Bulletin of Geography. Physical Geography Series, No. 19 (2020): 31–41
http://dx.doi.org/10.2478/bgeo-2020-0008

The Effect of Using Multiple Coordinate Systems and Datum Transformations on the Calculated Coordinates in Palestine

ISSN 2080-7686

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Abstract. The recent developments in spatial data collection, management and software require the availability of proper geodetic infrastructures for integrating different types and sources of coordinates without causing effective changes in positions. Nowadays, positions are mostly collected by GNSS data collectors based on WGS84/ITRF reference systems. The data are then subjected to transformations and projections to a locally used system. Another possibility is direct data collection based on the local coordinate system by classical surveys using land surveying, photogrammetry, laser scanning, etc. The spatial data management is commonly operated using Geographic Information Systems (GIS) software for mapping, analysis, planning, and other services. The conversions between different coordinate systems should be well defined to guarantee the consistency of the coordinates on all systems and tools. In Palestine, the classical and local surveys are all based on the local coordinate system Pal1923Grid for engineering, cadastral and planning applications. The different GNSS RTK-service providers use different definitions and transformation methods between WGS84 or the International Terrestrial Reference Frames (ITRF) and the local Palestine1923Grid, whereas the Land authority has adopted a group of parameters to be implemented on the Global Navigation Satellite Systems (GNSS) data collectors, which do not fit with Palestine1923Grid properties. Additionally, different transformation methods are used in GIS applications for converting the coordinates between the different systems using WGS84 as an intermediate system. Here, the coordinates of a group of the geodetic network in the West Bank of Palestine are used to assess the accuracy of the different transformations and systems by comparing the transformed coordinates using the GNSS system and the originally registered coordinates. Furthermore, a grid of points covering the coordinate system extents is used to describe the differences between the transformations and systems. It was found that the parameters provided by GNSS service providers have results that are consistent with each other and the geodetic network in the West Bank of Palestine compared to GIS-software parameters. By contrast, all systems have extremely deteriorated coordinates in the Gaza strip and the further parts of the Pal1923Grid extents.

Key words:
Coordinate Systems,
Transformations,
WGS84,
Local Systems,
GNSS/GIS,
Palestine

Introduction

The classical survey operations using land surveying methods (Traverses, Resection, Intersections, Levelling, etc.) and photogrammetric mapping methods for engineering applications, cadastral surveys or mapping were commonly built based on local networks of horizontal triangulation points and levelling benchmarks. These points were used as a reference control for the surveying operations as well for mapping accuracy quality control (Ghilani and Wolf 2008). In Palestine, the geodetic triangulation network was established from the beginning of the 1920s to 1947 using angular triangulations and traverses. The network consisted of approximately 15,000 points of different classes from major points (2nd order) to fourth-order points, see Figure 1 (Gavish 2010). Extra points were sometimes prepared by local surveyors during their cadastral surveys. On the other hand, the levelling benchmarks network was established using precise differential levelling starting from a gauge point in the Mediterranean Sea in Gaza city in the 1920s and 1930s. A densification process between the major benchmarks was run from the middle 1970s to the middle 1980s. From the beginning of the 1990s, both horizontal and vertical networks were being destroyed due to urban expansions or intentional destruction by persons out of political curiosity (Younis 2018). In 1999, a selected group of points was observed as a GNSS network using static observation. The network was adjusted to WGS84 coordinates based on the ITRF96 coordinates system (Mason 1999). The original Pal1923Grid coordinates were used to calculate the transformation parameters as a single solution for Palestine and two additional solutions for the West Bank and Gaza strip, separately (Mason 1999). Finally, the geodetic network was subjected to effective earth kinematics for over 100 years because Palestine is located on the border between two tectonic plates (the Sinai and Arabian plates) along the Jordan Valley and the Dead Sea rift (GFZ-Potsdam 2019). As a result, the points had displacements up to 30 cm relative to each other (Younis 2019). Additional local movements due to stone industries and urban projects have also to be considered for some single points.

