On the improvement of the orthometric heights via GNSS-levelling: The case of Drama area in Greece

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Summary

In the present study we deal with the problem of the improvement of the orthometric heights, using a parametric model of four parameters. This application is widely used in practice from many researchers and agencies. We implement the aforementioned fitting model in the area of Drama in Greece. We estimated the correction surface and we compare our results with the officially released model for the orthometric heights. The orthometric heights of our study refer to the official state's benchmarks, belonging to the National Triangulation Network, maintained from the Hellenic Geographic Military Service. The total number of the used benchmarks is 12, covering an area of almost 450 km^2 (22.5 km × 20 km). The results confirm an improvement of the heights related standard deviation from 9.1 cm (official model) to 5.0 cm (parametric model), respectively. The new parametric model seems to widely absorb various systematic effects of the existing geodetic networks.

Zusammenfassung

In der vorliegenden Arbeit befassen wir uns mit dem Problem der Verbesserung der orthometrischen Höhen mit einem parametrischen Modell von vier Parametern. Diese Anwendung ist in der Praxis von vielen Forschern und Ämtern weit verbreitet. Wir implementieren das oben erwähnte Anpassungsmodell im Bereich Drama in Griechenland. Wir haben eine Korrekturfläche geschätzt und vergleichen unsere Ergebnisse mit dem offiziell veröffentlichten Modell für die orthometrischen Höhen. Die orthometrischen Höhen unserer Studie beziehen sich auf die offiziellen staatlichen Benchmarks, die zum Nationalen Triangulationsnetzwerk gehören, das vom Hellenic Geographic Military Service aufrechterhalten wird. Die Gesamtzahl der verwendeten Benchmarks ist 12 und umfasst eine Fläche von fast 450 km^2 (22,5 km × 20 km). Die Ergebnisse bestätigen eine Verbesserung der höhenbezogenen Standardabweichung von 9,1 cm (offizielles Modell) auf 5,0 cm (parametrisches Modell). Das neue parametrische Modell scheint verschiedene systematische Effekte der bestehenden geodätischen Netze weitgehend zu absorbieren.

Keywords: height determination, geoid, geodetic reference frame, height improvement, correction surface

1 Introduction

The currently official Greek geodetic reference system was realized in the year 1987, see Hellenic Mapping Cadastral Organisation (1987), Veis (1996), Rokos et al. (2010). Its officially accepted name is Hellenic Geodetic Reference Frame of 1987 (HGRS1987). The HGRS1987 is realized using satellite and classical terrestrial measurements, see Hellenic Mapping Cadastral Organisation (1987) and Fotiou (2007), which were finally assimilated. The HGRS1987 is carrying significant systematic errors and inconsistencies, see for example Katsambalos et al. (2010). These inconsistencies are caused (i) due to the old terrestrial measurements (which have taken place before 40 to 50 years, e.g. Hellenic Mapping Cadastral Organisation (1987) and Takos (1989)), and (ii) due to the intense geodynamical behavior of the Hellenic area.

In the year 2009, a new geodetic reference frame for Greece was released, called the Hellenic Terrestrial Reference System of 2007 (HTRS07, Katsambalos et al. 2010). The HTRS07 refers to the European Terrestrial Reference Frame of 2005 (ETRF2005), which was (now ETRF2005 is withdrawn) a realization of the European Terrestrial Reference System of 1989 (ETRS89, Boucher and Altamimi 2011). Katsambalos et al. (2010) published the algorithm for connecting the HTRS07 with the HGRS1987. However, the HGRS1987 remains the only official geodetic reference system of the country. The aforementioned connection between the HTRS07 and the HGRS1987 refers only to the associated projection coordinates and does not count for the heights. The projection system of the HGRS1987 is the Transverse Mercator (UTM) of one zone (zone of 9 degrees in longitude). The central meridian of the TM is 24 degrees (Fotiou 2007).

Regarding the heights, their majority was estimated by trigonometric levelling (Takos 1989) and only a small percentage of the network's benchmarks heights were computed from spirit levelling (Rokos et al. 2010, Takos 1989). The accuracy of the heights is not published and it cannot be easily verified and assessed. In addition, due to the many island complexes of the Greek area, the interconnection between the mainland and the islands is quite problematic. The height information (the orthometric heights of its consisting benchmarks) of the HGRS1987 is not rigorously investigated. Furthermore, the associated geoidal information derived is rather weak, in terms of its age and quality (Hellenic Mapping Cadastral Organisation 1987, Fotiou 2007).

