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Original Article

Revisiting the determination of Mount Olympus Height (Greece)

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Abstract: The present study deals with the determination of Mount Olympus summit (Mytikas), exploiting modern observations such as Global Navigation Satellite Systems (GNSS) and existing geodetic information. The last official Olympus height determination goes back 102 years by the Swiss surveyor M. Kurz. Since then, only unofficial measurement campaigns have taken place. There is a variety of released heights, which range from 2917 to 2919 meters. In September and October of 2022, we conducted a GNSS campaign, focusing on the area of highest Olympus peaks. Employing precise GNSS measurements (accuracy of 1-3 cm), in conjunction with height information from Greece's National

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Triangulation Network (5-10 cm accuracy) and an appropriate, recent geoid model (5-6 cm accuracy), we estimate through the so-called GNSS-levelling, the height of Olympus to 2917.727 m with respect to Greece's officially accepted mean sea level and 2918.390 m with respect to the global vertical datum. Our estimation of Olympus highest peak shows remarkable consistency at the level of 12.8 cm to that of M. Kurz in 1921.

Keywords: Olympus; Greece; Mountain height determination; GNSS leveling; Surveying

1 Introduction

Mount Olympus plays a significant role in Greek and global History and mythology (e.g. Mariolakos 2004). According to Greek Mythology, Mount Olympus was the "home" of the most significant Gods (Curtius 1879; Burkert 1985; Dillon 2002; Müller1852). The ancient Olympic Games were also named as dedication to Mount Olympus. Moreover, Olympus played a crucial role throughout the ages for Greek History (Graves 1995). Except for its obvious historical footprint, Mount Olympus is extensively scientifically investigated, in terms of Geology, Glaciers, Geodynmaics, Lithology, Meteorology and Botanology (e.g., Cvijic 1908; Strid 1986; Schremer 1993; Kilias 1995; Smith et al. 1997; Smith et al. 2006; Blake et al. 1981; Nance 2010; Bathrellos et al. 2017; Charalambopoulos et al. 2012). The Olympus highest peak is called Mytikas and it was conquered in 1913 by an amateur climber, Christos Kakalos (Nezis 2000). Fig. 1 shows the location of the Olympus area (as a guide map), while Fig. 2 gives the general view of Mytikas peak.

Fig. 2 View of Mytikas peak (red frame, background).