As the calculations of the geodetic networks are based on three-dimensional geocentric coordinates or equivalent geographic coordinates , a selected reference ellipsoid is used for calculating three-dimensional coordinates. After that, the three-dimensional coordinates are converted to horizontal easting and northing coordinates using a proper map projection. The horizontal coordinates are provided for surveyors and engineers to be used for cadastral, engineering and mapping surveys. All engineering and cadastral surveys in Palestine were established based on the coordinate system (Pal1923Grid) built on the Cassini-Soldner (Cassini) map projection (Epsg 2020). During World War II, a modified system was used for military mapping by applying the Transverse Mercator (TM) map projection named Pal1923Belt, which was based on the same datum of Pal1923Grid (Epsg 2020). Even though the two projections are cylindrical, both Cassini and Transverse Mercator are different in properties and applications, resulting in different coordinates and distortions (Snyder 1987). In 2018, the Palestinian Surveying Department has requested that the land surveyors add a group of parameters to their GNSS data collectors for the cadastral surveys, claiming that the resulting coordinates will be compatible with the Pal1923Grid coordinates, even if Transverse Mercator Projection and different parameters are applied. This system, named New Pal-TM, was copied from the IGD05/12 system, which is based on ITRF2000 at epoch 2004.75 (Georepository 2019). The defining parameters of the three projected systems that are used in Palestine are given in Table 1.

The intensive use of modern geospatial technologies and applications introduced the requirement to define the relations between different datum and coordinate systems. The data collection and surveys using GNSS technologies are based on the WGS84

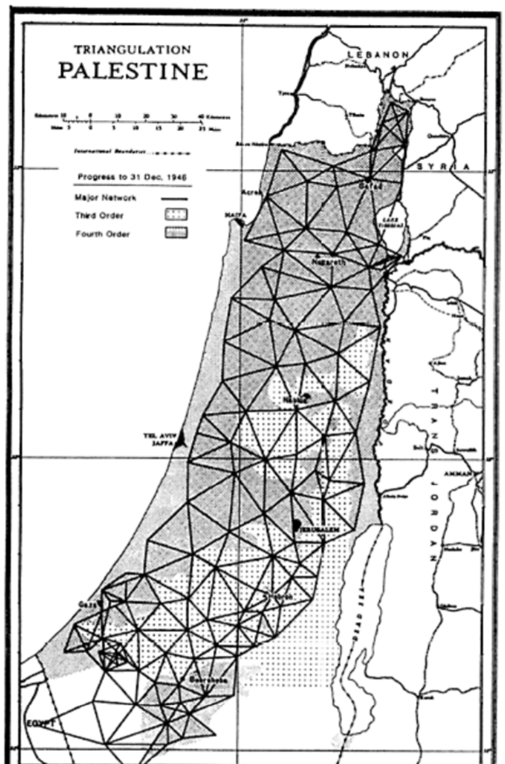

Fig. 1. Geodetic Network of Palestine (The Palestine Exploration Fund 2019)

or international terrestrial reference frames and systems (ITRF) (ITRF 2019). As well, the satellite images are based on different global systems. The geographic information systems (GIS) software deal with data from different sources. Most GIS software like ArcGIS and QGIS use WGS84 as an intermediate system to convert between different systems on the fly. Therefore, the relations between coordinate systems and datums must be clearly defined to enable the bidirectional calculations of the data between different data management systems, mapping applications and field data collectors.

The relations between different coordinate systems must have a clearly defined and unified datum transformation method and parameters. There are different methods for datum transformations, like grid shifts for projected (E, N) or geographic coordinates , polynomial transformations, 2D and 3D conformal transformations, Molodensky 3 or 7 parameters, or the most common method of 3D linearised Helmert transformation the Earth Centred Earth Fixed (ECEF) coordinates in Eq. 1 (Lu et al., 2014).

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{Local} = (1+s)\begin{bmatrix} 1 & r_z & -r_y \\ -r_z & 1 & r_x \\ r_y & -r_x & 1 \end{bmatrix}\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{WGS84} + \begin{bmatrix} T_x \\ T_y \\ T_z \end{bmatrix} \quad (1)$$

In Eq. 1, s is the scale factor in parts per million (ppm). The rotation angles about the X, Y, and Z axes are substituted in radians. Finally, are the shift of the origin (Altamimi 2018). Here, the angles are measured positive counter-clockwise; this form is named "coordinate frame". This is mostly used in the US. On the other hand, the angles are measured positive clockwise in Europe, which is named the position-vector form. The solutions are the same, except that the angle has a different sign for each form (ESRI 2019).

