

Vertical Gravimetric Calibration Baseline in the Tatra Mountains of Poland

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Abstract. This article describes the establishment of an alpine gravimetric calibration baseline in Poland's Tatra Mountains and the development of a methodology for performing static gravimeter calibration on that baseline. This baseline was established in response to the recent rise in geodynamic research in mountainous areas and the related need to calibrate the gravimetric scale used in such gravimeter research to a high degree of accuracy. The fact that the environmental conditions of such an alpine gravimetric calibration baseline differ considerably from those observed in flat terrains made it necessary to study the impact which rapid changes in atmospheric pressure and environmental temperature may exert on the performance of gravimeters used in such survey. It was also important to study how the method by which the instruments were transported (by automobile, cable car, or on foot) affected their performance. The project led to the establishment of an alpine gravimetric calibration baseline and yielded a set of recommendations for how to proceed with scaling the gravimeters at such a baseline.

Keywords: gravimetry, gravimetric metrology, vertical gravimetric calibration baseline

Received: 26 August 2009 /Accepted: 16 November 2009

1. Introduction

All gravimetric survey performed for the purposes of geodesy and geophysical prospecting, and especially works related to metrological problems bearing upon both fields, requires a knowledge of the value of gravity g , expressed in a uniform system comprising the necessary elements of a gravimetric reference level and the unit of gravity (Boedecker, 1988, 1989, 1991, 1998).

To verify the gravimetric reference level, periodic comparisons of absolute gravimeters are organized by the International Bureau of Weights and Measures in Sèvres, taking place predominately every four years. Similar comparisons are performed by the European

Centre for Geodynamics and Seismology in Walferdange, Luxembourg. These comparisons indicate that state-of-the-art absolute gravimeters now enable g to be determined with an error not exceeding 4 μGal (Kryński et al., 2003; Francis and van Dam, 2006; Vitushkin et al., 2007).

The adopted international gravimetric reference level, which constitutes an international standard, is transferred to the territory of individual countries through the establishment of national-level gravimetric control networks.

Poland's Gravimetric Control Network was set up by the initiative of the Institute of Geodesy and Cartography, Warsaw, in 1994-1997 and adjusted in 1997 (POGK97). After the results of this adjustment were analysed, the structure of the control network was improved by

establishing more than a dozen new points and taking supplementary measurements. The control network was adjusted for a second time in 1999, followed by a third time in 2004 after new absolute gravity points were added. This network has thus

been a subject to continual efforts to improve and modernize it. Figure 1 presents a sketch of the current status of the Polish Gravimetric Control Network.

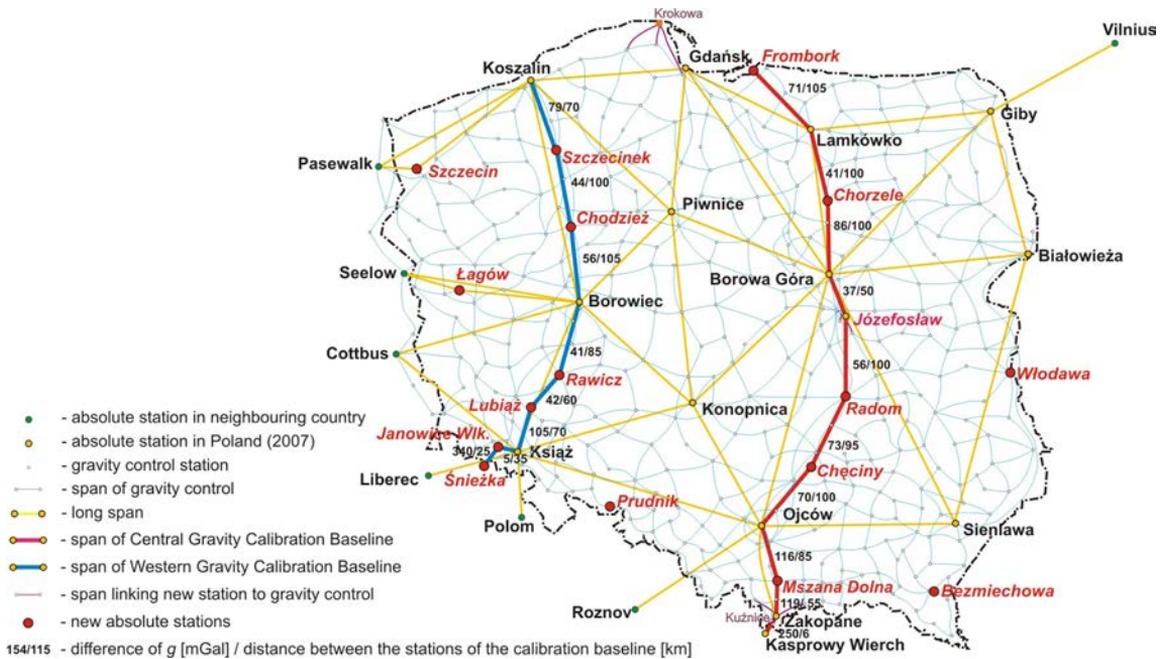


Fig. 1. Polish Gravimetric Control Network in 2009

The second element of the gravimetric standard is the unit of gravity. This term takes on special significance when the value of g is determined by means of relative surveying using static gravimeters, i.e. measurements which determine the difference in g between two points. If the value of g is known (determined) at one of those points, measuring this difference enables g to be determined at the other point.

Briefly put, the relative static gravimeters currently in use operate by measuring the change in the position of a test mass which serves as a gravity sensor, reflecting the change in the value of g once the instrument is moved from one measuring point to another (Barlik and Pachuta, 2007).

