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Regularised computation of 3D coordinates and orthometric heights for northern Cyprus: new network computations for northern Cyprus

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ABSTRACT This study covers the restoration of 124,910 parcels between 2013 and 2016 within the scope of the digital cadastre renovation work of northern Cyprus. The renovation work was commissioned by the Republic of Turkey Land Registry and Cadastre General Directorate via the tender process and turned over to the Turkish Republic of Northern Cyprus (TRNC). The geodetic infrastructure of the project consisted of 37 C2 and 68 C3 geodetic control points. 3D location calculations of the C2 and C3 networks were obtained based on the Continuously Operating Reference Stations Turkey (CORS-TR) System (in reference epoch 2005.00 and datum ITRF96) and interpolation was determined via annual velocity vectors. In order to include the C2 and C3 networks in the TRNC Vertical Control Network, nine compatible vertical control points were included in the calculations. In this study, an orthometric elevation model specific to northern Cyprus was formed by using the 3D position information obtained via the Global Navigation Satellite System and the Cyprus geoid data.

Key words: CORS-TR, geoid undulation, velocity vector, ellipsoidal height, orthometric height, GNSS levelling.

1. Introduction

The restoration of cadastral parcel measurements in northern Cyprus is the beginning of the transition to a modern cadastre system. For many years, land information in northern Cyprus had been recorded using paper-based maps and land registers. The transfer from a paper-based system to a digital recording system began in 1988, but by 2009 only 5% had been transferred. In addition, only copies from the property maps were available and these were in poor condition. By 1960, most of these copies had disappeared. As a result, cadastral maps lost their applicability and parcel boundaries could not be determined due to a lack of accurate coordinate and measurement values (Sahin *et al.*, 2015). The Republic of Turkey was founded in 1920 and in 1924 began on a small scale to work with cadastral reform (Demir *et al.*, 2008). Turkey, through transfer of its experiences, contributed within the framework of a protocol with the Turkish Republic of Northern Cyprus (TRNC) to the cooperation on the restoration of cadastral plots (Toker, 2015). Development of multi-purpose cadastral systems in the world allows us to determine land position in space and register all rights (Matuk, 2019). To this end, the "Cadastre Renovation and

Deed Automation Project in the Turkish Republic of Northern Cyprus" was launched in 2013 by the Republic of Turkey to determine the boundaries and register the parcels. Within the scope of this project, 124,910 parcels were restored. In order to develop the geodetic infrastructure of the project, C2- and C3-degree networks were established within northern Cyprus. In this study, facilities, measurements, processes and postprocess information, and results related to 3D location networks and 1D elevation networks, created for geodetic infrastructure purposes, are given within the scope of the renovation and automation project which has been successfully implemented.

2. Continuously Operating Reference Stations Turkey (CORS-TR)

The Global Navigation Satellite System (GNSS) is a multi-constellation system that is available to all users and extensively used in many areas (Inyurt *et al*., 2017; Elaksher *et al*., 2018). The Continuously Operating Reference Stations Turkey (CORS-TR) project has opened a new era in Turkey and northern Cyprus for real time and static GNSS surveying (Eren *et al*., 2009). The CORS-TR project was completed in May 2009. This project is based on the general principles of 24/7 geographical location in Turkey and northern Cyprus in Real Time Kinematic (RTK) as well as postprocessing, and is defined as being fast, economical and sensitive. Within the scope of the project, a total of 146 continuous operating stations and two control centres were established (Fig. 1). Four of these stations (DIPK, GYUR, LEFK, and MGOS) were set up in northern Cyprus. The data collected from these stations at 1-s intervals are sent via a centralised control system to Ankara. These data are, then, modelled and distributed to users (Mekik *et al*., 2011a). In 2019, the system was expanded to 158 stations (TKGM, 2019).

Fig. 1 - CORS-TR stations (https://www.tusaga-aktif.gov.tr/Sayfalar/IstasyonHaritasi.aspx).

3. Mathematical modelling in GNSS networks and determination of velocity vectors

The GNSS networks contain an excessive number of measurements. Consequently, these measurements are adjusted using the least squares method. Measurements and corrections of them are expressed depending on the coordinates of the station points.

To perform this operation for the measurement of an S_{ij} base in a GNSS network where points A and B are located, the equation is written as:

$$\begin{bmatrix} X_i \\ Y_i \\ Z_i \end{bmatrix} = \begin{bmatrix} X_j \\ Y_j \\ Z_j \end{bmatrix} + \begin{bmatrix} \Delta X_{ij} \\ \Delta Y_{ij} \\ \Delta Z_{ij} \end{bmatrix} + \begin{bmatrix} v_{xij} \\ v_{yij} \\ v_{zij} \end{bmatrix} \qquad (1)$$

The measurement equations for each base component measured are written in Eq. 1 in a manner similar to that shown for an *ij* base.

Equations of measurement in a matrix representation are expressed as:

$$Ax = l + v \qquad (2)$$

The numerical values of the elements of the matrix l are determined by rearranging the measurement equations. The first three elements of the matrix l are the components ΔX, ΔY and ΔZ of the *ij* base, respectively.

