Determination of the Transformation Parameter between the Turkish and European Vertical Reference Frames

(Türkiye ve Avrupa Düşey Referans Çerçeveleri Arasındaki Dönüşüm Parametresinin Belirlenmesi)

Mehmet SİMAV[1], Ali TÜRKEZER[2], Erdinç SEZEN[1], Ali İhsan KURT[1], Hasan YILDIZ[1]

[1]General Directorate of Mapping, Ankara, Turkey
[2]Licensed Office of Surveying and Cadastre, Kuşadası, Turkey
mehmet.simav@harita.gov.tr

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ABSTRACT

The Directive 2007/2/EC of the European Parliament and of the Council aims to ensure geospatial standards in the production and exchange of geospatial information and data in Europe. The so-called INSPIRE Directive urges the EU Member States to take necessary measures for the full implementation of this Directive no later than 2021. The implementation rules and the technical guides created to provide INSPIRE specifications on coordinate reference systems (CRSs) require Member States to use European Terrestrial Reference System 1989 (ETRS89) and European Vertical Reference System (EVRS) or to document and provide transformation parameters between their own CRSs and ETRS89/EVRS. Turkey, as a candidate country for EU membership, has been adapting the INSPIRE Directive in many spatial data themes. Since national CRSs are in use in Turkey rather than ETRS89 and EVRS, transformation parameters must be provided in order to comply with the INSPIRE Directive. This study explains the overall process for determining the transformation parameter between Turkish and European vertical reference frames. High precision levelling and gravity connection measurements conducted through the Turkish-Bulgarian border result a transformation parameter of -0.405 ± 0.067 meters between the European (EVRF2007) and Turkish (TUDKA-99) vertical reference frames. This value should be added to the normal height given in TUDKA-99 to obtain its corresponding normal height value in ETRF2007.

Keywords: *Vertical Reference System, INSPIRE, EVRS, EVRF2007, TUDKA-99, Transformation Parameter.*

ÖZ

Avrupa Parlamentosu ve Konseyinin 2007/2/EC sayılı direktifi Avrupa içerisinde coğrafi bilgi ve veri üretiminde ve değişiminde standartları sağlamayı amaçlamaktadır. INSPIRE olarak bilinen bu direktif, AB Üye Devletlerini, bu direktifin 2021'den önce tam anlamıyla hayata geçirilmesi için gerekli tedbirleri almaya çağırmaktadır. Koordinat referans sistemleri (KRS) ile ilgili INSPIRE gereksinimlerini gösteren uygulama kuralları ve teknik rehberler, AB Üye Devletlerinden Avrupa Yersel Referans Sistemi 1989 (ETRS89) ve Avrupa Düşey Referans Sistemini (EVRS) kullanmayı ya da kendi KRS'leri ile ETRS89/EVRS arasındaki dönüşüm parametrelerini sağlamalarını talep etmektedir. Avrupa Birliği aday ülkesi Türkiye, INSPIRE Direktifini birçok mekânsal veri temasına uyarlamıştır. Türkiye'de ETRS89 ve EVRS yerine ulusal KRS'ler kullanıldığından INSPIRE Direktifine uyum için dönüşüm parametrelerinin sağlanması gerekmektedir. Bu çalışma, Türkiye ve Avrupa düşey referans çerçeveleri arasındaki dönüşüm parametresinin belirlenmesi sürecini açıklamaktadır. Türkiye-Bulgaristan sınırında gerçekleştirilen hassas nivelman ve gravite bağlantı ölçüleri Avrupa (ETRF2007) ve Türkiye (TUDKA-99) düşey referans çerçeveleri arasında -0.405 ± 0.067 metre dönüşüm parametresi olduğunu göstermektedir. Bu değer TUDKA-99'da verilen bir normal yükseklik değerinin EVRF2007'deki karşılığını bulmak için TUDKA-99 normal yükseklik değerine eklenmelidir.

Anahtar Kelimeler: *Düşey Referans Sistemi, INSPIRE, EVRS, EVRF2007, TUDKA-99, Dönüşüm Parametresi.*

1. INTRODUCTION

Turkey, as a candidate country for European Union (EU) membership, has been approximating and aligning its national legislations to EU norms. One of the norms to be followed is the geospatial standards in the production and exchange of geospatial information and data. These standards are imposed to EU countries by the Directive 2007/2/EC of the European Parliament and of the Council (EU Official Journal, 2007) adopted on 14 March 2007 that urges the EU Member States:

(i) to establish an infrastructure for spatial information in Europe (hereinafter referred to as INSPIRE) to support Community environmental policies, and policies or activities which may have an impact on the environment,

(ii) to adopt implementing rules in number of specific areas (metadata, data specifications, network services, data and service sharing and monitoring and reporting procedures),

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(iii) to make their own spatial data available according to these implementing rules,

(iv) to bring into force the laws, regulations and administrative provisions necessary to comply with this Directive.

