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GNSS/Levelling Data in Assessing the Fit of the Recent Global Geoids in Turkey

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ABSTRACT

Global Geopotential Models (GGMs) are representations of the long and medium wavelength components of the Earth's gravity field with spherical harmonic coefficients and thereby of the geoid. In order to improve especially the local geoid models, the choice of the best GGM for the region is essential. If the local data are not used during the design process of the models, the errors of parameters derived from the models will increase significantly depending on the topography. In general, it is suggested that the accuracy of GGMs should test with comparing the GGM-derived gravity field quantities with local data. In this study, accordingly, the geoid heights computed using EGM96 and EGM2008 (the combined GGMs) have been compared with geoid heights obtained by GNSS/levelling. The evaluation of results is achieved for three different study areas including Bursa, Zonguldak and Istanbul GPS Triangulation Network (IGTN).

This study aims to investigate which GGM is optimum for local geoid determination for the study areas. All results have revealed that EGM2008, offers the spatial resolution ~9 km depending on latitudes, is agreed considerably better with GNSS/levelling than EGM96. Its standard deviation fits with GNSS/levelling is 4.5 cm for Bursa. Also, these values for Zonguldak and IGTN have been improved by applying the outlier detection. It is supposed that deficiencies of GNSS/levelling (e.g. observation errors) may expand these differences.

The results show that EGM2008 can be used in the study areas for geoid determination.

KEYWORDS: Global Geopotential Model, GNSS/Levelling, Geoid Height, EGM2008, EGM96.

1. INTRODUCTION

GGMs are used to determine the Earth's external gravitational field and its functionals (e.g. disturbing potential, geoid heights, gravity anomalies, etc.). The accuracy level of the quantities derived the models vary from region to region. Therefore, the performance of any GGM needs to be validated in a regional scale by comparisons with other external data depending on the same gravity field (Smith and Milbert, 1997; Kiamehr and Sjöberg, 2005; Merry, 2007; Erol, *et al.*, 2009; Kılıcoglu, *et al.*, 2009; Ellmann, *et al.*, 2009; Ellmann, 2010; Hirt, 2011; Guimaraes, *et al.*, 2012). The accuracy of the models, commonly, has been assessed by using GNSS/levelling data. Also, the comparisons may be based on the other data sets including terrestrial gravity data and altimeter data over sea, etc.

Several previous studies have demonstrated various comparisons of the geoid heights obtained from the GGMs and the GNSS/levelling data in both absolute (at individual points) and relative (for baseline of varying lengths) sense (Featherstone, 2001; Bilker, 2005; Kotsakis, *et al.*, 2010; Kotsakis and Katsambalos, 2010). Moreover, there are many studies about the accuracy of the GGMs tested with the terrestrial gravity data (Denker and Roland, 2002; Amos and Featherstone, 2003) and the altimeter data (Klokocnik, *et al.*, 2002). Featherstone and Olliver (2013) have used the vertical deflections to evaluate EGM2008. It has been stated (Kotsakis and Katsambalos, 2010) that although the results from such evaluation studies depend on several factors (e.g. quality of the external data, consistency of their datums, applied testing methodology, etc.), they can mostly enable to a reliable assessment of the accuracy level of GGMs over different areas.

Nowadays, GNSS/levelling can be considered as an alternative for practical height determination (Featherstone, *et al.*, 1998; Erol, 2011). In the GNSS/levelling, the orthometric heights H are determined by converting the ellipsoidal heights h with respect to a reference ellipsoid by applying the fundamental equation $H = h - N$ (N: geoid height) (Heiskanen and Moritz, 1967; Hofmann-Wellenhof and Moritz, 2006). Hence, determining the geoid heights through an accurate geoid model (or GGM) enables to obtain the orthometric heights with sufficient accuracy using the GNSS positioning. In relation to this case, a requirement for a high precision geoid model preferably referring to a global geocentric datum arised. Accordingly, many countries have continued to make efforts to develop their own high-precision geoid model. In this context, GGMs have important meanings as reference surface for calculating a local geoid. Also, the GNSS/levelling data are very important factor to fit gravimetric geoid models to local vertical datum. Considering all of these, a precise geoid model is an important component for GNSS/levelling (Erol and Celik, 2004).