The GIS applications use different datum transformation parameters between WGS84 for Palestine. Sometimes only three translations are used. In addition, seven parameters are sometimes used according to Eq. 1 (ESRI 2019). The GNSS data collectors for field surveys or staking out points have used different parameters that were originally provided by service providers. The available three GNSS service companies are mostly providing RTK-corrections based on two different datum transformations for cadastral projects and engineering surveys. As well, many GNSS data processing software programs use different parameters for transforming the calculated points and baselines to the local datum. A group of the common transformation parameters used in Palestine is presented in Table 2.

From the beginning of the 1930s to now, the cadastral, land property, engineering, planning and mapping surveys have been prepared based on the geodetic network of Palestine using the coordinate system Pal1923Grid. Also, GIS users are assumed to have the same coordinates by selecting Pal1923Grid as the coordinate system of their projects. As well,

Table 1. Projected coordinate systems in Palestine (Epsg 2019)

Parameter	Pal1923Grid	Pal1923Belt	New Pal-TM[1]
Ellipsoid	Clarck 1880	Clarck 1880	GRS 80
Semi-major axis	6378300.789m	6378300.789m	6378137.00m
Inverse flattening	293.4663155389802	293.4663155389802	298.257222100882
Projection type	Transverse Cylinder	Transverse Cylinder	Transverse Cylinder
Projection Name	Cassini-Soldner	Transverse Mercator	Transverse Mercator
Latitude of origin	31.73409694444445°	31.73409694444445°	31.73439361°
Central meridian	35.21208055555556°	35.21208055555556°	35.20451694°
False easing	170251.555 m	170251.555 m	169529.584 m
False northing	126867.909 m	126867.909 m	126907.39 m
Scale	1	1	1.0000067
Datum	Palestine_1923	Palestine_1923	ITRF00/2004.75
EPSG code	28191	28192	--
Usage	Cadastral/Engineering	Cartography/Mapping	Cadastral/Engineering

The transformed three dimensional coordinates projected coordinates are assumed to be equal to Pal1913Grid coordinates, although the different map projection and reference ellipsoid are integrated with a different datum.

engineers of official departments in Palestine use the GEOMOLG open data GIS-server, provided by the ministry of local government (www.geomolg.ps), as their reference for mapping and checking engineers' drawings (GeoMOLG 2020). Alternately, the private service, by the Palestine explorer website (www.mstkshf.com), is used by surveyors and engineers (Palestine-Explorer 2020). The transformation methods for GIS software and GIS-servers depend on the transformation parameters of methods A, B, or C in Table 2. In contrast, land surveyors are mostly using GNSS with different methods for data collection and staking out of point positions. In practice, the applied transformation parameters are mostly the values of the methods D and E in Table 2. In Table 2, the method of transformation (E) is connected to the new Transverse Mercator (TM) projection, which was introduced by the Palestinian surveying department, in 2018. Ambiguously, it was claimed that the resulting coordinates are equal to Pal1923grid. Because the data can be transferred in different formats from GIS to GNSS data collectors and *vice versa*, the problem of storing the measured points using different coordinate systems and applying different back transformations will cause there to be points with the new positional coordinates in the global or the local coordinate system. Therefore, the effect of using different transformations and coordinate systems needs to be studied and evaluated.

Methodology

To evaluate the accuracy of the different transformation methods, a group of 55 points from the geodetic triangulation network of Palestine was observed with static and fast static GNSS observations for measuring the WGS84 (X, Y, Z) coordinates with an estimated accuracy in the range of ±2 cm. These points already have the fixed (E, N) coordinates as provided by the official departments. The points are distributed in the West Bank area of Palestine, where the official surveying and mapping processes are being applied. The evaluation and comparison between the accuracy of the different datum transformations and coordinate systems are achieved by applying statistical analysis of both transformed and the originally fixed (E, N) coordinates. The comparison values are based on average, minimum, maximum and the root mean square error (RMSE) of the easting, northing and radial components (r) Eq. 2a to 2d (Ghilani and Wolf 2017).

$$RMSE_E = \sqrt{\frac{\sum(E_{fixed} - E_{obs})^2}{n}} \quad (2a)$$

$$RMSE_N = \sqrt{\frac{\sum(N_{fixed} - N_{obs})^2}{n}} \quad (2b)$$

$$RMSE_r = \sqrt{\frac{\sum r^2}{n}} \quad (2c)$$

$$r_i = \sqrt{(E_{fixed} - E_{obs})^2 + (N_{fixed} - N_{obs})^2} \quad (2d)$$

Table 2. List of the most common datum transformation parameters used in Palestine (ESRI, ArcGIS 10.7.1 and ArcGIS Pro 2.4 Geographic and Vertical Transformation Tables 2019)

