

Comparison of Various GPS Processing Solutions toward an Efficient Validation of the Hellenic Vertical Network: The ELEVATION Project

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Abstract: A research project called ELEVATION (Evaluation of the HelLEnic Vertical Network in the FrAme of the European SysTems and Control Networks InterconnectiON—Application in the Areas of Attica and Thessaloniki) for the validation of the Hellenic vertical network is currently in progress. Two investigation areas in central and northern Greece were chosen for the project. The areas include several benchmarks of the national trigonometric and leveling networks. In the current research, static global positioning system (GPS) observations as well as classical terrestrial leveling were performed to assess the internal accuracy of the two networks. This paper presents some of the numerical tests based on GPS and leveling measurements and outlines the goals of the project. The strategies followed in the processing of GPS data are presented, with emphasis on their future use within this project. GPS observations were processed using various commercial as well as scientific software packages to examine the influence of the processing algorithms on the final results. Significant differences between the results of the various software packages were revealed, particularly in the case of challenging observation conditions. Finally, comparisons of the estimated geoid heights at GPS benchmarks (BMs) to Earth Gravitational Model 2008 (EGM2008) geoid information are presented as a first step toward the evaluation of the Hellenic vertical network. These comparisons indicate that the two investigation areas are of different internal accuracy, namely, 8.3 and 15.8 cm in terms of the standard deviation of the differences at the Attica and Thessaloniki test areas. DOI: [10.1061/\(ASCE\)SU.1943-5428.0000164](https://doi.org/10.1061/(ASCE)SU.1943-5428.0000164). © 2015 American Society of Civil Engineers.

Introduction

Highly accurate determination of three-dimensional (3D) positions is feasible with the use of modern global navigation satellite system (GNSS) positioning techniques. In contrast, the determination of vertical positions is much more demanding, mainly because of the inherent connection between the vertical reference systems and Earth's gravitational field. Height information, determined from an equipotential surface, is of particular importance for a variety of

applications, from coastal management to construction and monitoring of civil engineering projects, such as highways, railways, metro systems, and bridges.

A project for the validation and quality control of the Hellenic vertical network called ELEVATION (Evaluation of the HelLEnic Vertical Network in the FrAme of the European SysTems and Control Networks InterconnectiON—Application in the Areas of Attica and Thessaloniki) is currently in progress. Two investigation areas, one in Attica (central Greece) and another in Thessaloniki (northern Greece), were chosen for the project. The areas include several height benchmarks (BMs) of the national trigonometric and leveling networks. In the current research, static global positioning system (GPS) observations as well as classical spirit leveling in combination with trigonometric leveling were performed to assess the internal accuracy of the two networks. This paper presents numerical tests based on GPS and leveling measurements and discusses the goals of the project. The main objective of the current research is the control and re-evaluation of the Hellenic vertical network. Height information of high accuracy and reliability in a common reference system is essential. Especially today, with the pan-European effort for the establishment of a common European vertical network (Sacher et al. 2007), the validation of the Hellenic network seems a prudent decision. To highlight the importance of reference system unification, it should be mentioned that the International Association of Geodesy (IAG) established a Special Study Group (SSG), EUREF, for the connection of various reference systems in Europe. In 1989, EUREF introduced the European Terrestrial Reference System of 1989 (ETRS89). The connection of the Hellenic 3D network with ETRS89 was established through the Hellenic Positioning System (HEPOS). HEPOS is a national real-time kinematic (RTK) network based on 98 reference stations established for the modernization of the geodetic infrastructure of Greece (Gianniou 2008). In coming years the vertical datum will be connected with Europe under the European Community

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directive called INSPIRE. Before this connection is made, validation of the vertical network must be carried out.

The first-order vertical control network of Greece was established and measured by the Hellenic Military Geographical Service from 1963 to 1986 (Milona-Kotroyanni 1989). Approximately 11,000 km of traverses and 11,000 vertical control BMs characterize the Greek vertical network. The tide gauge in Piraeus harbor is the fundamental point of the network. The first-order Hellenic trigonometric network also gives some height information as a result of its trigonometric leveling lines. This vertical information has not been validated since the network's creation. Thus, validation of the vertical reference network before the establishment of the European interconnection is essential.

The European committee for the continental control networks works under the auspices of the European Council on the measurement and establishment of both a horizontal and a vertical European reference system. A vertical system is characterized by its datum (point of reference) and the type of height used. The datum point is estimated by the mean sea level (MSL) in the area, as determined by tide gauge measurements. Tide gauges exist in various regions in Europe: in the Baltic Sea, the North Sea, the Mediterranean, the Black Sea, and the Atlantic Ocean. Level differences between various tide gauges can reach several centimeters. In addition, national vertical datum points are based on historical facts and not always referenced to the MSL; for example, the zero point of the Amsterdam tide gauge is defined as the mean high tide in the year 1684 (Mäkinen 2005).

Another issue is the use of various types of heights around Europe. Orthometric heights are used in Belgium, Denmark, Italy, Greece, and other areas, and normal heights are used in France, Germany, Sweden, and the Eastern European countries. The integration of national systems began in 1945, and the establishment of a common system throughout Europe was divided into various solutions in Western and Eastern Europe for political reasons.

Greece, in particular, has not yet been connected with any of the unified vertical reference systems. As a consequence, difficulties arise in planning and executing cross-border projects, such as roads, railways, and pipeline constructions. A prerequisite for the Hellenic vertical datum connection is its evaluation. The validation of the height data must be based on an evaluation of the internal consistency of the solution, along with testing of its external accuracy with the use of independent control data.

The first stage of the ELEVATION project was dedicated to the compilation/validation of existing data and the collection of new observations. These observations were collected during the first stage of the project (August–October 2012) and referred to the update and enrichment of the existing GPS and leveling database. GPS observations near leveling BMs of the Greek vertical network and on trigonometric pillars were collected. The connection between various BMs using classical spirit or trigonometric leveling with simultaneous reciprocal observations was also part of the first stage of the project. The second stage of the project involved data processing. GPS observations were processed using various commercial as well as scientific software packages to examine the influence of the processing algorithms on the final result.

Theoretical Background on Heights

Historically, the need to separate horizontal and vertical positions stems from the different levels of accuracy provided by terrestrial observations. Horizontal directions are measured with increased accuracy as compared with vertical ones. This is a result of the atmospheric refraction effect, which introduces greater uncertainty to

vertical positioning. For this reason, classical geodetic observations are divided into horizontal directions and distances for horizontal positioning and spirit leveling measurements for vertical positioning (Torge 2001).

Height data are referenced to suitable level surfaces, which represent characteristic elements of the observation environment. Heights are connected with human activity, and thus their link with physical characteristics is necessary. A characteristic surface is the MSL. This surface represents the traditional connection of all human activities with the natural environment. Practically, it is common knowledge that the MSL is a zero-height surface. Theoretically speaking, MSL on a global scale constitutes a balanced surface of waters and, excluding the presence of the quasi-stationary dynamic ocean topography, represents an equipotential surface of Earth's gravitational field. In this manner, the concept of geoid as a height reference surface is introduced. The geoid is an equipotential surface of the Earth's gravitational field that to a first approximation coincides with the MSL on global scale, provided that the effects of tides and ocean currents are removed. In a well-defined national vertical control network, heights are referenced to a datum point of zero altitude. Usually, the zero-height point is defined by local MSL observations from tide gauge records. In reality, the sea-level change is measured from a conventionally selected level, which is considered constant: the tide gauge zero.

Another reference surface used is the ellipsoid of revolution. The ellipsoid is a mathematical rather than physical surface, and it is conveniently used as an approximation of the Earth's surface and gravitational field because of the mathematical simplicity of the description of its surface and gravity field as compared with those of the actual Earth. Data from geodetic satellite missions can be referenced to an ellipsoid of revolution. In the current research, the data of such missions were used for the validation of the vertical network. The main height reference surfaces used in this work are depicted in Fig. 1 and analytically described in the methodology section.

