PhD THESES

EÖTVÖS-TORSION BALANCE MEASUREMENTS AND THEIR GEODETIC APPLICATIONS

ZITA JÚLIA ULTMANN

BUDAPEST UNIVERSITY OF TECHNOLOGY AND ECONOMICS,
DEPARTMENT OF GEODESY AND SURVEYING

Supervisor:

Dr. Lajos Völgyesi

University Professor

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I. Topicality and Background

In Hungary, about 60 000 torsion balance measurements had been carried out, mainly for the geophysical prospecting, in the 20th century before the end of the 1960s. Though data gained from Eötvös torsion balance measurement may be used in geodesy, their full potential for practical application in geodetic purposes is still not fully exploited. With the current, rapid penetration of GPS and various satellite-based techniques, there is an increasing demand for the high-precision definition of geoid shapes. Curvature gradients as measured by the Eötvös torsion balance serve as an important database for this task. At the Department of Geodesy and Surveying of Budapest University of Technology and Economics (BME), the use of Eötvös torsion balance data in geodesy has been intensely researched for decades, yielding several significant scientific results. A powerful software is available now for the interpolation of deflection of the vertical, the fine structure of geoid, the interpolation of vertical gradients and the definition of gravity and gravity anomalies using Eötvös torsion balance data. However, each scientific problem solved has given rise to new sub-problems and unsolved tasks. As an undergraduate, I joined the team to solve these problems and tasks. I presented my research results in several entries at the annual Scientific Contests for Students (TDK) and in my MSc thesis. As a PhD student, I performed a several-year long research in this field. My results have been published in 7 papers in foreign languages and in 5 Hungarian ones and I have also presented them at 14 different scientific seminars and conferences.

II. Research Objective

My research is based on my respect for traditions on one hand; I wished to carry on with the traditions of Loránd Eötvös's work. On the other hand, I wished to contribute to our invaluable national heritage and successfully exploit the data from the previous 60 000 Eötvös torsion balance measurements in geodesy.

My first important aim of research was to become fully familiar with the operation of the Eötvös torsion balance and the measuring techniques. As a related task, first I had to complete measurements with the AUTERBAL balance of BME's

Department of Geodesy and Surveying. This balance had been renovated using state-of-the-art technology.

As the change in gravity gradients between two points should be essentially linear in order to be able to interpolate Eötvös torsion balance data (deflection of the vertical, vertical gradients, gravity anomalies), my next important task was to test the data for linearity. An important aim of my research was to define vertical gradients. Vertical gradients cannot be directly measured by the torsion balance; however, interpolation is possible using horizontal and curvature gradients as measured by the Eötvös torsion balance.

Other aims of my research included the improvement of the existing interpolation algorithm by creating a system to automatically develop optimum interpolation networks fitted on Eötvös torsion balance stations where the triangle points facilitate the most precise interpolation possible by ensuring a change in curvature gradients along the edges of the triangles as close to linear as possible. I also had to consider changes in gravity gradients according to altitude. When defining high precision geoid shapes, gradient values measured at various altitudes should be converted for a uniform geoid (sea level).

III. Theses (Independent Scientific Results)

Thesis 1 Eötvös torsion balance measurements have become necessary again after almost half a century in Hungary for various reasons but mostly for examining the interpolation processes for vertical gradients. Having joined the project of renovating an AUTERBAL balance at BME's Department of Geodesy and Surveying, I performed a high number of measurements with the torsion balance, following various calibration tasks. I performed targeted tests to confirm, whether 40 minutes of damping after starting the device was enough to establish thermal equilibrium in field measurements and if not, how long would be the recommended duration before the first reading. **According to my results, 90 minutes is required in the majority of cases to establish the thermal balance, regardless of whether the measurements were performed with a hot device under cold conditions or the other way round, when the temperature difference did not exceed 5°C. Inside the torsion balance box, the**

temperature is still being balanced after 90 minutes; however, readings already change linearly then, thus the measured results are suitable for analysis. In another series of tests, I was examining the impact of the regularly occurring large temperature variations during measurements. **I found that readings vary according to the inside temperature of the torsion balance (i.e. that of the torsion wires) but they are also influenced almost immediately and very markedly by temperature variations in the reading arms. Changes in scale readings are lagged and significantly weaker compared to variations in the inside temperature of the torsion balance** and are rather manifested as a trend in readings. **The majority of small changes are caused by the sensitivity of torsion wires to temperature while virtually immediate changes result from the thermal expansion of reading arms**. The ultimate goal would be to develop a method to correct readings for temperature; however, several measurements and further tests are needed to achieve this. This is an important issue regarding precision, as my tests indicated an expressed sensitivity of the torsion balance to temperature variations already in the range of a few tenths of a degree Celsius, almost impossible to avoid under field conditions.

