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AN EXPERIMENTAL STUDY ON MAP PROJECTION TRANSFORMATION USING GIS TOOLS

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ABSTRACT

Topographical maps with the projection of Gauss-Krüger/Transverse Mercator (GK/TM) and Universal Transverse Mercator (UTM) are the primary inputs in many applications related to Geosciences. In these projections, each zone contains a separate coordinate system. For this reason, two adjoining map sheets located in different zones cannot be side by side theoretically. In such situations, map sheets must first be positioned on the same coordinate system in a geographical information system. In this study, three different transformations were performed using AutoCAD Map 3D, QGIS, MicroStation, ArcMap, Netcad, and Global Mapper: (1) among 3˚ adjoining GK/TM zones, (2) from 3˚ GK/TM to 6˚ UTM, and (3) from 3˚ GK/TM to the tangent and secant Lambert Conformal Conic (LCC) projection. The results were compared in terms of ellipsoidal values, projections, and programs. There were several limitations in the programs with regards to measurement, process precision, and deficiencies in terms of users. Since all three projections were conformal, angles were preserved. However, lengths that were different in each projection were also different from the ellipsoidal values, with the exception of secant LCC projection. Consequently, the appropriate method and program should be selected depending on the geographical location of study area, objective, expected accuracy, and precision.
Keywords: Gauss-Krüger, transverse Mercator, universal transverse Mercator, Lambert conformal conic projection, zone transformation, projection transformation.

CBS ARAÇLARIYLA HARİTA PROJEKSİYON DÖNÜŞÜMÜ KONUSUNDA BİR DENEYSEL ÇALIŞMA

ÖZ

Gauss-Krüger/Transversal Mercator (GK/TM) ve Universal Transversal Mercator (UTM) projeksiyonuna sahip topografik haritalar, yerbilimleri ile ilgili çok sayıda uygulamada birincil girdilerdir. Bu projeksiyonlarda her dilim ayrı bir koordinat sistemi içerir. Bu nedenle farklı dilimlerde yer alan iki komşu pafta teorik olarak yan yana gelmez. Böylesi durumlarda öncelikle paftaların coğrafi bilgi sistemi ortamında aynı koordinat sisteminde konumlandırılması gerekir. Bu çalışmada, AutoCAD Map 3D, QGIS, MicroStation, ArcMap, Netcad ve Global Mapper yazılımlarıyla üç ayrı dönüşüm gerçekleştirilmiştir: (1) 3°'lik komşu GK/TM dilimleri arası dönüşüm, (2) 3°'lik GK/TM'den 6°'lik UTM'ye geçiş ve (3) 3°'lik GK/TM'den teğet ve kesen Lambert Konform Konik (LKK) projeksiyonuna dönüşüm. Uygulama sonuçları; elipsoidal değerler, projeksiyonlar ve yazılımlar açısından karşılaştırılmıştır. Yazılımlarda ölçü ve işlem duyarlığı bakımından çeşitli kısıtlar ve kullanıcılar açısından eksikler olduğu tespit edilmiştir. Her üç projeksiyon da konform olduğu için açılar korunmuştur. Bununla birlikte, her bir projeksiyonda farklı olan uzunluk ölçüleri -kesen LKK projeksiyonu hariç- elipsoidal değerlerden farklıdır. Sonuç olarak, çalışma bölgesinin coğrafi konumuna, amaca, beklenen doğruluk ve duyarlığa bağlı olarak uygun yöntem ve yazılım seçilmelidir.
Anahtar Sözcükler: Gauss-Krüger, transversal Mercator, universal transversal Mercator, Lambert konform konik projeksiyon, dilim dönüşümü, projeksiyon dönüşümü.

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1. INTRODUCTION

Geographical Information Systems (GIS) are systems in which geometric and semantic data are stored, related, examined, queried, and analyzed. They are commonly used in many fields, such as engineering, defense, planning, education, medicine, etc. Geometrical data mostly depicts the objects that are subjects of topographic maps. In other words, the main input in geographical information systems is topographic maps. Although it differs depending on the country, large scale (<10K) standard topographic maps are produced in the Gauss-Krüger/Transverse Mercator (GK/TM) projection, medium and some small-scale standard topographic maps are produced in the Universal Transverse Mercator (UTM) projection as it is in Turkey [1, 2].

The Earth is divided into zones in both projections. While the width of zones is 6˚ in UTM as a de facto standard, the width of zones in GK/TM depends on the purpose of the projection, e.g. 3˚ in Turkey for the production of the large scale standard topographic maps. Each zone is projected onto different cylinders, and each zone has its separate coordinate system. For example, approximately 80 km distance emerges between 1:1000 scale Kırklareli F20-c-25-c-3-b and İstanbul F21-d-21-d-4-a map sheets with central meridians 27˚ and 30˚ respectively when they are projected onto two different cylinders in accordance with the theory as presented in Figure 1. For this reason, two adjoining map sheets located in different zones cannot theoretically be side by side without applying proper transformation. Therefore, if the study area is located on such two map sheets, these map sheets should be positioned at the common coordinate system using an available tool as GIS.