This change is measured, in linear or angular terms, as a certain number of intervals on the gravimeter's reading scale, which must then be expressed in gravity units. This is performed by means of special calibration tables provided for

each instrument by its manufacturer. Using these tables, gravimeter readings expressed in intervals on the instrument's scale are transformed into units of gravity, enabling the gravity difference Δg_{cal} to be determined. However, because the properties of the material from which the measuring elements are constructed changes over time, the relationship expressed in the calibration tables must be corrected to account for such changes. This correction is performed periodically (1-2 times annually) according to a special surveying procedure, at a sequence of absolute gravimetric points situated longitudinally, called the gravimetric calibration baseline. At the same time, this procedure enables gravity units to be ascribed to gravimetric data according with the gravimetric standard in the given country, and for that standard to be kept updated.

The scale change factor k with respect to the scale of the calibration tables is given by the formula:

$$k = \frac{\Delta g_{abs}}{\Delta g_{cal}}$$

where Δg_{abs} is the standard difference in g between the two points of the calibration baseline, while Δg_{cal} is the difference in surveyed g scaled using the calibration tables.

A gravimetric calibration baseline is a crucial element of the gravimetric control network, which currently consists mainly of points where gravity has been determined using absolute measurements. It enables the gravimetric unit to be transferred to the entire control network, and thus to all the gravimetric points tied to that network. This means that such a calibration baseline should cover the whole territory of the country in which it is used.

At present, the use of ballistic gravimeters has already become widespread. Theoretically speaking every two points situated more or less longitudinally with respect to one another, at which absolute g measurements have been performed using ballistic gravimeters verified with respect to the standard, constitute a standard for determining the gravimetric unit. However, the gravimetric calibration baseline concept has been retained in use as it was before, mainly because the baseline points, requiring special care and verification of the standard, cannot be too numerous for practical reasons. It would not be possible to properly verify the standard at all the absolute gravity points. It is significantly easier to perform regular verification at chosen absolute gravity points, delineating the spans of the gravimetric calibration baseline, than to perform verification for all the points in the zero-order network. Moreover, points may be selected for inclusion in the baseline while taking account of the need to achieve a large difference in g between the points, essential for gaining a high accuracy of the calibration factor for the chosen gravimeters.

The gravimetric calibration baseline must be divided into segments essentially not exceeding 100 km. This makes it possible to survey the difference in g values across a span four times

within a single day, thus increasing the accuracy of the calibration.

2. Justification for the need for a vertical gravimetric calibration baseline in Poland

Mountainous terrains have long been of interest to geologists, geophysicists, and also geodesists, especially those dealing with problems of geodynamics. For years, geodetic research has been carried out in mountainous areas using various methods, prominently including geodetic and gravimetric methods. This is due to the fact that the gravimetric method can be used to observe vertical movements at an essentially stabilized survey point, occurring between one measurement epoch and the next. This is an independent method that enables the results of levelling measurements to be confirmed or verified with great accuracy. We may note here that a change in the value g at a gravimetric point of 3 μGal corresponds to a change in height of about 1 cm. Moreover, gravimetric methods can reveal changes in density distribution within a rock body, for instance internally washed out by water, long before such changes become evidenced at the surface in terms of deformation.

One of necessary conditions for obtaining valuable gravimetric measurement results in geodynamic studies of mountainous regions is that determinations of g be performed with great accuracy. The special nature of such measurements, in particular the problems of transportation and the need to take a large number of observations, makes it necessary to use the largest possible number of gravimeters for geodynamic research. That is frequently achieved through joint international research projects in which teams that each possess several gravimeters pool together their efforts. The results obtained using these instruments must be characterized by an identical gravimetric unit. This can be achieved by calibrating all the gravimeters on the same calibration baseline. From the economic and organizational standpoint, the appropriate solution is to set up the calibration baseline in the region that is to be surveyed, i.e. in the mountains. An additional benefit of such a solution is the

ability to obtain a large g differences over a small distance, which enables the gravimeter scale coefficients to be determined with great accuracy. It also allows the gravimeter calibration process to be carried out very quickly, and if necessary to be repeated without excessive time loss.

In the 1950s, the Potsdam Geodetic Institute set up an alpine baseline between the points of Garmisch and Zugspitze with Δg of 530 mGal (Weiken, 1950). An alpine calibration baseline was also set up in the former Czechoslovakia at Jested (Wittinger, 1954). An alpine calibration baseline also exists in the Swiss Alps (Klinge and Khale, 1981; Arnet and Klinge, 1997), set up in 1980, with a range of 604.7 mGal. Gravity measurements were taken at the initial point (Interlaken, 567 meters above sea level) and the final point (Jungfraujoch, 3434 m.a.s.l.) of the baseline using the absolute method of gravity survey. Intermediate points were also established between those points, with Δg differences between them measured using LaCoste&Romberg (LCR) gravimeters.

The idea of establishing an alpine calibration baseline in Poland's Tatra Mountains arose in the mid-1950s at the Institute of Geodesy and Cartography (IGiK), Warsaw. Three measurements stations to be set up at indoor facilities were established. They form the two spans of this baseline. The first station was situated in the basement of the Tytus Chałubinski Museum of the Tatra Mountains in Zakopane, the second one in the basement of the sanatorium facility in Kuznice, and the third one in the lowest storey of the Kasprowy Wierch High-Altitude Meteorological Observatory, on the concrete foundation built directly upon the rock.

Following the project plans laid out by Bokun, the Head of the Geodesy Department of the Institute of Geodesy and Cartography (Bokun, 1957), measurements of Δg on the spans of this baseline were carried out by the team of the Faculty of Geodesy of the Warsaw University of Technology (Ząbek and Dobaczewska, 1957) within the framework of its collaboration with the IGiK. Taking into account the accuracy of the pendulum measurements performed on the spans of this baseline, Zakopane-Kuznice and Kuznice-Kasprowy Wierch, which was then determined as

± 0.3 mGal, the results then obtained are currently only of historic value.

However, the very idea of an alpine baseline remained attractive enough to be pursued by the Institute of Geodesy and Cartography, Warsaw, in 1999-2004, with the full acceptance and support of Poland's Head Office for Geodesy and Cartography.

