during network calculations. Additionally, an extra and separate network of precise leveling Bench Marks with orthometric heights was established to fulfill the needs of engineering projects [2].

The Survey Department of Palestine has selected Cassini-Soldner map projection for the Palestinian grid, which is a map projection with specifications suitable for narrow and longitudinal countries. Besides, it was commonly used worldwide at these times for cadastral mapping and engineering surveys [4]. The origin of the projection system was selected near Jerusalem at Mar Elias monastery hill located on the major triangulation point (82M). The parameters of the map projection system were chosen to keep all coordinates in the mapping operations in Palestine with positive values covering the whole triangulation network. But this left the southern part of the Negev desert to be located in negative values [1]. This system was named Palestine1923Grid. During the Second World War, another map projection was introduced for military uses and applications. This system used Transverse-Mercator projection applied based on the same datum Palestine1923Grid. The system was given the name of Palestine1923Belt using the basic defining parameters and the same origin of Palestine1923Grid. Although Palestine1923Belt is introduced nowadays in all surveying and mapping software, it is not practically used for cadastral or engineering surveys in Palestine. In table (1), the defining parameters of both Palestine1923Grid and Palestine1923Belt are introduced [5].

Table (1): The parameters of the map projections of Palestine [6].

Parameter	Palestine1923Grid	Palestine1923Belt
Semi-major axis	6378300.789	6378300.789
Inverse flattening	293.4663155389802	293.4663155389802
Projection type	Transverse Cylinder	Transverse Cylinder
Projection Name	Cassini-Soldner	Transverse Mercator
Latitude of origin	31.73409694444445	31.73409694444445
Central meridian	35.21208055555556	35.21208055555556
False easing	170251.555	170251.555
False northing	126867.909	126867.909
Scale	1	1
Datum	Palesine_1923	Palestine_1923
EPSG code	28191	28192
Usage	Cadastral/Engineering	Cartography and Mapping

To integrate the modern GNSS observations methods and techniques with the classical geodetic networks, the horizontal coordinates are calculated by applying datum transformations and map projection for point coordinates, while the GNSS measured ellipsoidal heights (h) can be integrated with the precise engineering/orthometric heights (H) by the use of the Geoid Undulations using a global geoid model like EGM2008 or an official local Geoid model by means of gravimetric methods, geometric solutions, GIS interpolations or integrated solutions [7]. The local orthometric height is then by as the difference between the ellipsoidal height (h) and geoid separation (N), which is interpolated by a locally define geoid model [8].

The networks of the triangulation points and benchmarks in Palestine points were subjected to dramatic intended or casual damages due to many reasons. Many points were destroyed because of the urban and infrastructure expansions without the care about keeping or replacing the points by people or municipalities [2]. On the other hand, a large number of points were intended to be damaged by people because of the cautions and the fair of political and military situations over the years in the Westbank. This was highly increased due to frequent visits by Israeli army and surveyors to some points of the network points, which increase the fair of settlement operations and private land property expropriation. Approximately, 80% of points in the Westbank area were damaged, and the rest is being distressfully damaged as noted by periodic visits to the points that are usually done by Geomatics students in Palestine polytechnic university. Lastly, the official land surveying departments and the local authorities/municipalities have neglected the protection and development projects for decades.

There is another major factor that is affecting the geometry and the accuracy of the geodetic network of Palestine which is the effect of the tectonic plates and local earth kinematics. It was noticed by repeated GNSS measurements that different points and moving with varying velocities. While Palestine is located in the Nubia tectonic plate, it is directly located on the border of the Arabian plate along the Jordan valley. Thus, direct transformations using the rotation rates by the tectonic plates defining parameters is not sufficient for integrating the geodetic GNSS observations. On the other hand, a model of the earth kinematics representing the 3D positional velocities at a position has to be introduced and provided for Multi-epoch GNSS observations. However, a companion project was run in Jordan by the GFZ-Potsdam (2006-2008) to compare the relative velocities about the Jordan valley rift (the border between Palestine and Jordan). The results of 3 years' observations with 2 sessions/year have shown differences in velocities values and direction as explained in figure (2). The direction of the velocities/movements are relatively different in magnitude and directions between both sides of the Jordan valley and the Dead Sea [9].

