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# Effect of vertical gravity gradient on the accuracy of gravimeter measurements based on Hungarian data

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In the last decade significant developments have taken place in gravimetry as a result of the world-wide use of absolute gravimeters (at present about 25 items of equipment are in use). Their accuracy is 3–4 μGal and the results are obtained directly in SI units ($ms^{-2}$). With the application of absolute gravimeters standardized gravity networks for large regions can be established economically. The political changes of the 1990s in Eastern Europe have made it possible to extend over the eastern part of the continent the Unified European Gravity Network (UEGN) established earlier in Western Europe. The gravity datum of the network is based on absolute stations. The densification of the network between the absolute points is carried out with LaCoste–Romberg (LCR) gravimeters. The increased accuracy of the measurements made it necessary to investigate the effect of the applied normal vertical gradient (0.3086 mGal/m) for elevation reductions. The author presents the results of his investigations in this field. High precision gravity measurements (calibration lines, microgravimetric measurements) require the determination of the actual vertical gradient (VG) because the application of its normal value would lead to errors higher than the accuracy of the measurement. The gravity value measured with absolute gravimeters refers to a certain height (depending on the type of instrument) above ground level. The gravity value obtained is reduced to the benchmark of the station by means of relative gravimeter measurements. Based on the author's experience the accuracy of this reduction — when the vertical gradient is measured with 1 or 2 gravimeters in one observation series only — does not reach the necessary ± 10–20 E units.

**Keywords: vertical gradient, gravimeters, calibration, Hungary**

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## 1. Introduction

The value of gravity ($g$) determined by absolute or relative gravimeters refers to the height of their sensing mass; it is called 'reference height'. To make them comparable to each other, the measured value should be reduced to a common reference point generally a benchmark on the ground level. The reduction is the 'reference height correction', which depends on the vertical gradient and the reference height. This latter one means the vertical distance between the sensing mass of the applied instrument and the benchmark.

## 2. Basic principles

Reference height correction (mentioned above ) can be determined if one knows the local **vertical gradient** ($VG$) value at the observation site. The vertical gradient is the vertical derivative of gravity ($\partial g/\partial h$), i.e. the change in gravity acceleration referred to an infinitesimally small vertical distance.

The vertical gradient's theoretical value can be deduced from Faye reduction. Using certain assumptions (the equipotential surface corresponding to sea level is a sphere of $R_0 = 6372$ km radius, and the mass distribution in the Earth is homogeneous), acceleration due to gravity at sea level is:

$$g_0 = k^2M/R_0^2$$

where $k^2$ is the gravity constant and $M$ is the mass of the Earth.

At a height '$h$' above sea level it is given by the relation

$$g = k^2M/(R_0+h)^2$$

In this case — after series expansion of the expression $1/(R+h)^2$ — the reduction value ($\Delta g_m$) is:

$$\Delta g_m = g_0 - g = k^2 M/R^2(2h/R_0 - 3h^2/R_0^2 + \dots )$$

Because '$h$' is small compared with $R_0$, it can be further simplified

$$\Delta g_m = -0.3086 \text{ mGal/m}^{**}$$

Although the Faye reduction and the reference height correction are not identical, in both cases the observation point is 'shifted' vertically in free air.

In those tasks where the required accuracy of relative gravity field measurements (hereafter: gravity measurements) is a few tenths or hundredths of a mGal, this theoretical value can also be used for calculating reference height correction.

The vertical derivative of gravity can be determined by measurement as well. This has two versions: one of them is called direct, the other one indirect determination.

For **direct determination** vertical gradiometers were constructed. In actual fact, these devices have failed to fulfil the expectations that they would be able to determine the value of vertical gradients with an accuracy similar to that of horizontal ones. As was pointed out by YUZEPOVICH and OGORODOVA [1980], the limits are basically set by the instruments themselves. In practice, therefore, indirect determination is the commonly used method (in Hungary, indirect determination is the only method used).