Parameter	Method				
	A	B	C	D	E
Source	Trimble TBC	Esri	Esri/QGIS	GNSS-provider A	GNSS-provider B
(ppm)	0	0	0	8.8471	5.4248
(sec)	0	0	-8.001	-11.1499	-0.33009
(sec)	0	0	-4.42	-8.56249	-1.85269
(sec)	0	0	-11.821	-5.04769	1.66969
(m)	230	219.247	275.722	121.451	-24.0024
(m)	71	73.802	-94.782	114.142	-17.1032
(m)	-273	-269.529	-340.894	-284.684	-17.8444
Ellipsoid	Clarck1880	Clarck1880	Clarck1880	Clarck1880	GRS80
Related Projected coordinates	Pal1923grid (Cassini)	Pal1923grid (Cassini)	Pal1923grid (Cassini)	Pal1923grid (Cassini)	New Pal-TM

To get the observed (E, N), the WGS84 geocentric coordinates (X, Y, Z) need to be transformed into the local Pal1923 datum geocentric coordinates (X, Y, Z). Then, the 3D (X, Y, Z) coordinates are converted to geographic based on the local system reference ellipsoid as defined by the related coordinate system (Torge and Müller 2012) (Table 1). Based on the coordinate system, the local geographic coordinates are converted to horizontal (E, N) coordinates by applying the related Cassini or transverse Mercator (TM) map projections. The processing steps for transformations are explained in Figure 2, where the (E,N) coordinates from both systems are claimed to be equivalent.

To compare the differences between the different systems and their related datum transformations relative to each other, a grid of points based on WGS84 coordinates is interpolated all over the extents of the Pal1923Grid. The grid has 168 points with a 20-km grid interval (Table 3). To enable more realistic results, height values were added to the values using interpolations from the ETOPO1 digital terrain model. This provides a larger overview of the effect of changing the transformations and coordinate system on calculated coordinates. Finally, the differences between the systems are statistically summarised in tables and explained by error distribution maps.

The distribution of both grid points and reference points is depicted in Figure 3. The triangulation points, in green, are important to estimate the accuracy of the transformation parameters in the West Bank area, where the Palestinian land surveying department and other official departments have access control over cadastral surveys and point positioning. These points have a good density on the western part of West Bank because the major part of the built-up and populated area under the Palestinian administration is mostly on this part. In contrast, the grid points, in pink, enable us to eval-

