Vertical Datum Evaluation Based on Heterogeneous Data Combination over Attica, Greece

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Key words: GPS/leveling, geoid, vertical datum, Attica, corrector surfaces

SUMMARY

The evaluation of the Vertical datum in the region of Central Greece (Attica) is presented. Local gravimetric as well as global geoid models are used in order to validate the vertical datum in specific GPS/leveling points. Two local geoids (HGFFT98 and HGIO2000), three global geopotential solutions (EGM96, GPM98b, EGM2008) and recent satellite-only based models are compared in GPS/leveling benchmarks. Corrector surfaces based on various parametric models are tested in order to fit a geoid solution at the control points. The best results in the benchmarks adjustment are obtained using a 3rd order polynomial model. An internal accuracy of 5.6 cm in terms of the sd of the differences between GPS-based and gravimetric geoid heights after blunder removal is achieved. Some remarks on the quality of the existing vertical control network are drawn and recommendations towards the improvement of the fitting quality are suggested. Finally, the future plans on a combined gravity/GPS/leveling geoid in the area are itemized.

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1. INTRODUCTION

The evolution of the satellite technology in precise positioning led the geodetic community to the use of GNSS systems in engineering and environmental projects. The frame of these applications is based on a well established and controlled reference network. The performance of this technology in the horizontal positioning is extremely high. On the contrary, vertical positioning is based on the characteristics of Earth's gravity field. Due to this reason, the accuracy in vertical positioning is depended on our knowledge of the gravity field. The importance of this statement is justified by the gravity-dedicated satellite missions of the last decade. The cm-geoid, a goal for recent geodetic research, can lead to an increased accuracy in vertical positioning using GNSS systems. The term "leveling by GNSS" will replace classical time-consuming spirit leveling in everyday surveyor applications. As the geoid accuracy increases, the need of a well established and controlled vertical datum becomes even more necessary.

The first-order vertical control network of Greece was established and measured from the Hellenic Military Geographic Service from 1963 to 1986. On the other hand, the first order Hellenic trigonometric network has some height information, due to some trigonometric leveling lines. This vertical information has not been validated since its creation. The validation of the vertical reference network before the establishment of the European interconnection is thus essential. As it is well documented (Kotsakis and Sideris, 1999; Fotopoulos, 2003; Tziavos et al., 2010), the availability of geoid models of high accuracy poses new potentials in order to validate available orthometric heights and subsequently correct blunders in the leveling databases. This is of special importance in countries like Greece where: a) the vertical reference network, realized through the network of leveling benchmarks, has not been commonly adjusted in a unified frame, b) the leveling benchmarks are delaminated in so-called "map-leaflets" which often have horizontal and vertical distortions (Tziavos et al, 2010). The latter creates significant problems to everyday GPS surveying applications when leveling benchmarks from neighbouring "map-leaflets" are used in a single traverse. The purpose of the present study is the examination of the above mentioned problems in the Hellenic vertical datum, as realized by specific benchmarks over Attica region.

2. THEORETICAL BACKGROUND

The well-known observation equation of the combination of GPS/leveling and gravimetric geoid height in a benchmark *i* can be written as (Kotsakis and Sideris, 1999; Fotopoulos, 2003, Tziavos et al., 2010):

$$\ell_i = h_i - H_i - N_i^{GRAV} = N_i^{GPS/L} - N_i^{GRAV} = \mathbf{a}_i^{\mathbf{T}}\mathbf{x} + v_i\,, \tag{1}$$

where h_i is the ellipsoidal height derived from GPS observations, H_i is the orthometric height of the benchmark and N_i^{GRAV} is the geoid height derived from pure gravimetric solutions. The common procedure of the above scheme evaluation is the fitting of GPS/leveling ($N_i^{GPS/L}$) and gravimetric geoid height differences using an adequate parametric model.

The $\mathbf{a}_i^{\mathbf{T}}\mathbf{x}$ part of the equation (1) represents the model part of the observation equation. The models used are usually some parametric equations of plane or more complicated surfaces. As mentioned in Fotopoulos (2003), in the past, researchers have often utilized a simple tilted plane-fit model, which in several cases has satisfied accuracy requirements. However, as the achievable accuracy of GPS and geoid heights improves, the use of such a simple model may not be sufficient, especially when dealing with larger areas. The problem is further complicated because selecting the proper model type depends on the data distribution, density and quality, which vary in each case.