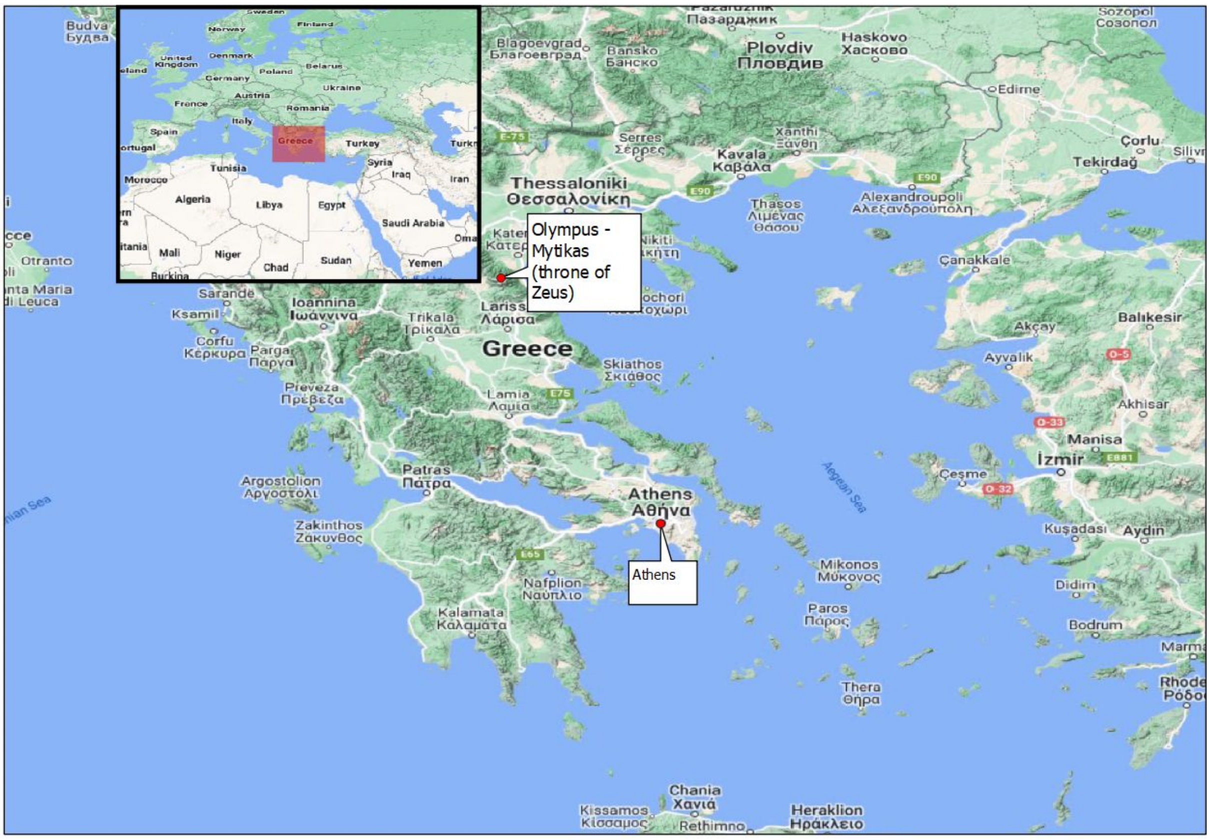

Fig. 1 Guide map of Olympus area.

Fig. 3 Contour lines of heights according to Kurz (1923). Mytika's height was measured at 2917.9 m.

Regarding the Mytikas' peak height determination, there are not many studies and campaigns focusing on it. Xenagoras (1st century BC, Fotiou 2015) measured the heights of lower peaks with remarkable accuracy (taking into account the instruments of this particular era). In 1873 officer R.N. Coperland measured Mytikas height at 2973 m. (Nezis 2000). The most extensive and detailed Mytikas height measurement was conducted by Marcel Kurz in 1921 (Kurz 1923). Kurz was invited by the Greek Government to study Mount Olympus as an experienced Surveyor. Using precise geodetic triangulations and photogrammetric methods (stereophotogrammetry) he estimated Mytikas height at 2917.85 meters (Kurz 1923). Fig. 3 visualizes the contour map of the area, according to Kurz (1923).

Katsampalos et al. (1997), using GPS and spirit levelling observations, found Mytikas height at 2918.8 ± 0.1 m. More recently, Mariolakos et al. (2013) referred to Mytikas height at 2918, without any particular details. We should also underline that the Hellenic Military Geographic Service (HMGS) published the official height as 2917 m. Finally, on internet sites and blogs, there is ambiguity, as the heights deviate from 2917 to 2919 m.

In the present study we focus on the optimal combination of heterogeneous height sources (orthometric heights form state's benchmarks, geometric heights from GNSS observations and geoidal undulations from a recent model) through the well-known methodology of GNSS-levelling (Kotsakis and Sideris 1999). The optimal combination leads to a new estimation for Mytikas summit's height with respect to different vertical reference systems.

2 Data and Methods

Since it is precarious to reach Mytikas peak with direct spirit leveling measurements (severe inclinations and safety issues), we exploit all the alternative data sets and methods for rigorous orthometric height estimation. We henceforth present the three sources of data we obtained and analyzed in order to estimate the height of Mytikas. Various recent studies exploited the three aforementioned height sources for orthometric height determination of mountain summits, e.g. Chen et al. (2006), Poretti et al. (2006), Dangol et al. (2021) exploiting a variety classical surveying measurements (astronomical observations, GPS-related heights and geoidal undulation from global models), estimated the height of Mount Everest. Xie et al. (2021) using the so-called shallow layer method, determined the height of Mount Everest. Finally, Mora et al. (2022) through GNSS observations calculated the summits of three main Ecuadorian mountains.

