

HUNGARIAN CONTRIBUTION TO THE RESEARCH IN GRAVIMETRY, GRAVITY FIELD MODELLING AND GEOID DETERMINATION - IAG COMMISSION 2

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The gravity field related research has relevant tradition and history in Hungary. Nowadays the most important instruments of the modern gravimetry are the absolute gravimeters, which measure the gravity based on the law of free fall. Our study gives a short summary about the related main research fields and applications, where an absolute gravimeter will provide essential contribution. Beyond some theoretical introduction the possible causes of the time-variable gravity are summarized, the importance of the equipment in gravimetric and geodetic networks is emphasized (Csapó et al, 2011a), and its applications in the geodynamical studies are described. The parameters and capabilities of the A10 absolute gravimeter are also shown (Csapó et al. 2011b).

The Hungarian Gravimetric Network (MGH) is maintained by the Geological and Geophysical Institute of Hungary (the former Eötvös Loránd Geophysical Institute). According to its condition in 2014, the MGH contains 20 absolute stations and 446 1st or 2nd order base points. The maintenance work includes checking the status of base points as well as substitution or installation of destroyed or new base points (Csapó and Koppán 2013). Between 2011 and 2014, 8 base points and one absolute station were reinstalled, and one base point was newly installed. These stations were linked to the 3 nearest MGH base points through relative measurements.

In order to improve the reliability and accuracy of the network, the gravity acceleration was re-determined on 11 absolute stations between 2011 and 2014. The measurements were carried out by using the AXIS FG-5 No. 215 absolute gravimeter operated by the staff of Výzkumný ústav geodetický, topografický a kartografický, v.v.i. (VÚGTK, Czech Republic). Before the absolute measurements, vertical gravity gradient (VG) was determined on every station by LCR-G gravimeters, using a 3-level arrangement and at least 6 series of measurements.

Whereas the VG can deviate significantly from the normal value (-0.3086 mGal/m) in Hungary, vertical gradients were determined on further 24 base points between 2011 and 2014.

To utilize the results of the latest absolute and relative measurements, a new adjustment of the MGH was carried out in 2013. The RMS error (μ_0) of the network was ± 0.0137 mGal (Csapó 2013).

A gravimeter calibration facility exists in the Mátyáshegy Gravity and Geodynamical Observatory of Geological and Geophysical Institute in Hungary. During the calibration a cylindrical ring of 3200 kg mass is vertically moving around the equipment, generating gravity variations. The effect of the moving mass can be precisely calculated from the known mass and geometrical parameters. The main target of the calibration device was to reach a relative accuracy of 0.1-0.2% for the calibration of Earth tide recording gravimeters. The maximum theoretical gravity variation produced by the vertical movement of the mass is ab. 110 μ Gal, so it provides excellent possibility for the fine calibration of LCR gravimeters in the tidal range.

The instrument was out of order for many years and in 2012 and 2013 it was renovated and automatized. The calibration process is aided by intelligent controller electronics. A new PLC-based system has been developed to allow easy control of the movement of the calibrating mass and to measure the mass position. It enables also programmed steps of movements (waiting positions and waiting times) for refined gravity changes. All parameters (position of the mass, CPI data, X/Y leveling positions) are recorded with 1 Hz sampling rate. The system can be controlled remotely through the internet.

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As it is well known, variations of the magnetic field can influence the measurements of metal-spring gravimeters, therefore magnetic experiments were carried out on the pillar of the calibration device as well, in order to analyze the magnetic effect of the moving stainless steel mass. During the movements of the mass, the observed magnetic field changes significantly. According to the magnetic measurements and modelling, a correction for the magnetic effect can be applied on the measured gravimetric data series (Kis et al. 2014, Koppán et al. 2014).