Turkey Hybrid Geoid Model-2009 (THG-09), the last regional gravimetric geoid model for the Turkey area, has an external accuracy level of ±9 cm (THG-09, n.d.). It means that the orthometric heights from the GNSS observations can be computed with the accuracy level of ±9 cm using THG-09.

The aim of this study is to evaluate to performance of GGMs in terms of the differences between gravimetric and geometric geoid heights in absolute sense. For that purpose, recent observations collected over various test areas in Turkey were used. This paper focuses on the evaluation of EGM96 and EGM2008 in Turkey using GNSS/levelling over the networks of

49, 117 and 455 points in Bursa, Zonguldak and IGTN, respectively.

2. GLOBAL GEOPOTENTIAL MODELS

Using the potential theory, the gravitational potential V outside the mass of the Earth can be expressed as a series of spherical harmonic functions (Hofmann-Wellenhof and Moritz, 2005)

$$V(r,\theta,\lambda)=\frac{GM}{R}\sum_{n=0}^{\infty}\left(\frac{R}{r}\right)^{n+1}\sum_{m=0}^{n}\left(\overline{C}_{nm}\cos m\lambda+\overline{S}_{nm}\sin m\lambda\right)\overline{P}_{nm}(\cos\theta) \quad (1)$$

where r, θ, λ are the spherical geocentric coordinates of the computation point: radial distance, co-latitude and longitude, respectively; GM is the geocentric gravitational constant; R is the reference radius; $\overline{C}_{nm}$ and $\overline{S}_{nm}$ are the fully normalized spherical harmonic (Stokes) coefficients with n, m being degree and order, respectively; $\overline{P}_{nm}(\cos\theta)$ are the fully normalized associated Legendre functions. A spherical harmonic approximation of the gravity field up to a maximum degree $n_{\max}$ consists of ($n_{\max}+1)^2$ coefficients. Such set of coefficients together with parameters GM and R to which the coefficients relate are called Global Geopotential Model (GGM) (Barthelmes, 2013). The GGM can be only an approximation of the reality gravity field and its accuracy depends on both the coefficients' accuracies and $n_{\max}$.

Considering from a geodetic positioning perspective, the GGMs play a key role for the unification of national height systems and the support of vertical datum modernization efforts based on precise GNSS positioning (Kotsakis and Katsambalos, 2010).

The spherical harmonic coefficients representing the Earth's density distribution are determined by integration of the gravity data obtained from the various sources such as satellite and terrestrial gravity, satellite altimetry and satellite gradiometry. Accordingly, the GGMs can be classified into three groups, namely, satellite-only, combined and tailored gravity field models (Featherstone, 2002; Amos and Featherstone, 2003). The satellite-only GGMs are primarily derived from the analysis of the satellite-tracking and satellite gradiometry data. The satellite data including satellite altimetry and Satellite Laser Ranging (SLR) are combined with land, airborne and marine gravity data to yield high degree combined GGMs. Besides, in the tailored gravity field models, the coefficients of the satellite-only models or the combined models are improved with regional updated gravity data and topography data for a specific area (Wenzel, 1998).

The spatial resolutions of GGMs is related to the maximum degree of the expansion (spatial resolution=20000/$n_{\max}$ [km]). As the resolution of the model increases, it represents the local effects of mass distributions better (Abbak, 2011). $n_{\max}$ parameter corresponds to the spatial coverage and quality of the observations. Especially, since the launch of dedicated satellite gravity missions (CHAMP, GRACE and GOCE), the deficiencies (e.g. the global coverage and precision) have been improved and a number of GGMs have been released by the different groups around the world. However, the accuracy of the combined models is not still homogeneous over the whole Earth due to uncertainties in terrestrial data. If the model does not include enough dense and accurate terrestrial gravity data from the study area, it can not be obtained the expected accurate results for the geodetic and surveying applications.

Since terrestrial data recover gravity signals at shorter wavelengths compared to the satellites data, they are crucial.

As stated previously, related to the model coefficients, the various gravitational functionals computed from the GGMs can be affected by errors due to factors such as different geodetic datum, measurement, design and computation failures (Pavlis and Saleh, 2005). Therefore, to be informed of the accuracy of the GGMs, it is essential to decide whether they can be used in the geodetic applications (e.g. local geoid determination). The accuracy of the model can either be determined from the estimated error degree variances concerning the coefficients (Featherstone, 2002; Tepekoylu, 2008) or comparison of the gravitational functionals calculated from the model with their terrestrial measurements directly (the studies has been cited previously).