The Hellenic Cadastre and Cartographic Association S.A. (HCCA S.A) computed a preliminary geoid model for Greece (HCCA S.A developed a related software which is publicly available), which can be implemented for the estimation of the orthometric heights, using the well-known formula (Heiskanen and Moritz 1967), pointwise:

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$$H_i = h_i - N_i, \tag{1}$$

where H_i is the orthometric height, h_i is the geometric height w.r.t. ETRS89 and N_i is the geoidal undulation. The geometric height refers to the HTRS07 and the geoidal undulations derived from the interpolation of the differences between the orthometric and geometric heights, respectively, from 2200 state's benchmarks (Kotsakis and Katsambalos 2010). This is the so-called "geometric-geoid" of the HTRS07. We should underline that this model is not an official one and there is a disclaimer regarding its use. For simplicity reasons, the orthometric heights estimated from the aforementioned methodology will be called within the paper the HCCA-derived heights.

In the present study, we will apply a four-parametric model in order to improve the accuracy of the height determination procedure on a local scale. The parametric models are widely used in practice for the height estimation improvement. We tested the method in the area of Drama at the northern part of Greece (region Eastern Macedonia and Thrace) and we found a significant improvement of the height estimation statistics compared to the heights derived from the HCCA-derived heights, respectively.

2 Methodology

For the improvement of the orthometric heights determination, we used the following well-known four parametric models for the heights corrections (e.g. Kotsakis and Sideris 1999, Kotsakis et al. 2012, Pikridas et al. 2011, Fotiou and Pikridas 2012) for the state's benchmarks pointwise:

$$\begin{aligned} h_i - H_i - N_i^{GGM} &= a_0 + a_1 \cos\varphi_i \cos\lambda_i \\ &+ a_2 \cos\varphi_i \sin\lambda_i + a_3 \sin\varphi_i + e_i, \end{aligned} \tag{2}$$

where h is the geometric height referring to HTRS07, H the orthometric height, N^{GGM} the geoidal undulation of a global geopotential model, a_0, a_1, a_2, a_3 the unknown parameters, φ, λ the curvilinear coordinates (w.r.t. HTRS07) and e is observation error. The aforementioned model absorbs the total effect of various biases (from all types of observations) in terms of a constant term and three translations. Eq. (2) could be solved for multiple points, using the classical least squares approach (Koch 1999) as follows:

$$\hat{\mathbf{x}} = \left(\mathbf{A}^{\mathrm{T}}\mathbf{P}\mathbf{A}\right)^{-1}\mathbf{A}^{\mathrm{T}}\mathbf{P}\mathbf{y}, \tag{3}$$

where $\hat{\mathbf{x}} = \left[\hat{a}_0 \; \hat{a}_1 \; \hat{a}_2 \; \hat{a}_3\right]^T$ is the vector of the estimated parameters, $\mathbf{A}$ is the design matrix is:

$$\mathbf{A} = \begin{bmatrix} 1 & \cos\varphi_i \cos\lambda_i & \cos\varphi_i \sin\lambda_i & \sin\varphi_i \\ \vdots & \vdots & \vdots & \vdots \\ 1 & \cos\varphi_n \cos\lambda_n & \cos\varphi_n \sin\lambda_n & \sin\varphi_n \end{bmatrix}.$$

$\mathbf{y} = \left[h_i - H_i - N_i^{GGM} \cdots h_n - H_n - N_n^{GGM}\right]^{\mathrm{T}}$ is the vector of the observations and $\mathbf{P}$ is the (diagonal) weight matrix (see Eq. 4).

$$\mathbf{P} = \mathbf{C}_{\mathbf{e}}^{-1} = \begin{bmatrix} \frac{1}{\sigma_{e_i}^2} & 0 & \cdots & 0 \\ 0 & \ddots & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \frac{1}{\sigma_{e_n}^2} \end{bmatrix}. \tag{4}$$

