Assessment of the Greek Vertical Datum – A case study in central Greece

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Abstract

In this study, the consistency of the Greek Vertical Datum (GVD) is examined, focusing on an area in central Greece and following similar efforts made in previous researches for the establishment of an International Height Reference System (IHRS). High precision GNSS measurements are available at trigonometric benchmarks located along the Gulf of Corinth, with benchmarks residing on both coasts along. First, the zero-level geopotential value (W_o^{LVD}) for the two areas, north and south coast, is determined, based on the classical Helmert theory using GNSS/leveling data and surface geopotential values derived from GOCE-based global geopotential models (GO-DIR-R5, GO-TIM-R5, GOCO05s and GECO) and EGM08. Then, the relative offset between the two areas is estimated while subsets of the computed benchmark values are also examined. Significant inconsistencies are detected that depend on the choice of benchmarks used in the computations. Moreover, a per benchmark analysis showed that the inconsistencies present a random spatial distribution and are attributed mainly to the orthometric height values of the benchmarks. Furthermore, the local W_o^{LVD} estimates are compared with previous results related to the GVD and the VD of the Greek islands and the corresponding value adopted by the IHRS. Finally, some remarks are drawn on the feasibility of the unification of the GVD with a global one.

Keywords

Local Vertical Datum, World Height System, Greek Vertical Datum, zero-height geopotential level

1 Introduction

The establishment of a consistent and unified National Vertical Datum is a fundamental prerequisite for using reliable heights and their associated accuracy in a wide list of applications and studies including infrastructure development, public works and monitoring of natural risks and disasters. This is not though the case for the Greek Vertical Datum (GVD). The GVD is a tidal-based datum with different points of origin for the Greek mainland and the Greek islands. The point of origin of the mainland datum is located at the tide gauge station at the Piraeus harbor, while each island has its own point of origin set at the tide gauge station located on it. Additionally, there is not available a consistent connection between the mainland and the islands. The GVD currently includes a set of leveling BenchMarks (BMs) that form the 1st order national leveling network, as well as a set of trigonometric BMs, which belong also to the Horizontal Greek Datum. The trigonometric BMs are the ones that are most commonly used in current studies, applications and engineering projects.

The orthometric heights of the 1st order national leveling network were derived by performing two separate adjustments for the mainland (Peloponnese was adjusted separately from the rest of the mainland) and one for the island of Crete. These adjustments were carried out in 1986 and they were based on spirit leveling measurements carried out between 1963 and 1986 (Mylona-Kotrogianni, 1990). Moreover, in 1989 the orthometric heights of the trigonometric BMs were derived from several adjustments carried out in different parts of the country based on its division in map-sheets of the Greek Geographical Military Service. The data employed within the adjustment processes did not take into account the adjusted heights of the 1st order leveling network, although the unadjusted heights of the trigonometric BMs were measured by spirit or trigonometric leveling with reference to the BMs of the leveling network. The estimated adjustment accuracy of the orthometric heights of the trigonometric network is of the order of 1-2cm (Takos, 1989) and the final accuracy has a mean value of approximately 2 cm although for some BMs it exceeds 10 cm.

Based on the above discussion, it is evident that there are inherent inconsistencies and shortcomings in the GVD that need to be further investigated. It should be noticed that these inconsistencies are further strengthened by the fact that there is no practical long-term monitoring of the VD variation with time, although Greece is an area of high seismicity with strong geodynamic features and peculiarities. These inconsistencies were detected also in previous researches, which were mainly conducted for the determination of zero-level geopotential values (W_o)