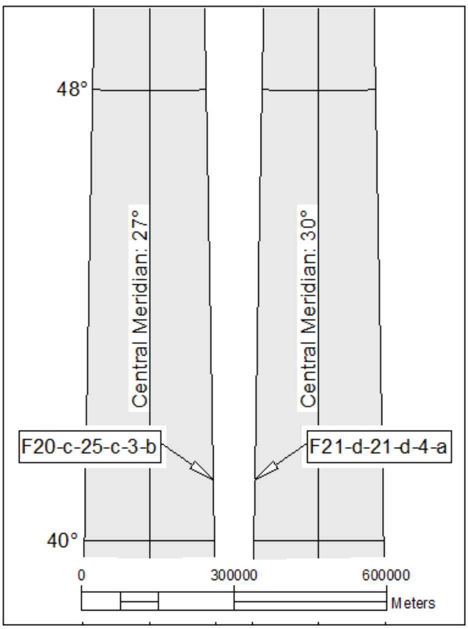

Figure 1. Two adjoining map sheets positioned on two adjoining GK/TM zones without transformation (Central Meridians: 27˚ and 30˚).

The repositioning process of adjoining sheets may be performed by applying the transformation (a) among 3˚ GK/TM zones (Figure 2), (b) from 3˚ GK/TM zones to 6˚ UTM zone (Figure 3), and (c) from GK/TM and UTM to a different projection (e.g. Lambert Conformal Conic (LCC)).

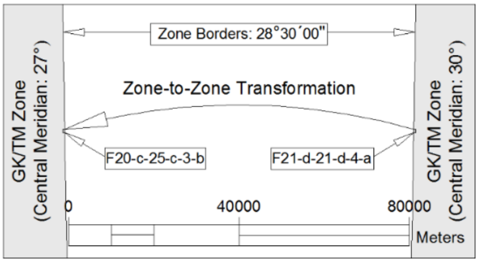

Figure 2. Transformation among 3˚ GK/TM zones.

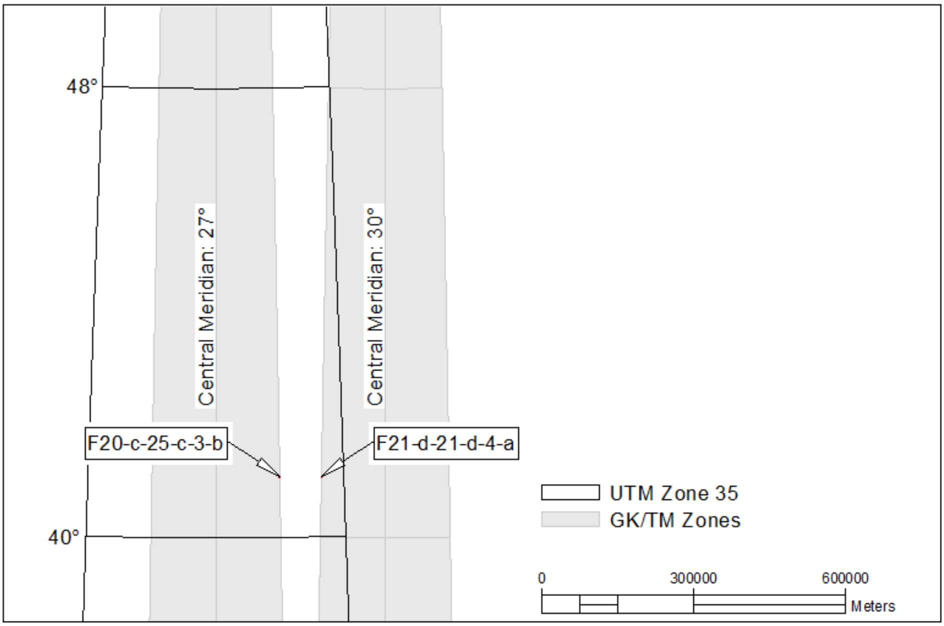

Figure 3. Transformation from 3˚ GK/TM zones to 6˚ UTM zone.

Detailed explanations and criticisms about map projection and transformation could be obtained from the numerous books which have been produced by authors including, Maling [3], Fiala [4], Snyder [5], Yang et al. [6], Koçak [7], Uçar et al. [8] and Hooijberg [9]. Many commercial and open source GIS programs offer various tools for both zone transformation and projection transformation.

In this study, zone and projection transformations were made by the use of so called program packages, i.e. AutoCAD Map 3D, QGIS, MicroStation, ArcMap, Netcad, and Global Mapper, on 1:1000 scaled standard topographic maps of Turkey. The equations used in the program packages are not known as they are not openly declared. This issue can only be clarified by a series of test and comparison. It was one of the aims of this study. Measurements obtained in cartometrical analyses(coordinates, length, bearing, and area) were compared in each resulting map to determine the effects of methods and algorithms applied in the programs for zone and projection transformation. In order to determine the preferable method in between zone-to-zone and projection transformations for repositioning adjoining sheets, the above stated measurements were compared with ellipsoidal values.