Depending on the area under consideration, various parametric models can be used. The $\mathbf{a}_i^{\mathbf{T}}$ array contains rows of the design matrix $\mathbf{A}$ and the $\mathbf{x}$ is the vector of the unknown parameters. The base functions used in these models are usually formed by differences of ellipsoidal or planar coordinates (see eq. (2)). After measuring GPS/leveling points and estimate gravimetric geoid height in the specific place, the estimation of the model parameters in a least-square procedure follows. The unknowns $\hat{\mathbf{x}}$ form the shape of a surface that can be used to transform (correct) GPS ellipsoidal height to orthometric height in every other point of the area. This is the reason why these models are often called in the bibliography “corrector surfaces”. A general form of the $\mathbf{a}_i^{\mathbf{T}}\mathbf{x}$ model part is given in equation (2)

$$\mathbf{a}_i^{\mathbf{T}}\mathbf{x} = \sum_{n=0}^{N}\sum_{m=0}^{M} dy_i^m dx_i^n \mathbf{x}\,, \tag{2}$$

where $dy_i = \varphi_i - \varphi_o$ and $dx_i = (\lambda_i - \lambda_o)\cos\varphi_m$ with φ_o, λ_o the latitude and longitude of a base point and φ_m the mean latitude of the area under study. In the case of a 3rd order polynomial surface the $\mathbf{a}_i^{\mathbf{T}}\mathbf{x}$ part is:

$$\begin{aligned}\mathbf{a}_i^{\mathbf{T}}\mathbf{x} = \sum_{n=0}^{3}\sum_{m=0}^{3} dy_i^m dx_i^n \mathbf{x} = x_0 + x_1 dx_i + x_2 dy_i + x_3 dx_i^2 + x_4 dy_i^2 + x_5 dx_i dy_i + x_6 dx_i^3 + \\ + x_7 dy_i^3 + x_8 dx_i^2 dy_i + x_9 dx_i dy_i^2\end{aligned} \tag{3}$$

with 10 unknown parameters as described in matrix notation:

$$\mathbf{x} = \begin{bmatrix} x_0 \\ x_1 \\ \vdots \\ x_9 \end{bmatrix}, \text{ and } \mathbf{a}_i^{\mathbf{T}} = \begin{bmatrix} 1 & dx_i & dy_i & dx_i^2 & dy_i^2 & dx_i dy_i & dx_i^3 & dy_i^3 & dx_i^2 dy_i & dx_i dy_i^2 \end{bmatrix} \quad (4)$$

Another popular model is the 4 parameter spherical model which corresponds to a 7 parameter similarity transformation (Heiskanen and Moritz, 1967). This model was widely used in geodetic literature, especially over extended areas. The model part of the observation equation is presented in equation (5):

$$\mathbf{x} = \begin{bmatrix} x_0 \\ x_1 \\ x_3 \\ x_4 \end{bmatrix}, \text{ and } \mathbf{a}_i^{\mathbf{T}} = \begin{bmatrix} 1 & \sin\varphi_i & \cos\varphi_i \sin\lambda_i & \cos\varphi_i \cos\lambda_i \end{bmatrix}. \quad (5)$$

3. DESCRIPTION OF DATA

3.1 GPS/leveling data

In our study we used a total of 66 benchmarks with known orthometric heights. The majority of these points (63) belong to the Hellenic national trigonometric network. The heights of these points have been estimated by the Hellenic Military Geographic Service using trigonometric leveling. In addition, we used 3 benchmarks of the national leveling network. All benchmarks are located in the broader area of Attica.

In order to estimate geoid undulations on these benchmarks, their ellipsoidal heights had to be assessed. This has been done by means of GPS measurements. Dual frequency receivers (Topcon HiperPro) were used and the data were collected using a sampling interval of 15 sec and an elevation mask of 10^o. The occupation time at each point was 90 minutes.