2.1 Orthometric heights

Around the Olympus area there are numerous official (State's) benchmarks, belonging to the National Triangulation Network (NTN) (Takos 1989), which is maintained by the HMGS. Our plan was to occupy, with GNSS measurements, fifteen benchmarks belonging to NTN. In practice, we found eleven out of fifteen benchmarks, which are not completely destroyed or severely inclined. The orthometric heights of the aforementioned benchmarks are estimated through trigonometric leveling (Takos 1989). The orthometric heights refer to mean sea level of Piraeus tide-gauge, which is the fundamental point of Greece's continental vertical datum (Takos 1989; Kotsakis et al. 2010). Regarding their accuracy, we assume that it ranges from 5-10 cm (there is no officially published accuracy specifications). The aforementioned accuracy of 5-10 cm for the orthometric heights is mainly empirically derived from analyses of various GNSS-levelling campaigns, taken place in continental Greece. Fig. 4 shows some of the occupied benchmarks and stations, which were found during the campaigns.

2.2 Geometric heights

At the eleven NTN's benchmarks we obtained GNSS measurements, using geodetic receivers of double frequencies (Topcon Hiper Pro). Apart from the NTN's points, we also measured five new stations around Olympus area and the Mytikas peak. The occupation time varied from 2 to 24 h, depending on weather conditions and the accessibility of the points.

We solved the 3D geodetic network using the Bernese Software vol. 5.2 (Dach et al. 2015). The estimated heights refer to the Hellenic Terrestrial Reference System of 2007 (HTRS07, Katsambalos et al. 2010), which is a local densification of the European Terrestrial Reference System of 1989 (ETRS89). The reference ellipsoid for the geometric heights is GRS80. The height accuracies range from 1-3 cm. The GNSS campaign was conducted between 30/9 and 2/10 of the year 2022. At Mytikas peak a concrete benchmark of 1.1 m height was built by the HMGS with a height reference point at its base. However, the benchmark (Fig. 5) on Mytikas peak does not belong to the NTN. Table 1 refers to the stations occupied by GNSS.

2.3 Geoidal undulations

For the needs of our study, the most recent gravimetric geoid model of HMGS is used (HELLAS GEOID 2022, Kagiadakis et al. 2022). The HELLAS GEOID 2022 is aligned to Greece's height system with a consistency of 5 cm, nationwide (Kagiadakis et al. 2022). The HELLAS GEOID 2022 was created using the global geopotential model EIGEN6C4, terrestrial and sea gravity measurements. Fig. 6 depicts the geoidal undulations (with respect to the HELLAS

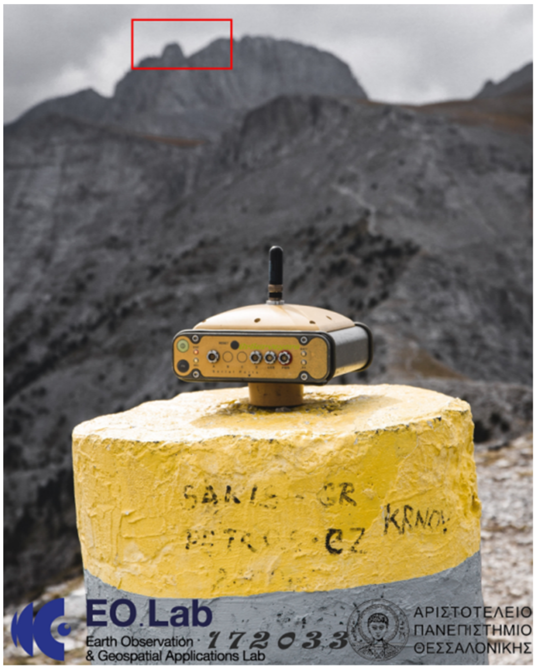

Fig. 4 GNSS receiver at NTN benchmark and the Mytikas peak in background (red frame).