Relative gravimeters are the tools for **indirect determination**. Here, it might be appropriate to emphasize the following:

— Relative gravimeters measure the difference in gravity between two points;

— The resolution of relative gravimeters does not allow any measurable change in gravity to be detected between two points with infinitesimally small separation;

— Because of the resolution constraints, the vertical gradient (defined earlier) is considered as the difference in gravity between two points separated by a distance of 1 m referred to the midpoint of the perpendicular line section between the two points.

Because the local perpendicular line is always a space curve, the vertical gradient belonging to a point on the Earth's surface changes depending

** 1 mGal = $1 \cdot 10^{-5}$ ms$^{-2}$, 1 μGal = $1 \cdot 10^{-8}$ ms$^{-2}$

on the position of the selected section to be measured along the given local perpendicular line.

Reference is important because experience has shown that, on the one hand, values of *VG* change in different sections of the perpendicular line at the given site and, on the other hand, the change is non linear [SZABÓ, CSAPÓ 1985].

Because the reference height for absolute gravimeters slightly changes even within one observation set, a reference height correction should always be applied referring to the height of the given drop [CHARLES, HIPKIN 1995]. The problem is made more complicated by the presence of the observation pillar and nearby masses in the laboratories (where the observations are made) and these cause various inhomogeneities in the gravity field [SAGITOV 1984]. (I would call attention here to the calculations performed in the Central Institute of Earth Physics in Potsdam [ELSTNER et al. 1986] as an example of how these effects can be taken into account). In order to make the observation results independent of the uncertainties resulting from the reduction to the benchmark, in the literature generally two *g* values, one for the reference level and one for the benchmark are given. The reliability of measurement refers to the value obtained on the reference level.

Mention should be made of the basic contradiction of gravimetry with regard to the reliability of measurements; the reliability is lower by an order of magnitude for vertical gradients measured in any way than that of horizontal gradients, the latter can be determined with a reliability of about 1E ( 0.1 μGal/m) using an Eötvös torsion balance.

The measurement accuracy for the new generation of absolute gravimeters (US made AXIS–F5 gravimeters) is 3–4 μGal [MARSON et al. 1995].

As a result of recent developments of the most up-to-date relative gravimeters (LaCoste–Romberg types, Scintrex CG–3) application of electronic levels, double thermostats, and feedback electronics, similar accuracy can be achieved under laboratory conditions.

The increasing number of absolute gravimeters, and the widening of international collaboration provide a 'common mGal unit' for gravity base networks for all over the world. In addition to other scientific and economic goals, the linking of these networks makes it possible to construct unified geophysical maps for large, contiguous areas [BOEDECKER et al. 1995].

Because of the improved measurement accuracy the theoretical value of free air reduction — 0.3086 mGal/m — does not provide satisfactory accuracy for the reduction of gravity from the reference height to the benchmark. The vertical gradient must be determined at each absolute station [CSAPÓ 1987]. Similarly, more accurate correction is required if the highest possible reliability is expected in surveys performed with relative gravimeters (establishment of calibration lines, laboratory or microgravimetric measurements).

In what follows the results of *VG* measurements carried out at the stations of the national calibration line, along the horizontal microbase established in the Mátyáshegyi Cave and at the other absolute stations in Hungary are presented. We want to show, on the one hand, possible deviations in *VG* values from the theoretical value, and, on the other hand, to provide an idea on the most cost-effective achievable reliability of *VG* measurements performed under different ambient conditions. Moreover, to show what kind of error might be caused by inaccurate knowledge of the *VG* value in gravity measurements.