3. Description of the Tatra Mountains Vertical Gravimetric Calibration Baseline

Poland's two gravimetric calibration baselines (Western and Central) established in 1994-1999 as part of work on the new Gravimetric Control Network, did not encompass the entire range of g variability on Polish territory. Regions of the country to the south of the Książ – Ojców – Sieniawa line remained outside the range covered by the calibration baselines. In response to this situation, an absolute gravity measurement station was set up in Zakopane, as a missing point on the Central Gravimetric Calibration Baseline. At the same time an identical station was established at on the Kasprowy Wierch peak, with the Zakopane-Kasprowy Wierch span constituting a Polish vertical gravimetric calibration baseline. The idea of extending the baseline to Kasprowy Wierch was all the more justified in that the mountain regions, especially the Tatras, have for years attracted interest from specialists dealing with modern geodynamic phenomena (e.g. Makowska, 2003).

Efforts were made to situate the two stations in precisely same locations where the pendulum measurements had been taken years before. That proved to be possible only at the point located at the Observatory of the Institute of Meteorology and Water Management on Kasprowy Wierch itself. In Zakopane, on the other hand, a new location for the planned absolute measurements was chosen at the Hydrological-Meteorological Station. A location was proposed in a basement room, which was built as a nuclear shelter during the Cold War times and has walls and foundation made of a thick layer of concrete (Sas et al., 2005).

For each of the points of absolute gravity measurements, two excentric points were chosen. For the absolute point in Zakopane, which was

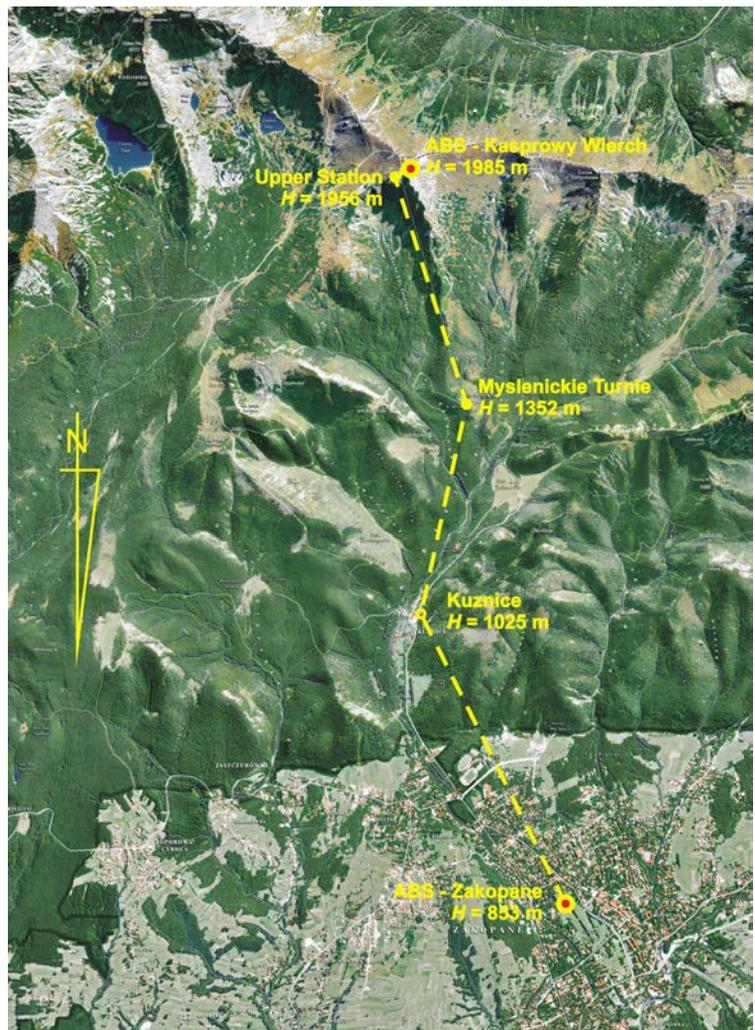
given the symbol A-ZAKO, parts of the former calibration baseline from 1968 were chosen. Those points were given the symbols ZAKO-Ex1 and ZAKO-Ex2, respectively. Both of these excentric stations are stabilized with concrete blocks measuring $75 \times 75 \times 100$ cm with a metal bold, included in the Polish Gravity Control Network as points numbered 354 and 355.

On Kasprowy Wierch, one of the excentric points was situated in the hall of the High-Altitude Meteorological Observation, the other on the stairway landing of the main entrance to the Observatory. These points were given the symbols KASP-Ex1 and KASP-Ex2, respectively. They were stabilized with metal bolts bearing 18 mm spherical heads, mounted into the concrete foundation.

Relative measurements were taken at the absolute and excentric gravity points. This involved linking each absolute gravity point to its respective excentric points in a three-span closed traverse. This was aimed at determining the dependency between the gravity values at the absolute point and at its excentric points. Vertical gradients of gravity were also determined at the absolute and excentric gravity points.

The Tatra Mountains Vertical Gravimetric Calibration Baseline was divided into spans based on intermediate points. Point B1 in Kuznice (the lower cable car station), point B2 in Myslenickie Turnie (the midway station of the cable car line), and point B3 on Kasprowy Wierch itself (the upper cable car station). Situating the intermediate points in these locations facilitates the use of the cable car line as a means of transport in measurement work.

The point in Myslenickie Turnie was chosen in view of the need to shift the gravimeters to another car between the two segments of the cable car line. Notably, the establishment of this intermediate point enables the procedure of calibrating the gravimeters used for measurements in lower sections of the mountains to be shortened. The intermediate points were stabilized with metal bolts mounted into the concrete foundation. The intermediate points plus the absolute gravity points formed 4 spans in the alpine baseline (Fig. 2).