The accuracy of its observations is defined using the formula

$$\sigma_{e_i} = \sqrt{\sigma_{h_i}^2 + \sigma_{H_i}^2 + \sigma_{N_i}^2}, \tag{5}$$

where $\sigma_{h_i}, \sigma_{H_i}, \sigma_{N_i}$ are the standard errors of the geometric, orthometric heights and the geoidal undulations derived from a global geopotential model. The associated residual vector is

$$\hat{\mathbf{e}} = \mathbf{y} - \mathbf{A}\hat{\mathbf{x}}. \tag{6}$$

Our aim is to compute the orthometric height for any arbitrary point j using the straightforward relation:

$$\begin{aligned} \tilde{H}_j &= h_j - N_j^{GGM} - \hat{a}_0 - \hat{a}_1 \cos\varphi_i \cos\lambda_i \\ &- \hat{a}_2 \cos\varphi_i \sin\lambda_i - \hat{a}_3 \sin\varphi_i. \end{aligned} \tag{7}$$

Eq. (7) gives the opportunity to the user to compute the orthometric height of any arbitrary point, using the GNSS-height (geometric), the geoidal undulation from a global geopotential model and the estimated parameters of the fitting surface.

3 Numerical application for the area of Drama

Drama is located in the region of Eastern Macedonia and Thrace at the northern part of Greece. For the needs of our numerical application, we occupied fifteen (15) state's benchmarks, covering an area of almost 450 km^2. Our initial plan was to measure more than twenty five points. Nevertheless, we found at least ten of them destroyed, moved or severely inclined. The orthometric heights of the benchmarks were determined using trigonometric levelling. Unfortunately, there is no officially published report regarding the accuracy of the orthometric heights. However, taking into account previous studies and tests, an accuracy of 3 to 4 cm can be considered as realistic for the orthometric heights uncertainty. We must also refer that Greece is divided into 387 map sheets (according to the release of the Hellenic Geographic Military Service-HGMS which is the responsible agency). Drama's map sheet (code 96) comprises 100 state's benchmarks.

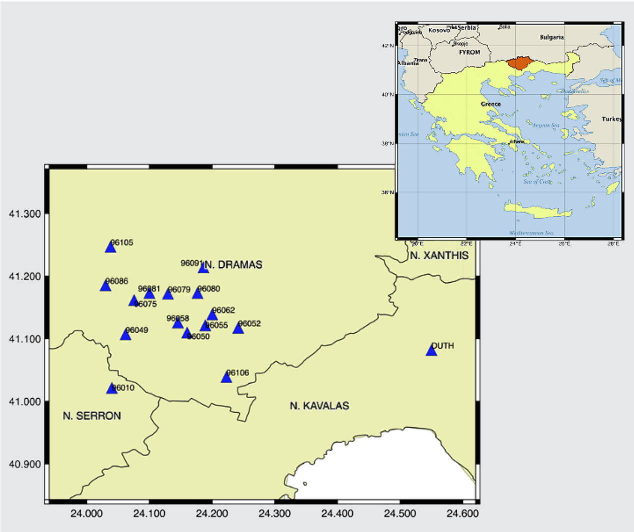

Fig. 1: The benchmarks located in the Drama region

Hence, within this campaign we measured 15 % of the associated sheet's benchmarks, which seems sufficient for the estimation of the 4 parameters.

The geometric heights were estimated using GNSS measurements (static observations of at least three hours duration). The GNSS campaign was started at 14th May and ended at 16th May of 2014. In order to tailor them to the HTRS07, we used as fixed station the DUTH (located in the city of Xanthi). DUTH belongs to the European Permanent Network (EPN, www.epncb.oma.be, Fotiou and Pikridas 2012). The mean distance between this station and the benchmarks is almost 70 km. The DUTH coordinates w. r. t. the HTRS07 (ETRF2005, epoch 2007.5) are: X = 4362690.120 m, Y = 2026647.882 m, Z = 4174234.068 m. Fig. 1 depicts the area and the measured benchmarks. For the solution of the associated network we used the following software: Topcon tools (Topcon Tools Reference Manual.) and Bernese 5.0 Software (Dach et al. 2007). Between these two softwares, we find coordinate agreement at the level of 2 cm (RMS). GPS data was analysed using a satellite elevation cut-off angle of 15 degrees and final precise orbits information were used. The Saastamoinen model with the (dry+wet) Niell mapping function was used in processing. All the initial phase ambiguities of carrier frequencies were resolved using the SIGMA strategy (Dach et al. 2007). Finally for our analysis, we choose to proceed with the Bernese-estimated coordinates. The associated mean standard error of the estimated geometric heights is 0.7 cm.