A point in space can be identified using three coordinates: latitude, longitude, and height. The horizontal coordinates are referenced to the surface of a reference ellipsoid of revolution, which is a geometrical-mathematical surface related to the MSL on a local or global scale. The height of a point P can be reckoned along the normal to the ellipsoid passing through the point P and is called ellipsoidal height, h_P .

However, in some applications the altitude of a point must be referenced to the MSL, or more precisely to the vertical reference system. The ellipsoidal model does not coincide with the MSL but has a deviation from -100 to 100 m, globally. The dependence of the vertical reference system on the gravitational field seems obvious, because an equipotential surface of this field is the first approximation of the MSL on a global scale.

A height reference surface must be related to the physical environment through an equipotential surface of Earth's gravitational field, a surface of constant value of Earth's gravitational potential W

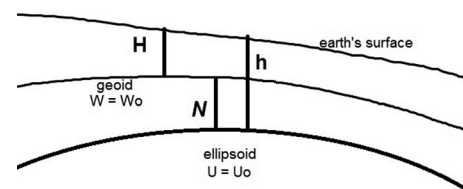


Fig. 1. Height reference surfaces

(Hofmann-Wellenhof and Moritz 2005; Martinec 1998). Specifically, the surface $W = W_0$, which is approximated by the MSL, is known as the geoid. Therefore, in the past, the height above MSL was defined as the height above the geoid. However, this is not completely accurate because of the presence of dynamic ocean topography, which in the past was neglected. Let P_0 represent a point near a tide gauge, with a gravity potential of W_0 . There exist different kinds of heights depending on the potential definition at the point of interest. This potential difference is known as geopotential number (Hofmann-Wellenhof and Moritz 2005)

$$C_P = W_0 - W_P \quad (1)$$

where W_P is the gravity potential of point P on Earth's surface. The vertical differences (in length units) are observed using classical spirit leveling. By taking the measured track perpendicular with the equipotential surfaces (plumb line), one can solve along the vertical length, H_P , called orthometric height (Hofmann-Wellenhof and Moritz 2005), as follows:

$$H_P = \frac{C_P}{\bar{g}_P} \quad (2)$$

where \bar{g}_P is the average gravity along the plumb line. In this specific case, a density model for the masses inside the Earth is needed. This fact dictates the direct dependence of orthometric height on the density model used.

The relation between ellipsoidal heights, measured from GNSS and orthometric heights, is

$$h = H + N \quad (3)$$

where h is the ellipsoidal height along the straight line normal to the ellipsoid; H is the orthometric height from the geoid surface, measured along the plumb line; and N is the geoid undulation (distance from the geoid to the ellipsoid) along the ellipsoidal normal. According to the definition, the orthometric height is independent of the ellipsoid model used. However, the geoid undulation is based on the ellipsoid choice because it is expressed as the difference from a specific model. Geoid heights can be derived using local gravity information in combination with global features provided by a geopotential model. The most recent global geopotential model calculated from a special spectral combination of terrestrial and satellite data is Earth Gravitational Model 2008 (EGM2008) (Pavlis et al. 2012).

Data Collection and Analysis

GPS Measurements

The main purpose of the GPS measurements was the determination of the ellipsoidal heights of the trigonometric and leveling BMs. Leveling BMs are often established on vertical elements, such as walls or columns, and thus they are not adequate for GPS measurements. In such cases, we established new points offering good satellite visibility on sites as close as possible to the original BMs (distances up to 200 m). These newly established points were connected to the original BMs by means of double-run spirit leveling. Figs. 2 and 3 depict the location of the trigonometric and leveling BMs in Attica and Thessaloniki, respectively.

To ensure high accuracy in the determination of the ellipsoidal heights of the BMs, the GPS measurements were designed carefully. A key parameter for this work was the selection of

an adequate geodetic reference frame. The latest International Terrestrial Reference Frame (ITRF), ITRF2008, would be the best choice, as it ensures the highest possible accuracy. However, this solution would require the connection of the BMs to reference stations with well-known ITRF coordinates, that is, International GNSS Service (IGS) and/or EUREF Permanent Network (EPN) stations. Because there are no IGS stations in Greece (except two proposed stations in Athens and Chania), the length of the baselines to the closest IGS stations would be of the order of hundreds of kilometers, imposing observation times of at least 24–48 hours. Such occupation times were not feasible for the current project because of the large number of BMs to be measured and their locations (tops of hills). The next possibility examined was the use of EPN stations. Two of the six Greek EPN stations are located in the two project areas—NOA1 in Athens and AUT1 in Thessaloniki—at distances up to 60 km away from the BMs. However, the connection of every point to at least two permanent stations, as desired in the current study, would impose the use of other Greek EPN stations, leading to baseline lengths of the order of hundreds of kilometers. So, instead of using EPN stations, the current research used HEPOS stations (Gianniou 2008). The high density of the HEPOS network allowed for the connection of each BM to two permanent stations and, at the same time, ensured short baseline lengths. The baselines measured in the area of Attica and Thessaloniki are shown in Figs. 4 and 5, respectively. The corresponding mean baseline length for each area was 20.9 and 23.4 km, respectively. The maximum baseline length was 44 km, and only four vectors among a total number of 134 baselines exceed 40 km. Given the aforementioned baseline length, the rapid-static method could have been used. However, to increase the accuracy of the results, the static method was used, consisting of a minimum occupation time of 1 hour at each point. In cases of challenging observation conditions, such as obstacles, canopies, and so forth, the measurement duration was increased (up to 3 hours). These occupation times were expected to ensure a horizontal accuracy of 1 cm and a vertical accuracy of 2 cm. The measurements were conducted using dual-frequency receivers, the Topcon HiperPro in Attica and Leica SR520 in Thessaloniki. The logging interval was 15 s and the elevation mask 10° . The antenna heights were measured with an accuracy of ± 1 mm. More details about this campaign can be found in Anastasiou et al. (2012). The HEPOS stations are equipped with Trimble NetRS receivers with Trimble Zephyr Geodetic Antennas with spherical Trimble domes. Table 1 summarizes the number of trigonometric and leveling BMs in the two areas of the ELEVATION project. Figs. 4 and 5 depict the location of the benchmarks and the HEPOS stations used for the processing of the baselines in Attica and Thessaloniki, respectively.

Leveling Observations

Given the availability of a number of GPS/leveling benchmarks with collocated GPS and leveling observations, the first step was the selection of new BMs to be measured. The new BMs were selected from the National Trigonometric and Leveling Network, established by the Hellenic Military Geographical Service (HMGS) to guarantee the connection to the national horizontal and vertical networks. The main problem of the established Greek vertical datum is its inherent systematic distortions, which cannot be modeled properly without knowledge of the accuracy of the orthometric heights of the BMs. This accuracy is largely unknown because of insufficient adjustment documentation; therefore only some assumptions can be made on its accuracy. Moreover, the original leveling traverses and the error covariance matrix of the adjustment solution are not available, which prevents proper reanalysis. An