Rys. 2. Alpine calibration baseline marked on a tourist photomap of the Polish Tatra Mountains (Drachal, 2002), scale 1:20 000, by the IGiK, Warsaw, 2002

ABS Zakopane	–Kuznice station (B1)	$\Delta H = 172$ m
Kuznice station (B1)	–Myslenickie Turnie (B2)	$\Delta H = 327$ m
Myslenickie Turnie (B2)	–Kasprowy Wierch station (B3)	$\Delta H = 603$ m
Kasprowy Wierch station (B3)	–ABS Kasprowy Wierch	$\Delta H = 30$ m

The length of the first segment of the cable car line, from Kuznice to Myslenickie Turnie, runs 1974 m and spans a difference in elevation of 358 m, entailing an average slope of 18%. The second segment from Myslenickie Turnie to Kasprowy Wierch runs 2208 m and spans a difference in elevation of 606 m, yielding an average slope of 27%. Each segment has three supports holding up the bearing cable. The travel time for the first segment is around 7 minutes, for the second around 8 minutes, proceeding at the speed of 5 m/s. On the first segment the wagon changes elevation at a rate of 0.84 m/s, on the second segment at 1.25 m/s.

Vertical gradients of gravity were determined at all the intermediate stations of the alpine calibration baseline. The values of the vertical gradients at the absolute gravity points and their excentric points are given in Table 1.

Table 1. Vertical gradients of gravity at the points of the alpine calibration baseline

Point symbol	Point name	Gradient [mGal/m]	Error [mGal/m]	Notes
A-ZAKO	Abs. Zakopane	0.2490	± 0.0011	
ZAKO-Ex1	Zakopane-exc.1	0.2960	± 0.0032	
ZAKO-Ex2	Zakopane-exc.2	0.2671	± 0.0047	
B1	Kuznice station	0.2582	± 0.0050	
B2	Myslenickie Turnie	0.4246	± 0.0035	point destroyed
B2A	Myslenickie Turnie	0.3606	± 0.0023	
B3	Kasprowy W. station	0.4390	± 0.0031	
B3A	Kasprowy W. station	0.4288	± 0.0015	temporary point
A-KASP	Abs. Kasprowy W.	0.4788	± 0.0037	
KASP-Ex1	Kasprowy W - exc. 1.	0.4792	± 0.0070	
KASP-Ex2	Kasprowy W - exc. 2.	0.4944	± 0.0016	

4. Determination of absolute gravity values at the Kasprowy Wierch and Zakopane points

In October 2004, absolute measurements of gravity g were taken at the two points of the alpine calibration baseline at Zakopane and Kasprowy Wierch, performed by Jaakko Mäkinen from the Finnish Geodetic Institute in Helsinki using ballistic gravimeter FG-5 No. 221 (Sas et al., 2005). The absolute measurements taken at Zakopane extended the Central Gravimetric Calibration Baseline to the south by a range of 236 mGal. As a result, this baseline now encompasses the entire range (660 mGal) of variability in gravity g on Polish territory.

Measurements were taken at Kasprowy Wierch in 59 series, each consisting of 50 drops and lasting a duration of 30 minutes.

The value of gravity measured by a ballistic gravimeter is defined for a point situated at a certain height, fixed by the manufacturer. This height differs for different types of instruments. Reducing that value to floor level requires that the vertical gravity gradient be taken into account. It is worth mentioning that such gravity measurement are subject to numerous corrections to account for geodynamic, meteorological, and instrumental factors. The geodynamic factors include luni-solar corrections, corrections to account for the oceanic and atmospheric load, and corrections for polar motion. Meteorological factors include corrections for changes in atmospheric pressure and temperature. The instrumental factors include corrections of rubidium clock and laser interferometer (Barlik, 1996).

Figure 3 illustrates the dispersion of the average values of gravity g from each of the 59 series of measurements. The header of the diagram states the value of gravity at the height of measurement, as well as two error values. The first, $\pm 1.69 \mu\text{Gal}$, represents the standard deviation of the results obtained from the 59 series. The second, $\pm 1.96 \mu\text{Gal}$, represents the sum of the corrections errors and gradient errors that affect the determined g value. The total error in determining g using this apparatus at the Kasprowy Wierch station came to $\pm 2.59 \mu\text{Gal}$.

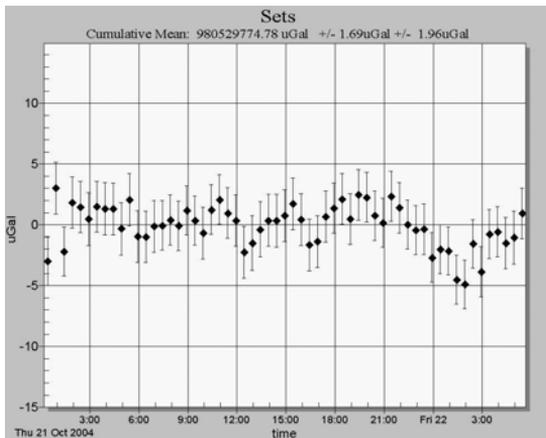


Fig. 3. Dispersion of the values of gravity g from 59 series of measurements at Kasprowy Wierch

At the station in Zakopane, in turn, 53 series of measurements were taken, with 50 drops in each. Figure 4 presents the dispersion of the values of gravity g obtained in the individual series of measurements.

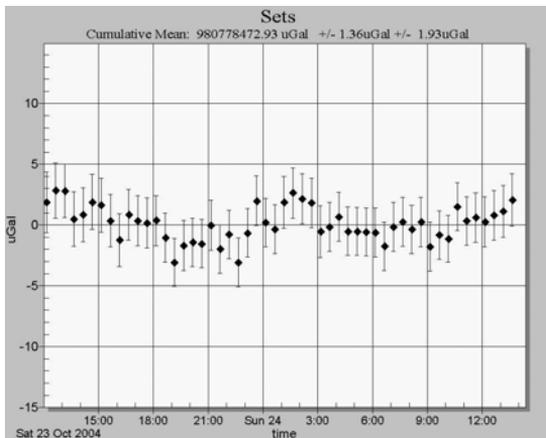


Fig. 4. Dispersion of the values of gravity g from 53 series of measurements at Zakopane

As above, the header of the diagram states the value of g at the measuring height plus the two error values: the first is $\pm 1.36 \mu\text{Gal}$ and the second is $\pm 1.93 \mu\text{Gal}$. The total error in determining g using this apparatus at the Zakopane station came to $\pm 2.36 \mu\text{Gal}$.