These elements are calculated as in the equation:

$$\begin{bmatrix} l_X \\ l_Y \\ l_Z \end{bmatrix} = \begin{bmatrix} X_i \\ Y_i \\ Z_i \end{bmatrix} + \begin{bmatrix} \Delta X_{ij} \\ \Delta Y_{ij} \\ \Delta Z_{ij} \end{bmatrix} \qquad (3)$$

For an AB baseline, the other elements of l matrix are calculated from Eqs. 1 and 2. Measurement equations for adjustment GNSS networks are linear and the elements of matrix A are 0, 1 or -1. In determining relative position with GNSS, the three base components measured are correlated. Thus, a covariance matrix of 3×3 in size is obtained as a product of the least squares method of the carrier phase measurements for each base. This covariance matrix is used to weight the measurements in the network compensation for each base. Thus, for any GNSS network, the weight matrix is a block diagonal type with a unique 3×3 matrix for each base measured from its diagonals. All other elements of the matrix are zero.

In the adjustment of GNSS networks A, $P^{-1} = Q_{ll}$ and l matrices are formed:

$$N = A^T PA \text{ and } n = A^T Pl \qquad (4)$$

x is the unknown vector which is calculated by (Leick, 1995; İnal and Turgut, 2002).

$$x = N^{-1} . n \qquad (5)$$

In the evaluation of the measurements, the coordinates of the station points whose positions are known are shifted to the measuring epoch (*T*) and used in the evaluation. The epoch shifting process is performed with the following equation (Soler *et al.*, 2004):

$$\begin{bmatrix} X(T) \\ Y(T) \\ Z(T) \end{bmatrix} = \begin{bmatrix} X(T_0) \\ Y(T_0) \\ Z(T_0) \end{bmatrix} + (T - T_0) \begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix} \tag{6}$$

Here, T_0 represents the reference epoch coordinates of the station with the known coordinate point, and v_x, v_y, v_z are the geocentric velocity vectors expressed in ITRF96 datum (Deniz *et al.*, 2008).

4. TRNC Vertical Control Network and GNSS levelling

In northern Cyprus in 1987, 14 first degree routes with a total length of 306 km were established and the TRNC Vertical Control Network was set up. To establish the Vertical Control Network Datum, sea level measurements were carried out for one week in Famagusta and Kyrenia and the mean sea level was determined. The values obtained between the two points were compared with sensitive geometric levelling and a difference of ±4 mm was obtained. In order to use the Helmert orthometric elevation system in practice, TRNC Vertical Control Network was re-evaluated with the methods given in Ayhan and Demir (1992) and Demir (1999). For the determination of the TRNC geoid, the gravimetric geoid was calculated using 105 gravity points homogeneously distributed over the surface of the country and satellite sea gravity values obtained from altimeter measurements along with topographic heights at 450×450 m grid spacing. This was then combined with the GPS-levelling geoid and the TRNC Geoid-2003 (KG-03) was calculated with ±3 cm accuracy suitable for direct use with GPS (TRNC, 2013).

With GNSS, the latitude, longitude, and ellipsoid height of points are determined in a global geocentric coordinate system. In the map making and engineering studies, the orthometric heights of the points are used. Orthometric heights are traditionally determined by geometric levelling measurements, depending on the National Vertical Control Network. However, this means that the ability provided by GNSS technology to determine 3D coordinates is not being fully utilised. Therefore, in order to transform the ellipsoidal heights obtained by GNSS directly to orthometric heights, it is necessary to determine and use suitable geoid models.

The undulation of the geoid (*N*) can be calculated from the ellipsoidal height of point (*h*) which is derived by GNSS and the orthometric height (*H*) obtained by spirit geometric levelling and gravimetric data (Ghanem *et al.*, 2002; Fanos *et al.*, 2018):

$$N = h - H. \tag{7}$$

Due to the existing long wavelength effects in the KG-03 gravimetric geoid model, the orthometric heights obtained by using KG-03 and the orthometric heights calculated by geometric levelling based on the TRNC Vertical Control Network-2003 (KDKA-03) are incompatible with each other. There are significant differences between them that cannot be ignored. For this reason, the differences between the GNSS ellipsoid height and the orthometric heights obtained from the KG-03 geoid heights with the national height system (KDKA-03) must be modelled to be compatible. To do so, the GNSS-levelling geoid heights were determined.

The combination of KG-03 and the GNSS-levelling geoid is based on the modelling of these differences by calculating the differences between KG-03 geoid heights and GNSS-levelling geoid heights at known points of the GNSS-levelling geoid and interpolating the differences at any given point.

For this purpose, the geoid heights of the points ($N_{KG\text{-}03}$), where geoid heights of the points (N_{GNSS}) is determined by GNSS-levelling, are also interpolated from the grid register and

$$\delta N = N_{KG\text{-}03} - N_{GNSS} \tag{8}$$

is used to calculate the geoid height differences (δN) at common points.

