IZZIVI PRI DOLOČANJU VIŠIN GORSKIH VRHOV, KOT SO NAVEDENE V KARTOGRAFSKIH VIRIH

CHALLENGES RELATED TO THE DETERMINATION OF ALTITUDES OF MOUNTAIN PEAKS PRESENTED ON CARTOGRAPHIC SOURCES

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IZVLEČEK

Namen raziskave je bil izmeriti in določiti nadmorske višine 12 gorskih vrhov s kombinacijo meritev GNSS in lidarskih podatkov. Izbrane gore se nahajajo na jugu Poljske. Meritve GNSS smo izvedli s statično ali kinematično metodo v realnem času (RTK) izmere GNSS. Izmero GNSS smo obravnavali kot primarni vir podatkov, saj lahko le z neposrednimi meritvami na terenu določimo najvišjo točko na vsakem vrhu. Dobljene rezultate smo primerjali z zgodovinskimi, internetnimi viri in uradnimi podatki o nadmorskih višinah. Poleg tega smo vsako nadmorsko višino določili še z uporabo lidarskih podatkov Poljske iz programa ISOK, ki jih je zagotovila nacionalna agencija. Že pri analizi internetnega gradiva in zemljevidov smo zaznali odstopanja v višinah vrhov velika do nekaj metrov. Razlike med izmerjenimi in internetnimi viri višin gorskih vrhov so med 27 cm in 504 cm. Z raziskavo smo pokazali, da bo treba ponovna višine gorskih vrhov Poljske izmeriti še enkrat, pri čemer bo treba posebno pozornost posvetiti določitvi najvišje točke gorskega vrha.

ABSTRACT

This study aimed to measure and validate altitudes from existing sources with direct GNSS measurements and airborne lidar data. For this purpose, 12 mountain peaks located in the south part of Polish territory were selected. Measurements were performed using a GNSS receiver using the Real-Time Kinematic (RTK) or static techniques enabling altitude measurements with accuracy of 10 cm. GNSS was treated as the primary data source, as the direct field measurements can determine the highest point on each peak. The obtained results were confronted with historical, internet sources, and official altitude data. Moreover, each altitude was determined using lidar data from an airborne lidar dataset of Poland from the ISOK program and provided by the national agency. Significant discrepancies in data were already detected during the analysis of internet materials and traditional maps, up to a few meters. The differences between measured and internet sources in altitude of mountain peak range from 27 cm to 504 cm. This study has shown the need to re-measure the altitudes of the mountain peaks and determine the highest point correctly.

KLJUČNE BESEDE

višina, gora, GNSS, lidar, triangulacijske meritve, zgodovinska karta, primerjava meritev

KEY WORDS

altitude, mountain, GNSS, LiDAR, triangulation measurements, historical map, measurement comparison

1 INTRODUCTION

The oldest geodetic points in the territory of Poland were established almost 200 years ago. The first triangulation network was set up in Congress Kingdom (1815–1832), especially industrial districts (Banasik and Bujakowski 2021). It consists of 3080 triangles measured in the period 1829–1835 (Olszewicz 1921). The triangulation network was constructed as a three- or four- arc network, consisting of main, intermediate, and subordinate triangles. All angles were measured in the main and intermediate triangles. At the same time, the coordinates of the lowermost points were determined by cutting forward from three positions or by cutting back to four points. The accuracy limit for determining the position of a new point was assumed to be ± 5 cm with respect to the determining points (Ksawery 1959). The triangulation network in the former Austrian part included several mountain peaks, for example, Turbacz in the Gorce range or Hoverla in the Czarnochory range. To this day, a concrete obelisks which have replaced the old triangular towers have been preserved.

When looking for information on the altitude of mountain peaks, one can use an internet search engine, internet maps, traditional maps, and other written sources. When comparing the most popular websites, it can be noticed that the desired information searched for is not comparable with each other. Usually, databases have old altitude information resulting from historical measurements obtained with low-accuracy methods that are not used anymore at present. The importance of accurately determining the height of peaks is communicated not only by professional journals in the field of surveying but also, for example, by tourism (Apollo et al. 2020; Ziegler et al. 2021; Prokop, Nazarko, and Ziemiański 2021). The mountain peaks were measured everywhere in Europe since at least 1800 as part of basic triangulation measurements to enable the primary network for other measurements (later called coordinate systems). Such measurements started with Struve Geodetic Arc in 1816–1855 (Lamparska and Danch 2021). However, there is a little information in the current literature on similar past measurements.