One of the spatial data themes that the Directive 2007/2/EC addresses is the *Coordinate Reference Systems* (CRSs) used for uniquely referencing spatial information in space. INSPIRE Thematic Working Group responsible for the specification development have created a technical guideline *"D2.8.I.1 Data Specification on Coordinate Reference Systems"*, providing the INSPIRE specification on CRS (INSPIRE, 2014). According to this guideline, INSPIRE requires that:

(i) for the three-dimensional and two-dimensional (horizontal component) CRSs, the European Terrestrial Reference System 1989 (ETRS89) shall be used for the areas within the geographical scope of ETRS89,

(ii) the International Terrestrial Reference System (ITRS) or other geodetic coordinate reference systems compliant with ITRS shall be used in areas that are outside the geographical scope of ETRS89,

(iii) for the vertical component on land, the European Vertical Reference System (EVRS) shall be used to express gravity-related heights for the areas within the geographical scope of EVRS,

(iv) other vertical reference systems related to the Earth gravity field shall be used to express gravity-related heights in areas that are outside the geographical scope of EVRS,

(v) where requirements (ii) and (iv) apply, Member States shall make available information as to which system they use. The geodetic codes and parameters needed to describe these CRSs and to allow conversion and transformation operations shall be documented and an identifier shall be created, according to ISO 19111 (2007) and ISO/TS 19127 (2005).

Ministry of National Defense, General Directorate of Mapping (hereinafter referred to as GDM), by law the National Mapping Agency of Turkey, is responsible for the definition, realization, and maintenance of geodetic reference systems throughout the country. To discuss the adaptation procedure of the Turkish Geodetic CRSs to those mandated in INSPIRE technical guideline, GDM asked for two Technical Assistance and Information Exchange (TAIEX, 2018) instruments from the Directorate-General Enlargement of the European Commission. The first TAIEX event (expert mission) on horizontal and vertical CRSs and their realizations was held in Ankara, Turkey in 2009 by participation of Prof.Johannes Ihde from German Federal Agency of Cartography and Geodesy (BKG). The second TAIEX event (study visit) was realized as a visit of GDM delegation to BKG in Leipzig and State Survey Agency of Lower Saxony (LGN), Hannover, Germany in 2010 to view the conformance of INSPIRE requirements in CRS. After these event meetings, it was decided:

(i) to provide the descriptions of the Turkish Geodetic CRSs,

(ii) to estimate transformation parameters between Turkish Geodetic CRSs and the European CRSs (ETRS89 and EVRS),

(iii) to document the estimated transformation parameters in accordance with ISO 19111 (2007),

(iv) to publish the documentations at Information and Service System for European Coordinate Reference System web portal (CRS-EU, 2018).

The transformation parameters between ETRF89 and the Turkish National Reference Frame (TUREF) has been determined through the published transformation parameters between the ITRF-96 and ETRS-89 given by IERS (IERS, 2018) and EUREF (EUREF, 2018). However, since there is no direct link between European and Turkish National Vertical Reference Frames, it was decided to derive the vertical transformation parameter after the precise levelling and gravity measurements through the Turkish-Bulgarian border.

In the meantime, GDM contacted to Military Geographic Service of the Ministry of Defense of the Republic of Bulgaria (hereinafter referred to as MGS) and requested for trans-border levelling connections between the vertical control networks of the two countries. A working meeting was held by the participation of the representatives from GDM and MGS in 2010 at the border gate Kapıkule-Kapitan Andreevo. In the meeting, it was agreed:

(i) to construct one nodal benchmark at the Turkish side of Kapıkule-Kapitan Andreevo gate, and one more nodal benchmark at the Bulgarian side of Malko Tarnovo-Dereköy gate,

(ii) to conduct field measurements of spirit levelling and gravity in 2011 at the two border gates,

(iii) to exchange data for individual processing,

(iv) to have meeting to discuss the processing results.