2. PROJECTIONS APPLIED IN THE STUDY

2.1. Gauss-Krüger/Transverse Mercator (GK/TM)

The GK/TM projection was first analyzed in ellipsoidal form by the famous mathematician Carl Friedrich Gauss in 1822, and later, L. Krüger published its formulas that allow calculations on ellipsoid in his studies in 1912 and 1919. The GK/TM is a transverse cylindrical conform projection commonly used for large-scale standard topographic map productions. The GK/TM conformal projection system should be limited to a region bounded by a longitudinal distance from the central meridian (CM), which will depend on the purpose of the projection, zone system and its grid system [9]. Each zone is projected onto different cylinders. Zones are not enumerated and are referred by their central meridians.

As in all conformal projections, at one point, the scales in all directions are the same. Accordingly, small terrain features and areas are shown as similar to that of Earth within an average scale. Although the scale in all directions is the same at one point, it changes slightly from point to point. Since at one point the scale is the same in all directions, differantial sense angles at one point on map are equal to that of Earth. As a result of this, differantial sense parallels and meridians are always orthogonal to each other in all conformal projections [3, 4, 9, 10].

Gauss-Krüger X_g values are ellipsoidal x values. Conformal property of this projection is ensured by changing the ellipsoidal y values. For this reason, Y_g values are larger than they are on the surface. In this case, a 1 km ellipsoidal length around the border (1.5˚ far from the central meridian of a 3˚ wide zone) is 20 cm longer in the projection [11].

2.2. Universal Transverse Mercator (UTM)

The UTM projection was adopted by the United States Armed Forces in 1947 for military map production of the whole world. This projection was developed based on the Gauss-Krüger projection. In the UTM projection system, the Earth is divided into 60 zones with 6˚ meridian intervals starting from the 180˚ meridian. The zones are enumerated between 1 and 60, starting from 1 and ascending to the east. The projection surface cylinder is taken tangent to the reference surface along the zone's central meridian. The zone's central meridians (3˚, 9˚, 15˚, etc.) are east and west meridians.

To avoid the negative ordinates of points on the left of the zone's central meridian (abscissas (X) axis of the rectangular coordinate system), 500 000 m is added to Y_g values reduced with an m_0 scale factor (~0.9996). The zone's number is written at the beginning of the ordinate to introduce in which zone the ordinate is located. Since X_g values are positive on the northern hemisphere, adding a constant value is not necessary, and they are only reduced by m_0. In contrast, in the south hemisphere, 10 000 000 m is added to X_g values reduced by m_0. Therefore, the obtained coordinate values are known as easting and northing values.

The easting and northing values are used only for drawing. As a result, distance, direction, and area cannot be calculated using projection coordinates. It is necessary to go back from the easting and northing values to find the Y_g and X_g values for the aforementioned points and to make calculations using these values [7].

The UTM projection system is used in the production of medium and some small-scale standard topographic maps. 1 km ellipsoidal length around the border (3˚ far from the central meridian of a 6˚ wide zone) is 84 cm longer in the projection [11].

2.3. Lambert Conformal Conic (LCC)

The LCC projection was developed in 1772 by J. H. Lambert. In this projection, a cone can be placed on the reference surface (sphere or ellipsoid) as tangent along a parallel or as secant along two parallels. These parallels are known as standard parallels. In the LCC projection, the meridians are straight lines (converging at the pole), and the parallels are concentric circular arcs. In the projection with one standard parallel, deformations increase towards to north and south from the standard parallel, while length is preserved along the standard parallel. The projection method with two standard parallels was developed to reduce the deformations that take place in projections with one standard parallel. In this method, the distance along the meridian between two standard parallels is $2/3^{rds}$ of the distance along the meridian (north-south) between the latitude borders of the study area and $1/6^{th}$ of the distance along the parallel (east-west) between the meridian borders of the study area [12]. On the other hand, to specify the standard parallels, the following equations suggested by Kavraisky may also be used [3]:

$$\varphi_1 = \varphi_S + \frac{(\varphi_N - \varphi_S)}{K} \qquad \varphi_2 = \varphi_N - \frac{(\varphi_N - \varphi_S)}{K} \tag{1}$$

φ_N and φ_S indicate the northeast and southeast latitudes of the area, respectively.

For an area:

- with a small extent in latitude but large extent in longitude, K=7,
- with a rectangular outline with a longer axis north to south, K=5,
- with a circular or elliptical outline, K=4, and
- with a square outline, K=3.

In the secant LCC projections, the lengths of the standard parallels are preserved; the particular scale along the standard parallels is equal to one. While the particular scale between standard parallels is less than one, it is more than one beyond standard parallels.

3. EXPERIMENTAL TESTING AND RESULTS

In this study, two 1:1000 scaled standard topographic maps (Kırklareli F20-c-25-c-3-b and İstanbul F21-d-21-d-4-a) in the MicroStation SS3 DGN format, placed within the provincial borders of İstanbul were used. The stated maps were produced by the İstanbul Metropolitan Municipality using colored aerial images. Note that Kırklareli F20-c-25-c-3-b and İstanbul F21-d-21-d-4-a are referred to as Sheet-1 and Sheet-2 hereafter, respectively. The coordinates and map sheet designation of the maps were organized in 2005.0 epoch connected to the last updated Turkish National Fundamental GPS Network, GRS80 ellipsoid, and Transverse Mercator (TM) projection. Although these maps are in two different zones (CMs: 27˚ and 30˚), they are two adjoining sheets. As the experimental testing following test were applied: The cartometrical analyses (coordinate, length, bearing, and area measurements) were also applied in order to introduce the effects of methods and algorithms applied in the programs for zone and projection transformation. In this context, four buildings located at the corners of the maps were selected as reference geometries to be considered in cartometrical analyses as presented in Figure 4. The building corner points were enumerated from one to four starting from the northwest corner.