The historical trigonometrical measurements of mountain peaks that are still often referred to today are those of the most outstanding mountains, such as Mount Everest (Angus-Leppan 1982; de Graaff-Hunter 1955), Mount Blanc (de Beer 1956), Kilimanjaro (Saburi et al. 2000; TeamKILI2008 2009) or Rysy Mountain (Poland) (Makowska 2003). Later those peaks have been thoroughly remeasured using the Global Navigation Satellite System (GNSS) technique.

Moreover, terrestrial laser scanning or airborne laser scanning (lidar) has become more prevalent in recent years (Lenda et al. 2016; Prokop, Nazarko, and Ziemiański 2021; Tometzová et al. 2020)infrastructure of rail routes, or development of digital elevation models for a wide range of applications. These issues often require the use of a variety of scanning techniques (stationary, mobile. As we will later show, all peaks should have their altitudes verified due to either data obsolescence, use of different reference heights, or incorrect determination of the highest top of the peak. It is worth noting that often-erroneous information is contained in tourist maps, websites, and other sources used to plan tourist routes. In recent years, digital terrain models (DTM) have become more popular due to the post-processing of point clouds based on airborne lidar, but there is still a lack of such measurement. In 2019 a project was conducted (AGH 2019), where authors measured the highest peaks and additional peaks, which could also be among the highest peaks in 28 Polish mountains mesoregions. Finally, 40 peaks were measured using both GNSS and LiDAR techniques for each. Firstly, it turns out that seven out of 28 peaks are not the highest. Secondly, the height differences between GNSS vs. LiDAR reached up to 2.4 m. Thirdly differences between commonly known (catalogued) altitudes could reach up to 19 m because some points were incorrectly assumed to be on the top of the mountains, e.g., point marked at the top of the tourist/GSM towers. In this paper, unlike the one mentioned above, the entire mountain range was analysed rather than the individual mountain peaks in different ranges. This methodology was intended to verify, if less known or less frequently visited mountain peaks had altitudes determined with greater error than mountain peaks that are more known.

The study aims to thoroughly analyse the available information on the altitude of selected mountain peaks, but with different types of cover land (i.e., grass, trees, or rocks). We sequentially measured these peaks using GNSS technique and analysed the obtained results to assess the reliability and consistency among the different data sources. The procedure to get available information, analyse the data, select the measurement sites, and the GNSS techniques, measurement procedure, obtaining results and the analysis of such results is presented.

2 TEST AREA

Beskid Żywiecki is located in the south of Poland. It is the highest mountain group of the Polish Beskids and at the same time, the second-highest massif in the entire Western Carpathians (Solon et al. 2018). In this region, there are the peaks of Babia Góra and Pilska, the only ones in Western Beskids that rise above the forest line. This mountain range is made of sedimentary rocks known as flysch. Flysch is an alternating sequence of the grey colour of sandstones, and sometimes also conglomerates and clayey (Łoboz 2013). The selected 12 mountain peaks are located on the Polish-Slovak border in the Śląskie and Małopolskie voivodships (Figure 1, selected peaks – black dots).

Figure 1: Mountain peaks (black dots) location on the Polish-Slovak border (Map layer from (GUGiK 2022).

The mountain massif consists of 12 peaks located on the 31.3 km long route between mountains Babia Góra and Trzy Kopce. The altitudes of the selected peaks are between ~800 m and ~1730 m, as shown in the profile in Figure 2.

The selected peaks are characterised by different covers on the top of the mountain: Babia Góra (Diablak), Mała Babia Góra (Cyl), and Pięciu Kopców are covered by rocks. Jałowcowy Garb, Beskid Krzyżowski, Beskid Korbielowski (Westka) and Student (Zimna) have trees on the top, while Mędralowa, Munczolik have grass, Jaworzyna, Palenica and Trzy Kopce have trees as well as grass.

Figure 2: Profile of selected route of measurement (https://mapa-turystyczna.pl).