## 3. *VG* measurements and processing methods

Based on domestic and international experience, measurements have been carried out at the absolute stations established in buildings and at field sites in accordance with identical principles [CSAPÓ 1997]. At the site to be measured two tripods are set up one above the other. The height of the higher tripod is 110 cm ($P_u$) and that of the lower one is 6 cm ($P_l$). The gravimeter type equipped with electronic level and electronic output can be set up on the tripods applying forced centring; the maximum linear eccentricity is 10 mm. After setting up the instrument the distance between the upper plate of the instrument (black lid) and the tripod is measured with mm accuracy. The vertical distance between the upper plate of the instrument and the beam is known. Three readings are taken at each level and in each series in the following order:

$$P_l - P_u - P_l - P_u - P_l - P_u$$

The null position is set by means of a digital voltmeter equipped with filter and connected to the output of the gravimeter. The reading is taken by means of the nulling dial, using the so called 'interpolation method'.

In this way five (not independent of each other) $\Delta g$ values can be determined in each series; the value of *VG* in Eötvös units obtained from the series is the arithmetic mean of the corrected values interpolated to a height difference of 1000 mm. The observation results are then processed using our own (ELGI) software, applying corrections for air pressure (DIN 5450/1968.), earth tide, and instrumental drift.

The number of observation series and gravimeters is chosen so that the reliability of the measured *VG* value will be at least 30E in the case of field stations, and at least 20E in buildings.

## 4. Description of observation results

### *4.1. VG measurements performed along the national gravity calibration line*

The stations of the national calibration line are generally in churchyards (some metres away from the church itself) or at airports, they are permanently marked with concrete blocks buried at ground level, and they have a benchmark. The gravimeter set was transported by car to the sites just before starting the observation. At each site, observations started after carrying out the daily instrument check — measuring a complete series with each gravimeter, one after another. The gravimeter set was selected from LCR Model G meters of the Eötvös Loránd Geophysical Institute of Hungary (G–type meters: No–220, No–821, No–963, No–1919). The time required to measure one series was generally 50–60 minutes per instrument. *Tables I* and *II* summarize the results of the VG measurements; all observations at the Pécs calibration site are listed (Table II) as an example.

| name of point | location | H (m) | $n_S$ | $n_{GR}$ | VG (E) | $m_l$ (E) | $m_x$ (E) |
|---|---|---|---|---|---|---|---|
| Pécs | airport | 200 | 8 | 4 | 3180 | 86 | 30 |
| Mecseknádasd | church-yard | 194 | 8 | 4 | 2960 | 80 | 28 |
| Tolna | church-yard | 100 | 7 | 4 | 3107 | 100 | 38 |
| Dunaújváros | airport | 122 | 12 | 3 | 3087 | 34 | 10 |
| Ercsi | church-yard | 124 | 12 | 3 | 3093 | 73 | 21 |
| Budaörs | airport | 126 | 13 | 4 | 3082 | 98 | 27 |
| Mátyáshegy | quarry | 201 | 9 | 3 | 2625 | 34 | 11 |
| Dunakeszi | church-yard | 126 | 6 | 2 | 3079 | 51 | 23 |
| Rétság | church-yard | 193 | 7 | 4 | 3028 | 48 | 18 |
| Balassagyarmat | park | 147 | 8 | 4 | 3208 | 88 | 31 |
| | $\Delta_{VG}$ = 583 E | | | mean: | 3045 | 69 | 24 |

*Table I.* Results of vertical gradient (*VG*) measurements on the calibration line of Hungary *Legend*: *H* — elevation above sea level; $n_S$— number of determinations (measurement series); $n_{GR}$—number of instruments in the given gravimeter set; $m_l$— r.m.s. error of one determination in E units: $m_l = \pm (\Sigma vv/n-1)^{½}$; $m_x$— r.m.s. error of the most probable error after adjustment: $m_x = \pm [\Sigma vv/n(n-1)]^{½}$; $\Delta_{VG}$ — $VG_{max}-VG_{min}$

*I. táblázat.* A magyarországi graviméter-kalibráló alapvonalon végzett *VG* mérések eredményei