Three different experimental tests were performed: transformation (1) among GK/TM zones, (2) from GK/TM to UTM, and (3) from GK/TM to LCC. AutoCad Map 3D 2014, QGIS 2.2.0, MicroStation SS3, ArcMap 10.0, Netcad 5.0, and Global Mapper 15 were used as indicated in the outline of the study presented in Figure 5.

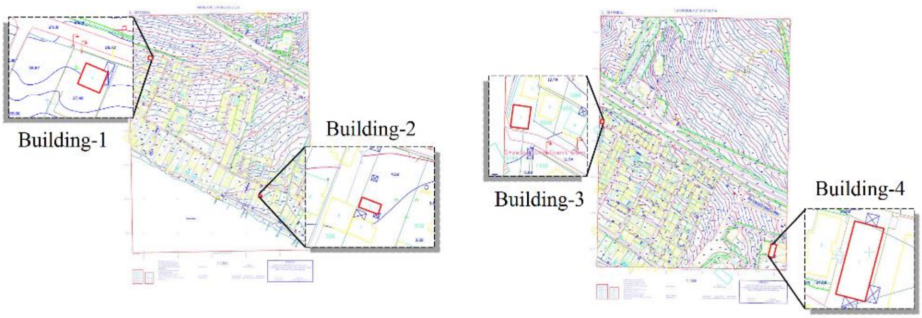

Figure 4. Buildings selected for cartometrical analyses.

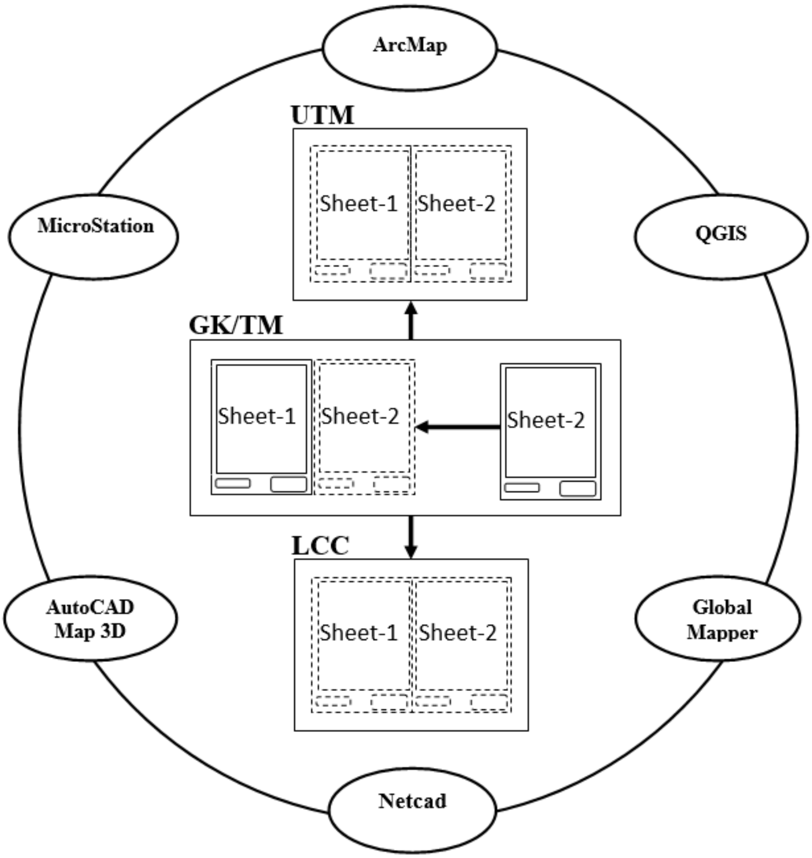

Figure 5. Outline of the study.

First, ellipsoidal and original projection values were measured in all the programs and compared. As presented in Table 1 and Table 2, the differences ranging from 2 to 7 mm emerged between the ellipsoidal and projection values of Building-3 and Building-4's frontages. A difference of 116 mm was identified between the ellipsoidal and projection values of the distance from Building-3 to Building-4 as indicated in Table 3.

Table 1. Building-3's frontages [m].

Frontage	1-2	2-3	3-4	4-1
Ellipsoidal Value	8.781	10.831	8.707	10.971
Sheet-2 (CM: 30˚)	8.783	10.833	8.709	10.973
Difference	0.002	0.002	0.002	0.002

Table 2. Building-4's frontages [m].

Frontage	1-2	2-3	3-4	4-1
Ellipsoidal Value	14.791	36.987	14.838	36.960
Sheet-2 (CM: 30˚)	14.794	36.994	14.841	36.967
Difference	0.003	0.007	0.003	0.007

Table 3. Distance between northeast corner of Building-3 and southwest corner of Building-4 [m].