An experimental development of a computer controlled photoelectric ocular system applied for the LaCoste and Romberg G949 gravimeter made the continuous observation of time variation of gravity possible. The system was operated for half a year in the Sopronbánfalva Geodynamical Observatory to test its capabilities. The primary aim of this development was to provide an alternative and self-manageable solution instead of the standard electronic (Capacitive Position Indicator) reading of this type of gravimeter and to use it for the monitoring of Earth tides. It, however, turned out (Papp et al, 2012) that this system is sensitive enough to observe the effect of variable seismic noise (microseisms) due to the changes of ocean weather in the North Atlantic and North Sea regions at microGal level ($1 \mu\text{Gal} = 10^{-8} \text{ m/s}^2$). Up to now little attention was paid to its influence on the quality and accuracy of gravity observations due to the large distance ($>1000 \text{ km}$) between the observation site (generally the Carpathian–Pannonian Basin) and the locations (centres of storm zones of the northern hydrosphere) of triggering events. Based on an elementary harmonic surface deformation model the noise level of gravity observations was compared to the spectral characteristics of seismic time series recorded at the same time in the observatory. Although the sampling rate of gravity records was 120 s, the daily variation of gravity noise level showed significant correlation with the variation of spectral amplitude distribution of the analysed high pass filtered (cut-off frequency = 0.005 Hz) seismograms up to 10 Hz. Available daily maps of ocean weather parameters were also used to support both the correlation analysis and the parameterization of the triggering events of microseisms for further statistical investigations. These maps, which were processed by standard image processing algorithms, provide numerical data about geometrical (distance and azimuth of the storm centres relative to the observation point) and physical (mass of swelling water) quantities. The information can be applied for characterizing the state of ocean weather at a given day which may help the prediction of its influence on gravity measurements in the future. Probably it is the first attempt to analyse quantitatively the effect of ocean weather on gravity observations in this specific area of the Carpathian–Pannonian region.

Based on the results described above an Austrian-Hungarian cooperation started to coordinate the Earth tide monitoring in the Alps-Carpathians-Pannonian Basin region to provide the best fitting tidal models for high precision absolute gravimetry on this specific area (Benedek et al. 2014).

In the 20th century, a large amount of torsion balance measurements have been made in Hungary mainly for geophysical purposes. Only the horizontal gradients were used for geophysical prospecting, the curvature gradients measured by torsion balance remained unused. The knowledge of the figure of the Earth, i.e. the geoid is an important problem from many scientific and practical aspects. The gravity data provide the essential basis for the study of the geoid. In the framework of a collaboration between the Geological and Geophysical Institute of Hungary and the Budapest University of Technology and Economics, the collection of past project reports on Eötvös torsion balance measurements has been started for more than a decade. The torsion balance data reported either in report sheets or on maps have been digitized and collected in uniform databases. Recently, the torsion balance database includes about 45000 records containing the curvature and/or gradient data of Eötvös measurements carried out on the historical territory of Hungary.

Gravity gradients are very important and useful data in geodesy. With the help of the gradients precise vertical deflections can be calculated by interpolation and the fine structure of the geoid can be derived. Based on the horizontal and the curvature gradients of gravity the full Eötvös tensor (including the vertical gradients) can be derived (Völgyesi 2012a, 2012b). A summary of the possible applications of torsion balance measurements can be seen on Figure 1.

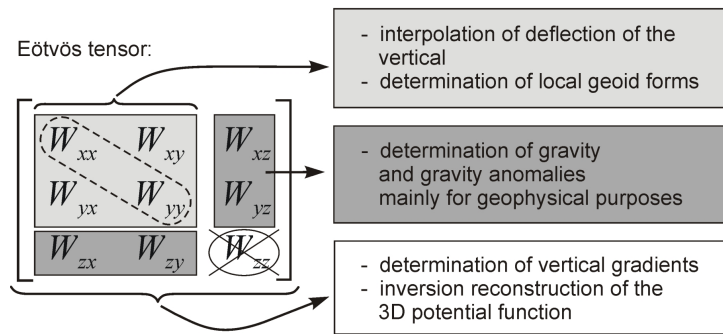


Figure 1. Possible applications of the torsion balance measurements

A laboratory has been developed to make various tests and measurements by the Eötvös torsion balance in the Budapest University of Technology and Economics. These tests were made with our AUTERBAL (Automatic Eötvös-Rybar Balance) equipment. Cameras with CCD sensors were mounted on the reading arms for automatic readout (Völgyesi and Ultmann 2012). Control of the cameras and taking shots was computer-driven with the necessary software developed under the Linux operating system. Since with these cameras several shots and readings per second for a long period of time can be taken, a new perspective is ahead of us to observe hitherto unknown phenomena.

Four shots per second were taken within several, 40-50 min long records in all azimuths to study damping of the balance. Time resolution was increased up to 12 shots per second (i.e. 0.08 s sampling period) to examine the finest details of the damping curve, whereas two 24-hour long records were taken to study possible long-period kinetics of the balance. It became feasible, for example, to study damping characteristics of the device in far more detail and accuracy than it was previously possible.