2.1 Use of GGMs in Geoid Heights Computation

The set of spherical harmonic coefficients of the Earth's external gravitational potential are not used directly to derive a model of geoid heights. To compute these quantities requires the use of equation 1 and additional information, combined in the generalized Bruns equation. Its causes are clarified by Smith (1998) in detail.

The generalized Bruns equation (to first order terms), which can be used to compute geoid heights, is written as follows:

$$N_{PQ} = \frac{T_P}{\gamma_Q} - \frac{W_P - U_Q}{\gamma_Q} \tag{2}$$

where P and Q are the points on geoid and ellipsoid, respectively; N_{PQ} is the geoid height between P and Q; T_P is the disturbing potential at point P; γ_Q is the normal gravity at point Q; W_P is the true gravity potential at point P; U_Q is the normal gravity potential at point Q. In equation 2, $W_P = W_0$, $U_Q = U_0$ and $W_0 \neq U_0$.

It has been pointed out (Smith, 1998) that a correction for the difference between the normal potential of GRS80 and the true potential of the geoid (as best we know it), should be applied to geoid height computations, when using GRS80 as the chosen reference field. The reason is that recent estimates of the size of a best fitting ellipsoid differ in semi-major axis with GRS-80 by many decimetres and also recent estimates of the true GM for the Earth differ significantly from the GM of GRS-80. In this case, zero-degree term arising from the differing GM values and the difference between U_0 and W_0 must be consider in the geoid height computations.

Moreover, it has been touched upon (Smith, 1998) the significance of that the GGM should include the permanent tide system of the model. While the shape of the geoid changes accordingly to the type of permanent tide system (mean, zero and tide-free), the value of W_0 does not change from one system to another. Tide-free geoid is recommended for using in transformation of the GNSS heights.

3. NUMERICAL EVALUATION

In the numerical evaluation, the GGMs-derived geoid heights were compared with the GNSS/levelling geoid heights over various test areas in Turkey.

3.1 Data Sets

The GGMs employed in this study in order to investigate their fit to the GNSS/levelling geoid heights are EGM96 and EGM2008 representing the most known combined models. The models can be freely available from web pages of the International Center for Global Gravity Field Models (ICGEM) (ICGEM, 2013).

3.1.1 Earth Gravitational Model 1996 (EGM96)

The EGM96 is a combined geopotential model consisting of the spherical harmonic coefficients complete to degree and order 360. The US National Imagery and Mapping Agency (NIMA) now National Geospatial Agency (NGA), the US National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) and the Ohio State University (OSU) collaborated in the determination of EGM96. The geoid accuracy of the EGM96 is better than one meter with the exception of areas void of dense and accurate surface gravity data (Lemoine, *et al.*, 1998). It offers level of spatial resolution of ~55 km (or ~30 arc minutes) for the recovery of any gravity field functional over the entire globe. For more information see EGM96 (2004).

3.1.2 Earth Gravitational Model 2008 (EGM2008)

Developed by the NGA, EGM2008 is the first-ever global model that is capable of resolving the Earth's gravity field beyond spherical harmonic degree 2000 (Pavlis, *et al.*, 2008; Hirt, 2011; Pavlis, *et al.*, 2012). The EGM2008 set of spherical harmonic coefficients is complete to degree 2190 and order 2159. With the release of the EGM2008, a considerable improvement has been in high-resolution global gravity field modeling. The model allows determination of the Earth's gravity field globally with a spatial resolution of ~9 km (or ~5 arc minutes) in the latitudinal direction, which is 6 times higher than that of EGM96. Pavlis, *et al.* (2012) have pointed out that the discrepancies between the EGM2008 geoid heights and independent GNSS/levelling values are on the order of ±5 to ±10 cm over areas covered with high quality gravity data. Also, they have claimed that the accuracy of EGM08, as gauged from comparisons with independent data, is 3 to 6 times higher than that of EGM96, depending on the gravitational functional.

Especially, unlike previous GGMs, the EGM2008 contains gravity data of 15' resolution for Asian regions. Furthermore, the gravity data provided by GRACE satellite system has greatly contributed to development of EGM2008. The detailed overview of the model can be found from EGM2008 (2013).