These calculated differences (δN) are modelled with a third-order 2D polynomial (with 10 parameters):

$$t_i = a_0 + a_1 x_i + a_2 y_i + a_3 x_i^2 + a_4 y_i^2 + a_5 x_i y_i + a_6 x_i^3 + a_7 y_i^3 + a_8 x_i^2 y_i + a_9 x_i y_i^2. \tag{9}$$

Here, (x_i, y_i) represents horizontal coordinate values of points, t_i is the trend value at point i and a_j represents unknown parameters of the fitting equations ($j = 0, 1, \ldots\ldots .., 9$; $n = 10$) (Yi-Shan and Fang-Shii, 2019).

$$dN_i = \delta N_i - t_i. \tag{10}$$

The trend differences (dN) are calculated with the equation. Trend differences are modelled by passing over a surface. The KG-03R geoid height value at any point ($N_{KG\text{-}03R}$) can be calculated by adding the KG-03 geoid height ($N_{KG\text{-}03}$), trend value (t), and trend differences (dN), as follows:

$$N_{KG\text{-}03R} = N_{KG\text{-}03} + t + dN. \tag{11}$$

As a result, KG-03R is the combined state of the gravimetric geoid (KG-03) and the GNSS-levelling geoid. The following equation can be used directly for the calculation of the orthometric heights of the ellipsoid heights calculated by the GNSS method (İnal and Yigit, 2004; Kiliçoglu and Firat, 2005):

$$H_{ORT} = h - N_{KG\text{-}03R}. \tag{12}$$

5. Unified network for northern Cyprus

The technical feasibility study for the northern Cyprus networks was completed by the General Directory of Land Registry and Cadastre (GDLRC) in 2013. Survey studies for networks were conducted by the contracting company. Network design studies were carried out in accordance with the current Large-Scale Map and Map Information Production in Turkey Regulation (Deniz *et al.*, 2008).

The network design plan was prepared for engineering services to be performed within northern Cyprus (Fig. 2). This plan includes: a) CORS-TR stations (Mekik *et al.*, 2011b), b) C2-degree Ground Control Points (GCPs), c) C3-degree GCPs and d) Northern Cyprus National Vertical Control Network (NCNVN) control points to be used in GNSS-levelling. The Unified Network design plan was approved by the General Directorate of Land Registry and Cadastre.

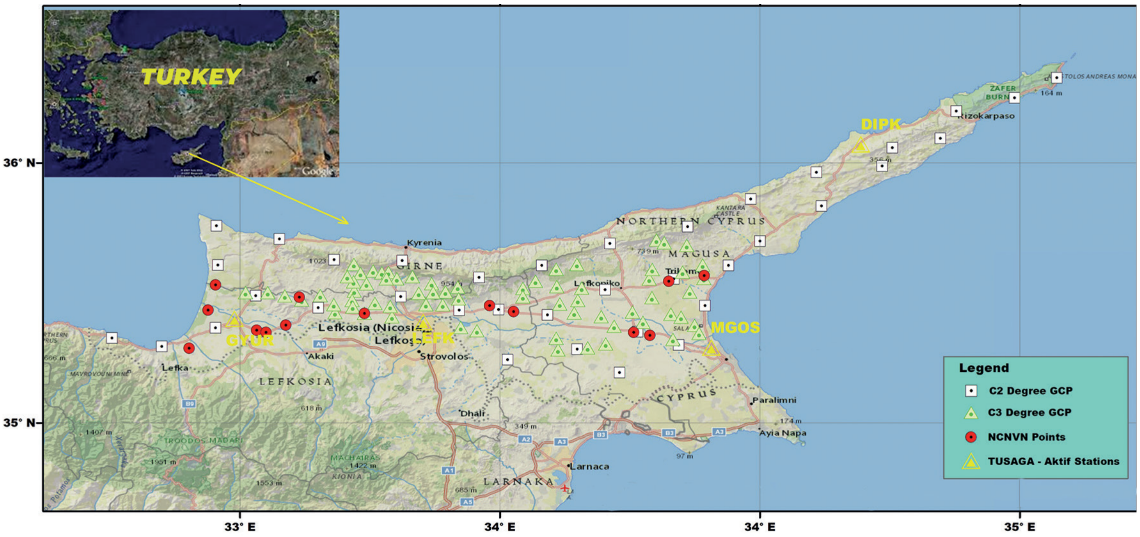

Fig. 2 - GNSS control network.

The Unified Network (horizontal and vertical network) was established to carry out the TRNC Renovation and Automation project and includes:

- 4 CORS-TR stations (known coordinates in the reference epoch 2005.00)
- surrounded by 9 NCNVN points (for determination of the Helmert orthometric heights).

For densification, 37 C2- and 67 C3-degree GCPs were installed in the Unified Network (Fig. 2).

Ground control points were established on the land according to the Large-Scale Map and Map Information Production Regulation. The C2-degree GCPs were installed as pillars (Fig. 3) and C3-degree GCPs were established as concrete blocks (Fig. 4). The facility operations of the GCPs were checked and approved by the General Directorate of Land Registry and Cadastre and by the TRNC Control Units in the field.

The distance between C2 GCPs is maximum 15 km, and also distances between C3 GCPs are on average 3 km.