The high accuracy of the gravity determined at both of the points, as evidenced by their standard deviations, confirmed that their locations were well-selected from the standpoint

of the special criteria set for absolute gravity measurement stations. It is worth mentioning that the specialist performing the measurements considered these to be the best accuracies he had ever obtained, of all the approximately 50 points he had surveyed using ballistic gravimeters on various continents.

The value of gravity at the absolute measurement points at Zakopane and Kasprowy Wierch and at their excentric points, referenced to the level of the survey mark, are presented in Table 2.

Table 2. Values of g at absolute points and their excentric points, referenced to the level of the survey mark

Point symbol	Point name	g value [mGal]	Error [mGal]
A-KASP	ABS Kasprowy Wierch	980530.342	± 0.003
KASP-Ex1	Observatory - hall	980530.166	± 0.007
KASP-Ex2	Observatory - landing	980.530.231	± 0.009
A-ZAKO	ABS Zakopane	980778.770	± 0.003
ZAKO-Ex1	354 Zakopane	980782.587	± 0.003
ZAKO-Ex2	355 Kuznice	980748.065	± 0.007

The new relative and absolute gravity measurements taken at the Zakopane points were included into the existing gravimetric databases at the Institute of Geodesy and Cartography, Warsaw, and the gravity network was adjusted once again.

5. Measurements of the gravity difference across the spans of the alpine calibration baseline

Differences in gravity between points of the baseline, with immediate control for drift, was performed according to the scheme below, $A(a_1, 2) - B(b_1, b_2)$, $B(b_3, b_4) - A(a_3, a_4)$, $A(a_5, a_6) - B(b_5, b_6)$, $B(b_7, b_8) - A(a_7, a_8)$, yielding four independent determinations of Δg during one measurement cycle with one instrument (Fig. 5).

The linear drift of the gravimeter across the span was determined for a unit of time from three pairs of observations: (a_1-a_2) and (a_3-a_4) , (b_3-b_4) and (b_5-b_6) , (a_5-a_6) and (a_7-a_8) . The following corrections were made in calculating Δg :

- luni-solar corrections calculated according to Wenzel's procedure,
- barometric corrections,
- corrections for drift assuming its linear change over time,
- corrections for differences in vertical gradients of gravity at the end points of each span.

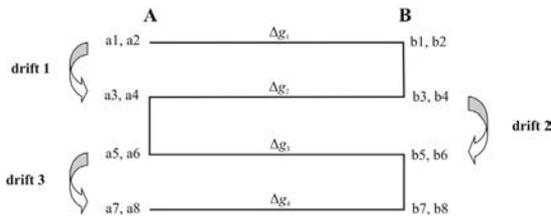


Fig. 5. Scheme of measurement across a gravimetric span

In late April 2006, the first measurement campaign was performed across the spans of the alpine gravimetric calibration baseline in the Tatra Mountains. The measurements were performed using four LCR gravimeters: G-1012, G-1036, G-1078 and G-1084. All the intermediate points of the baseline – B1, B2 and B3 – were accessible for measurement. At the beginning, in order to determine the calibration coefficients of the gravimeters, the span between the absolute gravity points in Zakopane and at Kasprowy Wierch was measured (twice). At Kasprowy Wierch, in view of the difficulty of frequently accessing the absolute gravity point, which entailed disruptions in the work of the Observatory, measurements were performed at the excentric point KASP-Ex1.

One should mention that relative gravity measurements are always performed at a certain height, related to the position of the measurement system inside the gravimeter apparatus. This height depends on the type of instrument and the height of the mounting stand. In the case of LCR gravimeters used for the measurements of this calibration baseline, this height was 0.15 m. Scaling the gravimeters requires a model Δg value obtained as the difference in g values at absolute stations. For the Tatra Mountain gravimetric baseline, as mentioned above, these were the absolute gravity station in Zakopane and the KASP-Ex1 excentric point at Kasprowy Wierch. The difference Δg between these stations, at the height of the survey

mark, is 248.604 mGal (Table 2). Taking account of the vertical gradients of gravity at both of these points, the value Δg was determined on the level of the relative measurements, i.e. at the height of 0.15 m. The corrected Δg value is 248.639 mGal. This value was used to determine the calibration coefficients k for all of the instruments used in this campaign. The scaling measurements for this campaign were performed twice. Based on the coefficients k so defined, the Δg values were determined across all of the calibration baseline spans measured.

At each measurement station, the atmospheric pressure was measured to record the difference between normal pressure and the pressure at the moment of observation. Barometric corrections, taking account of the influence of this difference, were made to the results of observations at all the points of the calibration baseline. The influence of these corrections on the results of the span measurements proved to be small. For example, Table 3 shows the results of measurements using gravimeter G-1012 across the Kasprowy Wierch-Zakopane span both with and without the influence of the barometric corrections.