3.1.3 GNSS/Levelling Data

The validation of the EGM96 and EGM2008 has been based on comparison with GNSS/levelling observations covering Bursa, Zonguldak as well as Istanbul GPS Triangulation Network (IGTN). The set of collocated GNSS and levelling data is ground on previously projects. Accordingly, the testing networks have comprised 49 (Bursa), 117 (Zonguldak) and 455 (IGTN). Figure 1 shows the distribution of the benchmarks.

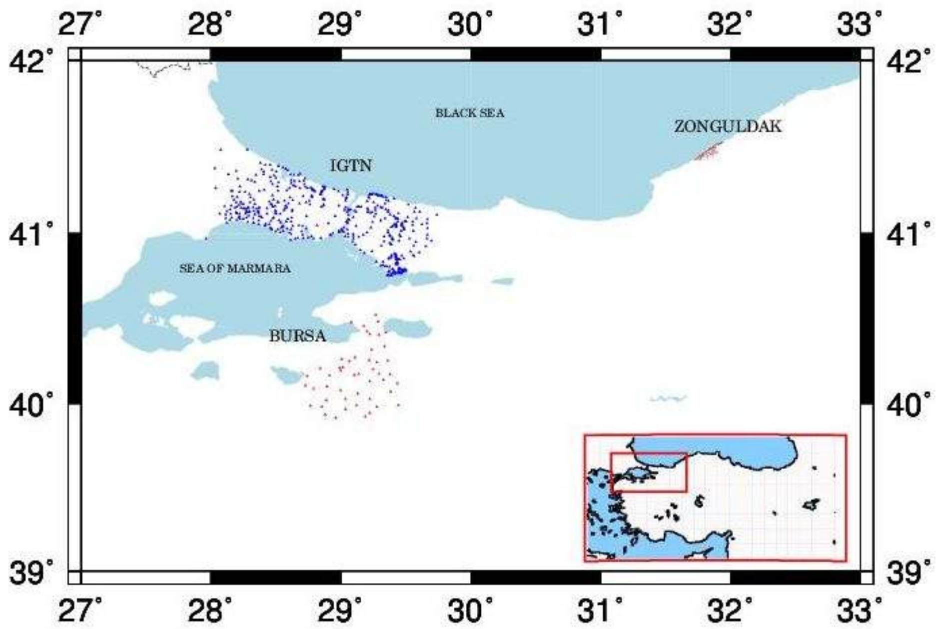

Figure 1. The distribution of the available GNSS/levelling benchmarks in the test areas.

These are the common points of C1, C2, C3 and C4 orders GPS benchmarks of Turkish National Fundamental GPS Network 1999-A (TNFGN-99A) and IV. and V. orders of levelling benchmarks of Turkish National Vertical Control Network 1999 (TNVCN-99). The Helmert orthometric heights of the benchmarks were determined by geometric levelling in TNVCN-99 (Demir and Cingoz, 2002). GNSS coordinates of the benchmarks refer to the International Terrestrial Reference Frame 1996 (ITRF96) datum. Table 1 summarizes the properties of the data.

Table 1. Description of the local GNSS/levelling networks

Description for Networks		Bursa	Zonguldak	IGTN
Network & Topography	Area (km^2)	50x70	5x22	75x200
	Number of benchmarks	49	117	455
	Density, benchmark per km^2	1/70	1	1/32
	Elevation between (m)	35-1315	2-511	1-485
GNSS Observations	GNSS receiver type	Dual frequency	Dual frequency	Dual frequency
	Coordinate datum	ITRF96	ITRF96	ITRF94
	2D coordinate accuracy (cm)	—	±1.5-4.4 cm	±1.5 cm
	h accuracy (cm)	—	±3.0 cm	±2.0 cm
Levelling	Levelling method	Precise	Geometric/Trigometric	Geometric
	H accuracy (cm)	—	±3.0 cm	±2.0 cm
	Vertical datum	TNVCN-99	TNVCN-92	TNVCN-99
Reference		BUSKI, 2009	Ayan, *et al.*, 1996	Ayan, *et al.*, 1999

3.2 Methodology and Numerical Tests

The principal aim of this study is to investigate the accuracy of the GGMs using sets of the precision geodetic points. In this study, the evaluation was only performed in absolute sense.