The main problem of torsion balance measurements is the long damping time, however it is possible to significantly reduce it by our solution. The damping curve can be precisely determined by CCD sensors as well as computerized data collection and evaluation. The first part of this curve makes it possible, at least theoretically, to estimate the final position of the arm at rest. A finite element solution of a fluid dynamics model based on Navier-Stokes equations was investigated to solve this problem.

Our study showed that these achievements may lead to making it possible in the near future to cut down measurement time in each azimuth from 40 to 10 minutes to obtain estimate of the home position of the balance with enough accuracy (Tóth et al. 2014).

Before starting the measurements by torsion balance it is necessary to set the starting azimuth to the astronomical North direction, using a special compass enclosed with the pendulum. Using this special compass the magnetic declination (angle between the astronomical and the magnetic North direction) should be taken into consideration.

The most common geodetic and navigational problem is to determine the precise geomagnetic declination on a given place and time. For lack of the known declination the compass cannot be used with reasonable accuracy neither for geodetic nor for navigational purposes. Determination of the true value of the magnetic declination by field measurements is a complicated and time consuming task. If such a field measurement is carried out, the great advantages, the speed and simplicity, of the application of the compass would be lost. The other remaining possibility is to determine the normal value of declination by computation. In practice, of course, the real value of the declination would be needed, but instead of this, the normal value is used only as an approximation. However, the normal value of the declination, except under very rare circumstances does not correspond to the real value and difference between these two values is the declination anomaly. Using the compass for geodetic or navigation purposes, declination anomaly is the error which biases the determined northern direction. In our study determination of the normal value of geomagnetic declination

$D(\varphi, \lambda, t)$ is discussed and the possible error sources of the determination is attempted to estimate (Völgyesi and Csontos 2014a, 2014b).

Linear variation of the gravity gradients between the adjoining network points is an important demand for different interpolation methods in geodesy (e.g. interpolation of the vertical deflection, geoid computations, and interpolation of the gravity values or the vertical gradients of gravity). To study the linearity of gravity gradients, torsion balance measurements were made both at the field and in a laboratory: one is at the southern part of the Csepel Island, and the other in the Geodynamical Laboratory of Loránd Eötvös Geophysical Institute in the Mátyás Cave.

On Figure 2 the results of the computations are summarized for the 7 points of the earlier torsion balance measurements E220, E218, E238, E208, E206, E204, E207 with and without topographic reduction respectively, and the results for the new torsion balance measurements 3.a-3.b-3.c-3.d-3.e between the points E238 and E208 can be seen.

Based on our results, decreasing the length of the measuring line improves the linearity of gravity gradients (since it increases the values of R^2). Data comparison shows that decreasing distances between the torsion balance points from 1000-1500 m to 150-300 m does not increase significantly the improvement of linearity (Völgyesi and Ulmann 2014).

Finally, it is concluded that the mean point density of the earlier torsion balance measurements does not meet the requirement of linear variation of gravity gradients between neighbouring network points.

Moreover the problem could not be solved even applying topographic reduction. The results of our investigations show that the linearity of the gravity gradients mainly depends on the given point density and the geological fine structure of rocks and shallow subsurface density. It seems the given point density of the earlier torsion balance stations may not be enough for some geodetic purposes, moreover the problem could not be solved applying topographic reduction of gravity gradients (Völgyesi and Ulmann 2014).

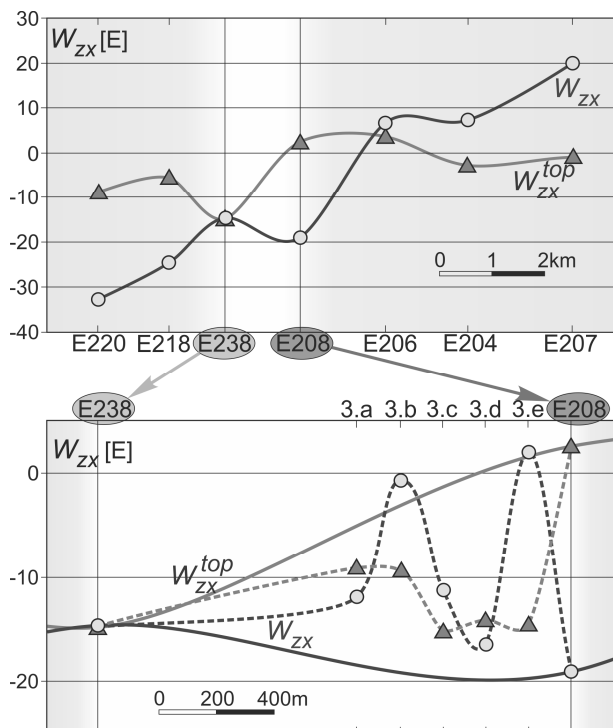


Figure 2. Linearity test of the torsion balance measurements: changing of the horizontal gradient W_{zx} on the original points (upper part of the figure) and on the denser net (lower part of the figure)

