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Accuracy analysis of the MOM Gi-B3 gyrotheodolite and extension of the orientation transfer by inertial navigation and autocollimation

Theses of the PhD dissertation

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1 Preliminaries

1.1 Technological and scientific background

Gyrotheodolite is a geodetic instrument for high-precision orientation, primarily used in the field of engineering surveying mainly for high-precision orientation transfer in connection with the construction of underground facilities. Applying the gyrotheodolite has, to date, been the most economic solution for orientation underground requiring some arc seconds' accuracy, though it is not the only solution any more. Gyrotheodolites are used for military purposes, as well.

The inertial-autocollimation procedure elaborated by the surveyors of the Chair of Geodesy of the Technische Universität München[1] after the millennium is also suitable for orientation with some arc seconds' accuracy. This procedure combines, for the purpose of orientation transfer, the measurement of angular rotation performed by an inertial measurement unit equipped with laser gyros and the autocollimation-based measurement of horizontal angles performed by autocollimation-theodolites in respect of a prism, mirror or theodolite physically connected to the measurement unit.

Different types of gyrotheodolites were manufactured in Magyar Optikai Művek (Hungarian Optical Works) from 1963 to 1990. Numerous publications primarily dating back to the '60-ies and '70-ies and the DSc Dissertation of Professor Halmos (Halmos, 1970-1971) submitted to the Hungarian Academy of Sciences are dedicated to the accuracy analysis and the geodetic applications of gyrotheodolites manufactured by MOM. The gyrotheodolite type MOM Gi-B3 supplied with a mechanism to autotrack the gyro's oscillation and analogous optical readout units is the last MOM gyrotheodolite manufactured in quantity production. Its application came to the fore in the early 2000's in connection with the construction of the Budapest Metro Line 4 finally started in 2006. There are only a few publications that can be related to this particular type of instrument, although the accuracy analyses published in respect of the instruments type Gi-B1 and Gi-B2 are also valid for the instrument type Gi-B3 in many respects. Certain issues of the accuracy analysis of the instrument type MOM Gi-B3, especially the effects of systematic and random errors due to temperature changes and centering and setup eccentricities, were not clarified at the time starting my PhD researches in 2004.

The transfer of the bearing by combination of autocollimation with a high-precision inertial navigation system along a vertical trajectory, which can be related to

[1] Technische Universität München, Lehrstuhl für Geodäsie

Professors Heister, Ingensand and Wunderlich and doctoral candidate Neuhierl, was published by Wunderlich, Neuhierl, Ingensand and their co-authors in 2005 and 2006 (Wunderlich and Neuhierl, 2005; Neuhierl, 2005; Neuhierl et al., 2006). The authors used the procedure at the time of the construction of the Gotthard Base Tunnel for the independent control of the transfer of the geodetic network orientation performed by gyrotheodolites. Based on the published results it can be established that by means of the inertial-autocollimation procedure it is possible to ensure an orientation transfer with an accuracy similar to that of the orientation accuracy of the gyrotheodolite. All the aforesaid is a significant new scientific achievement. However, part of the communicated precision and accuracy parameters fell short of expectations, so, in the hope of increasing precision and accuracy, in the autumn of 2005, i.e. at the beginning of my research work in Zurich, Professor Ingensand proposed to me to process the raw measurement data in an alternative calculation procedure.

1.2 Institutional and professional background, resources

Beyond the described status of technology and science, it is inevitable that the course of my professional advance and the research was influenced by several circumstances and the development of things and acquaintanceships. In the following I describe the chronology of these research preliminaries.

The preliminaries of my research work as a PhD student included a one-year professional traineeship spent in Zurich and the benefits of this traineeship organised by I.A.E.S.T.E. and Magyar Mérnökhallgatók Egyesülete. During this period I got acquainted with the Swiss Gotthard Base Tunnel Project as an "onlooker". I contacted Professor Ingensand specialised in geodetic metrology at the Institute of Geodesy and Photogrammetry of ETH Zürich[2] and the surveying engineers working on the Project. During a three-month traineeship spent at Swissphoto AG in the summer of 2003 I familiarised myself with the geodetic works of the Gotthard Base Tunnel, (which was) at that time under construction. I participated in different measurement campaigns and studied the geodetic guidance of the cutter head of the tunnel boring machine, which I later set forth in a scientific student association's paper at the Faculty of Civil Engineering of the Budapest University of Technology and Economics (BME).

In the spring of 2004 I prepared a diploma thesis entitled "The application of gyrotheodolites in the geodetic network of Budapest Metro Line 4" at the

[2] Eidgenössische Technische Hochschule Zürich, Institut für Geodäsie und Photogrammetrie

Department of Geodesy and Surveying of the Faculty of Civil Engineering of the Budapest University of Technology and Economics[3]. My supervisors were Dr. Károly Dede (BME Department of Geodesy and Surveying) and Ferenc Hörcsöki (Hungeod Kft.). The objective of my work prepared in cooperation with Hungeod Kft. of Budapest was to prepare for the use of gyrotheodolites in relation to the future construction of the metro line. At that time I used for my measurements an instrument type MOM Gi-B3 owned by a successor company of MOM.