Based on the basic relationship between geoid, ellipsoidal and orthometric heights, the geoid heights were computed at the set of all benchmarks as follows:

$$N_{GNSS/lev.} = h_{GNSS} - H_{levelling} \quad (3)$$

The corresponding GNSS/levelling-derived geoid heights have been compared with GGMs-derived quantities. Hence, the geoid heights were calculated by using ICGEM calculation service for EGM96 and EGM2008 as well (ICGEM, 2013). For the computations, considering the Turkish National Reference Frame, it were selected GRS80 as reference system. So, our computations incorporated zero-degree term. And the tide-free system was preferred as tide system.

In the assessment, the geoid heights differences between GGMs and GNSS/levelling were achieved for each benchmark. During validations, some of points were assigned as blunders and eliminated from the data sets. As a result of this, 2 benchmarks have been removed from the Bursa network, 1 from the Zonguldak network and 6 from IGTN for evaluation of the EGM96. On the other hand, for evaluation of the EGM2008, 8 and 17 benchmarks have excluded Zonguldak network and IGTN, respectively. The geoid heights residuals obtained after removing the blunders in the data and local topography of the test areas are shown in Appendix A, B and C.

Table 2. Validation results of EGM96 and EGM2008 models in the test areas, the geoid height differences at GNSS/levelling benchmarks in centimeter.

	EGM96					EGM2008				
	Min.	**Max.**	**Mean**	**Std. Dev.**	**RMS**	**Min.**	**Max.**	**Mean**	**Std. Dev.**	**RMS**
Bursa	20.8	103.5	56.2	24.4	61.2	-16.8	0.3	-7.8	4.5	9.0
Zonguldak	151.2	207.9	175.8	14.9	176.5	-30.7	-7.9	-21.1	5.7	21.9
IGTN	-65.1	62.4	-0.5	31.8	31.8	-47.7	37.5	5.3	12.7	13.8

The basic statistic of geoid heights residuals are represented in Table 2. Considering the validation results and statistics, the following conclusions on the performances of the models in Turkish territory are obtained:

- The EGM2008 fits the local gravity field better in each test area and standard deviations between 4.5 cm and 12.7 cm indicates the superior performance of this ultra-high resolution global model.

- The bias between -7 cm and -20 cm may indicate a systematic shift between the EGM2008 surface and local vertical datum in Zonguldak and Bursa. These systematic differences would be modeled and removed via de-trending the EGM2008 model in these areas.

- However in Istanbul case, the bias reaches is 5.3 cm with a standard deviation of 12.7 cm. When the geoid height differences in Istanbul are investigated, it seems that the observational errors at some of the data points could influence the assessment results. Hence, a more carefully check of the data is required before the analyses in Istanbul region.

- On the other hand, the EGM96 with maximum degree of 360 does not provide the performance as high as the EGM2008 with the maximum degree of 2190 for fitting the local gravity field in Turkey.

- Considering the EGM96 validation results in all three regions, it's seen that the model did not provide a standard deviation better than 14.9 cm.

- When the spectral resolutions of both models are compared, the superior performance of the EGM2008 versus the EGM96 is not a surprise. Although this result can be interpreted as the low commission error of EGM2008, to be exact on this inference spectral analysis of this model is necessary.

- From practical point of view, the EGM2008 provided quite satisfying results for transformation of GNSS ellipsoidal heights into local vertical datum for using in many geodetic and surveying applications. However, when the number of coefficients which constitute such an ultra-high resolution global geoid model is thought, the difficulties which could arise in its use in practice should be considered.

4. CONCLUSIONS

Geopotential models are valuable tools for several geodetic and surveying applications. A global geoid model, obtained from a high-resolution and high-accuracy GGM, can provide a cm level global vertical datum. The efforts concerning this goal go on in Turkey and in the world. The EGM2008, for example, contributes significantly to the geodetic community for a highly accurate reference model of Earth's gravity field.

This study was carried out to determine the best fitting global model for geodetic applications in Turkey depending on the tests applied using GNSS/levelling control data. For this aim, the numerical tests were done in Bursa, Zonguldak and Istanbul local GNSS/levelling networks. The outliers in the GPS/levelling data, caused by the errors in GPS and levelling observations, were detected considering geoid height differences at the benchmarks. And then the statistics as to computations analyzed.