The field surveys were conducted in the summer of 2011. The parties processed the data individually and exchanged the heights and other metadata of the common nodal benchmarks. This paper aims to explain the overall process for determining the transformation parameter between Turkish and European vertical reference frames. Chapter 2 contains theoretical information about the Turkish and European vertical reference systems and their latest realizations. Chapter 3 presents the fieldworks from benchmark reconnaissance to collection of precise levelling and gravity measurements. Chapter 4 focuses on the post-processing and analysis of the observations. Chapter 5 presents the conclusion.

2. VERTICAL COORDINATE REFERENCE SYSTEMS

CRS defines the constants, parameters and mathematical rules needed for uniquely referencing spatial information in space (Jekeli, 2016; ISO 19111, 2007.). It contains two different elements: the *datum* and the *coordinate system*. The datum means a parameter or set of parameters that define the position of the origin, the scale, and the orientation of a coordinate system, in accordance with ISO 19111 (2007). It defines how the CRS is related to the Earth and can be classified as geodetic, vertical and engineering datum. The coordinate system means a set of mathematical rules for specifying how the coordinates are to be assigned to points, in accordance with ISO 19111 (2007). It is the mathematical part of CRS describing how the coordinates are expressed in the datum. Therefore, the coordinate reference system means a coordinate system, which is related to the Earth by a datum. Schematically representation of the definition of any CRS is illustrated in Figure 1, and the application of this generalized representation for the vertical CRS is shown in Figure 2.

In general, a CRS is realized by a set of physical points and their coordinates. The realization is known as *reference frame*. The vertical or height datum is in most cases realized by mean sea level of one or more tide gauge stations and extended throughout the country by a network of benchmarks (Heiskanen & Moritz, 1967; Vanícek & Krakiwsky, 1986; Torge & Müller, 2012). The levelling networks consist of fixed benchmarks separated ~1-2 km from each other form the basis of conventional vertical CRS realization. Mean sea level is assumed to coincide with the geoid surface and regarded as zero height point. Starting from this point, precise leveling, 2D positional and gravity observations between the network benchmarks and the corresponding gravity related heights of benchmarks after data adjustment forms the national vertical coordinate reference frames.

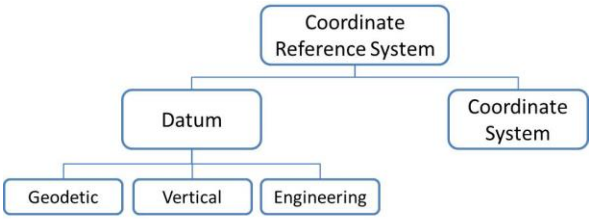

Figure 1. Schema of CRS Definition (ISO 19111, 2007).

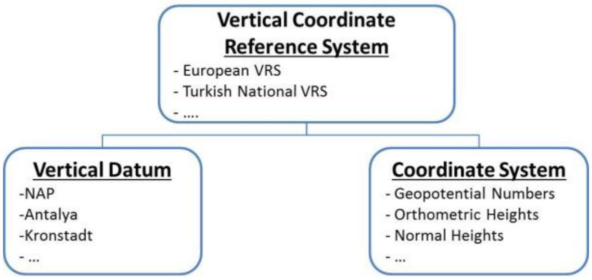

Figure 2. Schema of vertical CRS Definition.

The tide gauge stations of the national height systems in European countries are located at various oceans and inland seas: Baltic Sea, North Sea, Mediterranean Sea, Black Sea and Atlantic Ocean. The differences between the mean sea levels at these tide gauges can amount to several decimeters. They are caused by the various separations between the mean sea level and the geoid (BKG-EVRS, 2018). In addition there are also zero levels referred to the low tide or to the high tide rather than mean sea level. For example the Amsterdam zero point is defined by mean high tide in 1684 (BKG-EVRS, 2018). Regarding the coordinate system, gravity related height systems such as geopotential numbers, dynamic heights, normal heights, and orthometric heights are being used (Torge & Müller, 2012). Depending on the height system adopted, notable differences may exist between the corresponding heights of a single benchmark especially in the mountainous region. Examples for the use of orthometric heights are Belgium, Denmark, Finland, Italy and Switzerland. Today normal heights are being used in France, Germany, Sweden and in most of the Eastern European countries (BKG-EVRS, 2018).

