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

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1. Introduction and Problem

A consistent and unified National Vertical Datum is of main importance for a wide range of applications in geosciences and engineering projects, the latter including infrastructure development, public works and monitoring of natural risks and disasters. The inherent inconsistencies and shortcomings of the Greek Vertical Datum (GVD), mainly due to a) the lack of connection between the VD of the islands with that of mainland Greece, b) the lack of a unified adjustment of the old trigonometric network and c) the lack of any practical long term monitoring of the VD variation with time, pose a problem that needs to be tackled towards the support of engineering and other studies.

In the present study the consistency of the GVD is examined, focusing on an area in central Greece and following similar efforts already 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 (Wo) 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 and compared with previous results related to the GVD and the VD of the Greek islands. Furthermore, the local Wo estimations are compared with the corresponding adopted value for the IHRS. Finally, some remarks are drawn on the feasibility of the unification of the GVD with a global one.

2. Available data and models

In this study, two independent sets of GPS measurements on BenchMarks (BMs) of the Greek Trigonometric Network were available (see Figure 1). The first one (46 BMs) originates from Ktimatologio SA (Gianniou 2008), i.e., the organization responsible for the Greek Cadastre, while the second set was provided by the second of the authors. The BMs from Ktimatologio SA belong to a wider set that was used in the definition of the transformation between the Hellenic Terrestrial Frame 07 (HRTS07) and the Hellenic Geodetic Datum 1987 (EGSA87). The second set (76 BMs), used in this study for datum assessment, was measured by Trimble 5800 geodetic receivers (observation time at each BM 45-60 min) and baseline solutions ranging from 8 km to 40 km were carried out. The orthometric height of each BM is known and both datasets refer to the HTRS07.

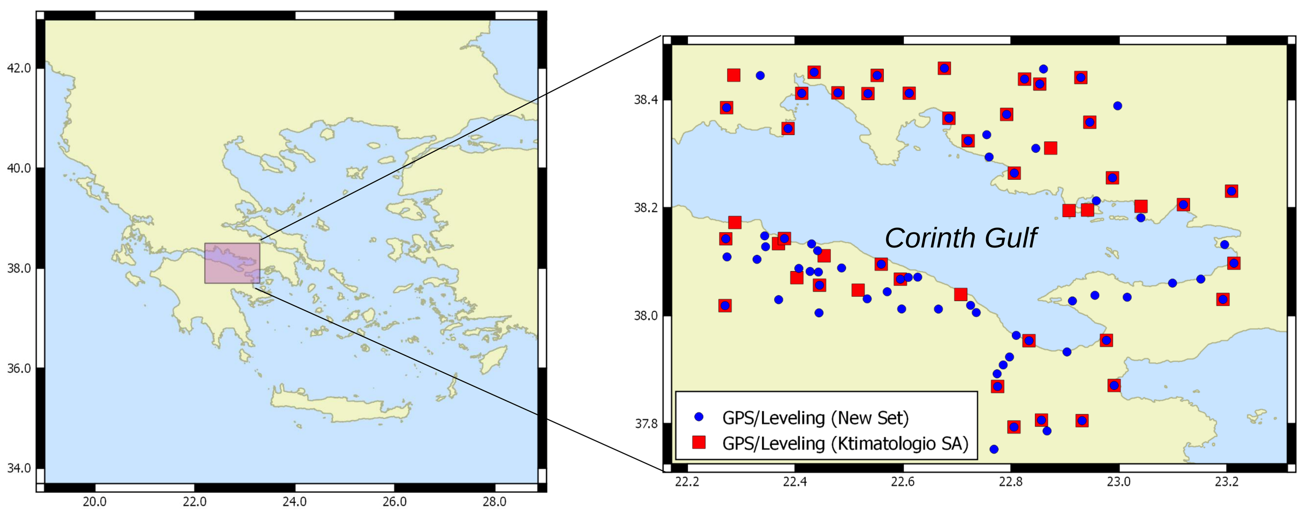

Figure 1: Distribution of the GPS/leveling data for the two available datasets. Overlapping points refer to the same benchmark station (35 common BMs).