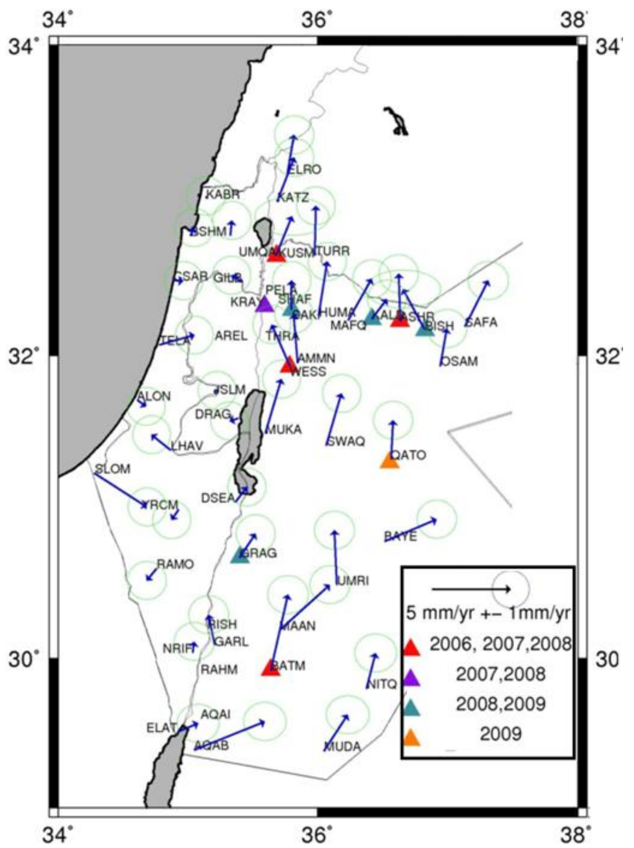

Figure (2): The relative earth kinematics on both sides of the Jordan Valley. [10]

II. KINEMATIC GNSS TRANSFORMATIONS

The three-dimensional tectonic plate kinematics and movements and local earth deformations are normally represented as velocities concerning to a terrestrial frame (ITRF) and a reference epoch [11]. The International GNSS Service (IGS) network of GNSS stations, the European Permanent Network (EPN) and a local group of continuously operating stations (CORS) with their daily raw observations are provided by the SOPAC service, which can be used to calculate the velocities of single points and afterwards for the modelling of the earth kinematics as a raster GIS interpolated surface for representing the absolute/relative movements or velocities. Using the velocity components at a specific location, the position at a given time concerning the reference time reads [12]:

$$X_t = X_{t0} + V_X(t - t_0) \quad (1a)$$
$$Y_t = Y_{t0} + V_Y(t - t_0) \quad (1b)$$
$$Z_t = Z_{t0} + V_Z(t - t_0) \quad (1c)$$

Here, (X,Y,Z) are the geocentric coordinates concerning the related ITRF at the epoch of the current or calculations time (t) and the reference time (t0). The positional velocities (Vx,Vy,Vz) are the velocities according to the reference ITRF at the time (t0) in the X,Y and Z directions as ECEF reference system. The velocities model in both horizontal and vertical directions can be converted from the local horizontal and vertical topocentric components (V_N, V_E, V_H) to an ECEF coordinate system based on ITRF system. This enables direct use of the ITRF transformation parameters and their rates to be used to transform velocities and positions of points between different ITRF system and their proper use in GNSS precise single points positioning or long baselines differential GNSS [13]. The transformation is based on topocentric-geocentric coordinate systems transformations to change the components of the velocity vectors from the local topocentric velocity components (V_N,V_E,V_H) to the geocentric velocity components (V_N,V_E,V_H) by apply two rotations about the longitude (λ) and the latitude (ϕ) in equation (2) [14].

$$\begin{bmatrix} V_X \\ V_Y \\ V_Z \end{bmatrix} = \begin{bmatrix} -\sin\phi\cos\lambda & -\sin\lambda & \cos\phi\cos\lambda \\ -\sin\phi\sin\lambda & \cos\lambda & \cos\phi\sin\lambda \\ \cos\phi & 0 & \sin\phi \end{bmatrix} \begin{bmatrix} V_N \\ V_E \\ V_H \end{bmatrix} \quad (2)$$

In equation (2), (ϕ,λ) are the geographic latitude and longitude of the point that is observed through GNSS techniques. The values of (V_N, V_E, and V_H) can be interpolated by the raster file of the velocities model. In another way, the local relative deformation and movements concerning the origin of the system were calculated using equations (3a) to (3c).

$$\Delta E_t = (V_E - V_{E0})(t - t_0) \quad (3a)$$
$$\Delta N_t = (V_N - V_{N0})(t - t_0) \quad (3b)$$
$$\Delta H_t = (V_H - V_{H0})(t - t_0) \quad (3c)$$