6. 3D Network GNSS measurements and process of base vectors

The 3D Network GNSS measurements of the TRNC Renovation Project were realised using 25 dual-frequency LEICA Viva GNSS receivers. The horizontal accuracy of the receivers is 5

Fig. 3 - C2-degree GCP (pillar).

Fig. 4 - C3-degree GCP.

mm + 0.5 ppm and the vertical accuracy is 10 mm + 0.5 ppm (Leica Geosystems AG, 2012). The GNSS measurements of the C2-degree GCPs were performed with simultaneous GNSS measurements based on the CORS-TR system. The GNSS measurements of the C3-degree GCPs were based on the C2-degree GCPs on the principle of simultaneous measurements. In order to eliminate antenna height and orientation errors, all of the antennas were directed to the north with a compass and the antenna height measurements were taken and recorded at the beginning and the end. The data logging interval is 15 s for C2 GCP measurements and 10 s for C3 GCP and GNSS level measurements. The cut-off angle is 15 degrees. At least 600 epoch data were collected at C2 points and at least 210 epoch data at C3 points. For each point, GNSS measurements were carried out from at least three reference points to form a base vector.

6.1. Scale and goodness-of-fit test

The CORS-TR Network is defined in Datum ITRF96 and epoch 2005.00. In order to continue the processes related to the measurements, it was necessary to test the position accuracy of the CORS-TR station, which is available 24/7 in northern Cyprus. To this end, a scale/goodness-of-fit test of the CORS-TR network was performed. As a result of the goodness-of-fit test, the CORS-TR stations were joined with the C-degree control points. The TRNC 3D Network measurements were carried out in measurement epoch 2013.80 and CORS-TR stations with well-known positions, annual speed vectors and 2005.00 reference epoch coordinates were shifted to the 2013.80 epoch via Eq. 1. The 3D Helmert transformation of the coordinates obtained from the solution made with the shifted data was performed using the Bursa-Wolf transformation model (Závoti and Kalmár, 2015). In the solution of GNSS networks, the desired scale factor as a result of transformation cannot be more than $1-\lambda = \pm 3$ ppm (Deniz *et al.*, 2008). The scale factor obtained in the TRNC GNSS network solution was 0.1930 ppm, the root mean square (rms) was ±0.0333 ppm. The residual values obtained from the Helmert transformation of the compatible reference points made in the 2013.80 epoch are given in Fig. 5.

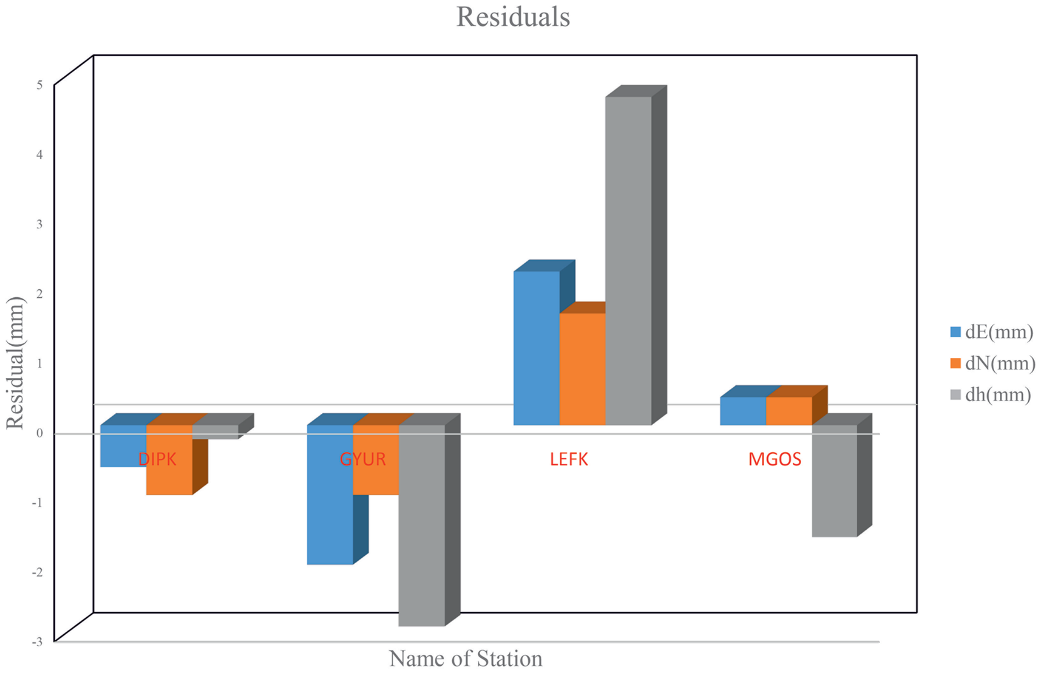

Fig. 5 - Residuals of Helmert transformation.