and/or in the frame of a global effort for establishing an International Height Reference System (IHRS). In this frame, it should be noticed that Andritsanos et al. (2016) detected these inconsistencies in their study for two regions, one in northern Greece (wider area of Thessaloniki) and one in southern Greece (area of Attica). Grigoriadis et al. (2014) determined the W_o for the entire Greek mainland and an attempt was made to model height-correlated errors towards the improvement of the results achieved in this study. On the other hand, Kotsakis et al. (2012) and Vergos et al. (2016) focused on the determination of W_o for the Greek islands, where, as mentioned before, tide-gauge station at each island defines its own local VD. The present paper aims to highlight and examine more thoroughly the aforementioned inconsistencies referred to the Greek mainland in combination with those found in a restricted test area. The latter is an area in Central Greece that covers part of Peloponnese and part of the rest of the Greek mainland (see Figure 1), where the available GNSS/leveling data at trigonometric BMs are contained in different map-sheets. Moreover, the specific area is characterized by sizeable earthquake phenomena and significant geological irregularities. The assessment is made after first determining the W_o based on the classical Helmert theory using GOCE-based Global Geopotential Models (GGMs) (Bruinsma et al., 2013; Brockmann et al., 2014; Mayer-Gürr et al., 2015; Gilardoni et al., 2016) and EGM08 (Pavlis et al., 2012).

2 Available Data and Models

The test area of the present study is located along the Gulf of Corinth in Central Greece (see Figure 1). The selected area lies about 70 km west from the point of origin of the GVD, i.e., the tide gauge at Piraeus Harbor. For the datum assessment, two independent sets of GPS measurements on BMs of the Greek Trigonometric Network were available (see Figure 1) that reside on both coasts along. The first set of GPS measurements (46 BMs) originates from Ktimatologio SA (Gianniou 2008), i.e., the organization responsible for the Greek Cadastre, while the second set was conducted by the second of the authors and her scientific group in 2009 in the frame of three field campaigns. The BMs from Ktimatologio SA belong to a wider set that was used in the transformation procedure between the Hellenic Terrestrial Reference Frame 07 (HTRS07) and the Hellenic Geodetic Datum 1987 (EGSA87). In the measurements of the second set (76 BMs) Trimble 5800 geodetic receivers (observation time at each BM 45-60 min) were used and the solution of baselines ranging from 8 to 40 km were carried out. The orthometric height of each BM is known and both datasets refer to the HTRS07. A number of 35 BMs belong to both data sets.

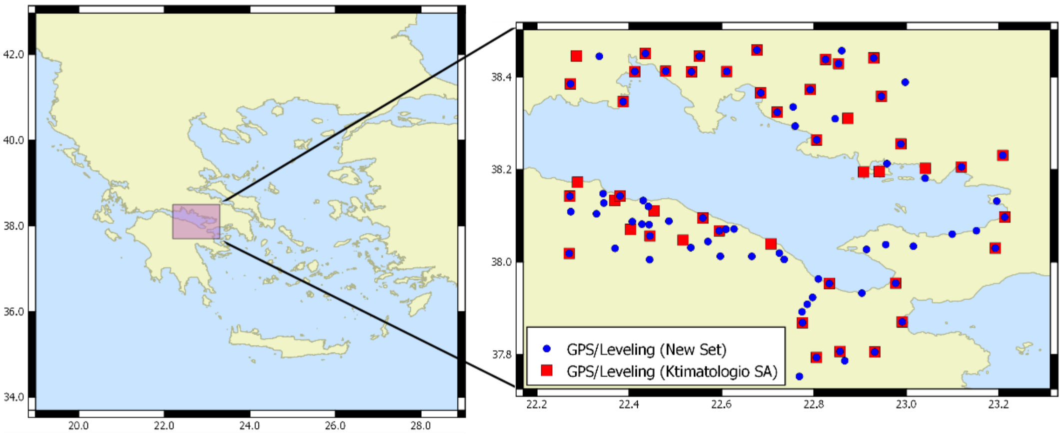

Figure 1. Distribution of the GPS/leveling data for the two available datasets. Over-lapping points refer to the same BM station.

Regarding the GGMs used in the assessment procedure, four GOCE-based models were selected along with EGM08 that are reported in Table 1. It should be noticed that EGM08 and GECO were used up to a maximum degree and order (d/o) of 2160. The rest of the models were used up to d/o 175 spectrally enhanced with EGM08 up to 2160 d/o. The choice of d/o 175 was made after considering the results of the spectral evaluation carried out by Tziavos et al. (2016) for the geoid error spectrum of different GOCE-based GGMs and selecting a value where the error spectrum is below that of EGM2008 for all models.