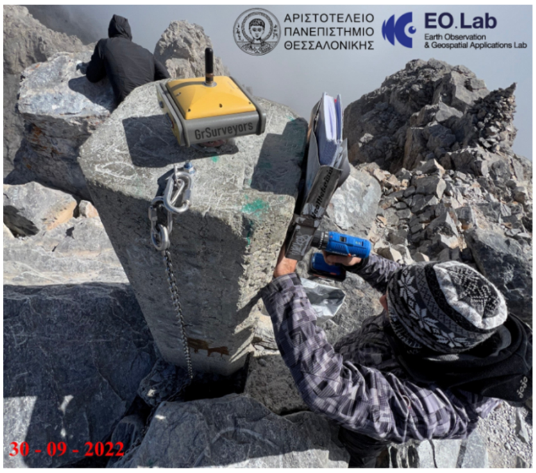

Fig. 5 GNSS receiver at Mytikas peak.

GEOID 2022) and the benchmarks employed for the GNSS leveling procedure, while Fig. 7 gives a closest view to the newly established stations.

2.4 Methodology

2.4.1 GNSS leveling principles

For the rigorous estimation of Mytikas orthometric height, we follow the GNSS-Leveling approach (Heiskanen and Moritz 1967; Kotsakis and Sideris 1999; Kotsakis et al. 2010; Tziavos et al. 2012; Deng et al. 2013). The main idea of the method is to optimally combine the three different types of heights

Table 1 Stations occupied by GNSS measurements. The coordinates refer to HTRS07 (approximate values)

Name	Latitude (N)	Longitude(E)	Geometric height (m)	Notes
172013	40.04257°	22.25852°	1056	NTN benchmark
172020	40.06457°	22.49065°	954	NTN benchmark
172024	40.07899°	22.33013°	2749	NTN benchmark
172026	40.08214°	22.34976°	2946	NTN benchmark
172032	40.09999°	22.25416°	1300	NTN benchmark
172033	40.10446°	22.38788°	2516	NTN benchmark
172037	40.11184°	22.46745°	979	NTN benchmark
172059	40.17175°	22.40344°	381	NTN benchmark
172068	40.19558°	22.45122°	114	NTN benchmark
172079	40.22177°	22.32516°	391	NTN benchmark
172083	40.23564°	22.35801°	299	NTN benchmark
Giosos Apostolidis Settlement	40.09485°	22.36141°	2737	In front of the gate/new station
Dasarxeio	40.09241°	22.36652°	2681	New station
Spilia	40.09005	22.34634°	2186	New station
Kakalos	40.09296°	22.36688°	2686	New station
Xionospilia	40.08858°	22.36542°	2603	New station