With the results of this study, the superior performance of EGM2008 in representation of the Earth gravity field in Turkey is clarified. According the results, drawn in the content of this study, its contribution to an upcoming cm precision regional geoid model of Turkey is highly expected.

In the next stage of the study, assessment of the EGM2008 as a reference global model in the gravimetric geoid determination for Turkey is planned.

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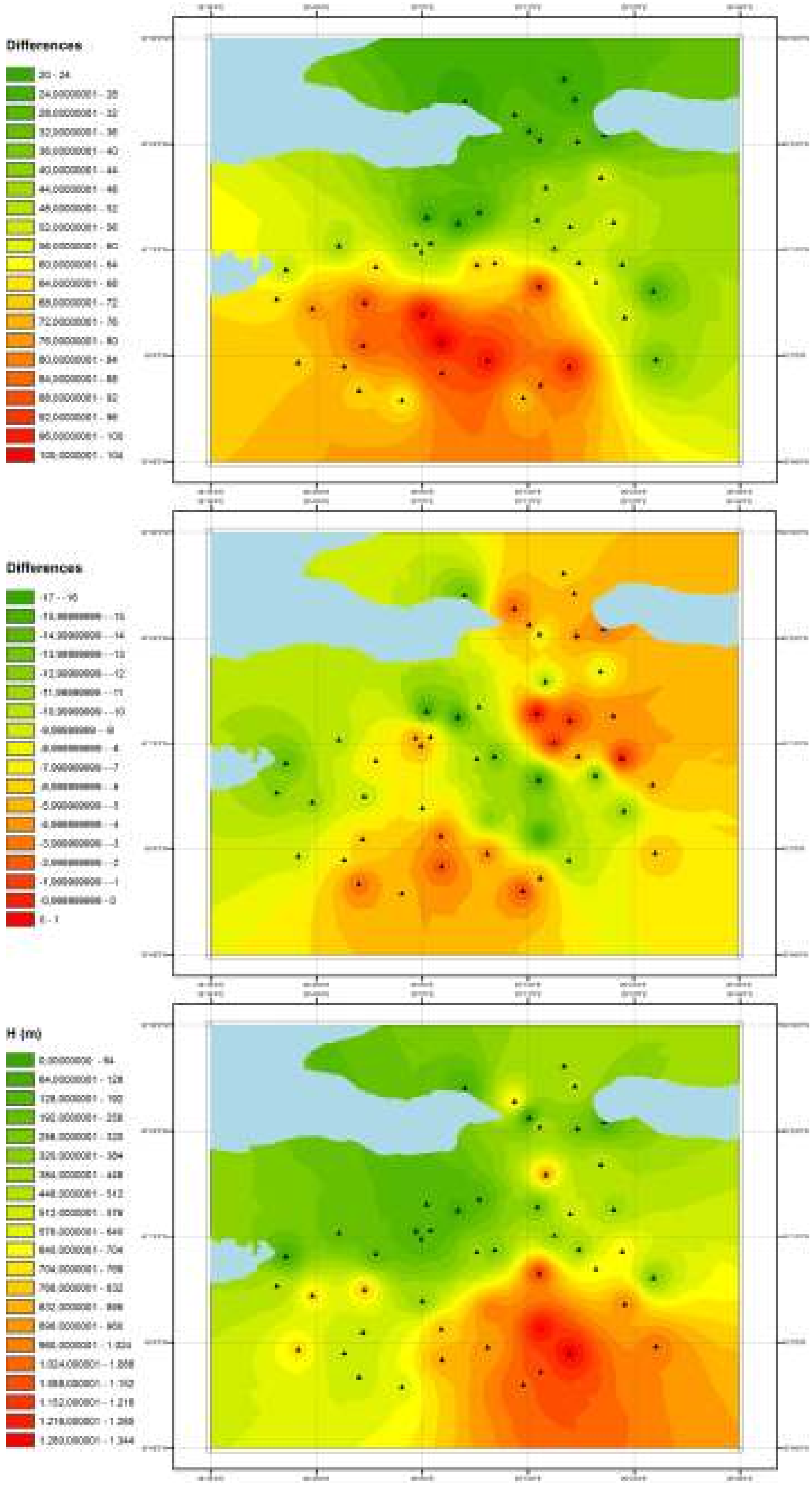