Regarding the geoidal undulations, the global geopotential model EGM2008 is employed (Pavlis et al. 2012), from degree 2 to 2160. In order to be consistent with the definition of the geometric heights from GNSS in each computed, we added −0.442 m (the null-term, see e.g. Heiskanen and Moritz 1967). The associated accuracy of the geoidal undulations for the associated area is at the level of 5 to 6 cm. It is worth to mention that several studies have been carried out in the test and broader area in order to evaluate the geoidal undulations accordingly (Andritsanos et al. 2000, Andritsanos et al. 2004, Pikridas et al. 2011). For the computation of the EGM2008 geoidal undulation, the software HarmonicSynth was used (Holmes and Pavlis 2008). Fig. 2 visualizes the EGM2008 undulations for the area of Drama. For the same benchmarks,

Tab. 1: The coordinates (decimal degrees) and the heights (units: meters) of the fifteen benchmarks located in the Drama area (h the geometric heights w. r. t. HTRS07, $H_{Official}$ from the state's agency, H_{HCCA} from the software and H_{model} from the fitting model)

Code	Lat.	Long	H	$H_{Official}$	N_{EGM08*}	H_{HCCA}	H_{mod}
96010	41.021	24.040	140.219	98.450	41.668	98.459	98.475
96049	41.107	24.062	111.463	69.920	41.692	69.900	69.942
96050	41.109	24.160	125.822	84.230	41.707	84.225	84.139
96055	41.121	24.189	163.040	121.380	41.754	121.373	121.442
96079	41.172	24.129	214.451	172.377	41.922	172.383	172.652
96091	41.214	24.186	404.904	362.600	42.109	362.602	362.519
96105	41.247	24.038	845.830	803.065	42.354	803.074	803.082
96106	41.039	24.222	107.875	66.300	41.525	66.309	66.279
96052	41.117	24.241	190.098	148.499	41.782	148.360	148.795
96058	41.126	24.145	144.591	103.104	41.754	102.917	103.199
96062	41.139	24.200	203.974	162.330	41.820	162.196	162.421
96075	41.161	24.075	165.312	123.530	41.851	123.343	123.551
96080	41.173	24.176	671.194	629.356	41.934	629.159	629.405
96081	41.173	24.102	200.856	158.941	41.934	158.773	158.856
96086	41.185	24.029	249.750	207.765	42.014	207.535	207.456

*Adding the null term (−0.442 m)

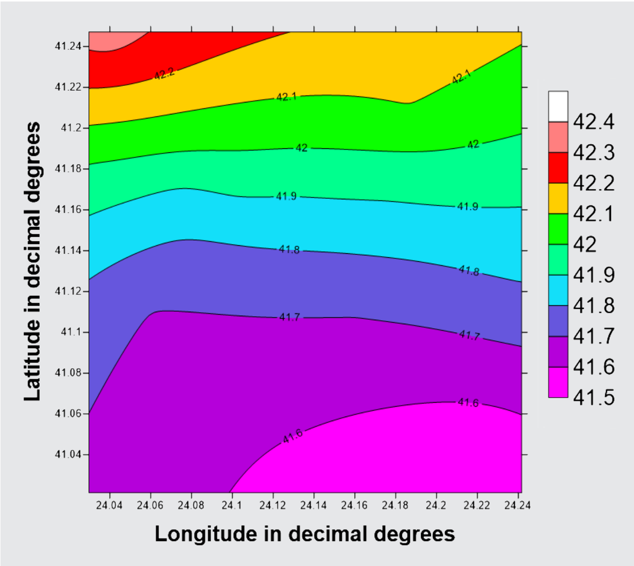

Fig. 2: The geoidal undulations of EGM2008

we estimated the HCCA derived heights. As previously said, HCCA has a particular disclaimer for the orthometric heights, so they cannot be considered as official heights, in any case. Tab. 1 presents the results of the estimated