Regarding the Global Geopotential Models (GMs) used in the assessment procedure, four GOCE-based models were selected along with EGM08 that are listed 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 combined with EGM08 up to 2160 d/o.

Table 1: The GGMs used in the assessment procedure

Model	Year	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. Wo estimation methodology

The Wo of the Local Vertical Datum (W_o^{LVD}) was computed using the following equation:

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

where W_o is set equal to 62 636 853.4 m^{2}s^{-2} (IAG Resolution No.1/2015), h_i is the geometric height of each BM derived by the GPS measurements, H_i is the known orthometric height of each BM, N_i is the geoid height derived from the GMs used, g_i is the gravity at each BM computed from GMs 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. 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

The first step of the assessment was to compare 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 provided 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^{2}s^{-2}, which corresponds to 2.7 cm approximately in terms of height difference. Two remarks can be drawn regarding the above mentioned results. The first one is that the new dataset includes 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 dataset from several hours of measurements at each trigonometric point. Moreover, it should also be noticed that the calculations with GOCO05s combined model show the lowest standard deviation.

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

	New Dataset				Ktimatologio Dataset			
GM	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

In order to further investigate the aforementioned results we computed W_o^{LVD} per map sheet (scale 1:50.000) following the cartographic breadboard of the Greek Geographical Military Service. The study area is represented in 8 different map sheets. Table 3 lists the new W_o^{LVD} estimates based on the new dataset and that of Ktimatologio. Considering the results a significant difference of more than 1 m^{2}s^{-2} is observed between the different map sheets with a maximum value of 1.89 m^{2}s^{-2} for the GOCO05s-based solution. These results indicate inconsistencies, which may be attributed to the GGM used, especially in the medium to high frequencies of the gravity spectrum, and/or the orthometric heights of BMs.

Table 3: W_o^{LVD} estimates computed per map sheet with respect to the IAG W_o value [m^{2}s^{-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

Further numerical tests were carried out in order to investigate an eventual offset between the BMs that lie in the northern and the southern coasts of the study area. The computed difference equals to 1.11 m^{2}s^{-2} with the northern area showing a smaller W_o^{LVD} value. This result also supports the previously stated conclusion that there are inconsistencies in the Greek trigonometric network.

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 4. From these values it may be concluded that the results of our study area are in close agreement with those given in previous studies 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.

Table 4: 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^{2}s^{-2}]

	GOCO05s	DIR-R5	TIM-R5	EGM08	GECO
New Dataset	6.47	6.48	6.49	6.40	6.42
Greek Mainland					
Grigoriadis et al. 2015	-	-	-	6.87	-
Andritsanos et al. 2016	6.41	6.41	6.46	6.26	-
Greek Island - Crete					
*Kotsakis et al. 2012	-	-	-	7.55	-
Vergos et al. 2016	-	-	7.78	-	-
Greek Island – Evia					
*Kotsakis et al. 2012	-	-	-	6.79	-
Vergos et al. 2016	-	-	6.47	-	-
Greek Island – Corfu					
*Kotsakis et al. 2012	-	-	-	9.34	-
Vergos et al. 2016	-	-	7.90	-	-
Greek Island – Lesvos					
*Kotsakis et al. 2012	-	-	-	8.37	-
Vergos et al. 2016	-	-	7.73	-	-

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

5. Conclusions

This study revealed local discrepancies in the Greek LVD. These discrepancies need to be further investigated by incorporating in the comparisons a high accuracy and resolution gravimetric geoid model. Additional GPS and leveling measurements would be also of importance for the interpretation of the detected differences. It is of importance that the results derived from the two different datasets are in a satisfactory agreement. It should be generally noticed that either the reliable connection of the LVD of the Greek mainland with that of the islands or the corresponding connection of the Greek LVD with a global one needs further investigation and re-consideration of the whole height system.

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