*Jelmagyarázat: H* — a pont tengerszint feletti magassága; $n_S$— mérési sorozatok száma; $n_{GR}$—az alkalmazott graviméter csoportban szereplő műszerek száma; $m_l$— egy *VG* mérés középhibája eötvös egységben $m_l = \pm(\Sigma vv/n-1)^{½}$; $m_x$— a *VG* legvalószínűbb értékének kiegyenlítés utáni középhibája: $m_x = \pm [\Sigma vv/n(n-1)]^{½}$; $\Delta_{VG}$ — $VG_{max}-VG_{min}$

| n | LCR-220 G | LCR-821 G | LCR-963 G | LCR-1919 G |
|---|---|---|---|---|
| 1 | 3193 | 3095 | 3160 | 3308 |
| 2 | 3162 | 3079 | 3138 | 3306 |
| | | *VG* = 3180 E | 30 E | |

*Table II.* Results (in Eötvös units) of vertical gradient (*VG*) measurements at the Pécs point of the calibration line

*II. táblázat.* A kalibráló alapvonal Pécs pontján mért vertikális gradiens (*VG*) értékek eötvös egységben

### 4.2. *VG measurements along the horizontal microbase*

The fourteen stations of the microbase are set up in the man-made entrance gallery of the Mátyáshegyi Cave in Budapest, on a concrete floor spread directly over the natural limestone base. The gallery of the cave has a vaulted shape: it is about 2.5 m wide and 2.5–4 m high. The distance between the stations is 2–5 m, their elevations above sea level are equal to within a few cm. The rock face rises steeply above them (the rock thickness above station 1 is some 30–40 m; above station 14, it is about 5–6 m). The daily change in temperature in the gallery is negligible, the seasonal temperature variation is ±1°C, the average temperature is 15°C. (During the campaign the gravimeters were stored at the site.) Because of the extremely high horizontal gradients (2000–10,000 E) caused by the steeply rising hillside the stations are designated with markers ensuring forced centring when setting up the instrument; this means that the mass of the meters is taken as that at a height of 115 mm ±5 mm above the marker at each station, and the horizontal eccentricity of the mass is less than 1 mm. The *VG* values obtained for the stations along the microbase are shown in *Table III.*.

### 4.3. *VG measurements at absolute stations*

The absolute gravity stations in Hungary are generally to be found at the lowest level of long-standing historic buildings (castles, mansions, etc.).

The *VG* values determined at the 15 absolute stations are listed in *Table IV*; at the Budapest station (in Mátyáshegyi Cave) all *VG* observations are shown in *Fig. 1*.

## 5. Discussion of measurement results

From the numerous conclusions that can be derived from a comparison of the data in Table I, attention is drawn to the following. It can be seen that

| Number of station | $n_S$ | $n_{GR}$ | VG (E) | $m_l$ (E) | $m_x$ (E) |
|---|---|---|---|---|---|
| 1 | 4 | 2 | 2581 | 26 | 13 |
| 2 | 5 | 2 | 2591 | 8 | 3 |
| 3 | 3 | 1 | 2578 | 22 | 13 |
| 4 | 6 | 2 | 2447 | 38 | 15 |
| 5 | 3 | 1 | 2386 | 19 | 11 |
| 6 | 7 | 3 | 2556 | 46 | 18 |
| 7 | 4 | 2 | 2432 | 47 | 23 |
| 8 | 10 | 3 | 2358 | 46 | 14 |
| 9 | 3 | 1 | 2286 | 15 | 8 |
| 10 | 11 | 3 | 2356 | 35 | 10 |
| 11 | 6 | 3 | 2283 | 57 | 23 |
| 12 | 4 | 1 | 2281 | 28 | 14 |
| 13 | 5 | 2 | 2236 | 27 | 12 |
| 14 | 6 | 2 | 2102 | 66 | 27 |
| $\Delta_{VG}$ = 489 E | | mean: | 2391 | 34 | 15 |

*Table III.* Results of vertical gradient (*VG*) measurements on the horizontal micro calibration line in Mátyáshegyi Cave, Budapest. Legend: See Table I.
*III. táblázat.* A Mátyáshegyi-barlang horizontális mikrobázis pontjain végzett *VG* mérések eredményei. Jelmagyarázatot lásd az I. táblázatnál

there is no correlation between the *VG* values (all the values presented were observed for a height of 620 mm ± 20 mm above the ground) and the elevation of the stations above sea level in the given range. But there is a close correlation between the reference heights and the corresponding *VG* values at the same site [see CSAPÓ 1987]. When using the instrument set consisting of the four given gravimeters and equal number of measurement series ($n_s = 8$) the r.m.s error of the most probable value after adjustment is nearly the same in all cases, viz. about 30 E.