3 METHODOLOGY

In this paper, each peak was measured by direct (field) measurements using dual-frequency GNSS receiver Leica GS16. On the peaks where a fix (precise) solution is available, RTK mode was used (six peaks) for three independent measurements of 30 s. Final altitude is a mean from these three values. In the case of obstructed view due to sky conditions and GSM signals, 1 h static GNSS measurements were made (six peaks). After that, in a post-processing using Leica Geo Office 8.4 (LGO) software altitudes were determined. On the peaks where the highest point was covered by trees or was impossible to lay on it GNSS antenna, an eccentric point (with good sky visibility), was established. With the use of geometric levelling, altitude differences between the top of the peak and eccentric point were determined. When GNSS was placed on the geodetic mark (Figure 5b) altitude was also reduced by height of the geodetic mark, to enable comparison with other measurements. In an RTK mode, the authors used the ASG-EUPOS (http://www.asgeupos.pl). On the selected territory, the nearest station was ZYWI (Zywiec, blue dot), located 18 km to 26.7 km from the selected mountain peaks (Figure 3).

Figure 3: ASG-EUPOS reference stations (GUGiK 2022).

The levelling was used when the top of the peak was ambiguous (Figure 4). The highest point at the peak was then located using a levelling instrument and a level rod in the grass.

Figure 4: An ambiguous identifiable highest point in Mędralowa.

The levelling instrument was set between the potentially highest points, and the measurement was performed in the same way. Then, after analysing the obtained differences, the highest point was selected, and a static or RTK measurement was performed.

The measurement trip took place on June 23, 2020; measurements were performed by two independent field teams using three Leica GS16 receivers. The first stage was to reach the top of each mountain, select the highest point, and proceed with the RTK measurement, if the sky visibility was sufficient. If the fix solution was unavailable, static measurement was performed, or the eccentric point was determined. Figure 5 shows the weather conditions during RTK measurement at the Babia Góra (left) and on the Jalowcowy Garb (right). The time difference between measurements at those two points is only 2 hours.

Figure 5: GNSS measurements at the Babia Góra (a) and the Jalowcowy Garb (b).

Due to the location of the peaks on the Polish-Slovak border and dense forest and grass on the majority of the peaks, there were problems performing RTK corrections through the GSM service. Therefore, in half of the peaks, it was decided to proceed with a GNSS static measurement (Table 2). The static observations were post-processed by LGO using the final IGS orbit in a combination of ionosphere-free phase observations based on a GPS survey. Then, the average heights were determined based on the height anomaly from the PL-geoid-2011 quasi-geoid model on the WGS-84 ellipsoid (Kadaj 2012). In the case of RTK measurements, average heights were established directly from the model, as mentioned earlier. The published results were provided according to the national height reference system Kroonstad ‚86, PL-KRON86-NH (Rada Ministrów 2012). Moreover, based on the DTM provided by the Polish government geodetic association called GUGiK (GUGiK 2022) and peak coordinates from GNSS measurement for each peak, altitudes from 1 × 1 m lidar grid were determined based on the airborne laser scanning ISOK project (Wężyk 2015).

The ISOK program data (aerial laser scanning (lidar) of Poland was performed between 2011 and 2014) was intended to be used for early warning and monitoring of natural disasters, mainly floods. This data set consists of a lidar point cloud, a DTM, and a digital surface model (DSM) in raster format. The lidar point cloud was acquired using an airborne platform consisting of an LMS-Q680i RIEGL laser scanner, GNSS antenna, and a camera installed on a plane flying about 950 meters. The lidar point clouds were created by registering flat rooftop surfaces. The surfaces were defined by four corners that were measured using tachymetry. Tachymetric measurements were taken from two sites determined using real-time kinematic GPS (RTK-GPS). The RGB colors were added to the registered point cloud from an orthomosaic of pictures taken during separate flights. The scanning parameters were as follows: the size of the laser beam on the surface was 0.29 m; the density of points varied, being denser in the direction parallel to the flight route at 0.45 m and less dense in the perpendicular direction of 0.47 m; and there was a 35 % the overlap between parallel scanning. The observed density varies within a typical inter-point spacing of 0.20 m to 0.45 m. During the 2011–2014 period, the research region was scanned with a resolution greater or equal to 12 pts/m^2 for cities with a population greater than 50 000 people and less than 4 pts/m^2 for the rest of the Poland territory. Thus, data presented in this paper have a ≥4 pts/m^2 resolution, which leads to <0.5 m distance between each point. Data were collected during leaf-off season (middle of October-middle to April) to avoid difficulties in penetration through the vegetation by laser beam.