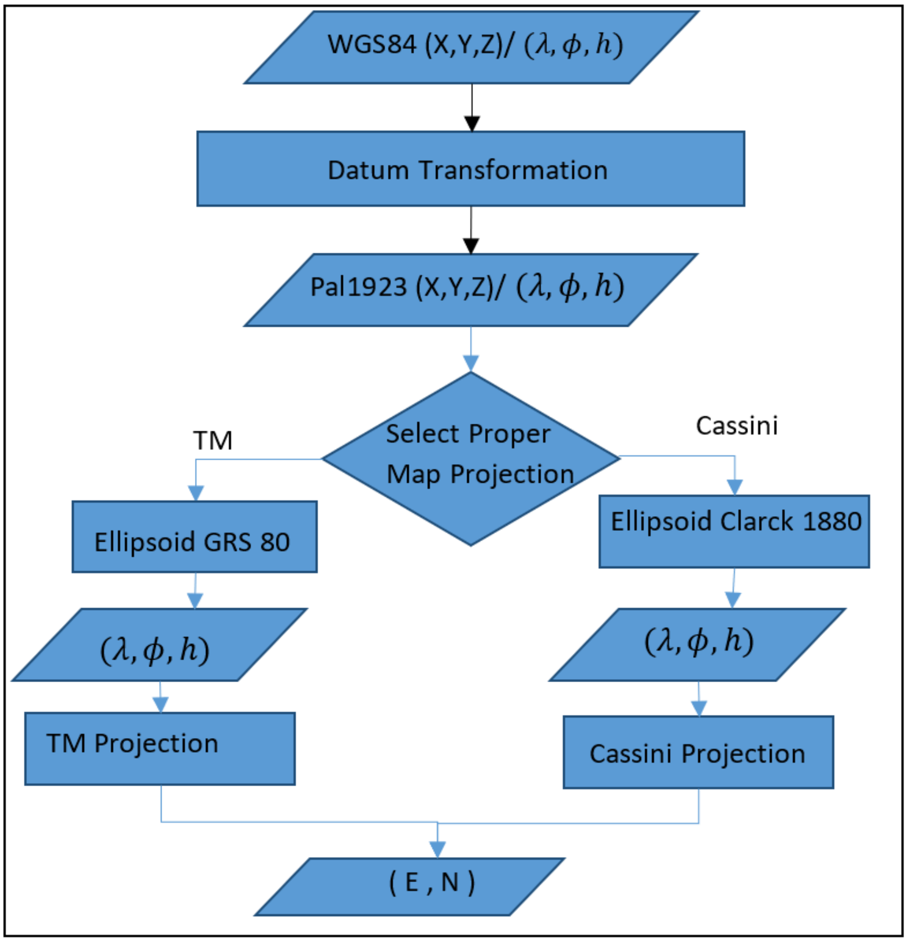

Fig. 2. WGS84 to Pal1923Grid calculations flowchart

Table 3. Properties of grid points

Parameter	Value
# points	168
Grid interval	20 km
Min latitude	29.2°
Max latitude	33.2°
Min longitude	34.2°
Max longitude	35.6°
Min height	-391 m
Max height	2,363 m

uate the differences between the results of the transformations all over the coordinate system extents. Therefore, they do not need to have original coordinates. Depending on the estimated accuracies of the different systems using the reference 55 triangulation points, the system with the best transformation results is to be considered to be the reference for comparing the different coordinate systems and transformation methods.

Results and analysis

The calculations procedures explained in Figure 2 were implemented into software using the Visual Basic 6.0 programming language. To enable the easy use of the multiple methods of datum and coordinate system conversions, the implemented software enables the use of different datum transformation parameters integrated with the related map projection (see Fig. 4). Additionally, it is possible to use a customised group of transformation parameters. The software enables the transformation of single points by manual input, text-files, or shapefiles. It is also possible to apply the coordinates conversions and transformations from WGS84 to Pal1923Grid and *vice versa* to validate the calculation process.

The 55 triangulation points, with observed WGS84 coordinates, were transformed to Pal1923Grid using the different transformation methods in Table 2. The estimated accuracies of the different systems and transformations are summarised in Table 4. It is clear that the transformation method (D) has the best transformation results, with approximately 20 cm in the easting component, 30 cm in the northing component, and 37 cm horizontal accuracies. Meanwhile, the resulting accuracy of the method (E) was within the same accuracy range with a slightly worse result. The two methods (D) and (E) were originally provided by different GNSS-service companies to transform from WGS84 to Pal1923Grid in real-time differential corrections. Differently, the use of the method (C) for the transformations had an accuracy of worse than 2 m, which is nearly used by all GIS users in ArcGIS, QGIS, and GIS web services like GeoMOLG service (www.geomolg.ps) and Pales-