Related publications: 1; 4; 10; 11; 22; 25; 26

Thesis 2 I also tested the magnitude of the impact of the incorrect setting of the starting azimuth on the gradients established by the Eötvös torsion balance. The position of the starting azimuth is established by the ’bussola’ (a special compass) supplied to the torsion balance. However, when adjusting the azimuth, the difference between the required astronomical (true) North and the magnetic North given by the needle of the compass should be considered, also bearing in mind that this difference known as magnetic declination shows significant variations in time and space. While also considering the difference between the normal and real values of magnetic declination as well as regular daily fluctuation and sudden magnetic storms **I found that the starting azimuth of the torsion balance may occasionally be maladjusted by several degrees** (At the gravity base point in Mátyás Cave, the deviance is 6°27’). I performed laboratory measurements in Mátyás Cave as well as field tests in the southern part of Csepel Island and also did model calculations to estimate the magnitude of deviances in computed gradients caused by a potential several-degree incorrect setting of the starting azimuth. **According to my findings, gradients established by**

the Eötvös torsion balance are extremely sensitive regarding the precise adjustment of the starting azimuth. Furthermore, the worst deviances were experienced in the case of curvature gradients i.e. the most important gradients for geodetic use. While horizontal gradients deviate by 20-25E between the true and the magnetic azimuth, the difference in curvature data may be as high as almost 50E. This is why the bussola should be applied with extreme care when setting the starting azimuth. At locations like the Mátyás Cave Geodynamical Station, the bussola is practically unsuitable for precisely setting the starting azimuth due to the marked adverse impact related to the presence of electric and magnetic equipments. At such locations, other geodetic methods may prove to be useful to determine the true North (e.g. using a girotheodolite). I also tested the correlation between gradient values and the precision of initially setting the starting azimuth under average field conditions, for example at one location in Makád on an ordinary plain with low gradient values. **I found that also here, gradients depended on the precision of setting the starting azimuth. Even at locations with low gradients, magnetic declination anomalies of a few degrees only could result in 5-10E deviations when compared to the measurement performed in the 0° starting azimuth.**

Related publications: 10; 11; 27

Thesis 3. In the case of practical calculations for the interpolation methods based on torsion balance results, the linear change of W_{zx}, W_{zy} gravity gradients and W_{Δ}, W_{xy} curvature values between two points is essential. While performing my research, I started to doubt whether the point density from the earlier hungarian torsion balance measurements always sufficed as the change in gradients cannot be considered linear even within short distances at locations with high gradients, due to the high amplitude of high frequency changes in particular. The accuracy of deflection of the vertical, geoid undulation and vertical gradients as determined by interpolation obviously depends on the linearity of gradient changes between two neighbouring Eötvös torsion balance stations. To clarify this relationship, I performed measurements and model calculations both in Mátyás Cave, characterised by marked gradient changes, and in the southern part of Csepel Island that shows minor ones. I found that in Mátyás Cave, only the changes in W_{zx} may be considered linear within 2 meters and even this applies to the North-South direction only. The location is characterised by a high variability within short distances. Changes in the horizontal gradient W_{zy} may only be considered generally linear within 30-60 cm and the same applies to the changes in the curvature data W_{Δ} and W_{xy}; for the latter two, changes could not be considered linear at some locations even within 60 cm. Changes in W_{Δ} in particular warn about **the uncertainty regarding the linearity of data, even within a few decimeters at locations with extremely large gradients like Mátyás Cave.** I considered useful to test linearity on Hungarian plains with a more ordinary topography. In the southern part of Csepel Island the torsion balance measurements performed in the 1950s applied the point density normally applied in Hungary. In 2007 and 2008, the same area was surveyed again but by a significantly higher point density. I also participated in this project. **Relying on the R^2 values of Csepel Island measurements and calculations, I found that linearity did not improve significantly when the distance between measuring points had been reduced from 1000-1500m to 150-300m.** This finding led to the conclusion that by the average point density used for the measurements on Csepel Island in 1950, the linearity of gradient changes between two neighbouring points could not be guaranteed. **I also found that topographic reduction could not improve this situation either, as gradient changes between two points as corrected by topographic reduction still could not be considered linear.** Even if density anomalies on the surface are corrected for by topographic reduction, too much variability in the density of subsurface rocks will bias results.