For the transformation between different reference ITRF systems at different time epochs for GNSS static and real-time observations, a four steps solution is explained in equations (4-7) [15]. The first step is that transformation parameters (P) between different frames as provided by the ITRF website have to be transformed from their reference epoch (t0) to the epoch of the observation (t) using their provided rates ($\dot{P}$) in equation (4), see the official ITRF parameters, which are provided by the International Earth Rotation Service (IERS) at the official ITRF website (http://itrf.ign.fr/trans_para.php). The second step is to transform the velocity components (V) of the different points from the frame of modeled velocities to the target frame using equation (5). The third step is to transform the position of the points from the source ITRFyy ($X(t_1)$) and epoch to the same ITRFyy at the reference epoch ($X(t_2)$) of the target ITRF system using equation (6). The final step is to calculate the new final position of the point at the target ITRFzz system using equation (7) [16].

$$P(t) = P(t_0) + \dot{P}(t - t_0) \quad (4)$$
$$V_{ITRF_{ZZ}} = V_{ITRF_{YY}} + \dot{T} + \dot{D}X_{ITRF_{YY}} + \dot{R}X_{ITRF_{YY}} \quad (5)$$
$$X(t_2) = X(t_1) + V(t_2 - t_1) \quad (6)$$
$$X_{ITRF_{ZZ}}(t) = X_{ITRF_{YY}}(t) + T(t) + D(t)X_{ITRF_{YY}}(t) \; RX_{ITRF_{YY}}(t) \quad (7)$$

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In equations (4-7), V represents the velocity component and X is the coordinate's vector. D, R, and T are the scale factor, linearized Helmert rotation matrix, and the translations of the original vector, respectively. On the other hand, $\dot{D}$, $\dot{R}$, and $\dot{T}$ the equivalent matrices and vectors of the rates of change with respect to a reference epoch.

III. DATA AND ANALYSIS

Although Palestine is practically located as a part of the Nubia/Sinai plate, the eastern borders of Palestine represent the real border between the Arabian plate and the Nubia/Sinai plate. This location of Palestine at the border between plates causes special ununiformed movements due to two-sided tectonic effects in Jordan valley and the Dead Sea rift. Using GNSS daily raw data over years, the velocities for 20 ITRF CORS points in the Palestinian side of Jordan valley have been solved by Scripps Orbit and Permanent Array Center (SOPAC) in the University of California (USA), While the data was available for only one site in the Jordanian side (Amman point) [17]. Looking at the summary of absolute velocities in table (2), the eastern movement of both sides of the Jordan valley same to be close (approx. 22.5 mm/year), While the northern element shows some differences. Although the vertical component varies on both sides, it is relatively small in amount compared to the horizontal components.

Table (2): Summary of the absolute velocities in both sides of the Jordan valley.

	Velocities in Palestine mm/y			**Velocities in Jordan mm/y**		
	North	**East**	**Vertical**	**North**	**East**	**Vertical**
Average	20.365	22.99	0.825	17.4	22.5	-4
Max	22.8	25.3	3.2	-	-	-
Min	18.9	21.8	-0.7	-	-	-

The earth kinematics of the crustal movements in Palestine can be easily implemented over a given time interval, as the velocity components of well-distributed CORS stations are determined [18]. Using 20 ITRF points with daily raw GNSS observation over 10-15 years provided by SOPAC online services, the velocities are of the stations are calculated and modeled [17]. The 3d components of the velocities were interpolated all over the country with reference to the ITRF2014 at the epoch 2010.0 using GIS tarter interpolation methods. However, all engineering/cadastral surveys and mapping activities are using the Palestine1923 triangulation network built in the 1920s- 1930s, it is approximately 100 years since the major (first-order) network was built. It must be considered that these points were subjected to long-term kinematics by plate tectonics and local deformations. In table (3), the absolute movements of the ITRF points are calculated using the SOPAC provided velocities [19]. These results are calculated with the assumption of linear systems of displacements using raw GNSS data for only the last 10-15b years, which is not enough period to extrapolate over 100 years interval.

Table (3): Summary of the absolute modeled movements in Palestine.

Movement (m)	**northing**	**easting**	**Horizontal**	**Vertical**
Average	2.039	2.297	3.073	0.084
Min	1.891	2.180	2.950	-0.073
Max	2.283	2.537	3.262	0.321
Std. dev.	0.115	0.096	0.097	0.088

The movements in about 100 years were large in the horizontal directions nearly 3 meters all over the country with the assumption of linear motion. However, there is a variation from a place to another as shown in table (3). These movements are caused by local deformations and the effect of the friction of Arabian and Sinai plates in the eastern borders of the country at the Jordan valley rift and Dead Sea area. On the other side, there is generally a very slow/small movement's components in the vertical directions less than 10cm in most parts of Palestine, which lead to a relative stability in the measured leveling Benchmarks.