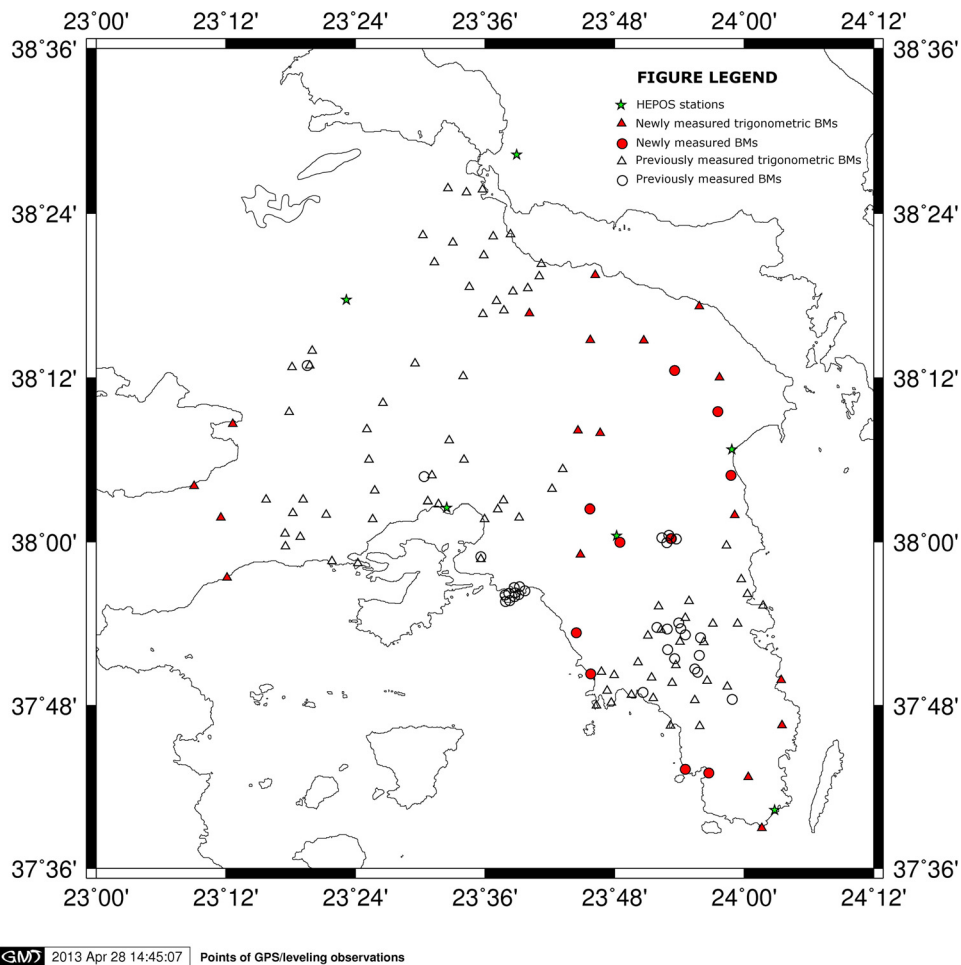


Fig. 2. Locations of the 103 points in the Attica region

overview of these distortions can be found in Kotsakis et al. (2010), who reported an estimated bias of 37 cm between the Greek vertical datum and EGM2008 with the use of GPS/leveling information on 1,542 BMs of the Greek trigonometric network. This represents an estimate of the systematic offset between the Greek vertical datum and a global one. In more recent studies, Grigoriadis et al. (2014) determined the systematic offset of the Greek vertical datum at 43 cm, employing once again EGM2008 along with a least-squares adjustment scheme, in which systematic distortions with respect to height were accounted for. Vergos et al. (2015) determined the bias at 40.7 cm by employing Release 5 of the Gravity Field and Steady-State Ocean Circulation Explorer (GOCE)/Gravity Recovery and Climate Experiment (GRACE) global geopotential models (GGMs). It should be noted that the latter reported value shows an inherent consistency at the 0.1–0.4-cm level with the use of various types of GGMs from the available GGM estimation strategies when employing GOCE data. Of the total number of height BMs that were found after the research in the two investigation areas, only some of them were chosen for conducting the leveling measurements in the current study. To reassess the leveling network in the investigation areas of Attica and Thessaloniki, a combination of ground-based techniques was used for the determination of orthometric height differences. Classical spirit leveling and special trigonometric leveling were the two types of techniques applied. More on the techniques used for the leveling observations as well as results and comparisons from the evaluation procedure can be found in Anastasiou et al. (2012) and Vergos et al. (2015).

Data Processing and Results

GPS Data-Processing Schema

Because of the challenging environment for GPS measurement at some BMs (e.g., foliage, obstacles, electromagnetic interferences), difficulties in data processing were expected. For better control over the quality of the results, independent computations were performed using five different software packages available at the three institutions participating in the research project. This facilitated an extended comparison of the software packages used. Table 2 summarizes the programs used and their characteristics.

For the processing with *Bernese* (BERN), IGS precise orbits were used. For the processing with the commercial software packages, broadcast orbits were used. The error in the baseline length introduced by the orbital error can be approximated by the formula (Teunissen and Kleusberg 1998)

$$\frac{db}{b} = \frac{dr}{r} \quad (4)$$

where db/b is the relative baseline error; and dr/r is the relative orbital error. Given that the maximum baseline length was 44 km and assuming an orbital error of 2 m, the maximum error in the baseline length resulting from the orbital error did not exceed 4 mm, which is fully sufficient for the purposes of the current research.

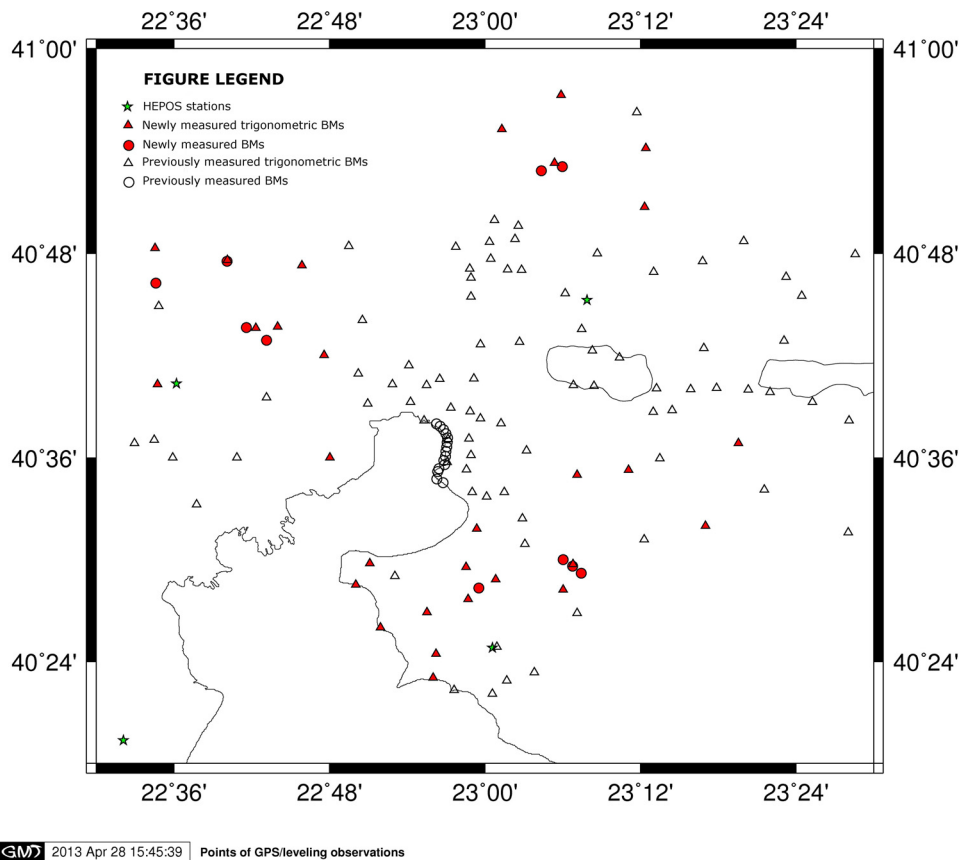


Fig. 3. Locations of the 127 points in the Thessaloniki region

With *BERN*, the processing parameters described in the CODE Analysis strategy (IGS 2015) were used. For fixing the ambiguities, the SIGMA algorithm (Dach et al. 2007) was used together with the L1/L2 method (for baselines up to 20 km) and the wide-lane/narrow-lane method (for longer baselines). With the commercial software packages, the default processing parameters of each software program were used. Antenna offsets and phase center variations were modeled using the calibration models available in all software packages.