Ellipsoidal Value	592.7488
Sheet-2 (CM: 30˚)	592.8645
Difference	0.116

3.1. Transformation among GK/TM zones

In this test, the zone transformation process of two adjoining sheets (two adjoining zones with 27˚ and 30˚ central meridians in the GK/TM projection) was analyzed. The map sheet that was placed in a zone with a central meridian of 30˚ was carried to the zone with a central meridian of 27˚ (Figure 5). The results obtained from the analysis are listed below:

a. Analysis in terms of Programs

1. With regard to building corner angle, bearing, building frontage, and distance between buildings, the same values were measured in all the programs.

2. In Global Mapper, measurement values can be obtained with the different precision. For example, distances up to 5 meters can be measured with the precision of 1/1000th of millimeter. Distances between 5 and 50 meters can be measured with the precision of 1/100th of millimeter. Distances between 50 and 500 meters can be measured with the precision of 1/10th of a millimeter. Finally, distances longer than 500 meters can be measured with a millimeter or lower precision. However, coordinate values are generally given with a millimeter precision. This is a weakness of this program, and in this study, this weakness occurred in coordinate and area measurements. For example, Table 4 shows the differences between Building-4's northeast corner coordinate values obtained using Global Mapper and other programs. While coordinate values are the same in a millimetric level, coordinate differences are the same in a millimetric level with only one exception. Table 5 shows area values and differences obtained using Global Mapper and the other programs regarding Building-4. Both area values and differences obtained with Global Mapper are different in the square centimeter level from the other programs.

Table 4. Coordinates of northeast corner of Building-4 [m].

	AutoCAD Map 3D		QGIS	
	Easting	Northing	Easting	Northing
Sheet-2 (CM: 30˚)	374307.1343	4542411.5089	374307.1343	4542411.5089
Sheet-2 (Trans. to CM: 27˚)	626690.5515	4542428.6511	626690.5515	4542428.6511
Difference	252383.417	17.142	252383.417	17.142

	MicroStation		ArcMap	
	Easting	Northing	Easting	Northing
Sheet-2 (CM: 30˚)	374307.1343	4542411.5089	374307.1343	4542411.5089
Sheet-2 (Trans. to CM: 27˚)	626690.5515	4542428.6511	626690.5515	4542428.6511
Difference	252383.417	17.142	252383.417	17.142

	Netcad		GlobalMapper	
	Easting	Northing	Easting	Northing
Sheet-2 (CM: 30˚)	374307.1343	4542411.5089	374307.1340	4542411.5090
Sheet-2 (Trans. to CM: 27˚)	626690.5515	4542428.6511	626690.5520	4542428.6510
Difference	252383.417	17.142	252383.418	17.142

Table 5. Building-4's area [m^2].

	AutoCAD Map 3D	QGIS	Micro Station	ArcMap	Netcad	Global Mapper
Sheet-2 (CM: 30˚)	547.944	547.944	547.944	547.944	547.944	547.944
Sheet-2 (Trans. to CM: 27˚)	547.947	547.947	547.947	547.947	547.947	*547.948*
Difference	0.003	0.003	0.003	0.003	0.003	*0.004*

3. Building corner angles can be directly measured with all the programs except Global Mapper. In Global Mapper, building corner angles can be measured as the difference of bearings.

b. Analysis in terms of Projections

1. When the coordinate values in the transformed map were examined, it was seen that the easting values changed more when compared to the northing values. In other words, while the points changed place both in the west and north, the change was less pronounced in the north.

2. The corner angles of Building-3 and Building-4 were measured in both the original and transformed map sheets, and it was seen that the post-transformation angles were preserved in a second level.

3. The bearings were measured both in the original and transformed maps, and the bearings of Building-3 and Building-4 changed in degree (approximately 2˚) (Table 6).

Table 6. Bearing between the northeast corner of Building-3 and the southwest corner of Building-4 [º].

	AutoCAD Map 3D	QGIS	Micro Station	ArcMap	Netcad	Global Mapper
Sheet-2 (CM: 30˚)	129.6481	129.6481	129.6481	129.6481	129.6481	129.6481
Sheet-2 (Trans. to CM: 27˚)	127.6793	127.6793	127.6793	127.6793	127.6793	127.6793
Difference	1.9688	1.9688	1.9688	1.9688	1.9688	1.9688

4. Frontages of Building-3 and Building-4 were measured both in the original and transformed maps. The frontages were preserved in millimetric level.

5. Table 7 shows the values of the distance between Building-3 and Building-4 both in the original and transformed maps. There is a one millimeter difference between the two values.

Table 7. Distance between the northeast corner of Building-3 and the southwest corner of Building-4 [m].