Further investigations are planned to study the effects of the nonlinearity on geodetic quantities, regarding e.g. the deflection of the vertical and precise geoid computation. Investigations would be important to study the connection between the spatial structure of the gradients of gravity field and the geological fine structure of rocks near-surface inhomogeneities and shallow subsurface density.

All the elements of the Eötvös tensor can be measured by torsion balance, except the vertical gradient. The knowledge of the real value of the vertical gradient is more and more important in gravimetry and geodesy (Völgyesi et al. 2012).

Determination of the 3D gravity potential $W(x,y,z)$ can be produced by inversion reconstruction based on each of the gravity data $W_z (= g)$ measured by gravimeters and gravity gradients W_{zx} , W_{zy} , W_{xz} , W_{xy} measured by torsion balance. Moreover, vertical gradients W_{zz} measured directly by gravimeters have to be used as reference values at some points. First derivatives of the potential W_x , W_y (it can be derived from the components of deflection of the vertical) may be useful for the joint inversion, too. Determination of the potential function has a great importance because all components of the gravity vector and the elements of the full Eötvös tensor can be derived from it as the first and the second derivatives of this function. The second derivatives of the potential function give the elements of the full Eötvös tensor including the vertical gradients, and all these elements can be determined not only at the torsion balance stations, but anywhere in the surroundings of these points.

For checking the 3D inversion algorithm, test computations were performed at the south part of the Csepel Island where torsion balance and vertical gradient measurements are available. There were about 30 torsion balance, 21 gravity and 27 vertical gradient measurements on our test area. Only a part of the 27 vertical gradient values was used as initial data for the inversion and the remaining part of these points were used for controlling the computation (Völgyesi et al. 2012).

The 27 vertical gradient measurement points can be seen on Figure 3, the structure and the spatial distribution of the values of vertical gradients is illustrated by isolines. The values of the isolines on the Figure 2 is in mGal/m ($1 \text{ mGal/m} = 10^{-5} \text{ 1/s}^2 = 10\,000 \text{ E} = 10\,000 \text{ Eötvös Unit}$), coordinates are in meters in the Hungarian Unified National Projections (EOV) system.

Comparing the measured vertical gradient data to the computed value at the 6 controlling points the root mean square of the differences is $\pm 11.6 \mu\text{Gal/m}$ which is the order of magnitude of the measurements of the vertical gradient.

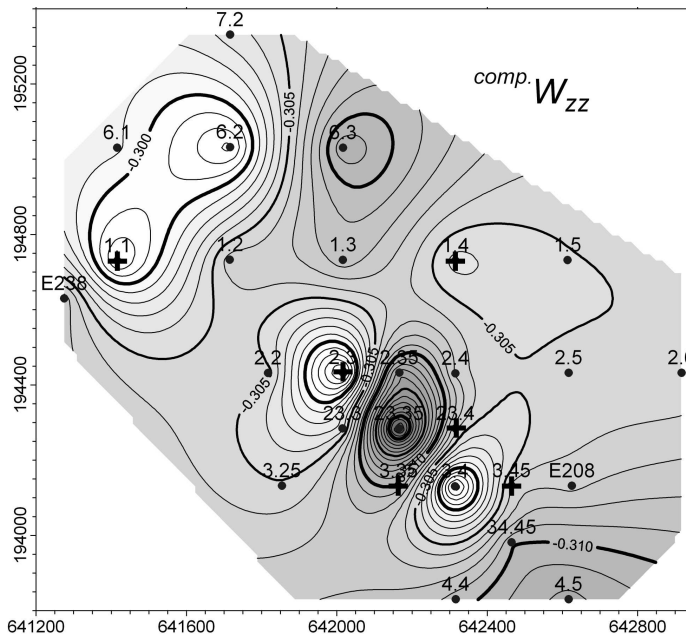


Figure 3. Computed vertical gradients W_{zz} from the joint inversion, values are in mGal/m

So this is a strong demonstration of the applicability of the inversion reconstruction of the gravity potential for the determination of the vertical gradients based on torsion balance data.