The GPS data processing was performed in two main steps. The first step was the reduction of the GPS baselines. The observations were processed by building double-differences to obtain integer values for the carrier phase ambiguities (fixed solutions). The second processing step was a least-squares adjustment of the GPS vectors to compute the final coordinates of the BMs. For each BM a pair of GPS vectors was available that connected the BM to two HEPOS stations, as depicted in Figs. 4 and 5.

GPS Data-Processing Results

Certain difficulties were encountered during the baseline processing as a result of the aforementioned unfavorable satellite signal reception at some BMs. For several baselines the initial processing (i.e., using all observed satellites) yielded fixed solutions but with poor statistics (flagged fixed), whereas for a limited number of baselines the initial result was a float solution (i.e., no integer values were estimated for the ambiguities). To improve the results, each float baseline was reprocessed after rejecting the observations with residuals considerably higher [in terms of root-mean square (RMS) and mean value] than those of the majority of the observations in the

particular baseline. In this way, most of the flags were removed and most of the float solutions became fixed. This procedure was followed with the commercial programs, which are suitable for these types of interventions. In contrast, such intrusions are quite complex in *BERN*, so no similar attempts were made with this software. Table 3 summarizes the initial and final results obtained from processing with each software program.

The results of the different software programs agreed quite well in the case of BMs that offered good observation conditions. On the contrary, for baselines involving BMs with unfavorable signal reception, significant differences resulted between the solutions of the different programs. For this reason, a comparison of the different software packages was done to distinguish between two classes of baselines: typical and problematic baselines. Two criteria were used for the classification of the baselines. The first criterion was the type of the baseline solution, fixed or float. In the case of the *BERN* solutions, the percentage of resolved ambiguities was also reported. The second criterion for the classification of the baselines was the closure error. Instead of using loop closures, the closure error was computed based on the difference between the coordinates computed for each BM from each one of the two baselines available for that BM (from the two nearest HEPOS stations). This approach to computing the closure errors was considered to yield more realistic results as compared with loop closures for our dataset, for two main reasons. First, the two baselines used for each closure check were uncorrelated. If the baseline between the two HEPOS stations was also solved, each triangle would consist of three correlated vectors. Three receivers measuring in parallel (in this case the rover on the BM and the two closest HEPOS stations) are able to produce only two stochastically uncorrelated baselines

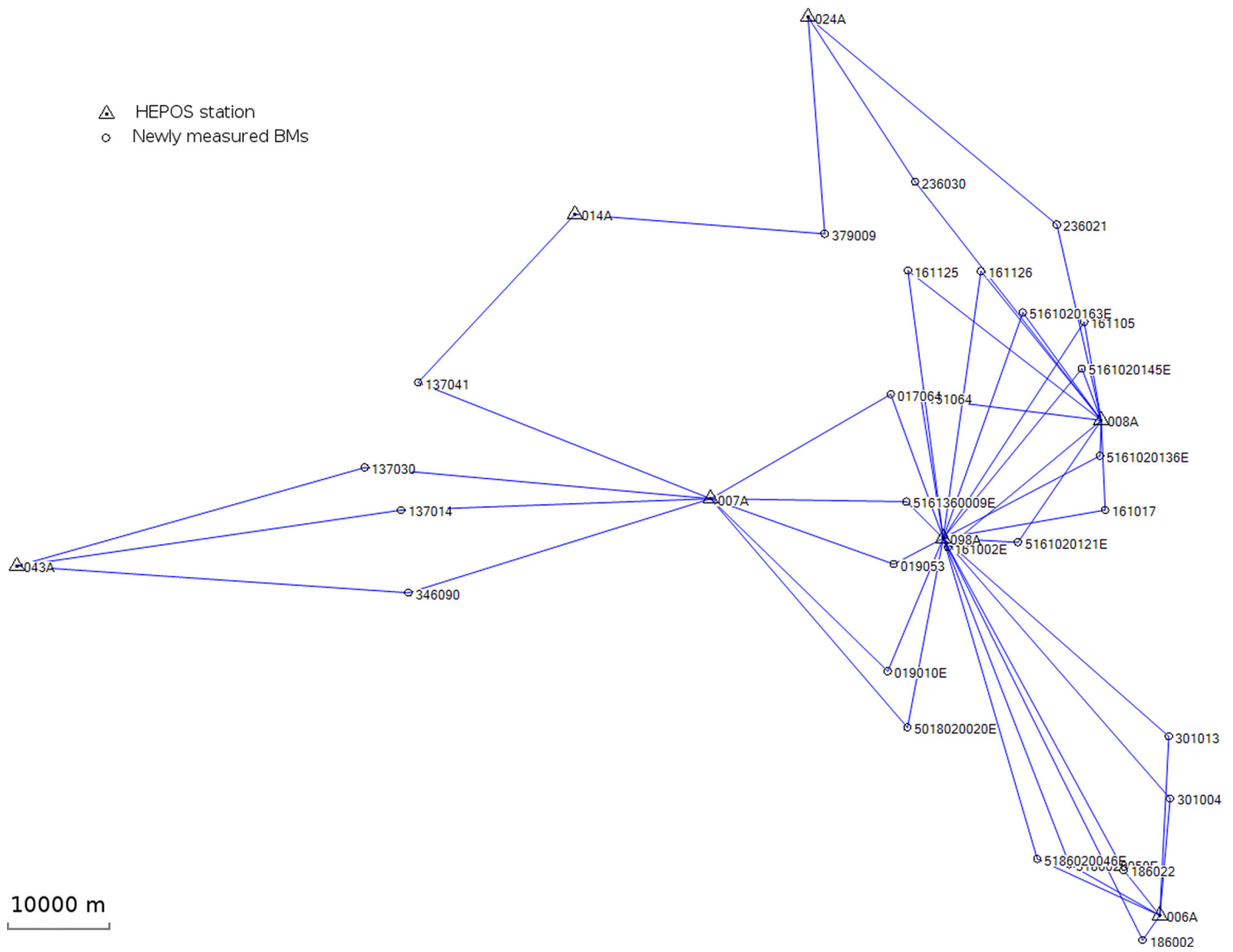


Fig. 4. The 56 GPS baselines measured in the Attica area

(Hofmann-Wellenhof et al. 2008). Second, the baseline between the HEPOS stations was in some cases twice as long as the baselines to the BMs, for example, 69 km between Stations 043A and 007A (Fig. 4). Baselines of such length cannot be precisely estimated from observations of 1 hour in duration. This would lead to increased loop closure errors. In the current study the horizontal closure error (dS) is

$$dS = \sqrt{(E_{RS_1} - E_{RS_2})^2 + (N_{RS_1} - N_{RS_2})^2} \quad (5)$$

where the indexes RS_1 and RS_2 denote the coordinates obtained from the baselines from the nearest and the next-nearest HEPOS reference station (RS), respectively. For the vertical closure, the absolute value of the difference between the ellipsoidal heights obtained from each pair of baselines was used, as follows:

$$|dh| = |h_{RS_1} - h_{RS_2}| \quad (6)$$

For the horizontal and vertical closure errors, thresholds of 3 and 6 cm, respectively (3-sigma values of the expected accuracy

mentioned in the GPS measurements section), were adopted. If dS or $|dh|$ was found to exceed these thresholds in at least two software packages, the baselines used to compute the closure error were designated as problematic. Of the baselines closures, 39% of those in Attica (11 of 28) and 23% of those in Thessaloniki (9 of 39) were found to exceed the thresholds. Of course, in the case of float solutions, the thresholds were exceeded by far greater amounts. For this reason all float solutions were excluded from the computation of the statistics. Thus, sets of baseline closures common for all software packages were obtained: 26 closures in Attica (17 typical and 9 problematic) and 37 closures in Thessaloniki (30 typical and 7 problematic). Tables 4 and 5 give the mean and maximum values of the horizontal and vertical closure errors for the typical and problematic baselines in Attica and Thessaloniki, respectively. The mean values are depicted graphically in Fig. 6 (Attica) and Fig. 7 (Thessaloniki). In addition, these figures include statistics computed over the entire sample of baselines for each area. The statistics over the entire sample are of interest from a practical point of view, as some problematic baselines are included in most of the measurement campaigns. A comparison of the results for the two areas shows that the baselines in Thessaloniki offered slightly lower accuracy, on the order of few millimeters to 1 cm, as compared with those of Attica. For