The processing of the GPS measurements has been done using Reference Stations of the Hellenic Positioning System (HEPOS). HEPOS is an RTK network consisting of 98 permanent GPS reference stations that fully cover Greece (Gianniou, 2009). The coordinates of the HEPOS stations are expressed in HTRS07 (Hellenic Terrestrial reference System 2007), which is a realization of ETRS89 in Greece (Katsampalos et al., 2009). The use of HEPOS allowed the estimation of precise ellipsoidal heights with respect to a common geodetic frame, i.e. HTRS07. The locations of the benchmarks as well as the reference stations of HEPOS that have been used are shown in Figure 1. For each benchmark two baselines were formed using the two nearest HEPOS stations. The final ellipsoidal coordinates of the benchmarks were computed by means of a least squares adjustment. This strategy enhances the accuracy and allows realistic assessment of the achieved precision. The mean sigma value of the adjusted ellipsoidal heights was 0.009 m.

Figure 1: Locations of the GPS/leveling benchmarks (green triangles: trigonometric points, green circles: points of the leveling network, red triangles: HEPOS stations).

3.2 Geoid models

In order to evaluate the vertical control points a number of global and local geoid models were used. The choice of these models was based on the comparison of various solutions aiming to a common strategy in data blunder removal. Using different geoid models of various resolution and accuracy gross-errors in control points are easily detected.

3.2.1 <u>Global Satellite only models</u>

Two satellite only models were used in our comparisons. The first one, GOCO01S (Pail et al., 2010) is a combination solution based on 61 days of GOCE gravity gradient data, and 7 years of GRACE GPS and K-band range rate data, resolved up to degree/order 224 of a harmonic series expansion. The combination was performed consistently by addition of full normal equations and stochastic modeling of GOCE and GRACE observations. The model has been validated against external global gravity models and regional GPS/leveling observations. While low to medium degrees are mainly determined by GRACE, significant contributions by the new measurement type of GOCE gradients can already be observed at degree 100. Beyond degree 150, GOCE becomes the dominant contributor.

The second satellite only model, EIGEN-51C (Bruinsama et al., 2010) is a combined global gravity field model full to degree and order 359. It consists of 6 years of CHAMP and GRACE data (Oct 2002 till Sept 2008) and the DNSC08 (Andersen et al., 2008) global gravity anomaly data set based on satellite altimetry data. The combination has been done on the basis of normal equations. The solution has been obtained from one full normal equation till degree and order 359. The reference epoch of this gravity field model is 01 Oct 2005.

3.2.2 Global combined models

Two additional models based on satellite as well as surface gravity data were used in the validation procedure. The first model Earth Gravitational Model 1996 - EGM96 (Lemoine et al., 1998) incorporates surface gravity data, altimeter-derived anomalies from ERS-1 and from the GEOSAT Geodetic Mission (GM), extensive satellite tracking data - including new data from Satellite Laser Ranging (SLR), the Global Positioning System (GPS), NASA's Tracking and Data Relay Satellite System (TDRSS), the French DORIS system, and the US Navy TRANET Doppler tracking system - as well as direct altimeter ranges from TOPEX/POSEIDON (T/P), ERS-1, and GEOSAT. The final solution blends a low-degree combiantion model to degree 70, a block-diagonal solution from degree 71 to 359, and a quadrature solution at degree 360. The model was used to compute geoid undulations accurate to better than one meter (with the exception of areas void of dense and accurate surface gravity data) and realize WGS84 as a true three-dimensional reference system. Additional results from the EGM96 solution include models of the dynamic ocean topography to degree 20 from T/P and ERS-1 together, and GEOSAT separately, and improved orbit determination for Earth-orbiting satellites.

The second global combined geopotential model is the state-of-the-art harmonic expansion geoid model based on various data sources, Earth Gravatational Model 2008 - EGM2008 (Pavlis et al., 2008). This model incorporates optimally surface gravity obseravtions, satellite altimetry data and newly available products from gravity dedicated satellite missions (GRACE). The spherical harmonic expansion of EGM2008 reaches degree 2190 and order 2160, resulting in a spatial resolution of 5 arcminutes (see Figure 2).