The change from one coordinate system to another based on the same datum is possible via a *coordinate conversion*. Clearly, given sufficient gravity information, the dynamic, orthometric, and normal heights can be converted from one to the other, because they all depend on the geopotential numbers. However, the change of coordinates from one CRS to another CRS based on different datums is only possible via a *coordinate transformation* (ISO 19111, 2007). Therefore, transformation parameter(s) between two CRSs must be known and can only be derived empirically by a set of points common to both CRSs. Since Turkey has its own vertical CRS defined and realized using different conventions and realization, a transformation parameter between Turkish and European vertical CRSs has to be estimated in order to relate these two vertical CRSs. This chapter briefly summarizes the Turkish and European vertical CRS and reviews the differences between them.

a. Turkish National Vertical Reference System

The vertical CRS of Turkey has been defined and realized in a conventional point-wise way (Demir, 1999). The geoid is approximated by mean of annual sea level data at Antalya tide gauge located at the Mediterranean coast of Turkey (Latitude: 36.8844N, Longitude: 30.7016E) over 1936-1971 period. By fixing this gauge to zero height in the least-squares adjustment of the geopotential numbers of a network of ~26.000 benchmarks, the National Vertical CRS has been realized. The latest realization of the system is declared as Turkish National Vertical Control Network-1999 (TUDKA-99). The year (1999) appended does not coincide with the mean epoch of the observations, it is the nation-wide adjustment conducted in 1999.

The recorded instantaneous sea level heights between 1936 and 1971 period are averaged over a long term in order to obtain the mean value of the local sea level $\mathrm{H_{MSL}}$ (Ayhan & Demir, 1992). By definition, geoidal potential W_0 is assumed equal to the geopotential on the mean sea surface at Antalya tide gauge ignoring sea surface topography, and following this definition, the geopotential number at Antalya is defined to be zero.

$$\mathrm{C_{ANTALYA}^{MSL}} = \mathrm{W_0} - \mathrm{W_{ANTALYA}^{MSL}} = 0 \quad (1)$$

The height of the tide gauge $\Delta\mathrm{H_{BM-TG}}$ is also measured with respect to the datum point R36 that is situated on land at a short distance from the tide gauge station. Using Eq.(2), the height $\mathrm{H_{BM}}$ and the geopotential number $\mathrm{C_{BM}}$ of the datum point R36 above mean sea level is estimated to be 1.4284 meters and 1.3997 kgal.m respectively, assigning a mean gravity value of $\bar{\mathrm{g}}_{\mathrm{BM}} = 9.7988393$ ms^{-2} to the datum point R36.

$$\mathrm{H_{BM}} = \mathrm{H_{MSL}} + \Delta\mathrm{H_{BM-TG}} = \frac{\mathrm{C_{BM}}}{\bar{\mathrm{g}}_{\mathrm{BM}}} \quad (2)$$

Helmert orthometric height system is adopted in Turkey where point heights at levelling lines are computed from levelling and gravity data. Almost 30,000 km spirit levelling measurements between 1935 and 1999 period (most of them re-measured between 1972-1992) supplemented by surface gravity observations are used to determine the geopotential numbers at benchmarks (see Eq.3).

$$\mathrm{C_{BM}} - \mathrm{C_P} \approx \sum_{i=1}^{n} \frac{\mathrm{g}_i + \mathrm{g}_{i+1}}{2} \Delta\mathrm{H_i} \quad (3)$$

Minimum constraint weighted least squares adjustment has been performed using the geopotential number differences as observation with weights inversely proportional to the distance between benchmarks. The temporal changes in mean sea level, height and gravity data are neglected in the adjustment. Geopotential number at the datum point R36 is held fixed during the adjustment to introduce the height datum. Parameters of the TUDKA-99 adjustment are the following:

- Number of fixed points	:	1
- Number of unknown points	:	25796
- Number of measurements	:	26335
- Degrees of freedom	:	538
- A-posteriori standard deviation referred to a levelling distance of 1 km (kgal.mm)	:	1.24
- Mean value of the standard deviation of the adjusted geopotential numbers (kgal.mm)	:	20.4