Creating the optimal geometry of the interpolation net is an important part of the computation of deflection of the vertical based on torsion balance measurements. The triangle network fitted to the torsion balance stations should be designed to be adequate for the interpolation, namely the distances between the adjacent points should be minimal and the curvature gradients between that selected torsion balance points should be as linear as possible. So far this task has been performed manually with huge efforts furthermore it has not always succeeded in finding the optimal geometry. Delaunay triangulation offers a new opportunity to solve the problem by computer. Selecting the most suitable pairs of points, the automatic creation of the interpolation network is successful by an appropriate modification of the Delaunay triangulation (Ullmann and Völgyesi 2013).

Global gravity field models are most recently refined by GOCE data. As GOCE presents band limited observations, an efficient spectral filtering method for eliminating the unreliable content of the observations is of high relevance. Polgár et al. (2013) has derived an appropriate filter for the purpose. Földvály et al. (2014a) has derived the errors of the filtered gravity gradients using the classical error propagation laws. Földvály et al. (2014b) then implemented the semi-analytical approach for the band-limited GOCE gravity gradient observations.

The unprecedentedly low altitude of the GOCE satellite (demonstrated by Figure 1 of Somodi and Földvály 2011) is also challenging from the orbit determination point of view. Considering purely dynamic orbits, error estimate of GOCE orbit determination has been performed by Somodi and Földvály (2011, 2012). The studies analyzed the “ever” effect of the near surface mass variations by inclusion of high degree gravity field information, an ocean tide model, a reliable estimate of solid earth tides and of polar motion. The investigation has been extended to GPS satellites (at altitude of 20200 km or so) as well, as they serve as the basis of the orbit determination of the GOCE satellite.

The GRACE satellites delivers monthly resolution gravity models enabling the determination of annual or longer periodic mass variations. In a warming climate, it is critical to accurately estimate ice-sheet mass balance to quantify its contribution to present-day sea level rise. In Földvály (2012) temporal mass variations in Antarctica are investigated based on monthly GRACE gravity solutions. In order to diminish the effect of large uncertainties in glacial isostatic adjustment models, an approach is developed to estimate the acceleration of the ice-sheet mass, assuming the presence of accelerated melt signal in the GRACE data. Though the estimate of accelerated melt does not provide an absolute value for the volume of the melting ice, it was found to be a viable tool for characterizing the present-day ice sheet mass balance. The method has been refined by separation of different regions of melt rates by Földvály et al. (2014).

A new quasigeoid model for Hungary was determined by combining gravity data, GPS/levelling and vertical deflections (Tóth and Szűcs 2011). Reduction of the measurements was performed by using Earth Gravitational Model 2008 (EGM2008) and Shuttle Radar Topographic Mission (SRTM) elevation data sets. Calculation method was Least Squares Collocation (LSC) with Forsberg’s self-consistent planar logarithmic covariance model. In the computations the weights of GPS/levelling data were large, in this way normal heights obtained from levelling are consistent with GPS heights and with the quasigeoid model. Astrogeodetic-gravimetric, pure astrogeodetic and pure gravimetric solutions have been calculated besides the combined solution to investigate the discrepancies among the different models. The combined quasigeoid model fits to the GPS/levelling data with standard deviation of ± 4.9 cm, nevertheless at some GPS/levelling sites large differences were indicated. Comparison of the astrogeodetic-gravimetric and combined quasigeoid solutions shows a mean bias of -2.74 cm and a standard deviation of ± 3.04 cm. These two solutions are very close to each other in most parts of the country (Figure 4.), except for the region in southeast, where the GPS/levelling observations do not fit well to the other observation types. This region is located in the Great Hungarian Plains, which is covered by young, unconsolidated sediments. In this context the main problem is that levelling and GPS measurements do not refer to the same epoch. First-order polygons of the Unified National Vertical Network (EOMA) were measured in the 1970s, the OGPSH network was established in the 1990s.