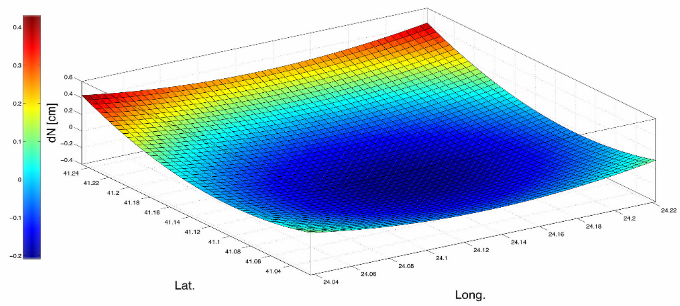

Fig. 3: The correction surface of the geoidal heights (Eq. 3)

heights (orthometric, geometric and geoidal undulations) from our test and in addition, the heights from the HCCA software.

Then we proceeded with the least squares adjustment, described in the previous section (Eq. 2–5). In order to eliminate possible blunders, we applied the 3-σ criterion for the adjusted residuals. This practically means that we excluded observations showing residuals larger than three times the standard deviation (of the residuals). Finally, the benchmarks with the code numbers 96052, 96079, 96086 were rejected, not fulfilling the 3-σ criterion. The estimated parameters (four terms) are shown in Tab. 2. Tab. 3 summarizes the differences between the official height records and the estimated one (from the parametric model and those computed by the HCCA software). Fig. 3 shows the corrector surface, computed from the adjustment (Eq. 3). Tab. 4 presents the associated statistics of the residuals and Fig. 4 depicts the residuals per benchmark.

Tab. 2: The estimated 4 parameters of the fitting surface for Drama's area

Parameter	Value
a_0	1693.123 ± 196.054 (m)
a_1	−1164.2896 ± 135.0587
a_2	−521.51795 ± 60.1966
a_3	−1113.1582 ± 128.6331

Tab. 3: The height differences between the official heights and the estimated one

Code	Differences between the official heights and the heights derived from the parametric model (cm)	Differences between the official heights and the heights from the HCCA software (cm)
96010	0.0	0.9
96049	1.4	−2
96050	−7.1	−0.5
96055	−4.8	−0.7
96058	8.0	−18.7
96062	7.7	−13.4
96075	−1.0	−18.7
96080	4.5	−19.7
96081	−5.6	−16.8
96091	−4.7	0.2
96105	2.1	0.9
96106	−0.5	0.9

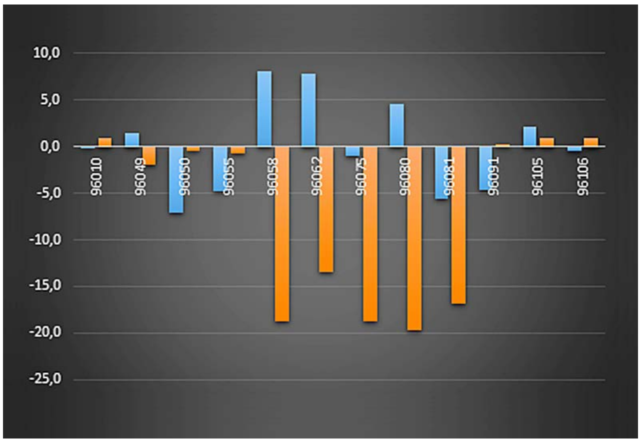

Fig. 4: The residuals per benchmark in cm (blue: after the four-parametric fitting, orange the HCCA derived heights)

Tab. 4: The statistics of the differences between the HCCA and the four-parameter model and the official heights

Statistic quantity	Four-parametric model (cm)	HCCA software (cm)
mean	0.0	−7.3
σ	5.0	9.1
min	−7.1	−19.7
max	8.0	0.9

From the results, we can imply that the heights from the HCCA software present a significant mean average of –7.3 cm and their standard deviation is at the level of 9 cm (w.r.t. the officially published heights of the state's benchmarks). This practically means that within the area there are some systematic effects or outliers which contaminate the heights' performance and lead to a distortion of the height information. Fig. 5 maps the differences between the computed heights from the model and the official heights, respectively.