Table 1. The GGMs used in the assessment procedure

Model	**Year**	$\mathbf{n_{max}}$	**Data**	**Reference**
GECO	2015	2190	S(GOCE), EGM08	Gilardoni et al, 2015
GOCO05s	2015	280	S(GOCE, GRACE, other)	Mayer-Gürr, et al. 2015
DIR-R5	2014	300	S(GOCE, GRACE, LAGEOS)	Bruinsma et al, 2013
TIM-R5	2014	280	S(GOCE)	Brockmann et al., 2014
EGM08	2008	2190	S(GRACE), G, A	Pavlis et al., 2012

Data: S = Satellite tracking, G = Gravity, A = Altimetry

3 Methodology

The W_o of the Local Vertical Datum (W_o^{LVD}) was computed using the following equation (Kotsakis et al. 2012; Grigoriadis et al. 2014):

$$W_o^{LVD} = W_o^{ref} - \frac{\sum_1^m (h_i - H_i - N_i) g_i}{m} \qquad (1)$$

where W_o^{ref} is set equal to 62 636 853.4 m^2s^{-2} (IAG Resolution No.1/2015; Sanchez et al. 2016), h_i is the geometric height of each BM derived by GPS measurements, H_i is the known orthometric height of each BM, N_i is the geoid height derived from the GGMs used, g_i is the gravity at each BM computed from GGMs and m is the total number of the available stations.

Each BM of the Greek network belongs to one of the 387 map-sheets that cover the wider area of Greece. As this map-sheet distribution is commonly used in practice and engineering applications, computations were carried out for both datasets as a whole and in parts based on the map-sheet the BMs belong to. Moreover, the BMs were also split into two subsets, the BMs that lie north of the Gulf of Corinth and those that lie south of the Gulf (see Figure 1). In all cases, the same methodology was applied for the computation of W_o^{LVD} and all calculations were carried out in a tide-free system.

4 Results and discussion

The first step of the assessment was the comparison of the W_o^{LVD} estimates computed from the new GPS dataset with those derived from the Ktimatologio one. Five different W_o^{LVD} values were estimated per dataset corresponding to the GGM used in the computational procedure (four GOCE-based GGMs and EGM08). The results of the W_o^{LVD} estimates are summarized in Table 2. It is seen that the two datasets are compatible in terms of the standard deviation, but a small offset is detected at the level of 0.28 m^2s^{-2}, which corresponds to 2.7 cm approximately in terms of height difference. Additionally, the range of height value differences varies between 4 and 5 m^2s^{-2} . Since the latter cannot be attributed to errors or blunders in the measurements, further investigation was carried out as it is described below. Moreover, several remarks are pointed out concerning the results contained in Table 2. The first one is that the new dataset contains more BMs for the study area than the one by Ktimatologio. The second remark is that the new dataset derived from measurements with an observation time of up to 1 hour per BM, while the Ktimatologio (Ktima) dataset from several hours of measurements at each trigonometric point. It should also be noticed that the calculations with GOCO05s combined model show the lowest standard deviation equal to about 1.2 m^2s^{-2} (marked in bold). The latter value corresponds to approximately 12 cm in terms of height difference which may be considered as significant like, for example, in geodetic applications.

Table 2. Statistics of W_o^{LVD} for the study area with respect to the IAG adopted W_o value [m^2s^{-2}]

GGM	New Dataset				Ktima Dataset			
	mean	**Std**	**min**	**max**	**Mean**	**std**	**Min**	**max**
GOCO05s (d/o 175 + EGM08)	6.472	**1.174**	3.871	9.282	6.762	**1.168**	4.398	8.862
DIR-R5 (d/o 175 + EGM08)	6.479	1.201	3.812	9.262	6.760	1.194	4.388	8.940
TIM-R5 (d/o 175 + EGM08)	6.489	1.183	3.861	9.291	6.778	1.176	4.408	8.901
EGM08 (d/o 2160)	6.396	1.253	3.763	9.066	6.653	1.240	4.330	8.989
GECO (d/o 2160)	6.417	1.252	3.744	9.223	6.694	1.252	4.271	8.960

Table 3. W_o^{LVD} estimates computed separately for the northern (W_o^N) and southern coast (W_o^S) of the study area with respect to the IAG W_o value and their corresponding differences [m^2s^{-2}].