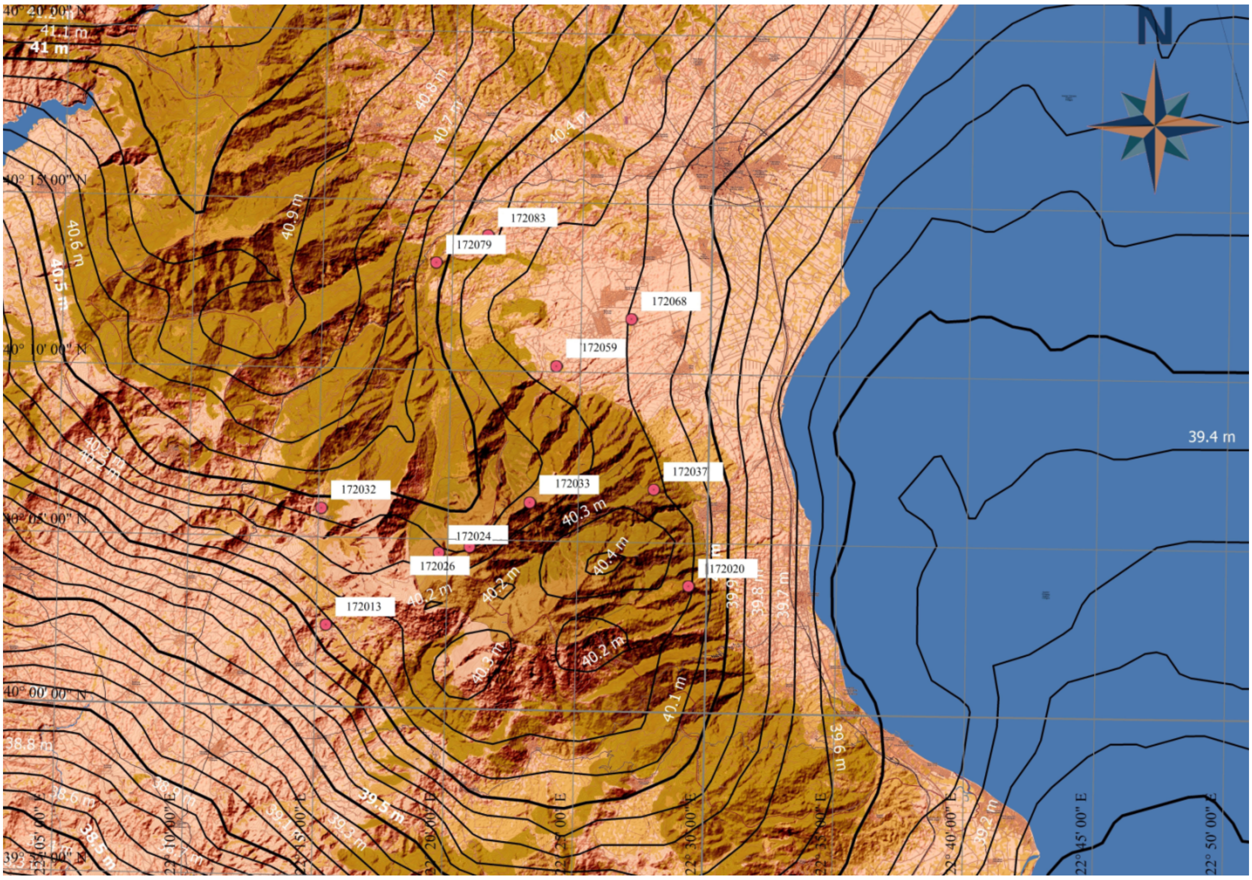

Fig. 6 National Triangulation Network (NTN) benchmarks and the geoidal undulation.

previously described (orthometric heights, geometric heights and geoidal undulations). This is dictated in the direction of mitigating different systematic errors, which are carried by the aforementioned heterogeneous height data

The general equation yield as follows, pointwise:

$$h_i - H_i - N_i = \mathbf{a}_i \mathbf{q}_i + e_i \tag{1}$$

where subscript *i*, a point of the NTN, *h,* the geometric height, *H,* the orthometric height, *N,*