3.2.3 Local geoid models

Two local geoid models for Attica area were used for the efficient vertical datum evaluation. The first model HGFFT98 (Tziavos and Andritsanos, 1998) was based on heterogeneous data combination using Fast Fourier Transform algorithm. The computations were carried out using (a) gravity anomalies for the land area and marine data derived from satellite altimetry and digitization of sea gravity maps and (b) a 1 Km digital terrain model. The EGM96 geopotential model was used as the reference field.

The second one, HGIO2000 (Andritsanos, 2000) is part of the national geoid estimation using Multilple Input – Multiple Output System Theory – MIMOST (Andritsanos et al., 1999, Andritsanos, 2000). It was based on an updated gravity database using the GPM98b global gravity model (Wenzel, 1999) as reference. The efficient combination of heterogeneous data through an error minimization critirion of the MIMOST algorithms led to a local combined solution of 3′ resolution (see Figure 3).

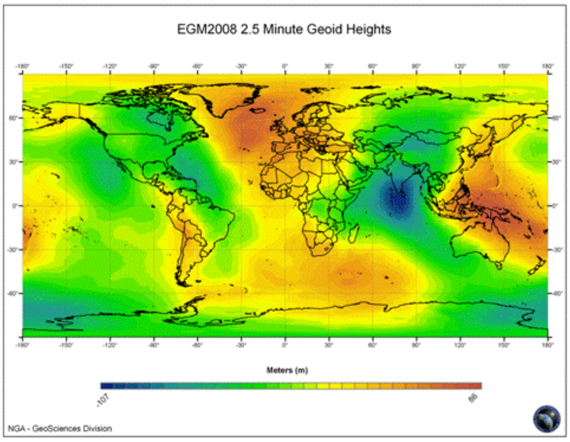

Figure 2: Global EGM2008 geoid solution (Courtesy: NGA)

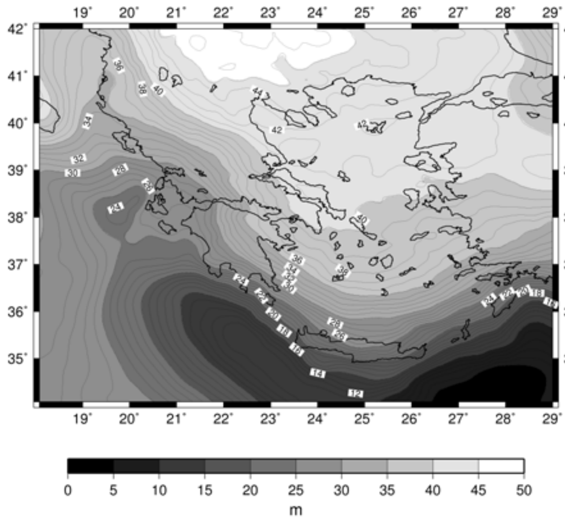

Figure 3: Local geoid solution HGIO2000

4. NUMERICAL ANALYSIS

The numerical tests were based on the comparison in terms of geoid height differences at 66 benchmarks in the area of Attica. As it is mentioned the benchmarks are part of the official trigonometric network of Greece. The geoid models chosen for the numerical tests cover the major part of the gravity anomaly spectrum, from low degree pure satellite data to combined sources of high degree and order. The variety of the model choice ensures the effective evaluation of the vertical datum as it is realized by the specific benchmarks.
For the construction of a corrector surface between GPS/leveling and gravity geoid heights four different parametric models were utilized. As presented in Section 2, a simple plane (3 unknown parameters), a curvature surface (6 unknown parameters), a 3rd order polynomial surface (10 unknown parameters) and the classical 4-parameter datum shift model corresponding to a 7 parameter similarity Helmert transformation were used as the mathematical models of the corrector surface.
In the following tables the statistics of the differences between GPS/leveling and gravimetric geoid heights are presented. Each table contains information from a specific gravimetric geoid model. Statistics before and after the parametric model fit are given.

Table 1: The statistics of the differences between GPS/leveling and gravimetric geoid model (GOCO01S) – all values in m.

$N_{GPS} - N_{MODEL}$ **Geoid model: GOCO01S n=m=224**	**min**	**max**	**mean**	**sd**	**Unknown parameters**
before parametric model adjustment	-0.409	0.642	0.228	0.201	
after 1st order polynomial fit	-0.637	0.414	0.000	0.156	3
after 2nd order polynomial fit	-0.187	0.267	0.000	0.097	6
after 3rd order polynomial fit	**-0.192**	**0.248**	0.000	**0.095**	10
after spherical datum shift model fit	-0.310	0.352	0.000	0.152	4

Table 2: The statistics of the differences between GPS/leveling and gravimetric geoid model (EIGEN-51C) – all values in m.