	GOCO05s		**DIR-R5**		**TIM-R5**		**EGM08**		**GECO**	
	New	**Ktima**	**New**	**Ktima**	**New**	**Ktima**	**New**	**Ktima**	**New**	**Ktima**
W_o^N	6.50	6.92	6.49	6.90	6.51	6.93	6.32	6.72	6.42	6.82
W_o^S	6.44	6.53	6.47	6.56	6.47	6.56	6.47	6.56	6.42	6.51
$\left\|W_o^N - W_o^S\right\|$	0.06	0.39	0.02	0.34	0.04	0.37	0.15	0.16	0.00	0.31

Additional numerical tests were carried out in order to investigate an eventual offset between the BMs that lie in the northern (map-sheets 46, 126, 137, 188 and

296) and southern coast (map-sheets 89, 173 and 274) of the study area (see Figure 2 for the map-sheet distribution). Table 3 presents the mean W_o^{LVD} values for the northern coast (W_o^N) and the southern coast (W_o^S) with respect to the IAG W_o value for all GGMs and GNSS datasets used in the present study. For the northern part of the test area 35 BMs from the new dataset and 27 BMs from the Ktimatologio database were used. It should be noticed that 22 BMs belong to both data sets. For the southern values, 32 and 19 BMs were used from the new and the Ktimatologio dataset, respectively, with 13 BMs contained in both data sets. Although the differences found with respect to the new dataset may be considered as negligible, as their values are lower than the accuracy of the available data, this is not the case for the Ktimatologio dataset (see Table 3). The Ktimatologio dataset presents five times larger differences than those of the new dataset. An unexpected exception for both datasets is the case of EGM08, where the differences are almost equal. Since the above mentioned results depend on the choice of the BMs, it was decided in a next step to focus on each map-sheet separately.

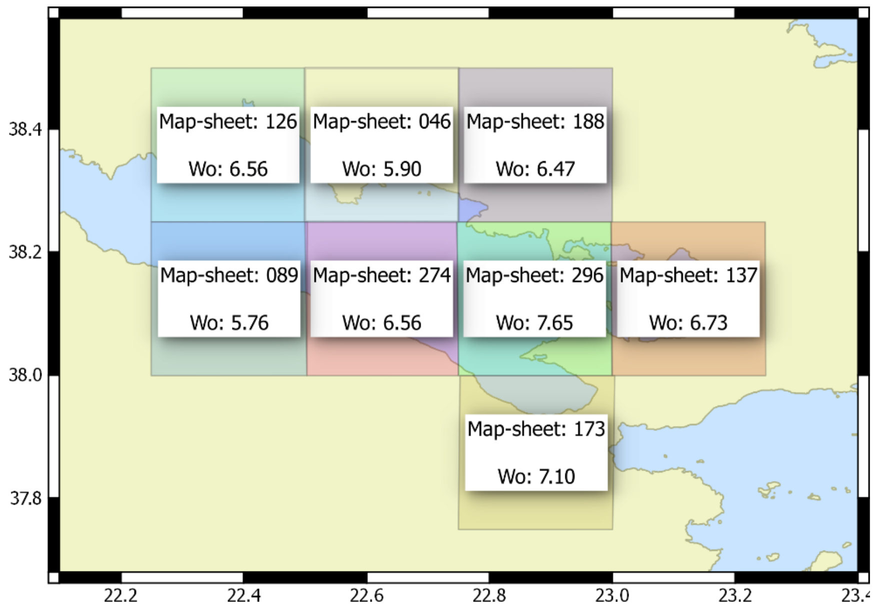

Figure 2. Map-sheet distribution in the study area with the corresponding W_o^{LVD} estimates computed per map sheet with respect to the IAG W_o value [m^2s^{-2}].