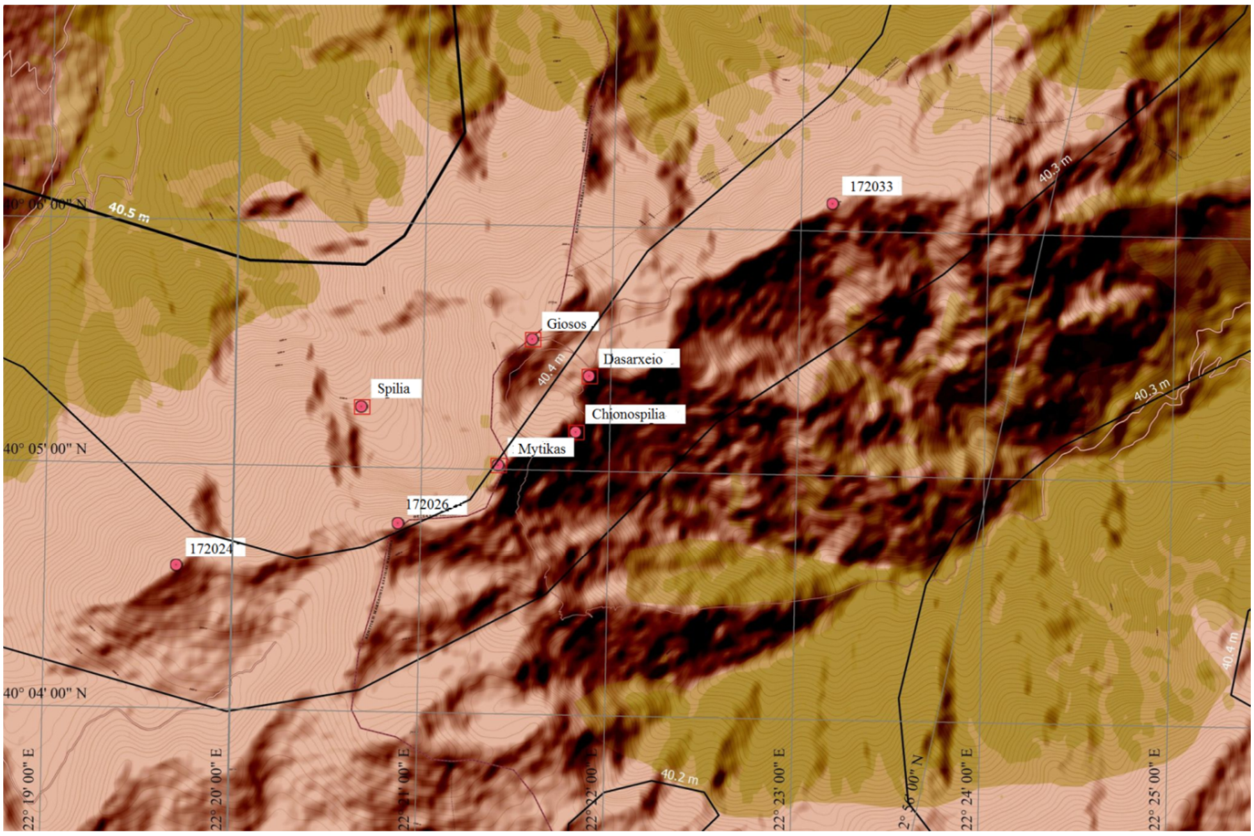

Fig. 7 Closer view of NTN benchmarks and the newly established stations around the top of Olympus.

geoidal undulations, $\mathbf{a}$, a set of parameters absorbing the systematic error and $\mathbf{q}$ *,* the set of the curvilinear coordinates (geodetic latitude and longitude, respectively) and e_i, the random error.

Practically, the set $\mathbf{a}$ of the parameters define a correction surface (e.g., level, ellipsoid) which is introduced for the mitigation of systematic errors. For our case, we apply the following model (4-parametric, pointwise, Kotsakis and Sideris 1999):

$$h_i - H_i - N_i = a_0 + a_1 \cos\varphi_i \cos\lambda_i + a_2 \cos\varphi_i \sin\lambda_i + a_3 \sin\varphi_i \quad (2)$$

where a_0, a_1, a_2, a_3 the unknown parameters and φ_i, λ_i the geodetic latitude and longitude, respectively. After the implementation of the LS adjustment and the proper statistical test for removal of outliers, the optimal parameters $a_0^{est}, a_1^{est}, a_2^{est}, a_3^{est}$ are estimated. The 4-parametric model needs at least four points for a simple solution for the unknown parameters and at least five for having redundant information. The removal of the blunders is done applying the well-known t-test (Koch 1999), with level of significance a=0.05.

The 4-parametric model is applied at the prediction points as follows: Consider an arbitrary prediction point in the area of interest. Its geometric height is estimated from GNSS measurements, the geoidal undulation is calculated through interpolation and there is no information about its orthometric height and thus, it should be calculated.