Table 3. Influence of barometric corrections of Δg values between the absolute gravity points of Kasprowy Wierch and Zakopane (difference in elevation = 1132 m, difference in normal pressures = 118.4 hPa)

Measurement date	Duration of measurement [hours]	Δg [mGal]		Difference [μ Gal]
		without barometric correction	with barometric correction	
21 April 2006	6.5	248.5230	248.5234	+0.4
26 April 2006	5.3	248.5485	248.5480	-0.5
23 April 2008	8.5	248.4906	248.4916	+1.0
27 May 2008	7.7	248.5364	248.5354	-1.0
1 June 2008	6.9	248.5517	248.5513	-0.4

It should be noted that the 3 types of transport were used to move the measurement apparatus when measuring the spans of the calibration baseline. Automobile transport was used on the span between the absolute gravity station in Zakopane and point B1 (the Kuznice station). For the next 2 spans, stretching between points B1-B2 and B2-B3, the gravimeters were transported by cable car. For the last span of the baseline, between points B3-and KASP-Ex1 (an

excentric point of the absolute gravity point on Kasprowy Wierch) the gravimeters were carried on foot. Overall, no typical signs were noted in the work of the instruments in connection with the change in environmental conditions as they were transported between the baseline points, as caused by the rapid change in altitude. This applies to both LCR and Scintrex gravimeters. The mean error of the measurement was $\pm 8.6 \mu\text{Gal}$ for spans which were measured using automobile transport, $\pm 8.2 \mu\text{Gal}$ for cable car transport, and $\pm 8.0 \mu\text{Gal}$ for manual transport on foot.

The only aspect which attracted attention was the increased frequency with which the thermostat sensors switched on for gravimeters situated in the upper portion of the baseline, where the environmental temperature fell lower. This factor is unfavourable to measurement-taking because it gives rise to auto-vibrations disturbing the observations.

Measurements were taken across the spans of the baseline using existing, well-tested procedures. Moreover, care was taken to always situate the gravimeters with identical orientation with respect to north, in order to eliminate the possible influence of the geomagnetic field on the results of observations. It should also be mentioned that one of the three mounting support screws of each instrument was kept immobilized in a fixed position, so as to ensure that the gravimeter would be positioned at identical height above each measuring point. This is especially important in mountainous areas, where the vertical gradient of gravity may differ significantly at individual measurement stations. In the case of our alpine calibration baseline in the Tatra Mountains, the reductions made to the measured Δg values across the spans in view of the differences in gradients at their endpoints varied within the bounds of 1 to 34 μGal .

After a break caused by the renovation of the cable car line, work renewed on developing the alpine calibration baseline in late April 2008. As a result of the renovation work, however, the previously used measurement point B2 at Myslenickie Turnie was permanently destroyed. This rendered it necessary to select a new point, which was marked with the symbol B2A. Point B3 near the Kasprowy Wierch station

was also temporarily inaccessible. As a result, measurements were taken at a temporarily selected station with the symbol B3A.

Both of the additionally selected stations were stabilized with metal bolts bearing spherical heads, mounted into concrete foundations. The vertical gradients of gravity were determined at these points, with values already given in Table 1 above. The measurements across the spans of the calibration baseline were performed identically to 2006. However, the experience that was gained during that expedition was also harnessed: in order to protect the instruments against rapid temperature changes, they were placed inside an additional thermal shield made of styrofoam, produced especially for this study. Figure 6 shows the gravimeters inside these thermal shields. This safeguarding measure proved effective in the further course of experimentation.



Rys. 6. LaCoste&Romberg gravimeters
inside styrofoam shields

Moreover, as before, care was taken to always situate the gravimeters with identical orientation with respect to north. Analogous steps were taken in subsequent campaigns.

After the instruments were scaled between the absolute points, and the k coefficients were determined, the value of the difference in gravity was measured and calculated between the intermediate points of the baseline. The subsequent measurement campaigns carried out in May and June 2008 proceeded similarly. These two campaigns used a Scintrex CG-3

gravimeter owned by the Krakow branch of the company PBG Ltd. in Warsaw.

This work yielded values of the coefficients k for each individual instrument for each measurement campaign, as shown in Table 4.

Table 4. Calibration coefficients k for the gravimeters investigated

Measurement date	Calibration coefficient k				
	G-1012	G-1036	G-1078	G-1084	CG-3
2006 April	1.0019181	1.0048107	1.0006987	1.0005787	-
2008 April	1.0020962	1.0048172	1.0007788	1.0006696	-
2008 May	1.0019193	1.0047892	1.0006987	1.0004490	0.9996060
2008 June	1.0018555	1.0046726	1.0005738	1.0004426	0.9995698
k_{mean}	1.0019473	1.0047724	1.0006875	1.0005350	0.9995879
$m_k \times 10^{-5}$	± 5.18	± 3.38	± 4.23	± 5.48	-

6. Analysis of determination of calibration coefficients k

Analysis of the results obtained indicates that the calibration coefficients k determined in April 2008 increased with respect to their values in April 2006. This applies to all 4 LCR gravimeters then in use. At the same time, the values of these coefficients systematically decreased over the three subsequent campaigns. The Scintrex gravimeter, which only took part in the final two campaigns, likewise showed a reduction in its k coefficient. We assume that this phenomenon was caused by the layer of snow cover on the summit of Kasprowy Wierch, with a thickness varying during the different campaigns, which may have thereby affected the gravity values recorded. The thickness of this snow layer varied as follows (Table 5):

Table 5. Snow conditions on Kasprowy Wierch during measurement campaigns

Date of measurement	Thickness of snow layer [m]	Notes
2006 April	0.5	compact snow
2008 April	1.0	compact snow
2008 May	0.5	compact snow
2008 June	0.0	-

For these thicknesses of snow cover, the value of gravity was calculated based on the assumption that the snow layer forms a cone of constant thickness and a radius of 300 m. The calculations furthermore assumed a 45° slope of the mountain

in the immediate vicinity of the measurement point and a snow density of 0.5 g/cm³, which corresponds to the average density of wet snow. Figure 7 depicts these assumptions graphically.