N_{GPS} - N_{MODEL} Geoid model: EIGEN-51C n=m=359	min	max	mean	sd	Unknown parameters
before parametric model adjustment	-0.259	0.697	0.245	0.212	
after 1st order polynomial fit	-0.394	0.382	0.000	0.167	3
after 2nd order polynomial fit	-0.188	0.253	0.000	0.096	6
after 3rd order polynomial fit	**-0.192**	**0.250**	0.000	**0.095**	10
after spherical datum shift model fit	-0.362	0.374	0.000	0.164	4

Table 3: The statistics of the differences between GPS/leveling and gravimetric geoid model (EGM96) – all values in m.

N_{GPS} - N_{MODEL} Geoid model: EGM96 n=m=360	min	max	mean	sd	Unknown parameters
before parametric model adjustment	-0.739	0.119	-0.222	0.204	
after 1st order polynomial fit	-0.366	0.337	0.000	0.152	3
after 2nd order polynomial fit	-0.217	0.229	0.000	0.094	6
after 3rd order polynomial fit	**-0.210**	**0.227**	0.000	**0.092**	10
after spherical datum shift model fit	-0.345	0.336	0.000	0.152	4

Table 4: The statistics of the differences between GPS/leveling and gravimetric geoid model (EGM2008) – all values in m.

N_{GPS} - N_{MODEL} Geoid model: EGM2008 n=2190, m=2160	min	max	mean	sd	Unknown parameters
before parametric model adjustment	-0.626	-0.209	-0.388	0.079	
after 1st order polynomial fit	-0.241	0.165	0.000	0.078	3
after 2nd order polynomial fit	-0.243	0.180	0.000	0.075	6
after 3rd order polynomial fit	**-0.198**	**0.131**	0.000	**0.065**	10
after spherical datum shift model fit	-0.233	0.164	0.000	0.078	4

Table 5: The statistics of the differences between GPS/leveling and gravimetric geoid model (HGFFT98) – all values in m.

N_{GPS} - N_{MODEL} Geoid model: HGFFT98 Local solution based on EGM96	min	max	mean	sd	Unknown parameters
before parametric model adjustment	-1.129	-0.250	-0.742	0.236	
after 1st order polynomial fit	-0.199	0.185	0.000	0.097	3
after 2nd order polynomial fit	-0.248	0.182	0.000	0.084	6
after 3rd order polynomial fit	**-0.208**	**0.132**	0.000	**0.075**	10
after spherical datum shift model fit	-0.231	0.172	0.000	0.092	4

Table 6: The statistics of the differences between GPS/leveling and gravimetric geoid model (HGIO2000) – all values in m.

N_{GPS} - N_{MODEL} **Geoid model: HGIO2000** **Local solution based on GPM98b**	**min**	**max**	**mean**	**sd**	**Unknown parameters**
before parametric model adjustment	-2.248	-1.638	-1.967	0.126	
after 1st order polynomial fit	-0.217	0.241	0.000	0.092	3
after 2nd order polynomial fit	-0.257	0.200	0.000	0.081	6
after 3rd order polynomial fit	**-0.211**	**0.129**	0.000	**0.070**	10
after spherical datum shift model fit	-0.249	0.228	0.000	0.086	4

With the careful consideration of the above tables, some remarks about vertical datum quality can be itemized. At first, as it is expected, using global models, the agreement between GPS/leveling and gravimetric geoid heights becomes better as the degree and order of the spherical harmonic expansion augments. This is quite reasonable, because the higher expansion of a global model leads to an increase of the geographically correlated gravity field details. As it is seen, a sd of 20 cm drops to 8 cm in the case of the ultra-high expansion model EGM2008. An interesting point is the remarkable agreement of the GOCO1S satellite model despite its low expansion degree. This is just a glance of what geodetic community expects from the gravity dedicated satellite missions. Both local and global models have a standard bias varying from -2 m to 0.30 m, approximately. Note that as the details of the gravity field representation increase, the mean value of the differences takes negative values (i.e., geoid from GPS/leveling surface above gravimetric geoid surface). This bias can be attributed to the datum inconsistencies of the different data sources used in the computations. The main problem in gravity field modeling, as it is well known, is the inconsistent datum of the data involved in the procedure. GPS data reference systems, vertical datum inconsistencies and gravity anomalies computation errors (e.g., which height is used in gravity anomaly calculation?) are responsible for this bias appearance.