To express resultant geopotential numbers in terms of Helmert orthometric heights, they are divided by the mean value of gravity taken along the plumbline. Since a pure orthometric height cannot be practically realized, the approximation given by Helmert has been used (Heiskanen & Moritz, 1967). The mean gravity value $\bar{\mathrm{g}}_{\mathrm{P}}$ is computed using the simplified Poincare-Prey reduction, that approximates the vertical gravity gradient by linear free-air gradient and models the topography by a spherical shell with a constant mass density of 2670 kgm^{-3}. The computation of the mean gravity value along the plumbline requires point height $\mathrm{H_P}$, therefore Eq.(4) is solved through iteration process. Although the Helmert orthometric heights are used officially in Turkey, normal heights of the levelling benchmarks are also computed based on the parameters of the Geodetic Reference System 1980 (Moritz, 1988). In the case of normal height, the denominator in Eq.(4) is replaced with the mean value of the normal gravity along the normal plumbline (see Eq.5).

$$\mathrm{H_P} = \frac{C_P^{adj}}{\bar{\mathrm{g}}_\mathrm{P}} = \frac{C_P^{adj}}{\mathrm{g}_P + 0.0424\mathrm{H_P}} \quad (4)$$

$$H_P^N = \frac{C_P^{adj}}{\bar{\gamma}_P} \quad (5)$$

There is no official definition on the tide system regarding the treatment of the permanent tidal effect (Ekman, 1989) in the Turkish Vertical CRS. No tidal correction is applied to the levelling data at all, thus the height differences approximately refer to the height of mean crust above the mean geoid. But, the gravity measurements are tidally corrected by eliminating both the periodical and permanent parts of the tidal effect from gravity observations which inevitably results in a conventional tide-free system. The tidal system of TUDKA-99 therefore is vague.

b. European Vertical Reference System

IAG Sub-commission for Europe (EUREF, 2018) started in 1994 with its activities for development and establishment of European height systems. The sub-commission aimed to establish a Unified Vertical Datum for Europe at the one-decimeter level with simultaneous extension of the Unified European Levelling Network (UELN) as far as possible to the Eastern European countries through the Resolution No. 3 of the EUREF symposium 1994 in Warsaw . The results of the adjustment were handed over to each participating country under the name UELN95/98 in the beginning 1999. One year later at the EUREF symposium 2000 in Tromsø a first definition of the European Vertical Reference System (EVRS) was approved, and the realization, European Vertical Reference Frame 2000 (EVRF2000), based on the UELN-95/98 solution was adopted (BKG-EVRS, 2018).

Half of the participating countries provided new national levelling data to the UELN data center after the release of the last solution EVRF2000. The need for an improved common EVRS were recognized at the workshop on “Vertical Reference Systems for Europe”, held in 2004 in Frankfurt am Main. Resolution No. 3 of the EUREF symposium 2005 held in Vienna recognized the need for a new realization of the EVRS. The EUREF symposium 2007 in London considered again that the progress in national levelling data information made possible an improved realization of EVRS. Therefore, new realization of the EVRS was computed and published under the name European Vertical Reference Frame 2007 (EVRF2007).

EVRS is a gravity-related and kinematical height reference system. Its definitions fulfill the following four conventions (BKG-EVRS, 2018):

(i) The vertical datum is defined as the equipotential surface for which the Earth gravity field potential is constant and in the level of the Normaal Amsterdams Peil.

$$\mathrm{W_0} = \mathrm{W_{0E}} = const. \quad (6)$$

(ii) The unit of length of the EVRS is the meter (SI). The unit of time is second (SI). This scale is consistent with the TCG time coordinate for a geocentric local frame, in agreement with IAU and IUGG (1991) resolutions. This is obtained by appropriate relativistic modelling.

(iii) The height components are the differences between the potential of the Earth gravity field through the considered points P, and the potential of the EVRS conventional zero level.

$$-\Delta\mathrm{W_P} = \mathrm{C_P} = \mathrm{W_{0E}} - \mathrm{W_P} \quad (7)$$

(iv) The EVRS is a zero tidal system (Ekman, 1989).

EVRF2007 is a set of physical points with precisely determined differences of geopotential relative to a reference potential W_0 at a defined epoch. The positions of the points are given in a specific terrestrial reference system. It is based on a combination strategy of three elements: the network, the vertical datum and the observation of the time evolution of the reference frame. The data is reduced, where possible, to the epoch 2000. The network is realized by a new adjustment of the UELN using geopotential numbers. The measurements in the UELN database have different epochs. This weak point of the project is remedied partly by the development of a kinematic network using information on the velocity of the points. The data in the main area of the Fennoscandian Postglacial Rebound is reduced to the epoch 2000 by differences of vertical velocities relative to the geoid from the land uplift model NKG2005LU (BKG-EVRS, 2018). Since the countries deliver their data in different tidal systems, mostly in the mean tide system, the geopotential differences are reduced from the mean tidal system to zero tide (BKG-EVRS, 2018).