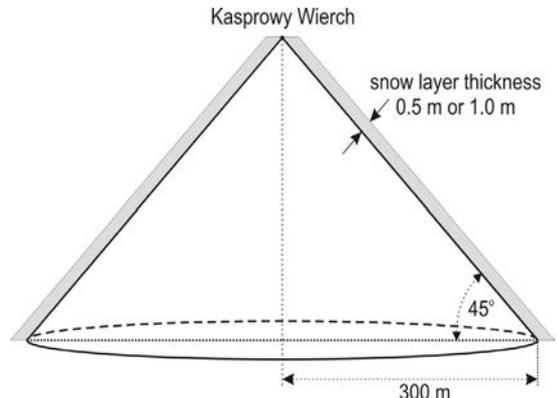


Fig. 7. Assumptions adopted in calculating the influence of the snow layer on the measured gravity values

These assumptions yielded a correction of 0.018 mGal for a snow layer 0.5 m thick, and 0.036 mGal for a snow layer 1 m thick. The measurements were next adjusted by these correction values. The re-determined calibration coefficients k are presented in Table 6.

In this case, the values of the calibration coefficients determined in the individual measurement campaigns do not show systematic variation. The mean error of the arithmetic mean of k for each gravimeter from each campaign was reduced, falling within the

range of $\pm 1.4 \times 10^{-5}$ to $\pm 2.5 \times 10^{-5}$. The changes in calibration coefficients k resulting from the

correction to account for the snow cover on Kasprowy Wierch are illustrated in Figure 8.

Table 6. Calibration coefficients k accounting for snow cover influence

Measurement date	Calibration coefficient k				
	G-1012	G-1036	G-1078	G-1084	CG-3
2006 April	1.0018454	1.0047376	1.0006261	1.0005052	-
2008 April	1.0019507	1.0046710	1.0006338	1.0005247	-
2008 May	1.0018466	1.0047160	1.0006261	1.0003765	0.9995336
2008 June	1.0018555	1.0046726	1.0005738	1.0004426	0.9995698
k_{mean}	1.0018754	1.0046993	1.0006149	1.0004622	0.9995517
$m_k \times 10^{-5}$	± 2.54	± 1.65	± 1.38	± 3.35	-

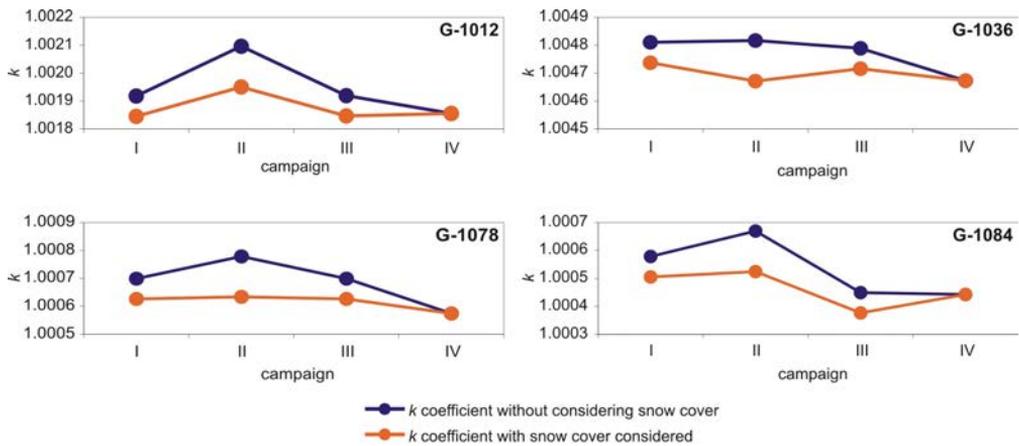


Fig. 8. Graphical representation of the change in coefficients k for gravimeters G-1012, G-1036, G-1078, G-1084

7. Calculation of g at the points of the baseline

Figure 9 shows a sketch of the spans measured during the four campaigns. They form a network comprised of 9 spans, across which 80 measurements of Δg were taken using five gravimeters.

In order to calculate the values of gravity at the points in the baseline, all the Δg values were adjusted using the parametric method.

The following were adopted as fixed points, treated as having no error:

- the absolute gravity point in Zakopane (A-ZAKO),
- an excentric point of the absolute gravity point at Kasprowy Wierch (KASP-Ex1).

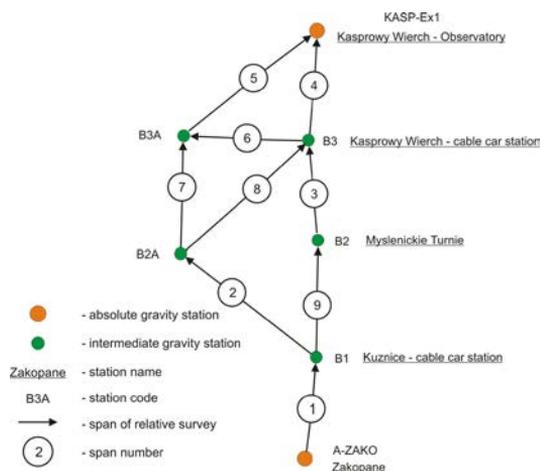


Fig. 9. Sketch of the spans in the alpine gravimetric calibration baseline

The adjustment proceeded with the Δg values across the spans, at the height of the relative measurements, i.e. 0.15 m above floor level for the LCR gravimeters. The measurements taken with the Scintrex CG-3 gravimeter, performed on the level of 0.17 m, were reduced to the level of 0.15 m in view of the differences in vertical gradients at the span endpoints. One should point out again that the Δg are measured on scales (taking account of the snow cover) determined for each instrument during each measurement session.

In order to unify the levels of gravity, the g values at the fixing points were reduced from the level of the absolute gravity measurements (i.e. floor level) to the level of the relative gravity measurements (i.e. 0.15 m above floor level). The final g values at the points of the alpine calibration baseline, reduced to the level of the absolute gravity measurements, are presented in Table 7.