The earth movements can be transferred to a local model relative to reference origin using the given absolute velocities or movements [20]. This can lead to the interpolation of the relative movements/velocities and get the local relative deformation that affects the coordinates of the triangulation network of Palestine. Variations over different parts of the country can also be clarified. The origin point of the triangulation network in the city of Jerusalem was selected as a reference point with velocities (V_{E0},V_{N0},V_{H0}) using equations (3a-3c).

Using the GIS interpolated map, the movements over 100 years in Palestine with respect to the origin of the system were varying from -8cm to 30cm in the north direction. And the value in the eastern component are varying from -13cm to 22cm. the maximum absolute horizontal movement was 31.2cm. It was clear that the directions of the horizontal movement in fig (3) were also varying from north-west movements in the north of Palestine to south-east movements in the south of Palestine. This leads to the conclusion that the crustal movements in Palestine are relatively different in both values and directions over the years. The vertical direction the relative movements were in the range of -10.6cm to 13cm in the past 100 years, which are relatively small leading to stability in the related network of benchmarks. But this needs to be further studied on how to apply corrections.

Currently, the GNSS surveying operations in Palestine are implemented by private sector companies providing real-time GNSS correction services. The stations' coordinates of the continuously operation networks of the GNSS providers are set up based on ITRF2000 reference system and reference of (2004.75) [21]. This means that any new precise positioning based on different reference ITRF systems, like ITRF96 or the current ITRF2014, or epochs has to be transformed to the reference frame (ITRF2000) and the epoch (2004.75).

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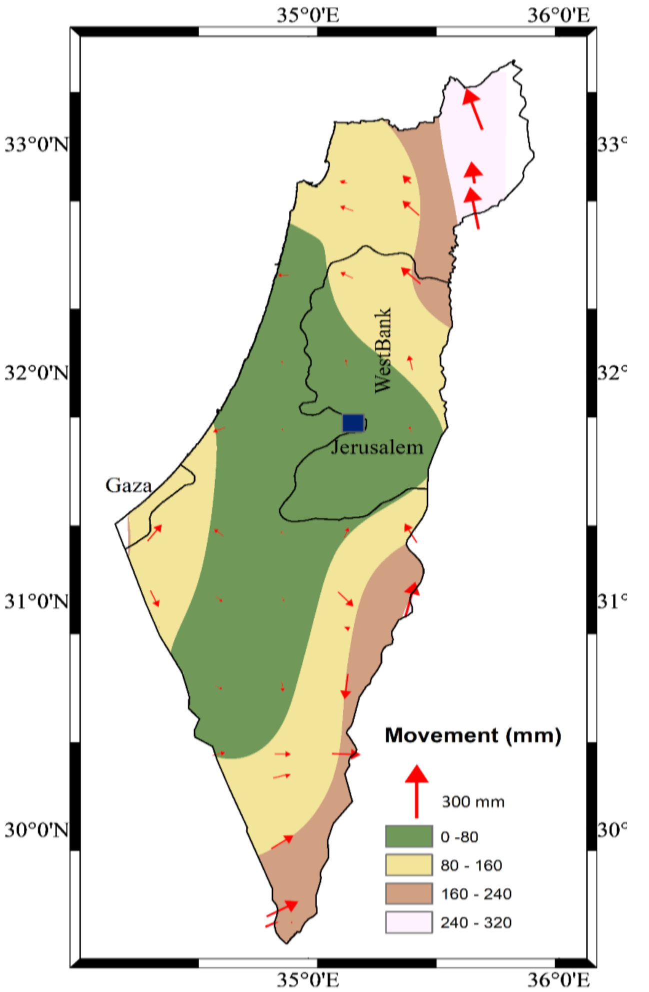

Figure (3): The relative movements of the earth's surface and their direction relative to the origin of Palestine1923 system.

The geodetic network of Palestine 1999, which was implemented in 1999 in Westbank and Gaza, was established by field observations of differential GNSS and IGS stations based on ITRF96 in epoch (1999) [22]. The network includes 24 points from the triangulation network of Palestine (Palestine1923) with GPS static observations of 12 hours distributed all over the Westbank and Gaza strip [23]. This network was assumed to be the new geodetic datum of Palestine. But it was not practically used due to the rear use of GNSS/GPS in Palestine at that time [24]. To use the calculated coordinates of the network in the current time for precise point positioning as a base point for baseline processing of new positioned points, the points have to compatible with the used GNSS reference frame and epoch to be used as control points in any least-squares solution of GNSS networks [25]. For this reason, a transformation from ITRF96 epoch 1999 to the desired epoch used by the GNSS providers is implemented in the four steps explained in equations (4-7). The official transformation parameters between ITRF96 and ITRF2000 as provided by IERS are given in table (4).