Related publications: 2; 3; 4; 5; 11; 12; 14; 15; 16; 18; 20; 21; 22; 25; 26; 27; 29; 30

Thesis 4. The analytical determination of potential surfaces requires vertical gradient values too. Unfortunately, these are the only values in the Eötvös tensor that cannot be measured by the Eötvös torsion balance. Their direct measurement is a rather long and costly process, this is why another method should be found with better applicability. Two methods are available at the moment to calculate vertical gradients. Fortunately, both methods rely on Eötvös torsion balance data. One method is given by the paper of Haalck (1950), while the other relies on the 3D inversion reconstruction of gravity potential functions. **I compared the results yielded by**

Haalck’s method to those of the inversion process. I found that the inversion process is less sensitive to nonlinear changes in the horizontal and curvature gradients as determined by the Eötvös torsion balance, thus providing more precise vertical gradient values than the other method.

Related publications: 4; 5; 7; 8; 17; 19; 22; 25; 26

Thesis 5. The most important applications of Eötvös torsion balance data in geodesy are the interpolation of the deflection of the vertical and the determination of fine structure of geoid. An important step when starting with the interpolation of deflection of the vertical based on torsion balance data is to fit an interpolation network on the measuring points where the points of the triangles building up the network facilitate interpolation with the highest possible precision by means of providing for a change of curvature gradients as liner as possible along the edges. These calculations have been thus far supported by a single, rather complicated software where the points of the interpolation network should be selected individually by the user and the pairs defining the edges of the triangles are also chosen manually. For larger areas, these tasks are extremely labour intensive; furthermore, the definition of optimum network geometry is also compromised. Our future goal is to determine deflection of the vertical for the almost 44 000 Eötvös balance measuring points in Hungary. This is only possible if this proven software is complemented with an algorithm that is able to automatically create optimised interpolation networks. **Using the principles of the Delaunay-triangulation and applying a specific fine tuning to it (i.e. applying a filtering threshold of *p = 1/2* based on the ratio of the lenghts of edges) I successfully automatised the thus far most labour intensive phase of the interpolation of deflection of the vertical based on torsion balance data, also considered as the weakest link of the process, the definition of optimum interpolation network geometry. According to my preliminary results, the geometry defined this way provides for higher precision interpolation.**

Related publications: 13; 22; 23; 25; 26

Thesis 6. When using Eötvös torsion balance data for geodetic purposes, the ultimate objective is usually the determination of the fine structure of the geoid forms.

When gravity gradients are used for this, values measured at various altitudes might need to be converted for the same potential surface that is the geoid (sea level). I tested the correlation between changes in various gradients and altitude. I used two mass models for my research. One of these was the model of the water mass for the 2002 flood on the Danube and the other one the model of the rapidly changing mass in the water reservoirs of Gellért-hegy. My most important findings are listed below. **I found that the most marked changes in gravity gradients are related to locations on the ground and directly below the surface above points characterised by lateral inhomogenous density (the edge of the examined mass models). These changes rapidly diminish with increasing altitude. By the sensitivity of currently used devices, this "edge effect" is practically undetectable in gradients at altitudes as low as 50-100m. In the case of extended masses examined by us, where the edge effect is less expressed, gradients change slower with the altitude over the centre point. Thus, gradient changes caused by inhomogeneous density may also be detected at higher altitudes. Nevertheless, by the currently available measuring technique, changes in gradients measured by the Eötvös torsion balance cannot be detected at all at altitudes exceeding a few hundred meters. The correlation between the vertical gradient, particularly important in gravimetry, and altitude and the deviance of vertical gradient values from normal values are caused by local factors, mostly by density inhomogeneities directly under the surface.**

Related publications: 6; 9; 22; 25; 26; 28

IV. Practical Relevance of Results

Gradient values measured by the Eötvös torsion balance from the beginning of the 20th century until the end of the 1960s are available for 44 000 points in Hungary, covering a significant part of the country. These data are stored in a digital database and available for geodetic utilisation. My research results complement those from previous works and as such facilitate the interpolation of deflection of the vertical and the related definition of high precision geoid shapes in Hungary relying on astronomical leveling.

Own Scientific Papers Related to Theses

Book sections or chapters

[1] *Völgyesi L, Ultmann Z* (2012): Reconstruction of a torsion balance, and the results of the test measurements. Geodesy for Planet Earth, Buenos Aires, Argentína. 2009. International Association of Geodesy Symposia, Vol. 136, Springer-Verlag; Berlin, Heidelberg, ISBN: 978-3-642-20337-4. pp. 281-290.