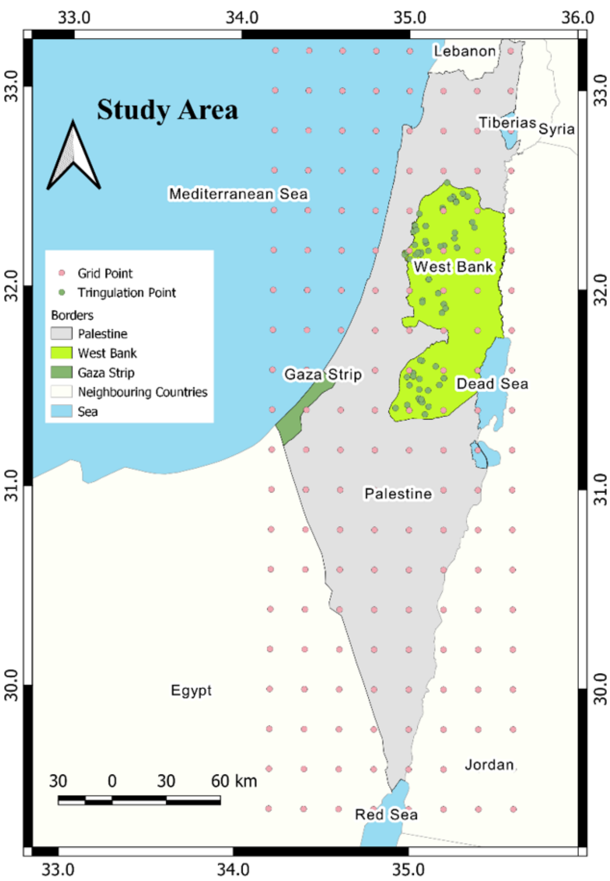

Fig. 3. Distribution of triangulation and gridded points

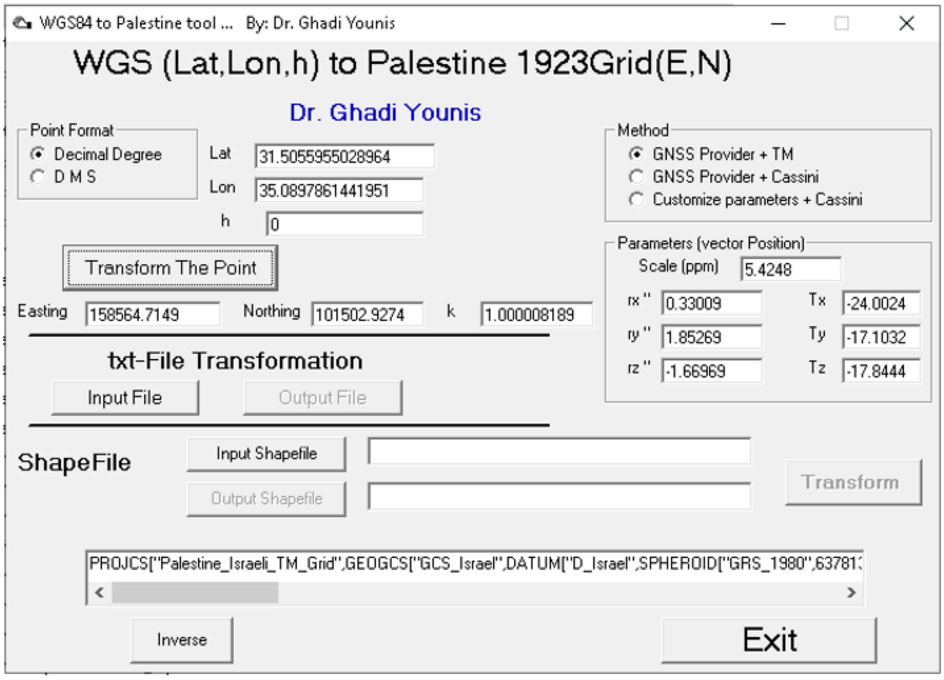

Fig. 4. Screenshot of the Implemented software program

tine Exploration (www.mstkshf.com). On the other hand, the transformation methods (A) and (B) had accuracies much worse than 6 m and 8 m, respectively. The reason for these large differences may be that both methods neglect the scale factors and rotations with the WGS84 coordinate system, see Table 2.

The differences of positions of the 55 reference triangulation points using the transformation methods (D) and (E) were calculated to compare the differences between both systems (see Table 5). Based on the performed calculations, it was established that both systems had radial horizontal differences in the range of 20 cm and a maximum difference of 23 cm. Therefore, the two coordinate systems, with their related transformation, are assumed to be close to each other in the area of the West Bank.

As the observed triangulation points are located within the West Bank of Palestine, they cover only the middle area of Palestine. Also, they are almost located close to the reference meridian of Cassini projection used in Pal1923Grid. As a result, the effect of changing the ellipsoid and the scale factor is expected to be relatively small, as seen from the estimated coordinate differences presented in Table 5. Therefore, the effect of changing the parameters and transformations of the system has also to be studied all over the system extents. For comparing the different methods all over the coordinate systems extents, the transformation method (D) was used as a reference for the other method, because it has the same projection parameters of the Pal1923Grid and the best accuracy results refereeing to the geodetic network. The discrepancies of the calculated positions using the different transformation methods relative to the method (D) is applied using the 168 grid points with given WGS84 coordinates, see the red points in Figure 3. The summary of the differences between the transformed coordinates is given in Table 6.