	AutoCAD Map 3D	QGIS	Micro Station	ArcMap	Netcad	Global Mapper
Sheet-2 (CM: 30˚)	592.8645	592.8645	592.8645	592.8645	592.8645	592.8645
Sheet-2 (Trans. to CM: 27˚)	592.8654	592.8654	592.8654	592.8654	592.8654	592.8654
Difference	0.001	0.001	0.001	0.001	0.001	0.001

6. The area of Building-3 in the transformed map did not change, and the area of Building-4 changed in terms of 30 square centimeters (Table 5).

c. Analysis in terms of Ellipsoidal Values

1. The value of the distance between Building-3 and Building-4 both in the ellipsoidal and transformed map sheets was measured and compared in all the programs. As seen in Table 8, there is a 177 mm difference between the ellipsoidal value and the value in transformed map sheet.

Table 8. Distance between the northeast corner of Building-3 and the southwest corner of Building-4 [m].

Ellipsoidal Value	592.7488
Sheet-2 (Trans. to CM: 27˚)	592.8654
Difference	0.117

2. The ellipsoidal value of the distance between Building-2 and Building-4 was measured in all the programs. In addition, the projection value of the distance between Building-2 in original map sheet and Building-3 in the transformed map sheet was measured in all the programs. Measurement values and differences are given in Table 9. The difference between the ellipsoidal value and the projection value of the distance between Building-2 and Building-3 is 56 mm.

Table 9. Distance between the northeast corner of Building-2 and the northwest corner of Building-3 [m].

Ellipsoidal Value	286.767
Sheet-1 (CM: 27˚) & Sheet-2 (Trans. to CM: 27˚)	286.823
Difference	0.056

3.2. Transformation from GK/TM to UTM

In this application, the adjoining sheets located in zones with 27˚ and 30˚ central meridians in a GK/TM projection are transformed into 6˚ wide UTM projection. For the results obtained to be analyzed independently from datum and ellipsoid parameters (ITRF, GRS80), they have been selected using the same method as with the original map sheets. The results obtained from the analysis are listed below:

a. Analysis in terms of Programs

1. With regard to building corner angle, bearing, building frontage, and distance between buildings, the same values were measured in all the programs.

2. While in area measurements all the programs except Global Mapper gave the same result at the 3rd position after the decimal point, different results were identified at 2nd and 1st levels of precision (Table 10). Because of the precision weakness of Global Mapper mentioned above (see the section 3.1-a.2.), Building-4's area was measured with a 7 cm^2 difference (Table 10), and some corner coordinates of the building were measured with a 1 millimeter difference (Table 11).

Table 10. Building-4's area [m^2].

	AutoCAD Map 3D	QGIS	Micro Station	ArcMap	Netcad	Global Mapper
Sheet-2 (Trans. to UTM)	547.5090	547.5090	547.5090	547.5091	547.5091	547.5090
Sheet-2 (Trans. to CM: 27˚)	547.9474	547.9475	547.9474	547.9474	547.9474	547.9480
Difference	-0.4384	-0.4385	-0.4384	-0.4383	-0.4383	-0.4390

Table 11. Coordinates of northeast corner of Building-4 [m].

	AutoCAD Map 3D		QGIS	
	Easting	Northing	Easting	Northing
Sheet-2 (Trans. to UTM)	626639.875	4540611.680	626639.875	4540611.680
Sheet-2 (Trans. to CM: 27˚)	626690.552	4542428.651	626690.552	4542428.651
Difference	-50.676	-1816.971	-50.676	-1816.971

	MicroStation		ArcMap	
	Easting	Northing	Easting	Northing
Sheet-2 (Trans. to UTM)	626639.875	4540611.680	626639.875	4540611.680
Sheet-2 (Trans. to CM: 27˚)	626690.552	4542428.651	626690.552	4542428.651
Difference	-50.676	-1816.971	-50.676	-1816.971

	Netcad		GlobalMapper	
	Easting	Northing	Easting	Northing
Sheet-2 (Trans. to UTM)	626639.875	4540611.680	626639.875	4540611.680
Sheet-2 (Trans. to CM: 27˚)	626690.552	4542428.651	626690.552	4542428.651
Difference	-50.676	-1816.971	-50.677	-1816.971

3. Although in the first test all measurements (frontages, distances between buildings, building areas) were obtained directly with programs, they were not obtained directly in the test. The reason is that calculations cannot be completed using UTM projection coordinates (easting and northing values), while the calculations can be completed directly with the GK projection coordinates. Furthermore, programs always do the calculations and the measurements with the projection coordinates, regardless of the projection. Therefore, after the UTM projection coordinates were transformed into GK projection coordinates, the measurements in this test were obtained using calculations.

b. Analysis in terms of Projections

1. After the UTM projection coordinates were transformed into GK projection coordinates, the obtained results (length, angle, and area) were the same as the results obtained in the first test.

2. For example, the measured distance between Building-1 and Building-2 in the UTM projection is shorter than the measured distance in GK/TM projection (Table 12).

Table 12. Distance between northeast corner of Building-1 and northwest corner of Building-2 [m].

Sheet-1 (Trans. to UTM)	508.177
Sheet-1 (CM: 27˚)	508.380

3. For example, the measured area of the Building-1 in UTM projection is smaller than the measured area in the GK/TM projection (Table 13).

Table 13. Building-1's area [m^2].