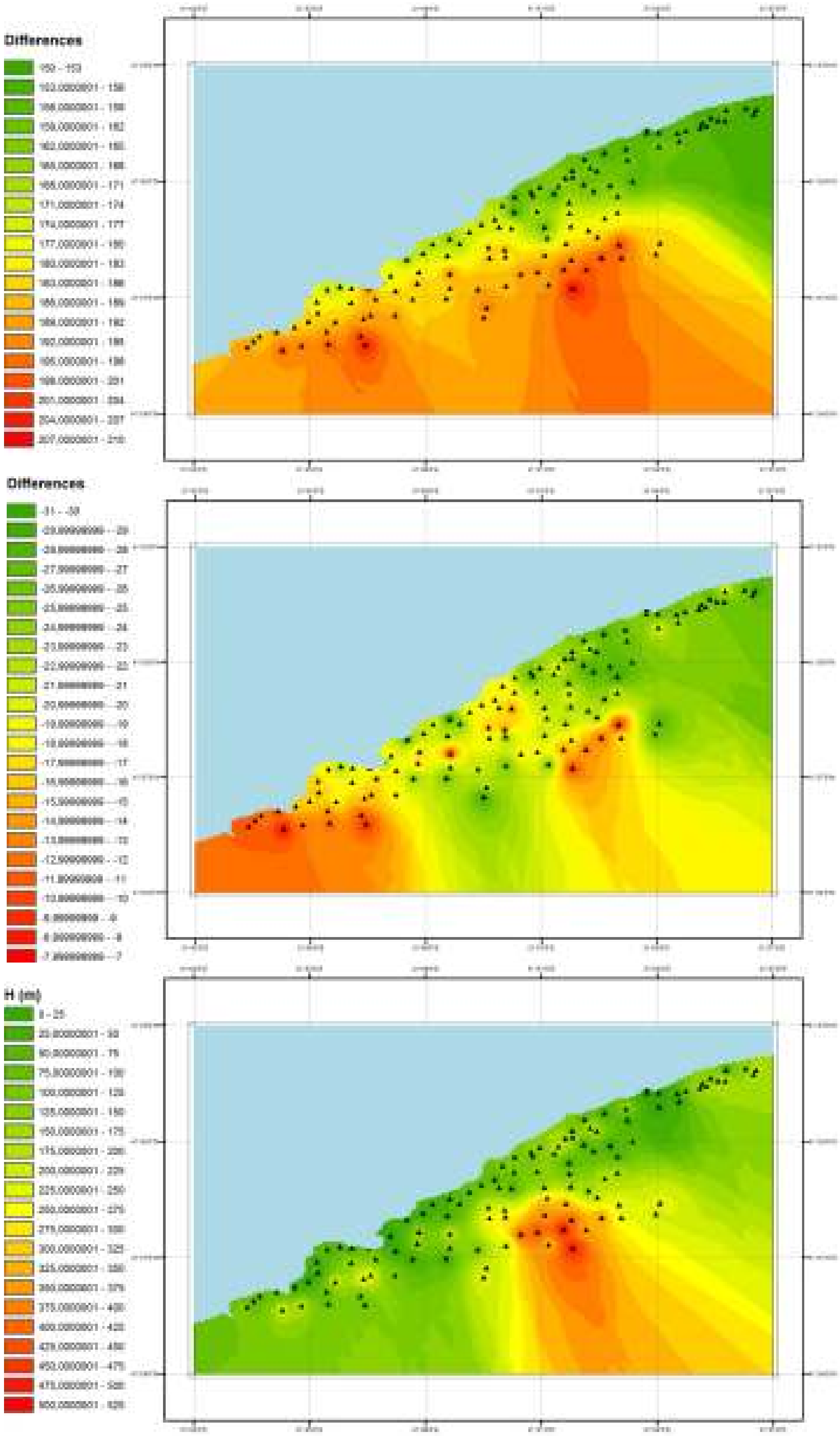
Appendix A. The differences between (a) EGM96, (b) EGM2008 and GNSS/levelling geoid heights in the Bursa network, (c) the topography of the Bursa test area.



Appendix B. The differences between (a) EGM96, (b) EGM2008 and GNSS/levelling geoid heights in the Zonguldak network, (c) the topography of Zonguldak test area.



Appendix C. The differences between (a) EGM96, (b) EGM2008 and GNSS/levelling geoid heights in the IGTN, (c) the topography of Istanbul test area.