6.2. Processing of baselines

Considering the accuracy of the network, the GNSS measurements were carried out in three different sections using the LEICA Geo Office version 7.0 software (LGO v7.0). In all base measurements, the ambiguity of the initial phase was correctly solved. In the solution strategy of base vectors, the maximum distance between different solutions of position was 3 cm and the maximum distance between different solutions for height was 5 cm. Process parameters were selected as default and precise ephemerides information was used. In the solution of base vectors, the bases in which initial ambiguity was successfully solved were evaluated and the accuracy of the solutions was checked by loop closing. Log files in the base vector solutions were analysed. The cycle-slip effect and distorted satellite data were determined and excluded in order to ensure optimum accuracy. It is possible to keep potential antenna height errors in check by using field sheets prepared by the operators. At the end of each day, the raw data from the receivers were compared with the measurement plan and the incorrectly recorded point numbers were rearranged in dd.mm.yyyy directory structure in RINEX format.

6.2.1. C2 network solution

A total of 38 points of the C2-degree geodesic network form the main geodesic network of northern Cyprus. The GNSS measurements of the CORS-TR stations (DIPK, GYURT, LEFK, and

MGOS) and the C2 network points were performed simultaneously (Fig. 6). This network was evaluated in the 2013.80 measurement epoch. The maximum and minimum standard deviation values calculated as a result of the base vector solutions are given in Table 1. Positional accuracy (m_p) values for the C2 GCPs are given in Fig. 7.

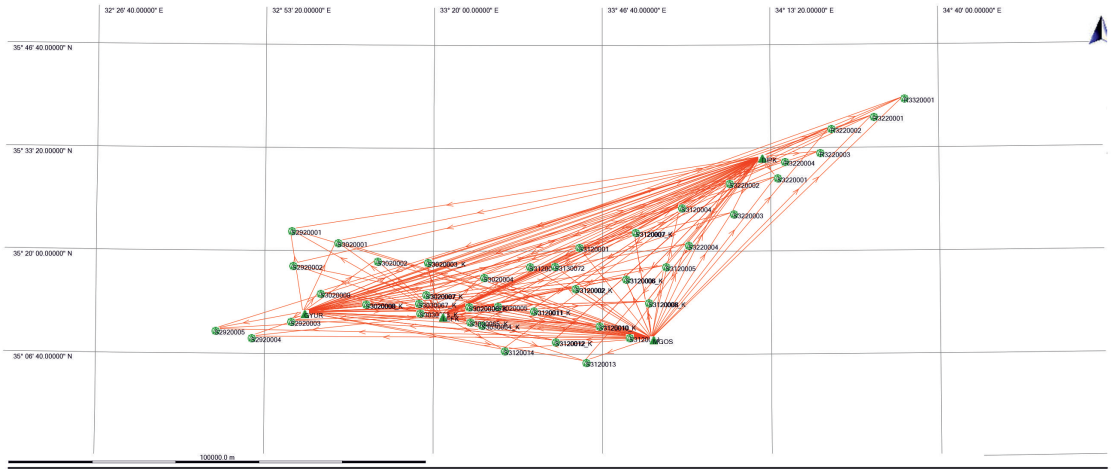

Fig. 6 - C2 network.

Table 1 - C2-degree GCP standard deviations.

#GCP	Sd.Easting (mm)	Sd.Northing (mm)	Sd.Height (mm)	Quality Pos+ Height (m_p)	Remark
S3020009	1.5	2.0	5.1	5.6	Min
S3120007	3.4	4.9	12	13.4	Max

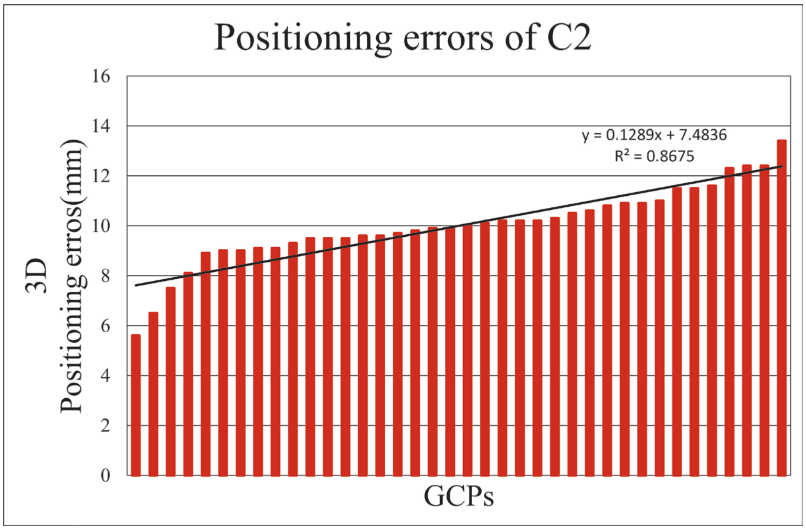

Fig. 7 - Quality of C2-degree GCPs.

6.2.2. C3 network solution

This network is a secondary main network which includes 71 C3-degree control points. Simultaneous measurements were carried out with the C2 GCPs which had known coordinates (Fig. 8). This network was evaluated in the 2005.00 measurement epoch. Maximum and minimum standard deviation values calculated as a result of the solutions of base vectors are given in Table 2. m_p values for the C3 GCPs are given in Fig. 9.