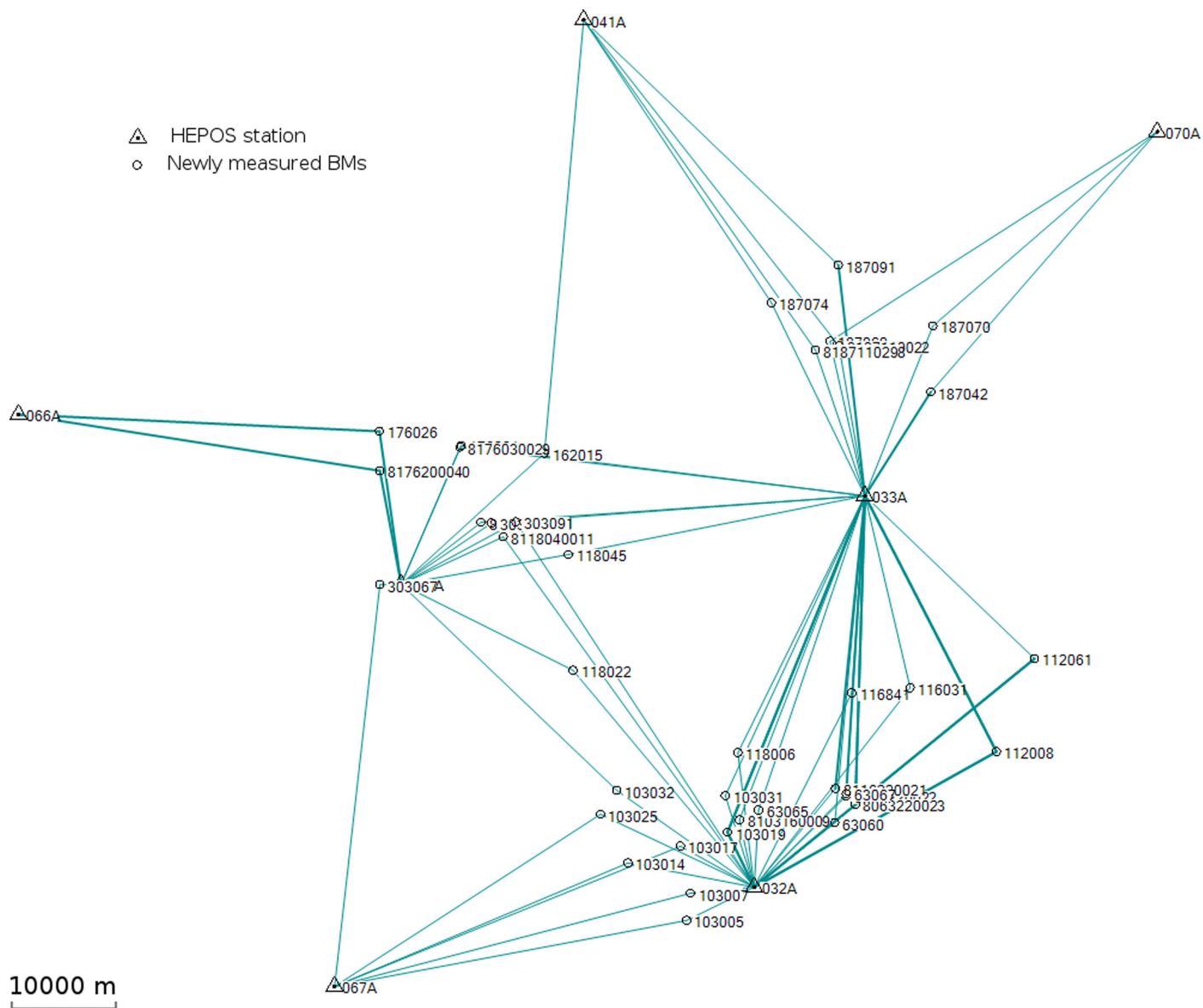


Fig. 5. The 78 GPS baselines measured in the Thessaloniki area

Table 1. Trigonometric and Leveling Benchmarks Used in the Project

Region	Trigonometric BMs		Leveling BMs	
	Previously measured	Newly measured	Previously measured	Newly measured
Attica	80	20	7	8
Thessaloniki	92	29	—	10

this reason, results were distinguished for the two areas. The lower performance in Thessaloniki can be mainly attributed to the fact that the measurements were conducted with receivers of older technology (Leica SR520) as compared with the receivers used in Attica (Topcon HiperPro).

To allow for a comparison of the closure errors of the different software programs, the ratio of the mean closure error of each program to the respective error of the best-performing software was computed. This comparison was done separately for each group of baselines (typical, problematic, and all), and for

Table 2. Software Packages Used for the GPS Data Processing

Software	Version	Release year	Manufacturer	Abbreviation in paper
<i>Bernese</i>	5.0	2007	Univ. of Bern	<i>BERN</i>
<i>Geomax Geo Office</i>	2.0	2009	Geomax	<i>GGO</i>
<i>GrafNet</i>	8.40	2012	NovAtel (XYZ Solutions)	<i>GN</i>
<i>Trimble Business Center</i>	1.12	2007	Trimble	<i>TBC</i>
<i>Topcon Tools</i>	7.5.1	2010	Topcon	<i>TT</i>

both the horizontal and vertical errors. Figs. 8 and 9 give the computed ratios for the baselines in Attica and Thessaloniki, respectively. The best-performing software can be easily recognized because its ratio equals 1. In each figure, six bars point at 1: for each group of baselines, one bar for the horizontal and one for the vertical error. In the case of Fig. 8, within each group of

Table 3. Baseline Solution Results

Initial solution	Final solution	Comments	Number of baselines per software				
			<i>BERN</i>	<i>GGO</i>	<i>GN</i>	<i>TBC</i>	<i>TT</i>
Float	Float	Solution not used	6 ^a	1	—	—	—
Float	Fixed	Fixed obtained after deactivating satellites	— ^a	3	—	6	7
Fixed flagged	Fixed	Solution improved by deactivating satellites	— ^a	10 ^b	3 ^c	19	19
Fixed	Fixed	Minor or no interventions	128	120	131	109	108

^aWith *BERN*, no attempts were made to improve the initial solutions.

^b*GGO* does not flag weak baselines; the averaging limit was used instead.

^cFor six flagged baselines it was not possible to obtain a nonflagged solution.

Table 4. Statistics of the Horizontal Closure Error (Values in Meters) for the 52 Baselines in Attica (34 Typical, 18 Problematic) and the 74 Baselines in Thessaloniki (60 Typical, 14 Problematic)

Software	Attica				Thessaloniki			
	Typical baselines		Problematic baselines		Typical baselines		Problematic baselines	
	Mean	Max.	Mean	Max.	Mean	Max.	Mean	Max.
<i>BERN</i>	0.028	0.060	0.075	0.120	0.054	0.152	0.108	0.205
<i>GGO</i>	0.012	0.031	0.016	0.045	0.037	0.117	0.053	0.125
<i>GN</i>	0.024	0.072	0.063	0.132	0.038	0.200	0.148	0.257
<i>TBC</i>	0.010	0.019	0.021	0.043	0.020	0.056	0.035	0.070
<i>TT</i>	0.012	0.027	0.034	0.104	0.020	0.050	0.061	0.140

Table 5. Statistics of the Vertical Closure Error (Values in Meters) for the 52 Baselines in Attica (34 Typical, 18 Problematic) and the 74 Baselines in Thessaloniki (60 Typical, 14 Problematic)