4 RESULTS

After selecting the mountain peaks, sources containing the peaks' altitudes, such as websites, mountain guides, and maps, were identified and initially analysed (Table 1). Source [1] (column 3) from Table 1 (Wikipedia) in Poland is treated as the official one, because it is constantly updated and monitored by the public and some moderators. Other internet sources, [2]-[5] ([2] https://mapa-turystyczna.pl, [3] http://igrek.amzp.pl, [4] https://zbgis.skgeodesy.sk, [5] https://mapy.hiking.sk), were developed by public or private companies or are sites created by private persons; thus, government or academic community has no direct influence on these sites and cannot be considered official. While all of the paper sources ([6]-[18], columns 8-20) are archival because they were up-to-date on the date of publication, and often the altitudes in these sources are directly copied from previous editions (compare sources [15] (Compass 2003) and [16] (Compass 2011) – no differences, one extra peak was added). It can be seen in the Table 1 that the year of source release has a significant impact on the completeness of the data for this route. The altitude differences of the same peaks from two different sources are within 10 m (e.g., Beskid Korbielowski). In most cases, the peak heights are usually rounded to the nearest 1 m, except for the Third Military Survey map where they are rounded to nearest 1 dm (Bargański et al. 2013). Even though there is no need to round the numbers in a mountaineering books, they are in most classes still rounded to meter as they are mainly copied from previous map sources.

One of the most popular sources in Poland is the Tourist map – TM, (polish *mapa turystyczna*, (TM 2021)), a website that allows route planning based on OSM (openstreetmap.org). Still, a commercial company maintains this web page, being ad-supported. Altitudes in the TM webpage are mainly rounded to 1 m.

Table 1: Comparison of the altitude of the examined peaks from various sources.

1	2	3					4	5	6	7	8	9	10	11	12	13	14	15	16
		Internet sources					1884	1934	1951	1957	1978	1986	1987	1993	1999	2003	2011	2013	2015
No	No of source / Peak	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]	[14]	[15]	[16]	[17]	[18]
1	Babia Góra	1725	1723	1724	1725	1725	1724	1724	1725	1724,8	1725	1725			1725	1724,6	1724,6	1725	1725
2	Mała Babia Góra (Cyl)	1517	1515	1517	1515	1517	1517	1517	1517	1514,6	1517	1517			1515	1515	1515	1517	1517
3	Jałowcowy Garb	1017	1017													1017	1017	1017	1017
4	Mędralowa	1169	1169	1169	1168	1169	1169	1169	1170	1168,1	1170	1170			1169	1169	1169	1169	1169
5	Jaworzyna	1047	1047	1050	1047	1047	1050	1050	1050	1046,5	1050	1050	1046	1046	1047	1047	1047	1047	1047
6	Beskid Krzyżowski	923	923		923	923			923	923,4			923	923	923	923	923	923	923
7	Beskid Korbielowski (Westka)	955	954		954	954	946	946	948	954,5			954	954	954	955	955	954	955
8	Student (Zimna)	935	935	935			935	935	935				935	935		935	935	935	935
9	Góra Pięciu Kopców	1534	1534														1542		1542
10	Munczolik	1356	1356				1356	1356		1350,5			1356	1356		1356	1356	1356	1356
11	Palenica	1343	1338	1343		1339	1343	1343		1338,8			1343	1343	1343	1343	1343	1338	1343
12	Trzy Kopce	1216	1216	1216			1216	1216		1211,4			1216	1216		1216	1216	1216	1216
Number of peaks in a source		12	12	7	6	7	9	9	7	9	4	4	7	7	7	11	12	11	12