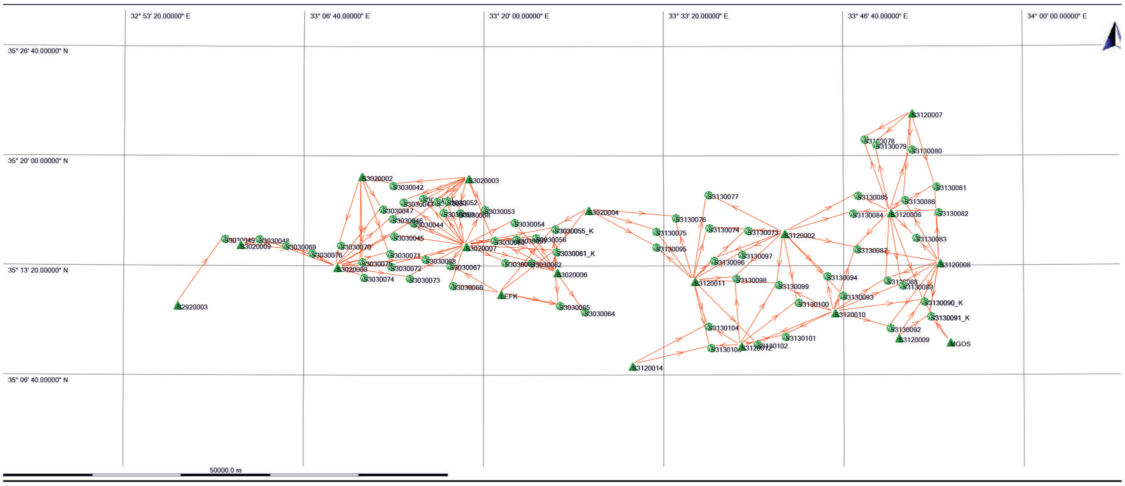

Fig. 8 - C3 network.

Table 2 - C3-degree GCP standard deviations.

#GCP	Sd.Easting (mm)	Sd.Northing (mm)	Sd.Height (mm)	Quality Pos+ Height (m_p)	Remark
S3030076	1.7	1.9	4.8	5.5	Min
S3130075	10.7	11.9	32.0	35.8	Max

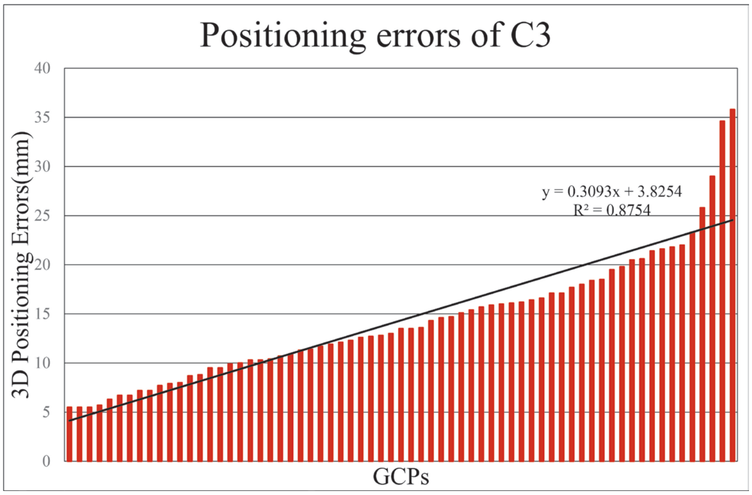

Fig. 9 - Quality of C3-degree GCPs.

The C2 coordinates in the measurement epoch obtained by constrained adjustment and the C3 coordinates in the reference epoch were shifted to the 2005.00 reference epoch by linear interpolation using Cartesian coordinates and annual velocity vectors (Vx, Vy, Vz) in the 2005.00 reference epoch of the DIPK, GYUR, LEFK and MGOS stations, and new velocity vectors were calculated. Information about the calculated vectors is given in Table 3 and Fig. 10.

Table 3 - C2 and C3 benchmark annual velocity vectors.

Component of Velocities	Max.(year/m)	Min.(year/m)
V_x	-0.0195	-0.0162
V_y	0.0087	0.0086
V_z	0.0108	0.0061

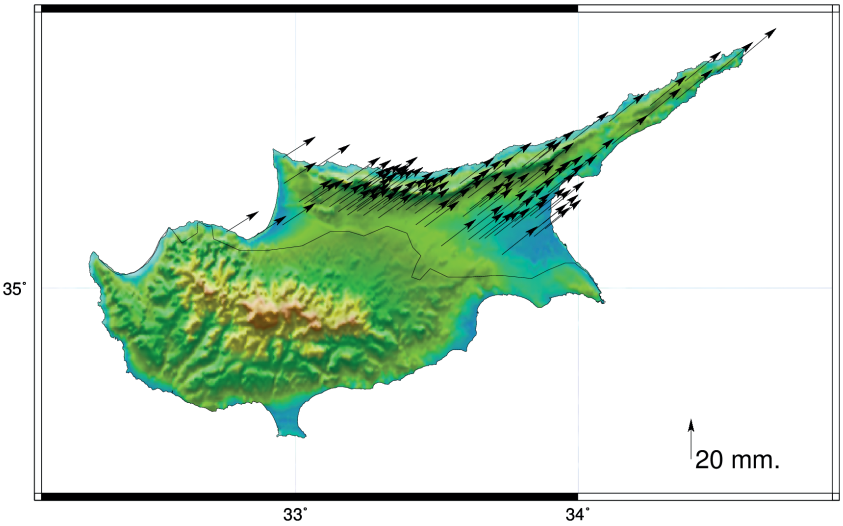

Fig. 10 - Velocity components of C2 an C3 benchmarks.