Software	Attica				Thessaloniki			
	Typical baselines		Problematic baselines		Typical baselines		Problematic baselines	
	Mean	Max.	Mean	Max.	Mean	Max.	Mean	Max.
<i>BERN</i>	0.057	0.184	0.101	0.204	0.062	0.169	0.149	0.385
<i>GGO</i>	0.040	0.074	0.038	0.074	0.033	0.115	0.045	0.112
<i>GN</i>	0.048	0.202	0.075	0.185	0.052	0.162	0.124	0.239
<i>TBC</i>	0.038	0.085	0.036	0.075	0.040	0.098	0.056	0.155
<i>TT</i>	0.041	0.094	0.053	0.110	0.041	0.122	0.063	0.146

baselines the lowest horizontal and vertical errors were obtained from the same software [*Trimble Business Center (TBC)* for the typical, *Geomax Geo Office (GGO)* for the problematic, and *GGO* for all baselines]. On the contrary, in the case of the more noisy observations in Thessaloniki (Fig. 9), the best performance in horizontal and vertical closures within each group of baselines was achieved by different software. As shown in Figs. 6–9 (and discussed in detail in the section presenting the discussion of GPS results) *GGO*, *TBC*, and *Topcon Tools (TT)* achieved about the same performance. For the final results, *TBC* was used. The final horizontal coordinates and heights of the BMs were computed by means of a least-squares network adjustment. The baseline vectors were adjusted, keeping all HEPOS stations fixed at their known coordinates. The estimated accuracies of the adjusted coordinates (mean values) were $\sigma_E = 0.007$ m, $\sigma_N = 0.009$ m, and $\sigma_h = 0.020$ m for the BMs in Attica, and $\sigma_E = 0.009$ m, $\sigma_N = 0.011$ m, and $\sigma_h = 0.023$ m for the BMs in Thessaloniki.

Discussion of GPS Results

Before discussing the results of the software packages used, it should be stressed that the purpose was not the assessment of the relative performance of the various software programs. Such comparisons require a much larger data set of baselines and the use of the latest versions of all programs, which was not the case in this study (see also Table 2 for the release year of each program). The goal was to demonstrate the importance of the processing software in the accuracy of the results, especially in the case of problematic baselines.

From an examination of the overall relative performance of the five programs (Figs. 6 and 7, *All baselines* columns), it is clear that the four commercial software packages yielded better results as compared with *BERN*. Of course, this conclusion does not reduce the value of this well-known program, which undoubtedly is among the best scientific GNSS processing software available worldwide. One should keep in mind that *BERN* mainly focuses on the processing of measurements of long duration (e.g., daily observations) collected at sites offering good observation conditions (e.g., reference stations) over long distances (baseline length of the order of several hundreds or thousands of kilometers). The detailed modeling of many error sources (ocean, atmospheric, and solid earth tidal displacements; Earth orientation variations; satellite phase center offsets and patterns; etc.) (Dach et al. 2007) is necessary for long baselines, but does not actually improve the solution of short baselines, because these errors cancel out when forming double-differences. In addition, the long duration of the observations is important for *BERN* to perform realistic estimations (e.g., for the tropospheric delay). On the other hand, one may expect that commercial software packages are designed to process not only data of good quality, but also problematic measurements collected under unfavorable field conditions.

Among the four commercial programs, *GrafNet* yielded more noisy results. *GrafNet (GN)* is part of NovAtel's GNSS postprocessing software package, which is well known for *GrafNav*, a kinematic baseline and precise point positioning (PPP) processor based on a Kalman filter. *GrafNav* and *GrafNet* use the same GNSS processing engine. This processing engine is proven to provide great results for kinematic measurements (Diep Dao et al. 2004; Bláha et al. 2011). Figs. 6 and 7 (*Typical baselines* and *Problematic baselines* columns) show that for static observations of good quality, *GN* yields somewhat worse results as compared with the other commercial software packages, but in the case of problematic baselines, the results were up to four times worse. This could be attributed to the processing engine, which is by design more suitable for kinematic measurements. Figs. 8 and 9 show that the performance of the three other programs is roughly on the same level. For example, *GGO* shows slightly better performance in the case of problematic baselines in Attica. On the other hand, one baseline in Attica could not

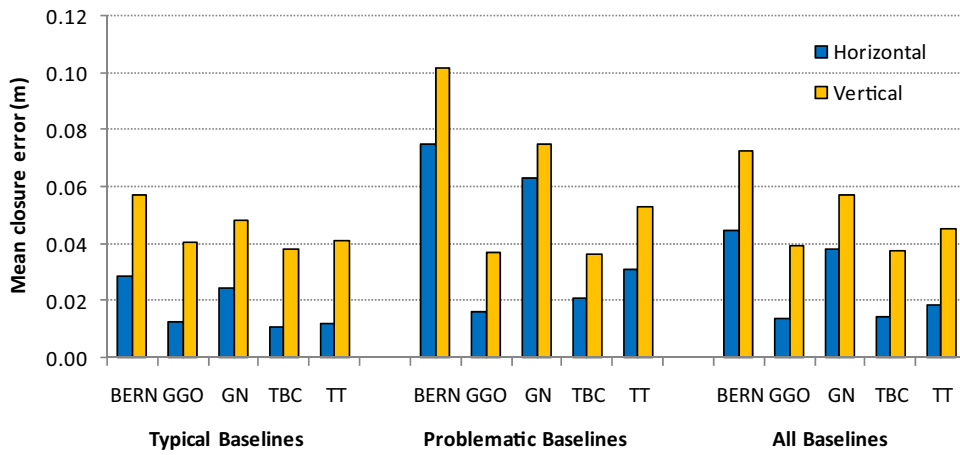


Fig. 6. Mean horizontal and vertical closure errors for the baselines in the Attica area

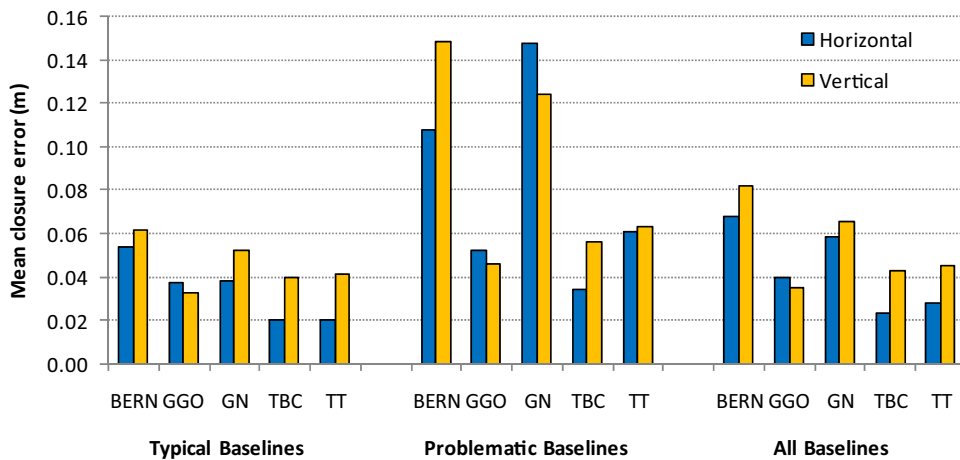


Fig. 7. Mean horizontal and vertical closure errors for the baselines in the Thessaloniki area