In order to control these bias effects and other long wavelength errors in gravity field modeling a common practice is the use of specific corrector surfaces as mentioned in the theoretical background part. The results of the best fit adjustment of the parametric models used in our study as well as the number of the unknown parameters of each model are given in Tables 1 – 6. As it can be seen, the 3rd order parametric model provided the best corrector surface in our area, regardless of the geoid model used. The statistics in terms of the sd of the differences are presented in bold characters. The 4-parameter datum shift model, which corresponds to a Helmert similarity transformation, is not the adequate model in our area, probably due to its small dimensions. Considering larger areas such a model is the best choice as well as its extension to a 5-parameter observation equation (Kotsakis and Sideris, 1999, Fotopoulos, 2003). The shape of the corrector surfaces used in our computations is depicted in Figure 4.

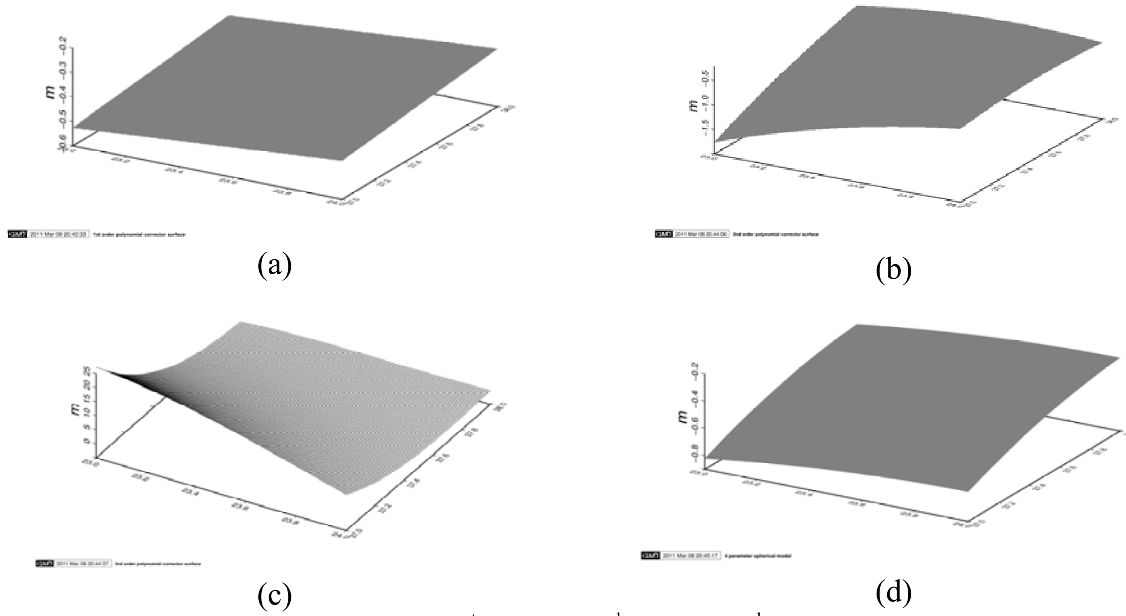

Figure 4. The corrector surfaces used: (a) a 1st order, (b) 2nd order, (c) 3rd order polynomial and (d) 4-parameter datum shift

Tables 4 – 6 point out the outstanding performance of EGM2008 global geoid model. This global model is fitted at the same level of agreement (even better) than previous local solutions. This fact is well documented in many previous papers (e.g., Kotsakis et al., 2008) where comparison in various areas of the greek territory are presented. The agreement between EGM2008 and local geoid solution is mainly due to new data assimilation in the global model, used also in previous local solutions. The local solutions used in our study are HGFFT98 based on EGM96 reference field and HGIO2000 based on GPM98b. These local solutions can be compared with EGM96, the best global model of its era. At that time (2000), a 2 cm optimization in terms of sd of the differences can be seen (Tables 3, 5 and 6). A new local geoid solution based on EGM2008 is needed in order to improve the local characteristics of the area with respect to an accurate global solution.