6.3. GNSS-levelling network solution

This network is the main network to determine the ellipsoidal/orthometric heights for northern Cyprus and includes 38 C2-degree control points and 15 vertical control points (Fig. 11). The GNSS-levelling measurements were carried out simultaneously with 15 GNSS receivers. In order to eliminate the antenna height errors, the antenna height at each point was changed by at least 10 cm for at least 2 h and a 2-h period of simultaneous GNSS observations were made. The GNSS observations were solved without error. The Cartesian coordinates of point S3120011 in the 2005.00 epoch were fixed and Δh ellipsoidal height differences were obtained. In addition, geometric levelling was performed between the NCNVN points with known Helmert orthometric height and the matching of the points was checked.

In this study, Generic Mapping Tools (GMT) (Wessel and Smith, 1998) codes were used in the calculations made with the KG-03 geoid model (Fig. 12).

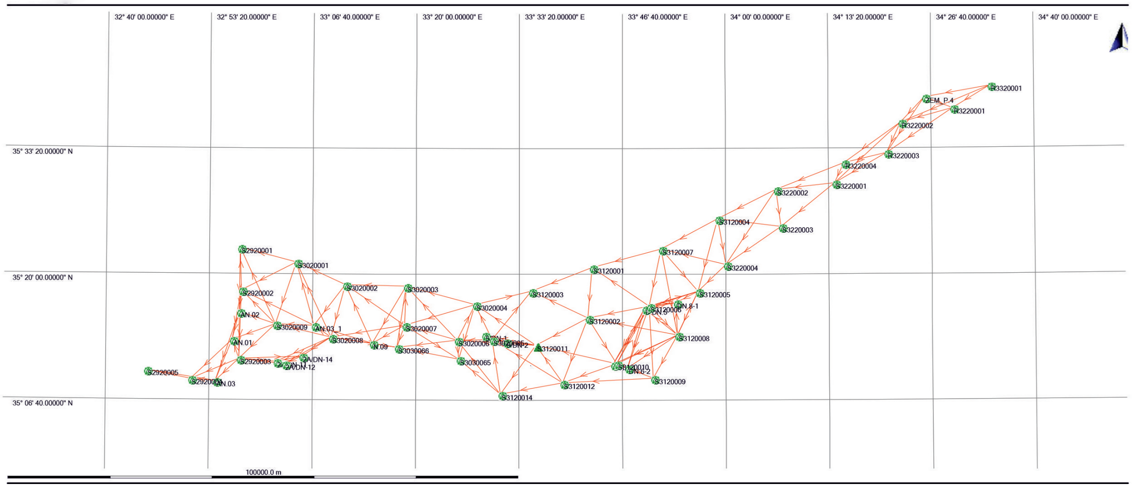

Fig. 11 - GNSS-levelling network.

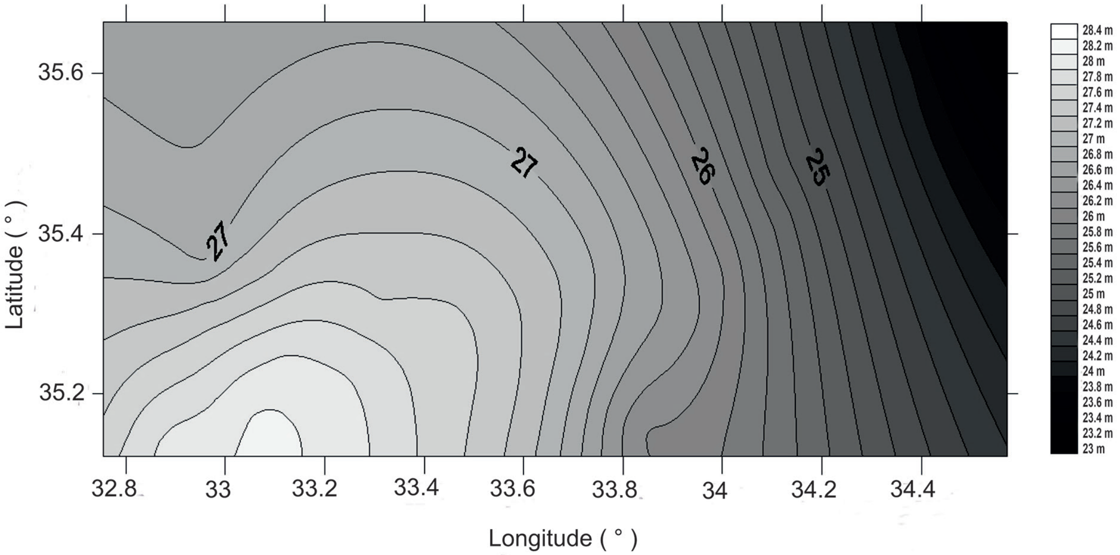

Fig. 12 - KG-03 geoid model.