In the frame of this specific numerical analysis the computation of W_o^{LVD} for each map-sheet (scale 1:50.000) was made following the cartographic breadboard of the Greek Geographical Military Service. In Table 4 the new W_o^{LVD} estimates are reported, which are based on the new dataset and that of Ktimatologio, while Figure 2 depicts each map-sheet and its estimated W_o^{LVD} using the new dataset and the GOCO05s model. From the results of Table 4 a significant difference larger than 1 m^2s^{-2} is observed between the different map-sheets, where the largest difference for the GOCO05s-based solution reaches 1.89 m^2s^{-2}. These results indicate inconsistencies, which may be attributed on the one hand partly to the GGM used (2.3 cm cumulative geoid error for the GOCO05s combination), especially in the medium to high frequencies band of the gravity spectrum, and on the other hand mainly to the orthometric heights of the BMs. This conclusion is in line with the conclusions reported in Tziavos et al. (2012), who indicated incompatibilities in the orthometric heights of BMs belonging to adjacent map-sheets. Therefore, further examination of the results was then carried out for each map-sheet on a per BM basis.

Table 4. W_o^{LVD} estimates computed per map-sheet with respect to the IAG W_o value [m^2s^{-2}]

Map-sheet	GOCO05s		DIR-R5		TIM-R5		EGM08		GECO	
	New	**Ktima**	**New**	**Ktima**	**New**	**Ktima**	**New**	**Ktima**	**New**	**Ktima**
46	5.90	6.30	5.83	6.23	5.90	6.30	5.51	5.91	5.59	5.99
89	**5.76**	**5.62**	**5.73**	**5.58**	**5.76**	**5.62**	**5.67**	**5.52**	**5.63**	**5.49**
126	6.56	6.95	6.44	6.58	6.54	6.83	6.11	6.93	6.18	6.51
137	6.73	6.92	6.84	7.21	6.77	7.03	6.97	6.97	7.02	7.15
173	7.10	7.33	7.20	7.44	7.15	7.43	7.29	7.38	7.20	7.53
188	6.47	7.13	6.46	7.09	6.48	7.12	6.26	7.15	6.41	6.94
274	6.56	6.97	6.58	6.93	6.58	6.99	6.52	6.99	6.51	6.92
296	**7.65**	**7.87**	**7.73**	**8.02**	**7.69**	**7.92**	**7.73**	**7.90**	**7.83**	**7.87**

The examination of each map-sheet separately revealed that even the BMs that belong to a specific map-sheet are not consistent. Additionally, no correlation between the orthometric height and the W_o of each BM was found. Table 5 presents the orthometric heights and the estimated W_o for the BMs of map-sheet number 188, as these were obtained from both GNSS datasets and GOCO05s. W_o ranges between 4.60 and 9.28 for the new dataset while for the dataset obtained from Ktimatologio, where less BMs are used, the values are between 5.13 and 8.37 m^2s^{-2}. It is interesting to notice that for the new dataset the minimum and maximum values occur on BMs that were not included in the Ktimatologio dataset. These BMs though are currently used in everyday engineering projects, while the accuracy of their orthometric height is claimed to be approximately 1 cm. From the presented results it may be deduced that the accuracies provided for the orthometric heights are overly optimistic.

Table 5. Orthometric heights (rounded to nearest integer) [m] and zero-geopotential values [m^2s^{-2}] computed with respect to the IAG W_o value for map-sheet 188 based on GOCO05 spectrally patched with EGM08.

	Map-sheet codes												
	01	**03**	**17**	**27**	**29**	**39**	**59**	**67**	**76**	**98**	**101**	**103**	**111**
H	225	441	243	1244	1452	698	553	998	169	396	300	201	308
W_O (new)	7.36	7.82	9.28	4.60	-	6.45	6.40	5.82	5.20	6.53	6.58	5.53	6.09
W_O (Ktima)	8.00	8.37	-	-	5.13	-	7.09	6.74	-	7.62	7.72	6.36	-

Table 6. Comparison of W_o^{LVD} estimates for the study area, mainland of Greece and Greek islands with respect to the IAG W_o value from the current and previous studies [m^2s^{-2}]