The predicted orthometric height is computed (according to Eq. 2):

$$H_j^{prog} = h_j - N_j - a_0^{est} - a_1^{est} \cos\varphi_i \cos\lambda_i - a_2^{est} \cos\varphi_i \sin\lambda_i - a_3^{est} \sin\varphi_i \quad (3)$$

where the subscript j indicates an arbitrary predicted point.

The meaning of Eq. 3 is that we obtain geometric heights and their associated geoidal undulations, of a set of points; we can predict their orthometric through the employed parametric model.

2.4.2 Heights with respect to the global vertical datum

The estimated value of Mytikas peak refers, as we mentioned before, to the Piraeus port mean sea level. Additionally, one can refer the height with respect to the global vertical datum (Sánchez at al. 2021), according to the following equation, pointwise (e.g. Kotsakis et al. 2012):

$$\delta H_i = \frac{W_O - W_O^{\text{Greece}}}{\gamma_i} \tag{4}$$

where δH_i the level differences between the local (Greek) mean sea level and the global vertical datum, respectively, W_0 the global zero geopotential (62636853.4 m²/s², Sánchez et al. 2021), W_O^{Greece} the geopotential of the Greek Vertical Datum (reference point: Piraeus Port) (62636859.8902+-0.015 m²/s², Vergos et al. 2018) and γ_i the normal gravity at the arbitrary point i. Thus, in order to be consistent with the global sea level we should subtract the δH_i term to the initially estimated one (which refers to the mean sea level defined by Piraeus mean sea level). Similar approach is followed by Mora et al. (2022). The final height with respect to the global vertical datum, yields:

$$H_i^{\text{Global}} = H_i^{\text{Greece}} - \delta H_i \tag{5}$$

where H_i^{Global} the orthometric height with respect the global datum, H_i^{Greece} the orthometric height with respect the mean sea level of Greece

3 Results and Discussion

We found eleven benchmarks of the NTN in relatively good condition. After collecting the GNSS data for all the receivers (nine benchmarks and five stations, including Mytikas) we solved the 3D geodetic network. Mytikas geodetic coordinates with respect to HTRS07 are estimated as follows (the uncertainties are in meters):

$$\varphi_{\text{Mytikas}} = 40.08622458\ deg\ \ \pm 0.010$$
$$\lambda_{\text{Mytikas}} = 22.35856086\ deg\ \ \pm 0.009$$
$$h_{\text{Mytikas}} = 2958.262 \pm 0.031$$

The interpolated geoid undulation (using the Inverse Distance Weight method-IDW) of HELLAS GEOID 2022 is calculated at 40.408 m. The IDW is the official interpolation model used by HGMS and all the geoidal undulations are calculated exclusively by IDW.

Subsequently, we apply the model of Eq.2 at the eleven benchmarks belonging to NTN. After the implementation of the statistical test, we finally excluded four benchmarks (172020, 172024, 172026, 172033). We believe that the orthometric height of these benchmarks carry significant errors, due to their estimation through trigonometric leveling (Chalaris 2022). The estimated parameters are (units: meters):

$$\hat{a}_0 = -19171.2495$$
$$\hat{a}_1 = 13577.7482$$
$$\hat{a}_2 = 5612.1003$$
$$\hat{a}_3 = 12316.3649$$

Implementing Eq. 3, we finally get the orthometric height (expressed in meters) of Mytikas peak (the correction term **aq** contributes 12.7 cm).

$$H_{\text{Mytikas}} = 2917.727 \pm 0.078$$

while, with respect to the global vertical datum (see Eq. 4, in meters):

$$H_{\text{Mytikas}}^{\text{Global}} = 2917.727 + 0.663 = 2918.390$$

The accuracy of Mytikas orthometric height is calculated using the method of Variance Component Estimation (VCE), described in detail by Amiri - Simkooei (2007). The statistics of the adjusted residuals are shown in the following Table 2, while Fig. 8 visualizes the adjusted residual per used benchmark.