Results of a *VG* determination are given in Table II. The maximum difference between the 8 determinations is 229 E (≈23 μGal/m), the r.m.s error of the most probable value obtained from the adjustment of *VG*s is ±30 E (≈3 μGal/m). Deviations might be larger in measurements carried out under extreme ambient conditions (strong wind, enhanced microseismic effects at vibration sensitive sites caused by intensive road traffic,

| Name and location of station | | Locality | $n_s$ | $n_{GR}$ | VG (E) | $m_x$ (E) |
|---|---|---|---|---|---|---|
| 81 | Siklós | castle | 22 | 11 | 3407 | 16 |
| 82 | Budapest | Mátyáshegyi Cave | 47 | 14 | 2519 | 7 |
| 85 | Kőszeg | town hall | 22 | 4 | 2661 | 24 |
| 86 | Szerencs | wine house | 40 | 3 | 2968 | 7 |
| 88 | Nagyvázsony | mansion | 18 | 5 | 2565 | 12 |
| 89 | Gyula | castle | 29 | 2 | 2913 | 11 |
| 90 | Szécsény | mansion | 15 | 5 | 3059 | 18 |
| 91 | Kenderes | mansion | 12 | 5 | 2662 | 24 |
| 92 | Madocsa | public building | 8 | 4 | 2552 | 16 |
| 93 | Iharosberény | castle | 19 | 6 | 2805 | 10 |
| 94 | Öttömös | wine cellar | 16 | 6 | 2634 | 10 |
| 95 | Tarpa | school | 15 | 5 | 2710 | 21 |
| 96 | Debrecen | garage | 12 | 4 | 3075 | 13 |
| 97 | Zalalöv | community house | 9 | 3 | 2633 | 12 |
| 98 | Penc | observatory | 12 | 4 | 3098 | 15 |
| | | $\Delta_{VG}$ = 888 E | | mean: | 2817 | 14 |

*Table IV.* Results of vertical gradient (*VG*) measurements on the absolute points of Hungary Legend: see Table I.
*IV. táblázat* A magyarországi abszolút állomásokon végzett *VG* mérések eredményei.

etc.); in our experience $m_x$ may reach the value of 50–60 E. In favourable cases, on the other hand, higher reliability could be achieved by a lower number of observation series (e.g. Dunakeszi, Rétság). In repeat measurements carried out at the same site with one and the same gravimeter, only rarely do differences greater than 100 E occur. Observation results are values corrected for this long-term change in the calibration factor. Because long-term changes in the calibration factor (at least based on the 12 such meters used in the measurements up till now in Hungary) have values between 0.996 and 1.005, the maximum effect of their possible error on *VG* values is 10 E. To reduce the effect of systematic errors, measurements are always performed with more than one instrument.

In relative measurements of gravity the sensor mass of LCR gravimeters used is 60–125 mm above the benchmark of the site. As a consequence, the error due to the neglection of *VG* anomalies could reach 6 μGal (see Table I). The value might be even more, because at the other stations of the