	GOCO05s	**DIR-R5**	**TIM-R5**	**EGM08**	**GECO**
Test area of the current study	6.47	6.48	6.49	6.40	6.42
Mainland					
Grigoriadis et al. 2014	-	-	-	6.87	-
Andritsanos et al. 2016	6.41	6.41	6.46	6.26	-
Island of Crete					
*Kotsakis et al. 2012	-	-	-	7.55	-
Vergos et al. 2016	-	-	7.78	-	-
Island of Evia					
*Kotsakis et al. 2012	-	-	-	6.79	-
Vergos et al. 2016	-	-	6.47	-	-
Island of Corfu					
*Kotsakis et al. 2012	-	-	-	9.34	-
Vergos et al. 2016	-	-	7.90	-	-
Island of Lesvos					
*Kotsakis et al. 2012	-	-	-	8.37	-
Vergos et al. 2016	-	-	7.73	-	-

* Computations were carried out in a zero-tide system.

A last step of our assessment methodology was to compare our W_o^{LVD} estimates with those derived by previous studies for the Greek mainland and four Greek Islands towards the unification of the GVD with a global one. The W_o^{LVD} values are tabulated in Table 6. Two of these previous studies (Kotsakis et al. 2012; Vergos et al. 2016) were based on the Ktimatologio dataset, while Andritsanos et al. (2016) used an independently measured dataset. The values given in the present study are practically equal to those provided by Andritsanos et al. (2016)

while there is a difference of 0.47 m^2s^{-2} with that given by Grigoriadis et al. (2014) for the Greek mainland. Regarding the islands, apart from Evia, which is directly accessible from the mainland, we notice that there are significant differences in the estimated values. As all studies are affected by the inconsistencies associated with the orthometric heights of the trigonometric BMs, any chosen value for the W_o^{LVD} would face severe difficulties in practice.

5 Conclusions and recommendations

In this study, two independent GPS datasets, GGMs and orthometric heights were used for carrying out an assessment of the Greek LVD in the wider area of the Gulf of Corinth in Central Greece. Different W_o^{LVD} values were computed from each GPS dataset and GGM. First, all BMs were used in order to estimate the mean W_o^{LVD} for the study area for all dataset combinations. Although the mean values of all estimates, considering all BMs each time, were consistent, the values estimated at the BMs had a range from 4 and 5 m^2s^{-2} and a standard deviation larger than 1 m^2s^{-2}. In the next assessment step, the W_o^{LVD} values were computed for two areas, the northern and southern coast of the Gulf of Corinth. The comparison of the results based on the two different GPS datasets showed that the choice of BMs used in the computations affects significantly the computed W_o^{LVD} values. Then, W_o^{LVD} was computed for each map-sheet of the test area. Adjacent map-sheets were found to have differences from 0.5 up to 1.2 m^2s^{-2} when using GOCO05s in the computations. Further examination of the BM values for each map-sheet revealed inconsistencies in terms of the determined zero geopotential-values. It should be noticed that no systematic errors were detected in the data used in the computations nor correlation between the estimated zero geopotential-values with height or the geographic location of the BM stations.

The discrepancies found between the different W_o^{LVD} values following a per BM investigation are mainly attributed to the orthometric height values of BMs and present a random spatial distribution. Since it is not possible with the available data to identify which BMs are problematic, additional GPS/GNSS measurements should be carried out and, most importantly, leveling measurements, in order to further extend our research and draw more safe conclusions. Thus, modern techniques as accurate trigonometric heighting (Lambrou, 2007; Lambrou and Pantazis, 2007), astrogeodetic leveling by means of modern automated instrumentation and procedures (Lambrou, 2015) followed by gravimetry measurements can also be applied in the future field work. A higher accuracy and resolution gravimetric geoid model would also be of benefit in the proposed procedure. It should be finally noticed that before the connection of the Greek LVD with a global one, it is mandatory to: a) resolve the inconsistencies detected by the present and previous studies for the Greek mainland and islands and b) introduce monitoring of the existing VD with time.

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