Contrary to the EVRF2000 which is realized by one datum point, EVRF2007 has been adjusted using a number of datum points distributed over Europe. But, the level of the EVRF2000 datum has been kept in the EVRF2007 by introducing the following condition equation to fit the new UELN adjustment to the EVRF2000 solution. Therefore, the EVRF2000 heights of these new datum points are introduced in the free adjustment of the UELN network.

$$\sum_{i=1}^{13}(C_{EVRF2007} - C_{EVRF2000}) = 0 \qquad (8)$$

Parameters of the EVRF2007 adjustment are the following:

- Number of fixed points : 13
- Number of unknown points : 8133
- Number of measurements : 10568
- Number of condition equations : 1
- Degrees of freedom : 2436
- A-posteriori standard deviation referred to a levelling distance of 1 km (kgal.mm) : 1.12
- Mean value of the standard deviation of the adjusted geopotential numbers (kgal.mm) : 16.2

3. LEVELLING AND GRAVITY MEASUREMENTS

Fieldworks for the implementation of the cross-border connection of Turkish National Levelling Network to UELN were carried out following three steps:

(i) Reconnaissance survey for inspecting and identifying the locations of the existing and newly established benchmarks,

(ii) Establishment of nodal benchmarks at the border gates,

(iii) Levelling and gravity measurements in Turkey and Bulgaria.

a. Turkey

There are existing first order levelling lines of TUDKA-99 in the proximity of the border (see Figure 3). The first line **b2** directing towards the Kapıkule-Kapitan Andreevo border gate and the second line **b3** directing towards the Dereköy-Malko Tarnovo border gate fortunately ending with secure and stable benchmarks at distance less than 300 m to the border, where no densification of benchmarks is required.

Figure 3. General view of the Turkish levelling lines near the Turkish-Bulgarian border.

Both lines were constructed and surveyed in 1977. Table 1 gives the description of the initial benchmarks used for the cross-border connection. To ensure that these initial benchmarks are reliable, a stability test has been carried out by making control precise levelling measurements between the benchmarks of the lines, comparing the observed values with the published ones. The benchmarks used for the stability test are also described in Table 1, whose locations are shown in Figure 4.

A reference nodal benchmark has been constructed by the Turkish surveyors in 24 June 2011 at the border gate Kapıkule-Kapitan Andreevo. It is a nickel-iron alloy carved into a wall located at the Turkish side of the border gate and signified as **NR 10**. The location of the benchmark is depicted in Figure 4(a) and close-up photo views are given in Figure 5(a).

Table 1: Turkish benchmarks used for cross-border connection and stability test. (*marker set into the wall, **marker set into the ground)

Line	BM	Lat.	Long.	H_{TUDKA} (m)
b2	*DN-39	41.7188	26.3848	53.460 ± 0.062
b2	*DN-32	41.6979	26.4384	57.134 ± 0.061
b3	**b3-70	41.9674	27.4606	660.233 ± 0.065
b3	*DN-67	41.9677	27.4587	647.683 ± 0.065

Double-run precise spirit levelling between the benchmark **DN-39** of the line **b2** and the nodal benchmark **NR10** at Kapıkule-Kapitan Andreevo and between the benchmark **b3-70** of the line **b3** and the nodal benchmark **NR7** at Dereköy-Malko Tarnovo have been carried out between 18 and 28 July 2011 by the Turkish surveyors, using Topcon DL-101C digital level with invar bar coded rods for instrumentation. Instructions for the first order levelling have been followed during the measurements. The raw levelling data is presented in Table 2. The root mean square error per one kilometer first-order precise levelling is found to be 2.1 mm / km.