The $\Delta H_{ij} = \Delta h_{ij} - \Delta N_{ij}$ correlation and Helmert orthometric height differences were calculated for each base vector by using ellipsoidal height differences (Δh_{ij}) and KG-03 geoid height differences (ΔN_{ij}) between the points measured in GNSS and generated as shown in Fig. 11 (Mainville *et al.*, 1992). The calculated Helmert orthometric height differences were taken as the measurement in the levelling network adjustment and the Helmert orthometric height was adjusted based on known points. The Helmert orthometric height (H) of the points was then calculated. Five separate GNSS-levelling routes were created and adjustment was performed. Ten points were taken as references (Tables 4 and 5).

Table 4 - Leveling route information.

#Route	[S](km)	Difference ($\Delta H_{Archive}$-dH_{Survey}) (mm)	Max. Acceptable Error(12*[$S_{Km}]^{1/2}$) (mm)	Ok/Reject
1	172.78	5.02	157.74	ok
2	124.70	4.11	134.00	ok
3	150.19	10.65	147.06	ok
4	65.04	1.35	96.78	ok
5	104.22	5.56	122.51	ok

Table 5 - Levelling adjustment results.

Height differences in the network	65
Points	54
Points without errors	9
Unknown points	44
RMS	1.06 mm
[Pvv]	23.4806 mm^2
[Pv]	-0.0010 mm

A goodness-of-fit test with polynomials was performed to check the accuracy of the calculated orthometric heights and it was decided that the test value of the calculated points was compatible because it was below the limit. Goodness-of-fit test summary information is given in Table 6.

Table 6 - Goodness-of-fit test results.

Points	53
Degree of freedom	17
Test limit value	2.931
Polinomial degree	5-36
RMS	0.025 m
Test value (Max.)	2.73
Test value (Min.)	0.01

After the calculation of the orthometric heights, ($N_{KG\text{-}03R} = N_{KG\text{-}03} + t + dN$) values were modelled with a 10-term third-degree polynomial. The Helmert orthometric and ellipsoidal heights at known reference points were obtained as the differences between the geoid heights calculated by the $N = h - H$ equation and the KG-03 geoid heights ($N_{KG\text{-}03}$). Table 7 shows the maximum and minimum differences. Table 8 shows improved geoid statistical results.

Table 7 - $N_{(KG\text{-}03)}$-$N_{(ort)}$ differences.

Points	Latitude	Longitude	Differences (m)
DN.11 DN.1	35.178456 35.226168	33.032618 33.480441	-0.0208 -0.0016
Mean RMS			-0.01365 ±0.01432

Table 8 - Improved KG-03 geoid statistical data.

Points	Latitude	Longitude	Differences (m)
S2920005 S3120014	35.163456 35.122209	32.754349 33.515085	-0.0212 0.0052
Mean RMS			-0.01363 ±0.01416

7. Results and discussion

The transition to digital cadastre, the maintenance of property assets and the establishment of GIS are considered revolutionary within the context of integration into the modern era. In order to accomplish the above mentioned issues, it is absolutely essential to establish a reliable geodetic infrastructure. The geodetic infrastructure of the project was realised and designed to cover northern Cyprus. The 3D fitting for the position accuracy of the reference CORS-TR stations was found to be quite successful. The scale factor of 0.193 ppm was attained, with the rms of goodness-of-fit test = ±0.0333 ppm. Access to the facilities is easy, allowing them to be maintained for many years. As a result of the C2-degree network evaluation and adjustment, the m_p values were obtained as a maximum of 13.4 mm. As a result of the C3-degree network evaluation and adjustment, the m_p values were obtained as a maximum of 35.8 mm. All points were obtained in the 2005.00 reference epoch and in the ITRF96 datum. Velocity vectors of the points were also determined as Max V_x = -0.0195 m, Max V_y = 0.087 m and Max V_z = 0.0108 m. The largest annual spatial change was calculated as ΔS = 2.39 cm.

The orthometric heights of the C2 and C3 points were included in the Vertical Control Network. For the cross-control, a goodness-of-fit test was applied to the points calculated with nine vertical control points compatible with GNSS-levelling. The critical test value was calculated as 2.931 and the goodness-of-fit test value of the other points was calculated as a maximum of 2.730. The reference points obtained by GNSS-levelling and Cyprus geoid data were used to determine an orthometric height model specific to northern Cyprus. A difference of 1.363 cm was calculated between the undulation data derived from the improved model and the KG-03 data. Based on these geodetic results, coordinate values of the cadastral parcel corner points within northern Cyprus were obtained numerically.

According to these results, using this developed model, orthometric heights in any part of northern Cyprus can be obtained by following the ellipsoidal height.

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