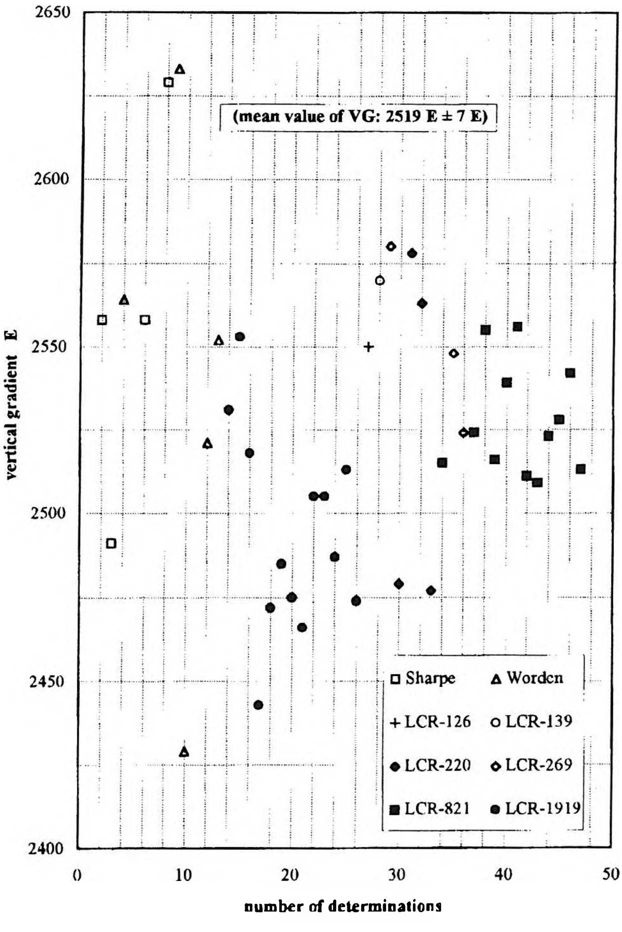


*Fig. 1.* Results of vertical gradient (*VG*) measurements at the Budapest absolute station
*1. ábra.* Budapest abszolút állomáson végzett vertikális gradiens (*VG*) mérések eredményei

national base network no *VG* measurements have been performed up till now. It is pointed out that the value of 6 μGal is higher than the measurement reliability achievable with these instruments! The magnitude of the effect is, of course, not proportional to the measured *g* value, it depends only on the surroundings of the observation site.

The results in Table III are examples of the effect of nearby large masses on the values of *VG*. The close correlation between the magnitude of the masses over the site and the *VG* values can be well demonstrated at the Budapest microbase. Between station 1 and station 14 the *VG* values continuously decrease (2591–2102 E) and all are much lower than those measured on the surface. (For comparison: site 1 called Mátyáshegyi Cave in Table I is in the open air but lies in a corrie-like strip pit about 50 m from site 14, which is in the gallery). The calculated average *VG* value (2391 E) is not more than 77% of the theoretical value. The negligence of local *VG* values would produce an error of 3 μGal (between sites 2 and 14). This value is comparable to the measurement reliability of the given LCR gravimeters under optimal observational conditions.

From Table III it is also evident that under optimal observational conditions (constant temperature, low level of vibration during transportation due to the closeness of sites and hand carrying of instruments) significantly higher reliability can be achieved in determining *VG* for microgravimetric purposes than at field sites where the frequently changing ambient conditions have an adverse effect on the observational results.

Table IV contains the most important parameters of *VG* measurements at the absolute stations in Hungary. To interpret the results Fig. 1 was also used where the results of all measurements at the Budapest absolute station are plotted. In addition to LCR instruments, observations were made with Sharpe and Worden gravimeter sets at this station. The scattering of the measurements performed with the latter is somewhat higher, especially if the scattering is compared with that of No. G–821 and G–1919 LCR gravimeters. One of the reasons for this is that *VG* determinations were carried out with these Sharpe and Worden instruments in connection with field measurements, generally after the daily field work. The maximum deviation between the obtained data is 250 E. The extremely high reliability of the *VG* value for the station is primarily due to the high number of series. It can also be seen that there is about 30 E difference of systematic character between the results of the two above mentioned LCR gravimeters; the probable reason for this is the determination problems of long-term changes in the calibration factor. The 47 measurement series were realized between 1980 and 1995. (Although the temporal stability of the vertical gradient of gravity has not yet been properly demonstrated, the possible change in time might not have a detectable influence on the results.) The disturbing effect of nearby masses can clearly be seen in the *VG* values of absolute stations; their scattering around the theoretical value is substantially higher than that of those measured in the open field.