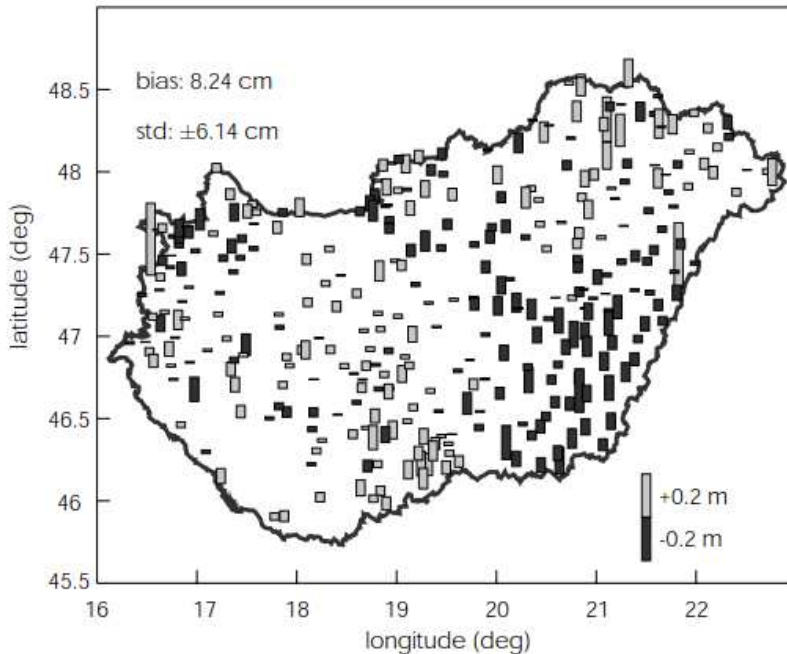


Figure 4. Differences of astrogeodetic-gravimetric quasi-geoid heights at OGPSH sites (bias removed)

Furthermore, levelling of the GPS/levelling sites was achieved using the third order levelling network of the country, not the first order one and besides of this GPS observations were carried out using rapid measurement technology. Processing of re-measurement data of part of the EOMA levelling network confirms a suspected recent subsidence.

Recent high degree geopotential models and certain computational procedures in physical geodesy require the evaluation of integrals (truncation coefficients) that are products of very high degree Legendre polynomials (or functions) with various kernels over a given domain. The oscillating character of integrands (more than 10,000 zeros) makes it difficult to evaluate such integrals. A highly accurate quadrature has been developed for fast computation of these integrals based on the Glaser-Liu-Rokhlin root finding algorithm and Gauss-Lobatto quadrature between the roots (Tóth and Fánicsikné 2013). Our procedure successfully eliminates the instability of the recursive algorithm developed by MK Paul for the solution of Stokes' integral at very high degrees. It can be applied in several fields of physical geodesy, e.g. for gravity field modelling based on surface or satellite gravity gradients.

Szűcs (2012) presents the validation of the first and second generation GOCE-only models using terrestrial data sets in Hungary. Besides GOCE-based GGMs satellite only GRACE models were evaluated to assess the improvements by GOCE observations with respect to GRACE in gravity field determination. EGM2008 as the state-of-the-art model and SRTM3 elevation model were applied to provide that measurements involving Hungarian data sets and model derived gravity field functionals have almost the same spectral content. Results with GPS-levelling and gravity data support that there is an improvement in the determination of medium-wavelength parts ($200 < \lambda < 250$ km) of the gravitational field with GOCE models. Although vertical deflections characterize the short-wave part of the gravity field, they are also capable of sensing the advancement of SGG observations.

Szűcs et al. (2014) investigated the spectral characteristics of terrestrial data sets mentioned above. They estimated the spectral contribution of gravity anomalies, vertical deflections and gravity gradients using both Fourier PSD and covariance analysis depending on the spatial distribution of data points. From the spectral characteristics of terrestrial measurements weights for spectral combination of a global gravity field model, gravity and gravity gradient data were derived. Besides the

frequency domain investigations the information content regarding the different wavelength structure comprised in terrestrial and EGM2008 model was investigated also in the space domain based on covariance analysis. As a combined validation process the gravity degree variances were transformed to the necessary auto- and cross covariance functions to predict geoid height from gravity anomaly, which ensures an independent validation process of the computed spectrum.