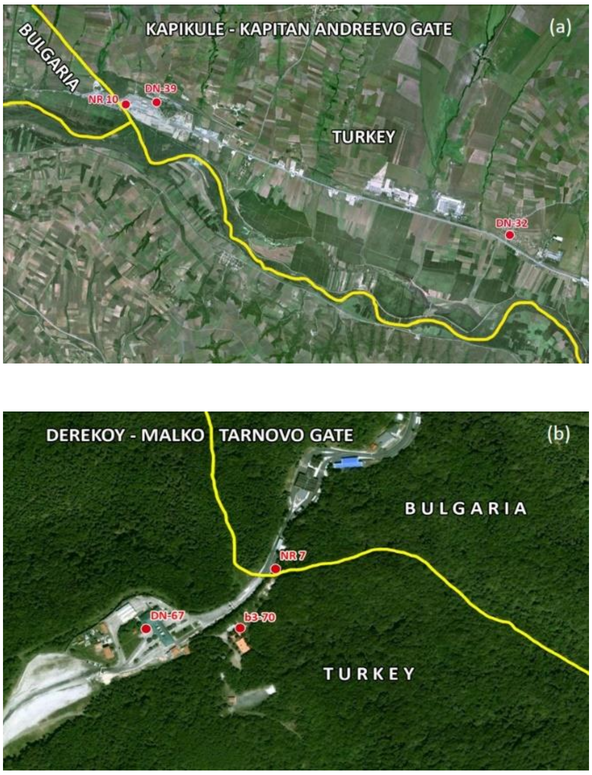

Figure 4: Levelling benchmarks in the vicinity of (a) Kapıkule-Kapitan Andreevo, and (b) Dereköy-Malko Tarnovo border gates.

Relative gravity measurements on the levelled benchmarks have been performed between 17 to 19 September 2011, using well calibrated Scientrex CG-3 gravimeter (#808451). Edirne absolute gravity station depicted in Figure 3 has been used as the starting point for relative gravity observations.

Table 2: Height differences between benchmarks obtained from precise levelling data in Turkey.

From	To	Dist. (km)	ΔH (m)
DN-39	NR10	1.20	-5.1972
NR10	DN-39	1.20	5.1979
b3-70	NR7	0.10	-6.2834
NR7	b3-70	0.10	6.2836

b. Bulgaria

Reconnaissance survey for the identification of the levelling benchmarks has been conducted in July 2011 in the regions of Svilengrad, Kapitan Andreevo and Malko Tarnovo. The benchmarks UELN No 2503722 situated near the town Malko Tarnovo and UELN No 2503968 situated near the town Svilengrad have been selected as the initial benchmarks for the cross-border connection. Descriptions of the points are given in Table 3. Since they are not close enough to the border gates for the direct connection, the levelling lines are extended to the gates with intermediate benchmarks.

One more reference nodal benchmark is established by the Bulgarian surveyors in July 2011 near the border gate Malko Tarnovo-Dereköy and signified as **NR 7**. The benchmark is vertical metal nail on a concrete foundation, stabilized south of Monument “BULGARIA” in territory of Bulgaria. The location of the benchmark is depicted in Figure 4(b) and close-up photo views are given in Figure 5(b).

Levelling measurement for determining the heights of two common nodal benchmarks signified as NR7 near Malko Tarnovo-Dereköy gate, and NR10 near Kapitan Andreevo-Kapıkule gate were carried out in accordance with 1^{st} and 2^{nd} order levelling instructions of Bulgaria.

The precise levelling measurements were carried out using Topcon DL-101C digital level, with invar bar code rods, in two opposite directions by different operators. The raw levelling data is presented in Table 4.

Relative gravimetric measurements on the benchmarks have been implemented by the GNU-K2 gravimeter. The estimated precision is ±0.3 mGal. Gravity reference points № 00086 situated in the town of Malko Tarnovo and № 00080 situated in the town of Harmanli are used.

Table 3: Bulgarian benchmarks used for cross-border connection.

BM	Lat.	Long.	$H_{EVRF2007}$ (m)
2503722	41.9799	26.5316	349.060 ± 0.026
2503968	41.4355	26.2123	53.615 ± 0.026

Table 4: Height differences between benchmarks obtained from precise levelling data in Bulgaria.

From	To	Dist. (km)	ΔH (m)
2503722	NR7	8.811	304.46297
NR7	2503722	8.811	-304.4650
2503968	NR10	15.778	-5.75575
NR10	2503968	15.778	5.75964

Figure 5: Reference nodal benchmarks: (a) **NR10** and, (b) **NR7**.

4. DATA PROCESSING AND RESULTS

a. Turkey

The normal heights of the nodal benchmarks **NR10** and **NR7** in TUDKA-99 datum have been estimated in three steps:

(i) Estimation of point gravity values from relative gravity observations,

(ii) Estimation of geopotential numbers from levelling and gravity data,

(iii) Estimation of normal heights.