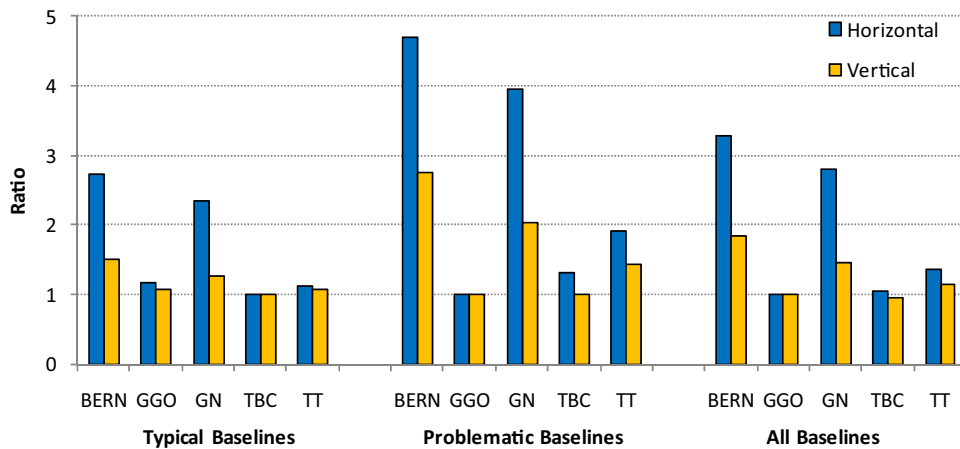


Fig. 8. Ratio of mean closure error of each software with regard to the best-performing software, computed separately for dS, ldhl, typical, problematic, and all baselines in Attica

be solved by *GGO*, a fact that is not reflected in the figure. In the case of problematic baselines in Thessaloniki, *TBC* performed significantly better than *GGO*. The data presented in the columns *All baselines* in Figs. 8 and 9 show that *GGO*, *TBC*, and *TT* provide comparable results. Considering jointly the results in both areas,

TBC shows the best performance. This superiority can be mainly attributed to the fact that *TBC* is the only program among *GGO*, *TBC*, and *TT* that gives a detailed baseline processing report that contains a graphical representation of the observation residuals. This functionality allows the detection and exclusion of noisy

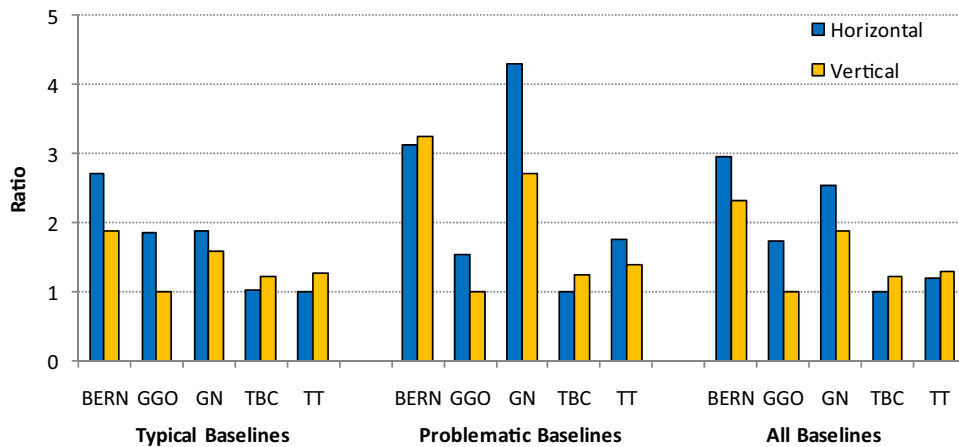


Fig. 9. Ratio of mean closure error of each software with regard to the best-performing software, computed separately for dS, ldhl, typical, problematic, and all baselines in Thessaloniki

observations, which considerably improves the solution. According to its manual, *TT* has the same capability, but it is available only if the Advanced Module for processing has been licensed (Topcon Positioning Systems Inc. 2009). Regarding *GGO*, one could expect that the graphical representation of residuals would be supported because this program is practically the same as *Leica Geo Office* (*LGO*); however, a comparison of the two software packages reveals that certain functionalities of *LGO* are not available in *GGO* (Leica Geosystems AG 2010).

An examination of the closure errors of typical and problematic baselines (Fig. 6) shows that although the horizontal errors were lower than the vertical errors, they increased up to almost three times in the case of problematic baselines (*BERN*, *GN*, *TT*). On the contrary, the increase of the vertical errors was limited to a factor of 1.8 (*BERN*). For the sake of clarity, it should be stressed that in the case of problematic baselines the vertical errors were still larger. However, the accuracy degradation caused by the problematic observations was higher for the horizontal component. This is a result of practical importance for professional surveyors, who often measure in difficult environments and are mainly interested in the horizontal accuracy.

Fig. 6 verifies the general rule that the vertical accuracy of GPS baselines is considerably lower than the horizontal accuracy. However, Fig. 7 shows some exceptions to this rule. More specifically, *GGO* provided smaller vertical errors for all group of baselines in Thessaloniki, and *GN* showed similar behavior in the case of problematic baselines. To some extent these results could be explained by the fact that the observations in Thessaloniki were characterized by increased noise, as discussed earlier. As explained in the previous paragraph, the relationship between horizontal and vertical precision differed in the case of problematic observations. However, even in the case of problematic observations, the vertical errors still remained generally higher. Thus, the different behavior of *GGO* and *GN* is believed to originate from the particular processing algorithms implemented in each software package. This investigation requires detailed comparison of the different GNSS processing engines, a task that is beyond the scope of this paper. In summarizing the discussion of GPS results, two conclusions of practical importance should be emphasized regarding the processing of problematic observations. First, it is of particular importance that the processing software outputs a detailed baseline processing report that includes the residuals of each observation, so that an effective observation editing is feasible. Second, the surveyor should be aware that in the case of problematic baselines the actual

accuracy of the results can be much lower than the reported baseline accuracy.

Comparisons with Global Geopotential Model EGM2008

The initial stage of the validation at GPS/leveling benchmarks was based on comparisons with external information. GPS/leveling provides the geometric connection between different height systems (geometric/ellipsoidal and orthometric height). According to Eq. (3), a geometric estimation of the geoid can be derived using ellipsoidal and orthometric height information. The determination of this geometric geoid is directly comparable to the physical one derived from a geopotential model of high accuracy and resolution. The resolution of the geopotential model is a function of the inherent resolution and accuracy of the data that were used in its development. The maximum achievable meaningful degree and order of its harmonic coefficients are dictated by these two factors, and its accuracy is based on the commission and omission errors estimated during the adjustment process (Hofmann-Wellenhof and Moritz 2005). It should be kept in mind, though, that a geometric geoid model in Greece is of limited, if any, theoretical rigor. This is because the formed $h - H$ differences do not realize the geoid, that is, a physical surface of constant gravity potential (W_0). Instead, they realize the difference between the two heights along the vertical lines, with any systematic distortions resulting from the different datum of h and H . The major problem of the established Greek vertical datum is its systematic distortion, mainly in the form of a bias with respect to a global vertical datum, which cannot be modeled properly because of the largely unknown accuracy of the BM orthometric heights. A thorough consideration of the accuracy of the network and comparisons over the mainland of Greece can be found in Kotsakis et al. (2010). The insufficient documentation on the adjustment procedure (constraints type and number) and the lack of the error covariance matrix estimation are the main obstacles to an internal evaluation based on error analysis.

The global geopotential model used in the comparisons was a state-of-the-art spherical harmonics expansion geoid model based on various data sources combined, EGM2008 (Pavlis et al. 2012). This model optimally incorporates surface gravity observations, satellite altimetry data, and newly available products from gravity dedicated satellite missions (GRACE). The spherical harmonic expansion of EGM2008 reaches a degree of 2,190 and an order of

2,159, resulting in a spatial resolution of 5 arc minutes. In the present study, EGM2008 contribution is utilized up to a degree and order of expansion of 2,159. According to recent studies, the maximum degree 2,190 showed only minor improvements in the Hellenic area (Tziavos et al. 2010). Fig. 10 presents the differences at the 103 benchmarks in the Attica region after the removal of 3 blunders resulting from instrument height reading errors (gross errors). A mean value of -0.362 m was calculated. This bias represents the W_0 offset expressed in length units of the Greek vertical datum with respect to EGM2008. It should be noted that the WGS84 version of EGM2008 was used, and the tide-free system for all height data was adopted to compute consistent height differences. The internal accuracy of the procedure can be expressed by the standard deviation of the differences computed as ± 0.083 m in the Attica region.