Special attention was paid to the evaluation of SRTM3 surface model which has been extensively used for residual terrain modelling recently. On a well surveyed local, partly forest-clad area Papp and Szűcs (2011) determined its deviation from a digital terrain model digitized from 1:10 000 topographic maps and found close correlation between the deviations and canopy heights reaching sometimes 10 m – 15 m. They transformed the height differences to a 3D mass density model discretized by rectangular prisms to derive gravity anomalies, geoid heights and second derivatives by forward gravitational modelling. The direct gravitational effect of the differences between surface and terrain models is insignificant (< 1 mm) on geoid heights but it is considerable if terrain corrections for gravity anomalies and torsion balance measurements are required for geophysical interpretation.

Szűcs and Benedek (2014) extensively investigated in which frequency band gravity gradients measured by Eötvös torsion balance could contribute to the refinement of gravity field features. They used different kernel modifications of the gradiometric boundary value problems in the numerical evaluation of integral transforms, especially the integrals transforming horizontal gravity gradients to vertical gravity gradient, to gravity anomaly and to potential. Closed-loop differences between gravity field quantities derived from integral transforms and their “true” value obtained from EGM2008 GGM were synthetically analysed for various wavelength bands both in space and in frequency domain.

In order to support the evaluation of different geoid solutions based on physical approaches (e.g. gravimetric geoid) the development of a digital zenith camera system (DZCS) has been started in the Research Centre for Astronomy and Earth Sciences, Hungarian Academy of Sciences. DZCS-s are astronomical-geodetic measurement systems for the observation of the direction of the plumb line. The DZCS key component is a pair of tiltmeters for the determination of the instrumental tilt with respect to the plumb line. Highest accuracy (i.e., 0.1 arc-seconds or better) is achieved in practice through observation with precision tiltmeters in opposite faces (180° instrumental rotation), and through application of rigorous tilt reduction models. A novel concept proposes the development of a hexapod- (Stewart platform)-based DZCS. However, hexapod-based total rotations are limited to about 30° - 60° in azimuth (equivalent to $\pm 15^\circ$ and to $\pm 30^\circ$ yaw rotation), which raises the question of the impact of the rotation angle between the two faces on the accuracy of the tilt measurement. Hirt et al. (2014) investigated the expected accuracy of tilt measurements to be carried out on future hexapod-based DZCS, with special focus placed on the role of the limited rotation angle. A Monte-Carlo simulation study is carried out in order to derive accuracy estimates for the tilt determination as a function of several input parameters, and the results are validated against analytical error propagation. As main result of the study, limitation of the instrumental rotation to 60° (30°) deteriorates the tilt accuracy by a factor of about 2 (4) compared to a 180° rotation between the faces. None the less, a tilt accuracy at the 0.1 arc-second level is expected when the rotation is at least 45° , and 0.05 arc-second (about 0.25 microradian) accurate tilt meters are deployed. Consequently a hexapod-based DZCS can be expected to allow sufficiently accurate determination of the instrumental tilt. This provides supporting evidence for the feasibility of such a novel instrumentation.

In view of the recent re-measurement campaign of the Hungarian Levelling Base Network the role of gravimetric observations was studied (Kratochvilla et al. 2011). Adjustment of the network was performed using geopotential numbers, which can be converted into an equivalent metric quantity, the normal heights. The normal heights can also be derived directly from raw observed height differences by adding two normal correction terms, K_1 and K_2 . Both of them have been determined based on an earlier network adjustment. The second term, K_2 is a function of Δg along the levelling line, which is implicitly an estimate of the effect of long-wavelength gravity field. The accuracy demand of gravimetric data for normal correction under different terrain conditions was discussed.

In the recent years several investigations have been performed on the newly constructed subway line of Budapest, line no. 4 (Metro 4). From the physical geodetic aspect the effect of the excavation on the gravity field (potential surfaces, plumb lines) is of interest. In fact, the change of the gravity field may affect the monitoring of the vertical deformation during the construction, as the method of repeated leveling assumes the local horizontal and vertical to be constant in time (Égető and Földváry 2011). In the study of Égető et al. (2014) the direct effect of the mass loss on leveling measurements due to the excavation of the two tunnels and of the stations of Metro 4 has been considered. The corresponding numerical accuracy issues are presented by Égető and Földváry (2013). The method has been refined by inclusion of the indirect effect of the actual vertical deformations (subsidence) of the physical surface on the leveling in Égető et al. (2013). According to the results, under certain arrangements of the leveling line, the direct effect can reach the 5 μm order of magnitude, which is equivalent to the precision of the precise leveling, while the indirect effect due to subsidence is below 0.1 μm , thus negligible.

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