Sheet-1 (Trans. to UTM)	131.289
Sheet-1 (CM: 27˚)	131.394

c. Analysis in terms of Ellipsoidal Values: In this test, since the UTM projection coordinates were transformed into GK projection coordinates, the results obtained were the same as in the first test (Section 3.1).

3.3 Transformation from GK/TM to LCC

In this test, the original map sheets in GK/TM projection were transformed into tangent and secant LCC projections. The standard parallels chosen were 39˚ for tangent LCC and 37˚ and 41˚ for secant LCC. The central meridian chosen was 35˚ for both. Equation (1) was used to select the standard parallels. To ensure that the results obtained were analyzed independently from datum and ellipsoid parameters (ITRF, GRS80), the datum and ellipsoid parameters were chosen as the same with the original map sheets. The results obtained from the analysis are listed below:

a. Analysis in terms of Programs

1. With regard to building corner angle, bearing, building frontage, and distance between buildings, the same values were measured in all the programs.

2. While in area measurements all programs except QGIS and Global Mapper gave the same result with square centimeter precision, different results were seen in higher precisions (Table 14).

Table 14. Building-4's area [m^2].

	AutoCAD Map 3D	QGIS	Micro Station	ArcMap	Netcad	Global Mapper
Sheet-2 (Trans. to Tangent LCC)	53.118	53.118	53.118	53.118	53.118	*53.119*
Sheet-2 (Trans. to Secant LCC)	53.053	53.054	53.053	53.053	53.053	53.054

b. Analysis in terms of Projections

1. When all building frontages measured in tangent LCC and secant LCC were compared, there was between a 3 and 23 millimeter difference (Table 15).

Table 15. Frontage differences between tangent and secant LCC [m].

Frontage	1-2	2-3	3-4	4-1
Bulding-1	0.007	0.007	0.007	0.007
Bulding-2	0.006	0.003	0.006	0.003
Bulding-3	0.005	0.007	0.005	0.007
Bulding-4	0.009	0.023	0.009	0.023

2. When the distance between Building-3 and Building-4 measured in tangent LCC and secant LCC were compared, a difference of 363 millimeters was identified (Table 16).

Table 16. Distance between the northeast corner of Building-3 and the southwest corner of Building-4 [m].

	AutoCAD Map 3D	QGIS	Micro Station	ArcMap	Netcad	Global Mapper
Sheet-2 (Trans. to Tangent LCC)	593.115	593.115	593.115	593.115	593.115	593.115
Sheet-2 (Trans. to Secant LCC)	592.752	592.752	592.752	592.752	592.752	592.752
Difference	0.363	0.363	0.363	0.363	0.363	0.363

3. When the bearings between Building-3 and Building-4 measured in tangent LCC and secant LCC were compared, a difference of 8″ was identified (Table 17).

Table 17. Bearing between the northeast corner of Building-3 and the southwest corner of Building-4 [º].

	AutoCAD Map 3D	QGIS	Micro Station	ArcMap	Netcad	Global Mapper
Sheet-2 (Trans. to Tangent LCC)	132.7544	132.7544	132.7544	132.7544	132.7544	132.7544
Sheet-2 (Trans. to Secant LCC)	132.7552	132.7552	132.7552	132.7552	132.7552	132.7552
Difference	-0.0008	-0.0008	-0.0008	-0.0008	-0.0008	-0.0008

4. The areas of all buildings measured in the GK/TM projection were smaller than the areas measured in tangent LCC but bigger than the areas measured in secant LCC (Table 18).

Table 18. All buildings' areas [m^2].

	Building-1	Bulding-2	Bulding-3	Bulding-4
GK/TM	131.395	53.074	95.347	547.944
Tangent LCC	131.506	53.119	95.428	548.407
Secant LCC	131.345	53.053	95.311	547.736

5. When the areas of all buildings measured in tangent and secant LCC projections were compared, a 0.0651-0.6714 m^2 difference was identified (Table 19).

Table 19. All buildings' areas [m^2].

	Building-1	Bulding-2	Bulding-3	Bulding-4
Tangent LCC	131.506	53.1185	95.428	548.407
Secant LCC	131.345	53.0534	95.311	547.736
Difference	0.161	0.0651	0.117	0.6714

c. Analysis in terms of Ellipsoidal Values

1. Ellipsoidal and tangent LCC projection values of the frontages of Building-3 and Building-4 were measured and compared in all the programs. As seen in Table 20 and Table 21, there are differences of 5 to 23 mm between the ellipsoidal values and projection values.

Table 20. Building-3's frontages [m].

Frontage	1-2	2-3	3-4	4-1
Ellipsoidal Value	8.781	10.831	8.707	10.971
Sheet-2 (Trans. to Tangent LCC)	8.786	10.837	8.713	10.977
Difference	-0.005	-0.007	-0.005	-0.007

Table 21. Building-4's frontages [m].

Frontage	1-2	2-3	3-4	4-1
Ellipsoidal Value	14.791	36.987	14.838	36.960
Sheet-2 (Trans. to Tangent LCC)	14.800	37.010	14.847	36.983
Difference	-0.009	-0.023	-0.009	-0.023

2. Both ellipsoidal and tangent LCC projection values of the distance between Building-3 and Building-4 were measured and compared in all the programs. As seen in Table 22, there is a 366 mm difference between the ellipsoidal value and projection value.