[1] https://pl.wikipedia.org [2] https://mapa-turystyczna.pl [3] http://igrek.amzp.pl [4] https://zbgis.skgeodesy.sk [5] https://mapy.hiking.sk [6] III. MS: the Third Military Survey (1875-1884) (Bargański et al. 2013) [7] III. MS 1920-1934_reamb.: the Third Military Survey – updated in 1920-1934 (Bargański et al. 2013) [8] (Pagaczewski 1951) [9] TM25 1952-1957: Military topographic maps 1:25 000 /1952-1957) (Bargański et al. 2013) [10] (Wojterski 1978) [11] (Miodowicz 1986) [12] (PPWK 1987) [13] (PPWK 1993) [14] (Warzecha-Tober, Stańczyk, and Figiel 1997) [15] (Compass 2003) [16] (Compass 2011) [17] https://merlin.pl/beskid-slaski-i-zywiecki-mapa-turystyczna-skala-150-000-expressmap/3066763 [18] https://goryiludzie.pl/mapy-online/beskid-zywiecki

The results obtained during the measurements are summarized in Table 2. They were compared with the most popular and accessible sources, TM and DTM. The comparison was made by calculating the difference in altitudes between GNSS measurement and the TM (which is the main result of the paper) and DTM altitudes (this is just quality control of lidar products by GNSS measurements).

Comparing the obtained results with the altitudes on the TM, the smallest difference in altitude occurs at the top of Beskid Korbielowski and is equal to 0.27 m, and the largest was at the Trzy Kopce, which is 5.04 m. The discrepancy is very large – the measurement on the Trzy Kopce was carried out using a static method and therefore, can be regarded as very accurate. Comparing the measurement results with the DTM with a 1 m × 1 m grid shows that the highest compliance is found at the two peaks, Palenica and Trzy Kopce, and is 0.06 m. The most significant discrepancy, equal to 0.60 m, is observed at the top of the Babia Góra. The remaining results are consistent within 0.17 m. Considering that the altitudes of the peaks on the maps are rounded to 1 m, then when comparing the TM and GNSS measurements, 7 out of 12 peaks (58%) are in range of 1m difference. No altitude on the TM is reported with a measurement accuracy of 10 cm (Figure 6). Moreover, half of the peaks (six peaks) are in the range of rounding error of 1 m (dashed blue lines), and only three values are more than ±2 m, which is still very good, considering the classic statistical behaviour of errors when checking the accuracy with three times better measuring method. Only Gora Pieciu Kopcow and Trzy Kopce (error > 4 m) might be treated as obvious measurement errors or erroneously adopted top of the peak in a previous measurement.

Table 2: Comparison of the altitude from GNSS measurement vs TM and DTM.

1	2	3	4	5	6	7	8	9	10
Nr	Peak	GNSS measurement method	Altitude [m]				Different in altitude [m]		
			GNSS	TM	DTM	Airborne data	GNSS-TM	GNSS-DTM	GNSS-Airborne data
1	Babia Góra	RTK	1723.60	1723.0	1723.0	1723.2	0.60	0.60	0.40
2	Mała Babia Góra (Cyl)	Static	1516.98	1515.0	1516.9	1517	1.98	0.08	-0.02
3	Jałowcowy Garb	Static	1016.54	1017.0	1016.4	1016.5	−0.46	0.14	0.04
4	Mędralowa	Static	1168.50	1169.0	1168.4	1168.4	−0.50	0.10	0.10
5	Jaworzyna	Static	1047.38	1047.0	1047.3	1047.4	0.38	0.08	-0.02
6	Beskid Krzyżowski	RTK	923.40	923.0	923.5	923.5	0.40	−0.10	-0.10
7	Beskid Korbielowski	RTK	954.27	954.0	954.1	954.2	0.27	0.17	0.07
8	Student (Zimna)	RTK	935.92	935.0	935.8	935.9	0.92	0.12	0.02
9	Góra Pięciu Kopców	Static	1536.82	1534.0	1536.9	1536.9	2.82	−0.08	-0.08
10	Munczolik	RTK	1351.43	1356.0	1351.5	1351.5	−4.57	−0.07	-0.07
11	Palenica	RTK	1339.46	1338.0	1339.4	1339.4	1.46	0.06	0.06
12	Trzy Kopce	Static	1210.96	1216.0	1210.9	1210.9	−5.04	0.06	0.06