Table 7. Values of g at the points of the alpine gravimetric calibration baseline, reduced to the level of absolute gravity measurements

Point symbol	Point name	Vertical gradient [mGal/m]	g [mGal]	Error [μ Gal]
A-ZAKO	ABS Zakopane	0.2490	980778.770	-
B1	Kuznice - station	0.2582	980741.998	± 2.9
B2A	Myslenickie Turnie	0.3602	980671.466	± 3.3
B3	Kasprowy Wierch - station	0.4390	980537.321	± 2.6
KASP-Ex1	Kasprowy W. - Observatory	0.4792	980530.166	-

Table 8, in turn, shows the adjusted Δg values across the spans on the height of 0.15 m above the floor of the survey mark, and the values reduced to the floor level, taking account of the differences in vertical gradients of gravity at the baseline points.

Table 8. Reduction of adjusted Δg values to floor level

Span	Adjusted Δg (at height +0.15 m) [mGal]	Reduction [μ Gal]	Reduced Δg (floor level) [mGal]
A-ZAKO – B1	-36.7734	+1.3	-36.7721
B1 – B2A	-70.5482	+15.5	-70.5327
B2A – B3	-134.1566	+11.6	-134.1450
B3 – KASP-Ex1	-7.1608	+6.0	-7.1548
Sum	-248.6390	+34.4	-248.6046

8. Summary and conclusions

The achievements of this project may be summed up in the following points:

1. The vertical gravimetric calibration baseline established in the Tatra Mountains is based on absolute gravity stations in Zakopane and on Kasprowy Wierch, ensuring that the calibration scales of the gravimeters are determined in keeping with the required international standard.
2. The establishment of the absolute gravity point in Zakopane extended Poland’s Central Gravimetric Calibration Baseline to the country’s southern border, thus facilitating the scaling of gravimeters used for measurement taking at points to the south of the Ksiaz – Ojcow – Sieniawa line (Fig. 1).
3. The establishment of the vertical gravimetric calibration baseline in the Tatra Mountains also allows for the calibration of gravimeters used in geodetic and geodynamic work in the territory of the Czech Republic and Slovakia.
4. The extension of the Central Gravimetric Calibration Baseline to Zakopane led to an increase in the standard g difference along that baseline, thereby increasing the accuracy of calibration.

Moreover, in terms of the technical and methodological aspects of developing the vertical gravimetric calibration baseline in the Tatra Mountains, our research has concluded that:

- The type of transport means used (by automobile, cable car, or on foot) was not seen to affect the results of gravimeter calibration.
- The influence of barometric corrections of the measurement results did not exceed one microgal (Tab. 3), and was therefore an order of magnitude smaller than the standard deviation of measurements across the spans. Atmospheric pressure proved to be very stable in the area during the time the research was carried out. However, a sudden change in pressure during calibration work, something likely in a mountainous area, could lead atmospheric pressure to exert a greater influence on gravimetric results. As a result, we recommend for weather forecasts to be consulted before such measurement work

commences so that gravimeter calibration can proceed under stable weather conditions. Even so, it is still recommended for atmospheric pressure readings to be taken at each point during calibration.

- The significant variability seen in vertical gradients of gravity (Tab. 1) at the points of the baseline render it necessary for these gradients to be taken into account in the measurement procedure. One of the three mounting support screws of each gravimeter should be kept immobilized in a fixed position, so as to ensure its positioning at an identical height above each measuring point. It is therefore recommended for vertical gradients of gravity to be stated in lists of g values at the points forming an alpine calibration baseline, and for the corresponding reductions be made to Δg values to account for the difference in gradients at the span endpoints.
- The influence of rapid temperature changes related to changes in altitude, giving rise to auto-vibrations triggered by the gravimeter thermostat devices switching on with increased frequency, can effectively be eliminated by placing gravimeters into a thermal shield made of styrofoam, such as that used in this study (Fig. 6).
- The time of year selected for calibration work is not unimportant. Calibration should be carried out after the snow cover in the region of the calibration baseline points subsides. For instance, a layer of snow may remain in place on the Kasprowy Wierch massif even as late as into May, and depending on its thickness it may exert a significant impact on the results of gravimetric observations. These theoretical considerations found confirmation in the measurement results, as shown in Tables 4 and 6 and in Figure 8. Taking account of the snow cover's influence on the calibration results halved the standard deviations for the calibration coefficients k for all the gravimeters.

Acknowledgements

This research was performed under a research project financially supported by the Polish Ministry of Science and Higher Education No 4 T 12 E 024 30 as well as partially under the statutory project "Problems of geodesy and geodynamics" of the Institute of Geodesy and Cartography, Warsaw.

The authors express their thanks to the staff of Kasprowy Wierch High-Altitude Meteorological Observatory, the Hydrological-Meteorological Station in Zakopane as well as Krakow branch of the company PBG Ltd. in Warsaw for their help during the survey.

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Wysokościowa grawimetryczna baza kalibracyjna w Tatrach

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Lucjan Siporski

Streszczenie. Przedstawiono prace związane są z założeniem górskiej grawimetrycznej bazy kalibracyjnej w Tatrach oraz opracowaniem metodyki przeprowadzania na niej kalibracji grawimetrów statycznych. Założenie takiej bazy wynika z nasilenia w ostatnich czasach badań geodynamicznych w górach i związaną z tym potrzebą ujednoczenia na wysokim poziomie dokładności skali grawimetrycznej, używanych do tych badań grawimetrów. Z uwagi na znaczące różnice warunków środowiskowych na bazie górskiej w porównaniu z tymi, jakie obserwuje się na bazach zakładanych w terenach płaskich, niezbędne było przeprowadzenie badań wpływu szybkich zmian ciśnienia atmosferycznego i temperatury otoczenia na pracę grawimetrów, które są używane w pracach pomiarowych. Niemniej ważne było zbadanie wpływu wykorzystywanego środka transportu (samochód, kolei linowa, ręczny transport instrumentów) na pracę instrumentów rodzaju. W wyniku przeprowadzonych prac utworzona została górska grawimetryczna baza kalibracyjna oraz podano zalecenia jak należy postępować przy skalowaniu grawimetrów na tej bazie.

Słowa kluczowe: grawimetria, metrologia grawimetryczna, wysokościowa kalibracyjna baza grawimetryczna