Table 22. Distance between the northeast corner of Building-3 and the southwest corner of Building-4 [m].

Ellipsoidal Value	592.749
Sheet-2 (Trans. to Tangent LCC)	593.115
Difference	-0.366

3. Both ellipsoidal and secant LCC projection values of the building frontages of Building-3 and Building-4 were measured in all the programs. The ellipsoidal and projection values were the same.

4. Both ellipsoidal and secant LCC projection values of the distance between Building-3 and Building-4 were measured and compared in all the programs. As seen in Table 23, there is a 3 mm difference between the ellipsoidal value and projection value.

Table 23. Distance between the northeast corner of Building-3 and the southwest corner of Building-4 [m].

Ellipsoidal Value	592.749
Sheet-2 (Trans. to Tangent LCC)	593.115
Difference	-0.366

To compare the projections in addition to the ellipsoidal values in terms of frontages, corner angles, areas, and bearings, the tables below were designed.

Table 24. Matrix of buildings' frontages [mm].

	Ellipsoidal	GK/TM	UTM	Tangent LCC	Secant LCC
Ellipsoidal	—				
GK/TM	Different	—			
UTM	Different	Different	—		
Tangent LCC	Different	Different	Different	—	
Secant LCC	*Same*	Different	Different	Different	—

Table 25. Matrix of buildings' corner angles ["].

	Ellipsoidal	GK/TM	UTM	Tangent LCC	Secant LCC
Ellipsoidal	—				
GK/TM	Same	—			
UTM	Same	Same	—		
Tangent LCC	Same	Same	Same	—	
Secant LCC	Same	Same	Same	Same	—

Table 26. Matrix of buildings' areas [cm^2].

	GK/TM	UTM	Tangent LCC	Secant LCC
GK/TM	—			
UTM	Different	—		
Tangent LCC	Different	Different	—	
Secant LCC	Different	Different	Different	—

Table 27. Matrix of bearings ["].

	Ellipsoidal	GK/TM	UTM	Tangent LCC	Secant LCC
Ellipsoidal	—				
GK/TM	Different	—			
UTM	Different	Different	—		
Tangent LCC	Different	Different	Different	—	
Secant LCC	Different	Different	Different	Different	—

There are differences between the distance values measured in GK/TM, as well as in tangent LCC and ellipsoidal values in a decimeter level. The distance values measured in tangent LCC differ from the ellipsoidal values more than the values measured in GK/TM (nearly three times) (Table 28 and 29).

Table 28. Distance difference between the northeast corner of Building-3 and the southwest corner of Building-4 [m].

Ellipsoidal Value	592.749
Sheet-2 (Trans. to Tangent LCC)	593.115
Difference	-0.366

Table 29. Distance difference between the northeast corner of Building-3 and the southwest corner of Building-4 [m].

Ellipsoidal Value	592.749
Sheet-2 (CM: 30)	592.8645
Difference	-0.116

The frontages measured in secant LCC are the same as the ellipsoidal values. Besides, the distance values measured in the secant LCC are closer to the ellipsoidal values than both the values measured in GK/TM and the tangent LCC (Table 30).

Table 30. Distance difference between the northeast corner of Building-3 and the southwest corner of Building-4 [m].

Ellipsoidal Value	592.749
Sheet-2 (Trans. to Secant LCC)	592.752
Difference	-0.003

4. CONCLUSIONS

This study concluded that though measurements with a precision higher than a millimeter can be obtained using AutoCAD Map 3D, QGIS, MicroStation SS3, ArcMap, and Netcad, only values up to the millimeter precision should be taken in the case that these have been measured using Global Mapper; this level of caution should be taken primarily because of Global Mapper's limited precision.

While the GK/TM to UTM transformations of all programs gave the same result with millimeter precision, in the zone-to-zone and GK/TM to LCC transformations, there were differences with values of a millimeter or higher. As is known, calculations cannot be done with easting and northing values in UTM projection because of the existing scale factor (~0.9996). However, all commercial software do the calculations with these values. In this sense, it would be useful to improve the software capabilities (a) in a way such that, when the projection information is defined as UTM by the user, the measurement and calculations are automatically completed using the Gauss-Krüger coordinates or (b) by providing a new tool to the user that has this function (e.g., "Measure in UTM"). Otherwise, the values obtained by the user would be wrong.

Since the study area is far from the standard parallel specified for the tangent LCC, the tangent LCC is not a good alternative for the GK/TM. On the other hand, the secant LCC is a good alternative for both the GK/TM and the tangent LCC because the study area is too close to the area of the standard parallels specified for the secant LCC. It will be also investigated what values the differences will reach as moved away from the standard parallels. Nevertheless, it is obvious that this projection can easily be used along the standard parallels.

When such a problem is encountered, there is no single solution or tool. The appropriate method and program should be selected depending on the geographical location of the study area, the objective, the expected accuracy, and precision. However, the values collected in the field should be used to obtain the coordinates, distances, angles and areas in an engineering project, because projections are not useful for precise measurement and are generally only used for representation of topography on a map.

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