Table 2 Statistics of the adjusted residuals.

Statistical quantity	Value (cm)
Min	-4.4
Max	4.0
Mean	0.0
standard deviation	2.9

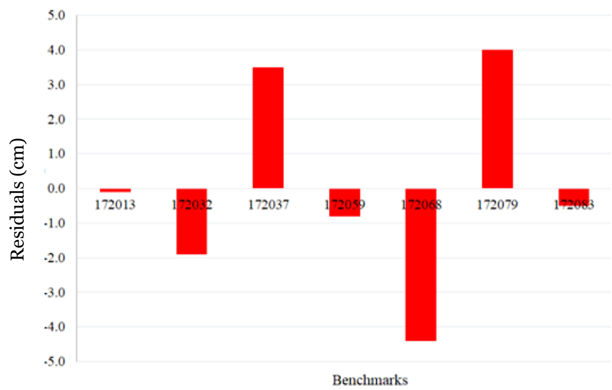

Fig. 8 Adjusted residuals per NTN benchmark.

The statistics of the adjusted residuals reveal good consistency among the three different sources (orthometric and geometric heights and geoidal undulations) at the level of 2.9 cm (standard deviation of the adjusted residuals). Though the fact of low number of redundancy (the initial number of degrees of freedom is 7), we believe that the t-test is successfully implemented due to the low estimated standard deviation of the residuals and the relatively small range of their extreme values (minimum and maximum residuals do not exceed 4.5 cm in absolute sense, respectively).

The uncertainty of 7.8 cm (below 1-dm) could be considered satisfactory, taking into account (a). the oldness of NTN orthometric heights (b). the questionable accuracy of NTNs orthometric heights and (c). the low number of the GNSS-occupied benchmarks. Regarding the sense of Mytikas orthometric height accuracy, we may refer that e.g., Chen et al. (2006) determine the orthometric height's accuracy of Everest at the level of 18 cm, while Xie et al. (2021) (again for Everest) using global geoidal undulation models, claim accuracy of tens of centimeters. Finally, Mora et al. (2022) orthometric heights accuracies for the Ecuadorian mountains vary from 5-15 cm.

We can observe that Mytikas orthometric height estimation is significantly consistent to the one released by Kurz (1923); their difference is at the level of 12.3 cm, which is rather remarkable, taking into account the instrumentation used by Kurz 102 years before. However, we do not have any further information regarding the methods and the conventions that Kurz followed (Mytikas peak exact reference point, accuracy of the measurements, vertical datum). The benchmark on Mytikas peak was constructed decades later from Kurz's expedition.

In addition, we found 107.3 cm deviation with respect to the estimation published by Katsampalos et al. (1997). In this particular article (not published for scientific purposes), we do not have any specific description of the methods and models employed for Mytikas height estimation. It is rather possible that some systematic errors were not taken into account and thus the final result was probably contaminated. Furthermore, we must keep in mind that in 1997 the only available navigation system was GPS and the satellites availability was significantly poorer than now with at least two satellite constellations and a considerably larger number of satellites.

4 Conclusions

In the present study, we are dealing with the estimation of Olympus highest peak (Mytikas) with the use of heterogeneous height sources: orthometric and geometric heights and geoidal undulation. Adopting a GNSS-leveling procedure under the application of a 4-parametric model, we end up with the estimation of Mytikas height at 2917.727 ± 0.078 m with respect to the Piraeus mean sea level and referring to the global mean sea level, 2918.390 m. The height computation is based on a robust mathematical procedure (GNSS leveling), removing possible blunders and taking all the advantages of the modern technologies (GNSS), relatively good geoid model (HELLAS GEOID 2022) and existing orthometric height information. Mytikas' peak height estimated here is relatively close to that of Kurz. We cannot verify if it is a random finding, a result of geological processes (vertical motions) or it is a matter of true consistency or a combination of these effects.

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