[2] *Völgyesi L, Ultmann Z* (2013): High-resolution measurements of non-linear spatial distribution of gravity gradients in Hungary. IAG Symposia series, Melbourne, Ausztrália. Vol. 139., Springer-Verlag; Berlin, Heidelberg (accepted to publication)

[3] *Ultmann Z* (2012): Linearity analysis of the Eötvös-tensor. Proceedings of the Conference of Junior Researchers in Civil Engineering 2012 (szerk: Józsa J, Lovas T, Németh R). Budapest, Budapesti Műszaki és Gazdaságtudományi Egyetem, ISBN: 978-963-313-061-2, pp. 262-266

[4] *Ultmann Z* (2013): Geodetic application of the Eötvös torson balance. Proceedings of the Second Conference of Junior Researchers in Civil Engineering 2013 (szerk: Józsa J, Lovas T, Németh R). Budapest, Budapesti Műszaki és Gazdaságtudományi Egyetem, pp. 23-30

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[5] *Csapó G, Laky S, Égető Cs, Tóth Gy, Völgyesi L, Ultmann Z* (2009): Test measurements by Eötvös torsion balance and gravimeters. Periodica Polytechnica, Civil Engineering. Vol. 53, Nr. 2 pp. 75-80. ISSN 1587-3773

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[9] *Völgyesi L, Ultmann Z* (2007): Height variation of gravity gadients, Geodézia és Kartográfia. Vol. LIX, Nr. 8-9, pp 11-23.

[10] *Völgyesi L, Égető Cs, Laky S, Tóth Gy, Ultmann Z* (2009): Reconstruction of a torsion balance, and test measurements in the Mátyás cave in Budapest, Geomatikai Közlemények, XII., pp 119-130.

[11] *Völgyesi L, Csapó G, Laky S, Tóth Gy, Ultmann Z* (2009): Közel fél évszázados szünet után ismét Eötvös-inga mérések Magyarországon, Geodézia és Kartográfia, Vol. LXI, Nr. 11. pp 71-82.

[12] *Völgyesi L, Ultmann Z* (2010): Question of linearity of the gravity gradients in the Mátyás-cave, Geomatikai Közlemények 2010, XIII/2. pp 123-128.

[13] *Ultmann Z, Völgyesi L* (2013): Creating optimal geometry by Delaunay triangulation for interpolation of deflection of the vertical, Geomatikai Közlemények, (accepted to publication)

Other Publications

Conference Proceedings

[14] *Ultmann Z* (2009): Computation of the gravimetric effect of Mátyás-cave and its surroundings, OTDK Konferencia-2009, Miskolc, Miskolci Egyetem

[15] *Ultmann Z* (2009): Computation of the gravimetric effect of Mátyás-cave and its surroundings, MFTTT Vándorgyűlés-2009, Nyíregyháza, Nyíregyházi Főiskola

[16] *Ultmann Z* (2010): Computations and measurements of gravity gradients in the Mátyás-cave, Ifjú Szakemberek Ankétja-2010, Mátrafüred, Hotel Avar

[17] *Ultmann Z* (2010): Comparing different mass models of the waterlevel fluctuations of the river Danube, Sixth PhD & DLA Symposium, October 25-26. 2010, Pécs

[18] *Ultmann Z* (2010): Computations and measurements of gravity gradients in the Mátyás-cave, Rédey István Geodéziai Szeminárium, 2010. április 1, BME

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[23] *Völgyesi L, Ultmann Z* (2012): Creating optimal geometry by Delaunay triangulation for interpolation of deflection of the vertical, VIII. Geomatika Szeminárium, 2012. november 8-9, Sopron

[24] *Völgyesi L, Ultmann Z* (2013): Precision analysis of the starting azimuth of the Eötvös-torsion balance, Rédey István Geodéziai Szeminárium, 2013. április 18, BME

[25] *Ultmann Z* (2013): Geodetic application of the Eötvös torsion balance, Kárpát-medencei Földtudományi Doktori Iskolák Nemzetközi Konferenciája, 2013.június 7-8, Pécs

[26] *Ultmann Z* (2013): Geodetic application of torsion balance, Second Conference of Junior Researchers in Civil Engineering, 2013. június 7-8, BME

Entry at the Scientific Contests for Students, National Level (OTDK)

[27] *Ultmann Z* (2009): Computation of the gravimetric effect of Mátyás-cave and its surroundings, XXIX. OTDK Műszaki Szekció Tanulmányai, pp. 45-49.; 3rd place

Entry at the Scientific Contests for Students (TDK)

[28] *Ultmann Z* (2006): Height variation of gravity gradients, BME Faculty of Civil Engineering, TDK, Session of Geodesy, Surveying and Photogrammetry, 2nd place

[29] *Ultmann Z* (2007): Computation of the gravimetric effect of Mátyás-cave and its surroundings; BME Faculty of Civil Engineering, TDK, Session of Geodesy, Surveying and Photogrammetry, 2nd place

[30] *Ultmann Z* (2008): Measurements with the Eötvös-torsion balance, BME Faculty of Civil Engineering, TDK, Session of Geodesy, Surveying and Photogrammetry, 3rd place