Table (4): The official IERS transformation parameters from ITRF2000 to ITRF96 [26].

Parameter T0=1997.0	**Translations (cm)**			**Scale (ppb)**	**Rotations (0.001″)**		
	T_X	T_Y	T_Z	D	r_X	r_Y	r_Z
Value	0.67	0.61	-1.85	0.0	0.0	0.0	0.0
Rate/year	0.00	-0.06	-0.14	0.0	0.0	0.0	0.02

The transformations of the Palestinian Network (1999) were applied for the coordinates measured by differential GNSS positioning based on the reference system the ITRF96 epoch 1999 by applying the official transformation parameters and the modeled velocities as explained in the transformations equations (4) to (7). However, many of the points were destroyed. About 10 points, which were still available in the area WestBank, could be measured again by GNSS. For testing the usability of the modeled earth kinematics in both classical surveying by real-time positioning and geodetic applications by the use of static measurements, points were measured in two ways. First; real-time positioning using local GNSS providers' networks with coordinates based on ITRF2000 epoch (2004.75). The transformations of the 1999 network was compared to the GNSS measured coordinates of network points using RTK GNSS services. The RMSE was about 1.3cm with a maximum and minimum differences of 2.3cm and -1.9cm, respectively. The second way is that the points were measured by static observations varying from 2 to 5 hours processed as differential GNSS with IGS stations based on ITRF2014 epoch (Jul.-Dec.2018). The official transformation parameters and their rates between ITRF2014 to ITRF2000 are given in table (5).

Table (5): The official IERS transformation parameters from ITRF2014 to ITRF2000 [27].

Parameter T_0=2010.0	**Translations (mm)**			**Scale (ppb)**	**Rotations (0.001″)**		
	T_X	T_Y	T_Z	D	r_X	r_Y	r_Z
Value	0.7	1.2	-26.1	2.12	0.00	0.00	0.00
Rate/year	0.1	0.1	-1.9	0.00	0.00	0.00	0.02

The transformation was applied using transformations parameters and the modeled velocities over a period of 15 years. The results were processed in different epochs using baselines of the test points with CORS station regarding ITRF2000 at epoch (2004.75) and with baselines with reference to ITRF2014 at epoch2018 connected to IGS stations. The differences were calculated between both systems. While, The RMSE was about 1.2 cm with a maximum and minimum differences of 1.8 cm and -2.0cm, respectively.

IV. CONCLUSIONS

The location of Palestine on the border separating two tectonic plates (Sinai and Arabia) has caused a special and irregular kinematic motions of the earth's crust.

It was clear that there is relatively fast absolute movement in the horizontal directions/components with relatively high velocity varying from 18 to 26 mm/year, while the vertical component seems to be more stable with slow velocity compared to the horizontal components with values varying between -1 to 3 mm/year, see table (3). The movements and their velocities are not systematically distributed all over the country. But different velocities in magnitude and directions affect the points at different locations from part to other parts of the country. This results that the GNSS processed points using PPP or differential GNSS need to be treated locally using site velocities by a model for the earth kinematics to be considered for applications of time-dependent position calculations. For modeling the earth kinematics in Palestine, 20 continuously operating GNSS stations with their positions and velocities and daily measurements were used in a GIS interpolated model of the velocities in both horizontal and vertical directions to support precise GNSS single point or differential positioning within 1 cm accuracy level. To model and evaluate the local/relative site kinematics, the relative kinematics model of the relative velocities were implemented with the assumption of the local coordinate system origin (in Jerusalem) as a reference point with zero velocity. As a result, the models have shown that the geodetic network of Palestine (1923) was subjected to earth kinematics causing the points at different sites were relatively different from one location to the other, as shown in fig(3). Also, the coordinates of current CORS stations of the private or any future public/private GNSS services should consider the local earth kinematics in the processing of baselines and station points position calculations. Finally, the earth kinematic should be considered in case of processing baselines across the borders to the east of Jordan valley rift. As many GNSS service providers are trying to connect their networks to partner networks working in Jordan for better coverage of GNSS corrections, relative earth kinematics of both sides of the borders have to be considered. This consideration should be defined clearly during the definitions of the stations coordinates and must be more frequently updated and modeled as the velocities are taking different directions and value with absolute differences compared to the reference system of Palestine, see fig (2).

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