The point gravity values are computed by the adjustment of reduced gravity readings as functions of unknown parameters, i.e. point gravity values and the linear drift correction. Before the adjustment, raw gravity readings have been reduced for the influence of tides, instrument height and external air pressure change in accordance with the recommendations of the International Gravity Commission. Gravity value of Edirne absolute point is held fixed to introduce a gravity datum. RMS of the standard deviation of the adjusted gravity values is about 0.035 mGal.

Once the point gravity values are computed, the geopotential numbers are estimated using Eq.(3). Finally the corresponding normal heights of the nodal benchmarks **NR10** and **NR7** are computed using Eq.(5). The resulting geopotential numbers and the normal heights in TUDKA-99 datum based on the parameters of GRS80 ellipsoid are presented in Table 5. The formal uncertainties of the parameters (e.g 0.06 m. for heights) represent the error accumulation in the network.

Table 5: The resulting geopotential numbers C_P^{adj}, the normal heights H_P^N and formal uncertainties of the nodal benchmarks in TUDKA-99.

BM	C_P^{adj} (kgal.m)	H_P^N (m)
NR10	47.313 ± 0.060	48.263 ± 0.062
NR7	641.029 ± 0.063	653.948 ± 0.063

b. Bulgaria

Calculations of normal heights are carried out by MGS jointly with the Geodesy Department at the National Institute of Geophysics, Geodesy and Geography at the Bulgarian Academy of Sciences. The results are present in Table 6.

Table 6: Normal heights H_P^N of the nodal benchmarks in EVRF2007.

BM	Lat.	Long.	H_P^N (m)
NR10	41.7169	26.3540	47.857 ± 0.049
NR7	41.9686	27.4610	653.543 ± 0.035

c. Transformation Parameter

Transformation parameter between Turkish Vertical Reference Frame TUDKA-99 and EVRF2007 is computed based on the normal heights of the nodal benchmarks in source and target system where TUDKA-99 is source and the EVRF2007 is target systems. The vertical transformation parameter between them is computed:

$$H_N^{EVRF2007} = H_N^{TUDKA99} + a \tag{9}$$

where $H_N^{EVRF2007}$ is the normal height of a benchmark in EVRF2007, $H_N^{TUDKA99}$ is the normal height of the same benchmark in TUDKA-99 and a represents the vertical transformation parameter. Table 7 gives the estimated transformation parameters between TUDKA-99 and EVRF2007 at two different benchmarks, where the mean value of the parameter is **-0.405 ± 0.067 m**. No significant difference exists between the transformation parameters at two benchmarks. The uncertainty of the parameter is computed based on the formal propagation of normal height errors in two reference frames.

Table 7: Estimated transformation parameter between TUDKA-99 and EVRF2007.

BM	$H_N^{TUDKA99}$	$H_N^{EVRF2007}$	a (m)
NR10	48.2634	47.8574	**-0.4060 ± 0.065**
NR7	653.9477	653.5430	**-0.4047 ± 0.068**

5. CONCLUSION

Turkey, as a candidate country for EU membership, has been adapting the INSPIRE Directive in many spatial data themes including CRSs. INSPIRE Directive urges the EU Member States to use ETRS89 and EVRS or to document and provide transformation parameters between their own CRSs and ETRS89/EVRS. In this study, we determine the transformation parameter between Turkish and European vertical reference frames using precise levelling and gravity measurements conducted at the two different Turkey-Bulgarian border gates. The estimated transformation parameter between the Turkish and European vertical reference frames is found -0.405 ± 0.067 m. This value should be added to the normal height given in TUDKA-99 to obtain its corresponding normal height value in EVRF2007. Since the transformation parameter is based on the normal heights in both frames, care must be taken when using TUDKA-99 benchmark heights, which are officially published in Helmert orthometric height system that can differ from normal heights by up to half meter in Turkey. General Directorate of Mapping can also provide the normal heights of the TUDKA-99 benchmarks upon request, which can directly be used in the transformation.

As it is also required in INSPIRE Directive, the abstract description of Turkish vertical CRS and the description of transformation between two frames is documented in accordance with EN ISO 19111 and published at Information and Service System for European Coordinate Reference System web portal.

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ORCID

Mehmet SİMAV https://orcid.org/0000-0002-3963-3871

Ali TÜRKEZER https://orcid.org/0000-0002-0040-561X

Erdinç SEZEN https://orcid.org/0000-0002-3822-3870

Ali İhsan KURT https://orcid.org/0000-0003-2367-2152

Hasan YILDIZ https://orcid.org/0000-0003-0104-7778

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