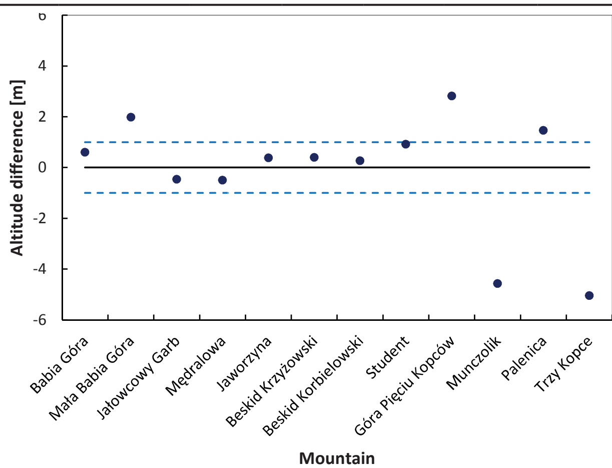

Figure 6: Altitude differences GNSS measurements and altitudes from TM.

Comparing the DTM data with the GNSS measurement, it can be noticed that the differences on 8 out of 12 peaks (67%) do not exceed 10 cm (Table 2, column 9), while all differences are within 1 m. With this we just made a quality control of lidar DTM data by GNSS measurements. Such a result is most satisfactory, and the differences should be explained by the small resolution of the model (1 m × 1 m), not its accuracy. The difference between the GNSS measurement and the DTM at Babia Góra is 0.60 m, which is different from the others, mainly due to the fact that its highest point was measured with the GNSS on the top of rock (Figure 5a), and not on the ground as with LIDAR. An interesting phenomenon is a fact that on five peaks: Mała Babia Góra (Cyl), Góra Pięciu Kopców, Munczolik, Palenica and Trzy Kopce, the differences GNSS-TM are the highest and in a range between 1.46–5.04 m, and at the same time at those peaks the differences between GNSS-DTM are the smallest, ranging from 0.06–0.08 m. This shows the need to change the altitudes of these peaks in the existing sources, as they do not contain reliable or up-to-date data. Table 2 column 10 shows the differences between GNSS measurement and the lidar data set from ISOK program. As shown those values are even smaller than GNSS-DTM, and only two values are greater than 10 cm. Comparing results from the DTM and lidar data, the results from the lidar data are much more similar to the GNSS measurements, most of them within 10 cm.

5 DISCUSSION

This paper presents the results of GNSS measurements of some selected peaks in the Beskid Żywiecki mountains. All measured altitudes are shown in a standard heights system, determined based on the height anomaly from the PL-geoid-2011 quasi-geoid model on the WGS-84 ellipsoid. The most comparable paper sources with TM are: [18] (https://goryiludzie.pl/mapy-online/beskid-zywiecki) with 11 mountain peaks having the same altitude among 12 checked mountain peaks (92% compatibility), [15] (Compass 2003) with 9 among 11 (82%) and [17] (https://merlin.pl/beskid-slaski-i-zywiecki-mapa-turystyczna-skala-150-000-expressmap/3066763) with 9 among 11 (82%). The most comparable internet sources with TM are: [3] (http://igrek.amzp.pl) and [5] (https://mapy.hiking.sk) with 5 among 7 (71% compatibility). After analysing the results, significant discrepancies (up to several meters) were noticed between the most popular sources (TM and some papers) and GNSS results. The main factor influencing this is the difference between the measuring equipment used in the past and today. There may also be differences resulting from the relationship between different height reference systems. The minor differences can be observed when comparing the GNSS and lidar data because they were made in a similar period.

Some difficulties with the availability of RTK fix solutions were encountered during the field measurement. In this case, a static measurement were conducted. Another problem are sky obstacles where the eccentric points was created and levelled (e.g., on Jaworzyna). The next issue is how to establish which is the highest point on the top of mountain peaks (e.g., on Jaworzyna and Mędralowa), there we also performed geometric levelling.

Due to such circumstances, the updating of the altitudes of the mountain peaks in Poland should be made by using DTM or lidar data. In case of significant differences, field verification by GNSS measurement should be performed. The last but crucial conclusion from this work is that the altitude data of mountain peaks from Poland available on the internet, tourist maps, and different paper sources are already out-dated.

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