Approximately the same situation was presented in the test area of Thessaloniki. The differences between GPS/leveling and the GGM geoid heights are charted in Fig. 11. The statistics of the 127 point differences demonstrated a mean of -0.588 m and ± 0.158 m standard deviation. There were not any gross errors in the Thessaloniki data. The clarification of a bias difference

(approximately 0.23 m) between the Attica and Thessaloniki areas results is part of the researchers' future research plan related to the unification of the Greek local vertical datum (LVD). At first glance, the bias can be attributed to datum inconsistencies in the vertical datum. The origin of the Hellenic LVD is at the Piraeus tide gauge station. This means that for the BMs over Thessaloniki, leveling traverses have been used to transfer orthometric heights from Piraeus (in Athens) up to the area of Thessaloniki in northern Greece. It is normal that the longer the baseline length and the distance from the LVD origin, the larger the error in the leveling observations. Therefore it is expected that the leveling data over Thessaloniki will contain larger errors than those in Athens.

The standard deviation of the differences ± 0.158 m reveals an accuracy degradation from the results of Attica, which initially was attributed to the rougher terrain of Thessaloniki area. However, a deeper investigation showed that the largest differences corresponded mainly to points with low elevations. Thus, the main reason for the large differences in Thessaloniki is probably the significant subsidence observed in the Thessaloniki plain (Stiros 2001; Psimoulis et al. 2007) and in other areas east of the Thermaikos

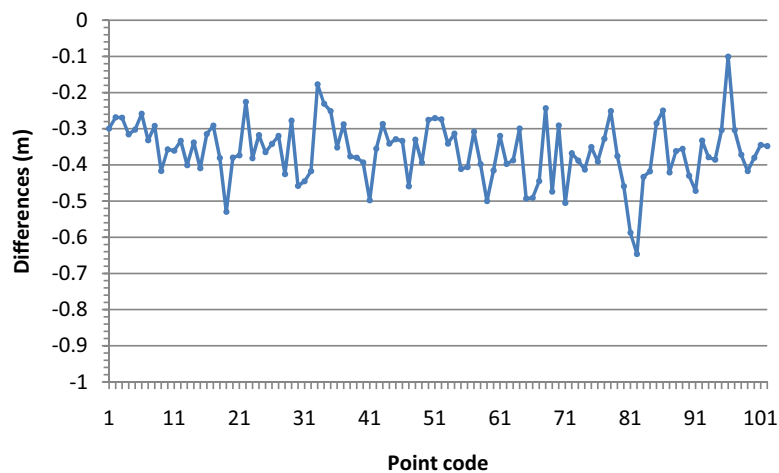


Fig. 10. Differences between GPS/leveling and geopotential model derived geoid at Attica test area after blunders removal

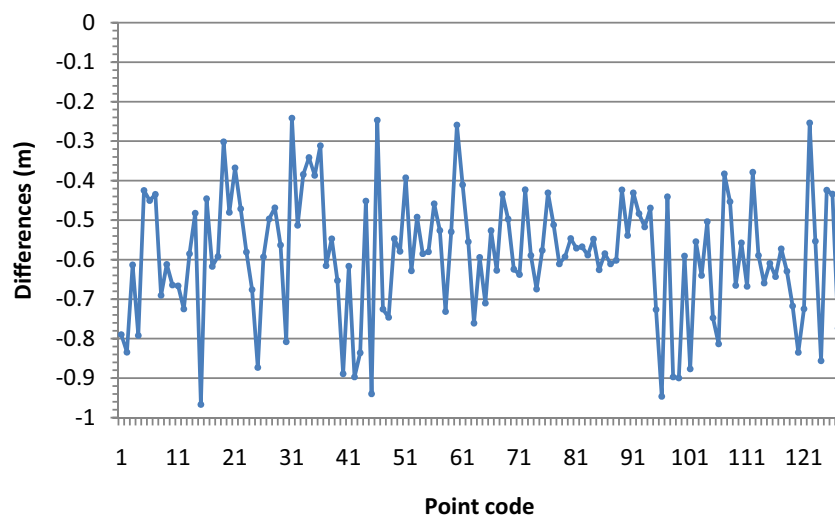


Fig. 11. Differences between GPS/leveling and geopotential model derived geoid at Thessaloniki test area

Gulf (Mouratidis and Costantini 2012). The 22.6-cm-lower mean difference of Thessaloniki supports the abovementioned interpretation. A detailed investigation of this degradation is the subject of ongoing work in the frame of the ELEVATION project.

Conclusions and Future Plans

The investigation of the internal and external accuracy of the Hellenic vertical network is the main goal of the ELEVATION project. Two test areas were chosen, and the initial assessment of the internal accuracy of the network was based on GPS measurements at benchmarks with known orthometric heights. Different GPS processing software packages were used and compared with one another to examine the accuracy of GPS data. The global geopotential model EGM2008 was utilized for the assessment of the external accuracy of the network. The chosen test areas in central and northern Greece contained 230 BMs (103 in Attica and 127 in Thessaloniki).

Based on the discussion of the GPS processing, some conclusions related to the performance of different software packages can be drawn. In the case of the baselines tested here (short baselines, a few tens of kilometers in length, observed for 1 hour) the commercial software packages perform better than the scientific one (*BERN*). The requirement of an increased amount of data for the proper modeling of a large number of parameters estimated by *BERN* is the main reason for its reduced performance. Under unfavorable measurement conditions (reduced satellite visibility and/or poor signal reception) there are noticeable differences in the performance of the various software packages. Differences exist among the commercial software packages originating from the solution strategy implemented in each of them, depending on the baseline length and the observation period. Some of these differences can be attributed to the processing engine, which is by design more suitable for kinematic measurements than for static ones.

The difficult measurement environment clearly affects the precision of the final result. This fact stands for all software packages used in the study. The precision degradation is found to be higher for the horizontal coordinates rather than for the heights, as the vertical component is always estimated with reduced accuracy because of the satellite geometry. This fact highlights the importance of the observation conditions during a GPS campaign. Careful planning of the measurements is of great importance for high-precision applications. Nevertheless, generally speaking, the horizontal closure errors are smaller than the vertical closures. However, certain software programs provide slightly better results in the vertical component. This remark requires further investigation.

The validation of the vertical datum in both test areas was performed using external information from the state-of-the-art global geopotential model EGM2008. The results in Attica show an agreement between “geometric” and “physical” geoid of 8.3 cm, in terms of the standard deviation of the differences. In Thessaloniki, this agreement is 15.8 cm. Different biases are observed in Attica and Thessaloniki. The -36.2 cm found in Attica can be attributed to the datum offset between the Greek datum and EGM2008; recall the -37 cm in Kotsakis et al. (2010). Internal distortions of the Greek vertical datum are responsible for the 22.6-cm relative offset/tilt between the average differences in Attica and Thessaloniki. This offset is the subject of ongoing work. To settle the question unambiguously, a high-accuracy leveling line connecting Attica and Thessaloniki is needed. Such a leveling line would provide the critical data that can help identify the origin of the relative bias between Attica and Thessaloniki. It should be noted that because of the absence of sufficient documentation and the repeated partial

adjustments performed since its creation, the actual accuracy of the Hellenic vertical datum is largely unknown. To examine the internal consistency of the Hellenic vertical datum would require investigation of exactly how the original vertical datum adjustment was done, which BMs may have been held fixed in the adjustment, how consistent or inconsistent these constraints are, and so forth. Such a careful re-examination of the original leveling observations and of the way that these were adjusted may help resolve several problems of the Hellenic vertical datum and possibly rectify at least some inconsistencies of its fundamental BMs. This is the plan for the researchers’ future work. The use of additional geopotential models, especially the recently available models from the GOCE satellite, will contribute to the efficient validation of the height datum with respect to its spectral characteristics.

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