In contrast to the small difference between the systems (D) and (E) in Table 5, the differences between the two systems increased dramatically by going far away to the east or west. The radial horizontal differences had values in the range of 1 to 4 m in the small area of the Gaza strip (see Fig. 5a). The reason is that the central meridian of both systems is located in the middle of the West Bank, while the Gaza strip is far away from the central meridian. Even if the transverse Mercator and Cassini projections are both cylindrical projections, they will have higher variation in the calculated coordinates and the scale factor in those areas due to the different properties of the projections. In Figure 5b, the differences have a systemic distribution from the north to the south. The reason is that the transfor-

Table 4. Estimates of accuracy of coordinate transformations using different methods in [m]

Value (m)		Method				
		A	B	C	D	E
Easting	Min	-3.085	-11.575	0.526	-0.395	-0.502
	Max	5.902	-2.580	1.524	0.460	0.405
	RMSE	2.950	8.004	1.028	0.207	0.235
Northing	Min	3.631	-3.068	1.424	-0.435	-0.609
	Max	7.930	1.154	2.614	0.822	0.630
	RMSE	5.915	1.450	2.021	0.307	0.311
Radial	Min	4.767	3.103	1.693	0.050	0.048
	Max	8.185	11.581	2.868	0.822	0.672
	RMSE	6.610	8.134	2.267	0.370	0.390

Table 5. Differences between calculated coordinates of methods D and E [m]

Value		Differences
Easting	Min	0.020
	Max	0.115
	RMSE	0.088
Northing	Min	0.164
	Max	0.202
	RMSE	0.180
Radial	Min	0.173
	Max	0.228
	RMSE	0.201

Table 6. Results of comparing transformation methods covering the coordinate system extents using grid points [m]

Value		Method			
		A	B	C	E
Easting	Min	-8.832	-17.260	0.543	-0.335
	Max	23.883	15.369	2.541	4.493
	RMSE	12.113	9.5573	1.557	1.592
Northing	Min	-3.760	-10.228	1.242	-0.652
	Max	10.033	3.203	3.320	0.084
	RMSE	4.695	4.762	2.262	0.245
Radial	Min	0.752	0.558	1.592	0.013
	Max	24.614	18.267	3.921	4.540
	RMSE	12.991	10.692	2.746	1.559

mation parameters of the coordinates system (C), which were provided by ESRI, were not originally calculated by direct field observations using the geodetic network. On the other hand, the variations of the methods (A) and (B) had increasing circularly-shaped values due to the neglect of transformations scale factor and rotation angles according to equations (1a to 1c), see the results in Figre 5c.

Finally, Table 7 shows an example of transforming the coordinates of two points in the area under the administration of the Palestinian land surveying department using the most common methods; the first point is located in the Gaza strip (GS) while the second point is located in the West Bank. Even though the coordinates using methods D and E were relatively close in the West Bank, the differences in the Gaza strip were getting larger than 2 m. Most of GIS desktop- and web-based users are mostly using method C for coordinate calculations and transformations, although the differences are considerably large when applying method C, as shown in Figure 5b.

Conclusions

The availability of different defining parameters for the coordinate system Pal1923Grid, as well as multiple datum transformation methods from the WGS84 coordinate system for the GNSS observed coordinates had caused wrong results and improper application during the forward and backward calculating between different coordinate systems. The