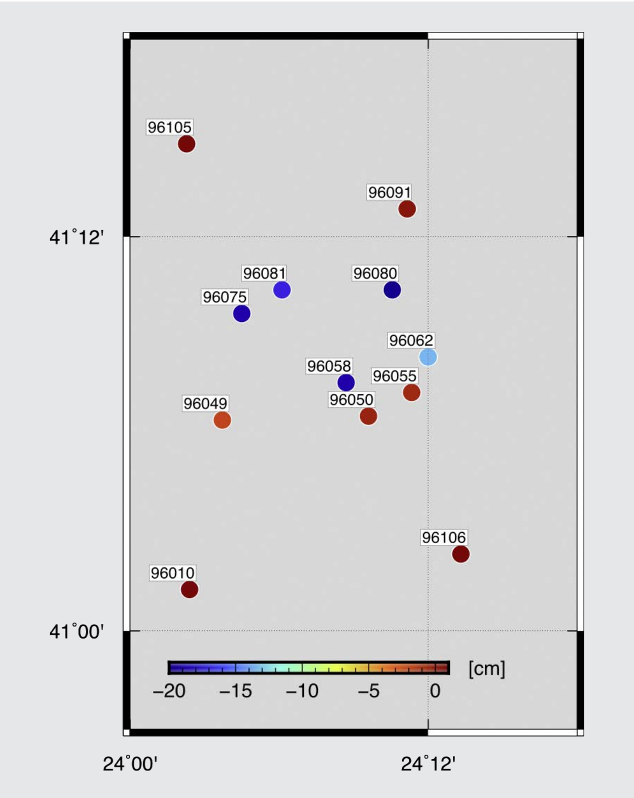

Fig. 5: The differences between the heights computed from the model and the official heights for each benchmark in the area of Drama, respectively (after the outliers removal).

On the other hand, the use of the parametric model presents null mean and its standard deviation is reduced by 44 % in comparison to the HCCA software results (at the level of 5 cm). The parametric model of the four terms, described above seems to enhance the height solution, giving more accurate solutions in the aforementioned area.

As far as the values of the estimated parameters are concerned, we must underline that they are significantly high and correlated, they do not attribute any physical meaning, for such a small area. In addition, the associated uncertainties are large too and unrealistic. This is caused due to the fact that we applied the model to a rather limited area. The parameters are just estimated in order to absorb the systematic effects in terms of a constant term and three translations. The parametric model gives adequate results when accuracies of 5 cm is needed. We should once again remind that the orthometric heights from the benchmarks of the state's network carry their own (not known) uncertainties and inconsistencies. The above mentioned threshold of 5 cm reflects sufficiently the current accuracy of the GNSS levelling for the examined area. For more precise results, one should employ spirit or precise trigonometric levelling. The problematic height information of the state's benchmarks does not allow the expansion of the aforementioned procedure to greater areas, preserving the same level of accuracy (5 cm). Thus, the orthometric heights determination using GNSS and a global geopotential model (for the existing infrastructure) should be applied in limited areas (e.g. one map sheet).

As a final comment we should note that we have also tested simpler models as the four-parametric one to fit, such as the simple mean average and the level surface. The estimated errors and their rms are worse than the four parametric one, so we conclude that the surface fitting presented above is the optimal one (for this case).

4 Conclusion and outlook

In the present paper, we implemented a well-known though significant process for the improvement of orthometric height information using GNSS, geoid and orthometric heights. We used a four-parametric surface in order to identify and eliminate possible height biases over the area of Drama, a prefecture located at the northern part of Greece. The use of the parametric model improves significantly the orthometric height determination in comparison to the results derived from the official procedure. This practically means the accuracy is improved from 9.1 cm (HCCA derived heights) to 5.0 cm (parametric model) which equals to almost 44 %. In advance, the parametric model seems to absorb the majority of the systematic effects, eliminating the bias term (the mean value of the residuals is 0). The level of 5.0 cm seems to be the threshold for the orthometric height determination using the so-called GNSS levelling method. This is caused by the existing limitations of the vertical networks in Greece.

However, none of the techniques ensures reliable results for achieving mm or even cm accuracy. This is due to the fact that the original data of the three sources (orthometric, geometric and geoid heights) might each carry its own inconsistencies and biases. For these cases, a precise spirit or precise trigonometric levelling is needed.

The above mentioned strategy (surface fitting in a limited area) should be expanded for the whole country in order to improve the existing height information as much as possible. Nevertheless, due to the significant inconsistencies of the Greek vertical/height network there is a necessity for a new campaign for the determination of orthometric heights all over the mainland.

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