Based on the results shown in Table IV the reliability of *VG* values at the absolute stations in Hungary lies between 7 and 24 E, which is in agreement with the results presented in the literature BECKER et al. [1995] on similar measurements.

## 6. Summary

It can be seen from the results described in the paper that knowledge of the local value of the vertical gradient is mandatory in high accuracy gravimeter measurements. The necessary (and satisfactory) number of measurements to achieve the accuracy required by the task can be planned based on the examples and method of determination presented here.

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## A nehézségi erő vertikális gradiensének hatása nagypontosságú graviméteres mérésekre magyarországi meghatározások alapján

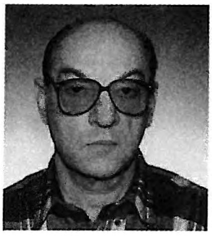
CSAPÓ Géza

Az elmúlt években nagyjelentőségű fejlődés következett be a gravimetria terén annak következtében, hogy világszerte elterjedtek az abszolút graviméterek (jelenleg mintegy 25 berendezést alkalmaznak különböző feladatokhoz), amelyek meghatározási pontossága ma már 3–4 mGal és az eredmények fizikai mértékegységben ($ms^{-2}$) adódnak. Velük nagy területekre vonatkozóan is gazdaságosan valósíthatók meg egységes gravimetriai alaphálózatok. A 90–es évek politikai változásai Kelet Európában lehetővé tették az eredetileg Nyugat Európa területére vonatkozó Egységes Európai Gravimetriai Hálózat (UEGN) kiterjesztését, amelynek referenciaszintjét az abszolút graviméterekkel mért állomások biztosítják. Ezen főpontok között a hálózat sűrítését LCR gyártmányú relatív graviméter csoportokkal végzik. A megnövekedett mérési pontosság és a homogén megbízhatóságra való törekvés szükségessé tette annak vizsgálatát, hogy a mérések magassági redukciójának számításához általánosan használt elméleti érték (0,3086 mGal/m) összhangban van-e az említett néhány mGal-os mérési pontossággal. A dolgozatban az ezirányú magyarországi mérések eredményeit ismerteti a szerző. Bemutatja, hogy nagy pontosságot igénylő relatív nehézségméré-

sekhez (kalibráló alapvonalak, mikrogravimertriai mérések, stb.) szükséges a nehézségi erő vertikális gradiense helyi értékének ismerete, mert az elméleti vertikális gradienssel számított műszermagassági korrekció a relatív nehézségi térerősség értékeket a meghatározási megbízhatóságot elérő, vagy meghaladó szabályos hibával terhelheti.

Az abszolút graviméterekkel — az adott műszerhez tartozó referenciamagasságra — meghatározott nehézséggyorsulási értéket ugyancsak relatív műszerekkel végzett mérésekkel vezetik le a földfelszínen elhelyezett magassági pontjelre. A szerző tapasztalatai szerint ezen levezetések reális pontossága — abban a gyakorlatban sokszor előforduló esetben, amikor a vertikális gradiens helyi értékét egy–két graviméterrel csupán egy mérési sorozattal határozzák meg — nem éri el a szükséges ± 10–20 E értéket.

## ABOUT THE AUTHOR



**Géza Csapó** graduated as a geodesist from the Technical University of Budapest in 1966. He then joined ELGI and specialized in gravimetry. In 1975 he was awarded a postgraduate degree and, in 1984, his Ph. D. —both of them in gravimetry. From 1970 to 1990 he carried out gravity measurements in many European countries, in South-America and in Mongolia. At present he is principal scientific officer in the Earth Physics Department of ELGI. His main field of interest is high precision gravimetry, instrument development, and calibration.