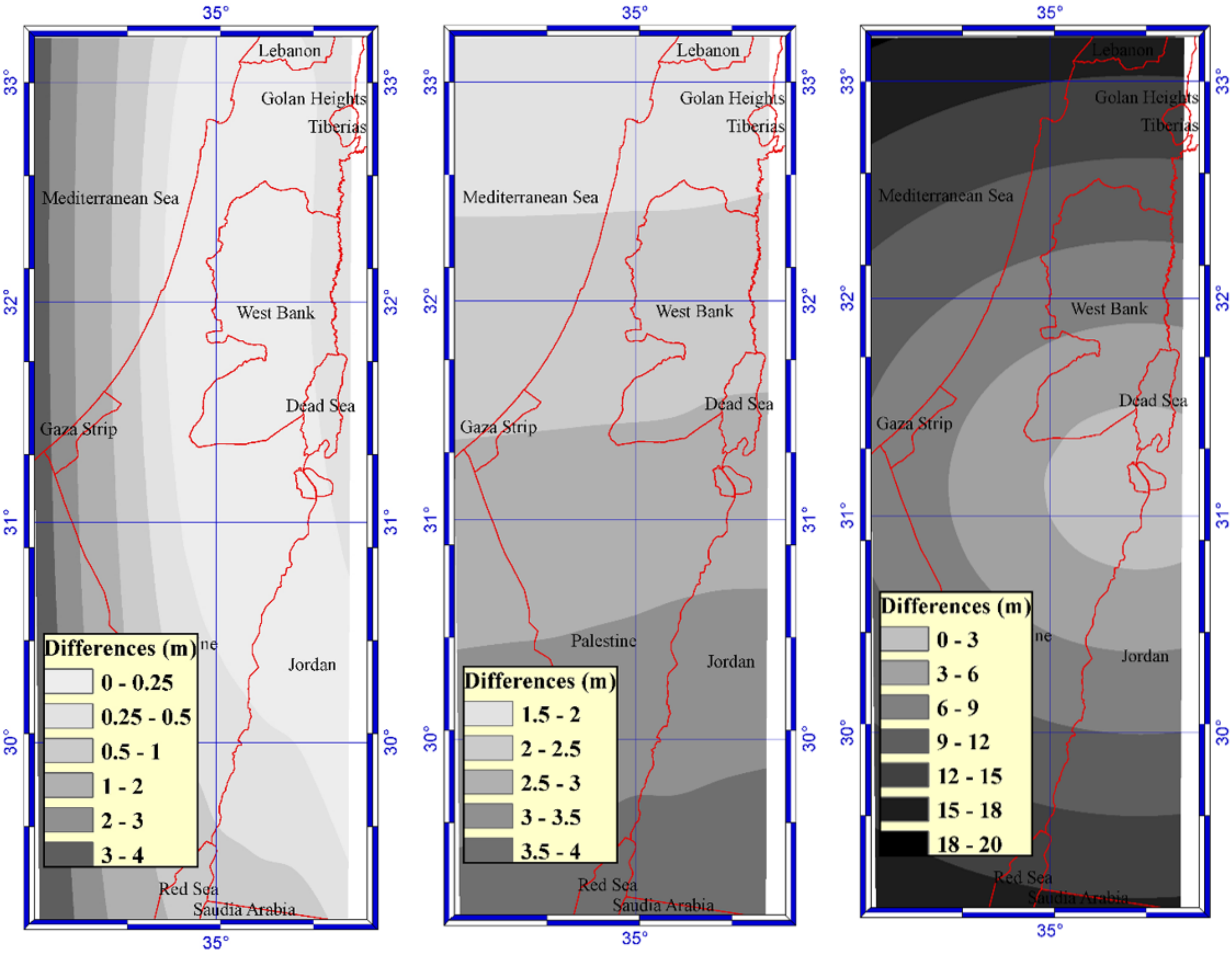

Fig. 5. Maps showing differences in different methods of coordinate transformation relative to method D

Table 7. Example of transforming two points in the West Bank and Gaza strip using the most common methods

Method	Source	Projection	Point 1 (GS)		Point 2 (WB)	
			E (m)	N (m)	E (m)	N (m)
C	GIS	Cassini	92949.833	90066.532	187854.232	200690.150
D	GNSS-A	Cassini	92951.360	90068.507	187855.074	200691.998
E	GNSS-B	TM	92949.610	90068.745	187855.176	200692.205

accuracy of the different coordinate systems and datum transformations was tested using points from the Palestinian geodetic network in the West Bank using GNSS static observations from the WGS84 coordinates and the reference local easting and northing coordinates. In addition, the consistency between the different systems and methods all over the extents of the Pal1923Grid system was tested using a grid of points based on the WGS84 coordinate system. These points were transformed into the local coordinates using the most common transformations and systems. Then, the locally transformed coordinates were also compared against each other. It was noted that the best results in the West Bank were obtained by using the parameters that were implemented by the GNSS service providers (see systems D and E in Table 1). The coordinates were consistent relative to each other and the national geodetic network. But the variations were getting high away from the West Bank to the east or the west in the direction of the Gaza strip (see Fig. 5). The accuracies of transformation parameters used in the GIS and GNSS data post-processing software had much worse results all over the country.

To guarantee consistent coordinate conversions and transformations, a unified and unique local coordinate system should be developed to be used by all users, data collectors and GIS software. As well, a clear procedure should be developed to transform the different maps and drawings to local or global coordinate systems. Additionally, a clear transformation method should be defined to update the geodetic network and all of the old cadastral and engineering surveys. For example, seven local parameters can be calculated. Other methods can be implemented to connect the old classical surveys with modern technologies, such as high order polynomials, grid methods or multiple area parameters.

Disclosure statement

No potential conflict of interest was reported by the author.

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Received 2 August 2020
Accepted 27 October 2020