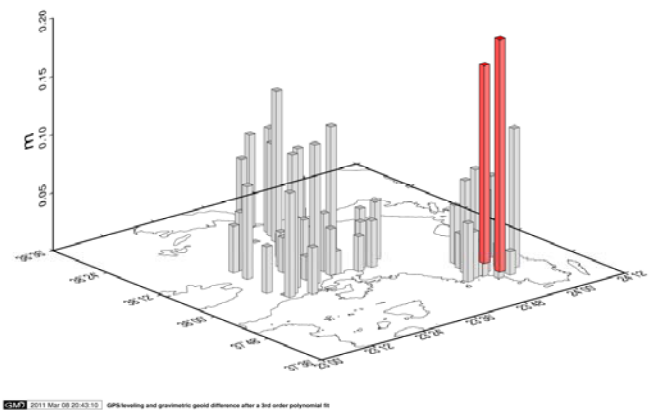

Figure 5. The differences between GPS/leveling and gravimetric geoid heights after a 3rd order polynomial fit. The two blunder benchmarks are denoted with red (values in m)

The differences of GPS/leveling and gravimetric geoid heights in all 66 benchmarks are depicted in Figure 5. Using this visual method some inconsistencies in the vertical datum over Attica can be identified. Especially, benchmarks 018019 and 018046 can be identified as blunders as they exceed a 3 rms blunder removal empirical test of the data. This statement can be justified by noting equivalent behavior of these points with respect to each geoid model (global and local) and each parametric corrector surface. The improvement of the statistics of geoid fit to the GPS/leveling data can be seen in Table 7 where the results before and after potentially blunders removal are tabulated.

Table 7: The statistics of the differences between GPS/leveling and gravimetric geoid model (EGM2008) before and after the blunders removal – all values in m.

N_{GPS} - N_{MODEL} Geoid model: EGM2008 n=2190, m=2160		**min**	**max**	**mean**	**sd**
3rd order polynomial fit	before blunder removal	**-0.198**	**0.131**	0.000	**0.065**
	after blunder removal	**-0.121**	**0.130**	0.000	**0.056**

In addition, only minor trigonometric points of Greece have accurate height information from classical spirit leveling. The main part of the Greek triangulation network received height information during 80’s using less accurate triangulate leveling, especially in mountainous areas. An improvement of 1 cm in terms of sd of the differences is achieved by excluding the suspicious points from the model parameter estimation. In this case, we used the classical 3 rms blunder removal empirical test. More sophisticated statistical tests have to be implemented provided that the GPS/leveling data in the area of study will be densified, especially in north-east and south-west areas of Attica. Additionally, statistical tests for each model parameter importance will justify the model choice (Fotopoulos, 2003).

5. CONCLUSIONS – FUTURE PLANS

A preliminary study on the vertical datum evaluation scheme in the area of Attica – Greece was presented. Various gravimetric geoid models of global and local scale were tested against GPS/leveling geoid heights in specific benchmarks of the Greek network. As it is expected EGM2008 and local geoid models gave the best agreement results in terms of the sd of the difference. Moreover, a corrector surface of a 3rd order polynomial was chosen in order to combine the heterogenous height data. An internal accuracy of 6.5 cm was achieved. The evaluation procedure led to the exclusion of 2 GPS/leveling points, which presented disagreements with the total of the geoid and parametric models used. After the blunder removal an internal accuracy of 5.6 cm is tabulated.
A careful consideration of the vertical datum of Greece using some specific areas as pilot projects is our basic future. A new local geoid based on newly available data from gravity dedicated missions and the EGM2008 global geopotential model will be the beginning of the validation procedure. A better distribution of the benchmarks points in the area is also needed

in order to achieve a common accuracy in the area under study and to lead to a complete validation of the vertical datum in Attica. In addition, some statistical tests based on the proper model choice and the number of important parameters will be performed in order to better validate our vertical control points.

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