I started my PhD studies at the Department of Geodesy and Surveying of the Faculty of Civil Engineering of the Budapest University of Technology in September 2004; my supervisors were Dr. József Ádám and Dr. Károly Dede. With the support of the Hungarian National Eötvös Scholarship I performed scientific research work under the supervison of Professor Ingensand at the Institute of Geodesy and Photogrammetry of ETH Zürich from 18 October 2005 to 19 May 2006. During this period I elaborated an estimation method to process the orientation transfer with inertial navigation and autocollimation. In the meantime, the BME Department of Geodesy and Surveying purchased a gyrotheodolite type MOM Gi-B3 which was investigated in collaboration with my fellow PhD student Csaba Égető using the climate chamber of the ETH Zurich in spring 2006. By carrying out experimental measurements we determined the temperature characteristic curve of this particular MOM Gi-B3 gyrotheodolite and applied it subsequently on the construction of the Gotthard Base Tunnel in Switzerland for orientation transfer.

In 2006 Hungeod Kft. and the BME Department of Geodesy and Surveying established a surveying consortium related to the construction of Budapest Metro Line 4. In this function the Department was entrusted with performing certain azimuth measurements determined by gyrotheodolite in connection with the construction of the metro line. These tasks were accomplished in the next two years with the participation of several colleagues of the Department.

As of the autumn of 2006, residing in Zurich I continued the research work in addition to part-time employment. As an employee of the Terra Vermessungen AG of Zurich, I joined the development work of calibrating a kinematic measuring system supplied with a laser scanner. Simultaneously with this, we performed field test measurements in Budapest, using the gyrotheodolite of the BME Department of Geodesy and Surveying. I arranged the results of the one-year gyrotheodolite, inertial and laser scanner work into three publications by the end of the autumn

[3] Budapesti Műszaki Egyetem, Építőmérnöki Kar, Általános- és Felsőgeodézia Tanszék

academic semester. They were published in April 2007. As of February 2007 I continued, with interruptions, the research work as a correspondence PhD student of the Department of Geodesy and Surveying of the Budapest University of Technology and Economics at my residence in Zurich and later on in Basel. From February 2008 to the summer of 2015 I was employed by the TBF+Partner AG engineering office of Zurich as a surveying engineer.

My researches dealing with the orientation transfer by means of gyrotheodolites such as the orientation transfer by inertial navigation and autocollimation resulted, as a logical continuation of both of these researches, in the idea of optimising and extending the latter procedure to a horizontal measurement trajectory. I could perform these measurements and the simultaneous comparison of the IMU autocollimation method and the orientation transfer by surveying gyroscope in October 2010, after one and a half year's consultative preparatory work, in the laboratory of the Chair of Geodesy of the Technische Universität München in cooperation with Professor Wunderlich, Head of the Department. Processing the inertial measurements with the previously described estimation method provided partially unsatisfactory results. As a consequence of this, I have elaborated a new functional and mathematical model, providing satisfactory results.

2 Objectives

The objectives of the research indicated in the title of the dissertation can be drawn up as follows:

- determining the earlier non-examined sources and effects of errors of the MOM Gi-B3 gyrotheodolite based on test measurements, with particular regard to becoming familiar with and eliminating the error effects that can be attributed to temperature changes and the centering equipment;
- optimising the precise azimuth determination and orientation transfer performed by MOM Gi-B3 gyrotheodolite; increasing their precision and accuracy and quantifying these parameters and setting forth the optimised procedure;
- examining the orientation of the different parts of a large engineering surveying network based on experimental measurements performed by MOM Gi-B3 gyrotheodolite;
- participating in the orientation transfer, orientation and control measurements related to the construction of Budapest Metro Line 4 performed by gyrotheodolite;

- increasing the precision and accuracy of orientation transfer by inertial navigation and autocollimation using a new calculation procedure and setting forth the accuracy parameters;
- optimising the orientation transfer by inertial navigation and autocollimation and extending it to an orientation transfer performed along a horizontal trajectory and setting forth the procedure;
- comparing orientation transfers performed by gyrotheodolite and inertial navigation and autocollimation based on experimental measurements conducted simultaneously.

3 Methodology

The examination methods of the research indicated in the title of dissertation were the following:

- examining instruments and performing experimental measurements by MOM Gi-B3 gyrotheodolite at different temperatures in laboratories supplied with climate chamber and in the field;
- performing measurements in a construction project environment by MOM Gi-B3 gyrotheodolite (Budapest Metro Line 4, Gotthard Base Tunnel, Switzerland);
- examining the different centering devices of the MOM Gi-B3 gyrotheodolite by high-precision angular measurement; quantifying the systematic errors of the devices and demonstrating the effects of these errors on azimuth determination by means of calculation;
- performing laboratory orientation transfer measurements using a MOM Gi-B3 gyrotheodolite and an iMAR iNAV-RQH-N inertial measurement unit simultaneously;
- comparing my own research results with experimental results and project-related reference values to be found in the literature;
- applying modern and classic mathematical methods and adapting them to solve the given problems raised in the paragraph "Objectives".

4 New scientific results[4]

Thesis 1

Based on the analysis of my experimental measurements I have established that the value of the azimuth and instrument constant Δ_2 determined by the MOM Gi-B3 gyrotheodolite is temperature dependent. On the basis of analysing my experimental measurements performed in a climate chamber I have determined, in the form of a temperature characteristic curve, the effect of the temperature dependent systematic error (i.e. the change of instrument constant Δ_2 of the gyrotheodolite) of the examined gyrotheodolite type MOM Gi-B3 (serial number: 1/310214) supplied with the gyro unit with serial number 1/310124/B, affecting the azimuth determination.

On the basis of my measurements performed in the field and in a climate chamber I have established that the value of instrument constant Δ_1 characterising the theodolite unit of the gyrotheodolite type MOM Gi-B3 is not exclusively temperature dependent. I have also established that in case of the permanence of the other atmospheric parameters there is a linear functional relationship between the change of the air temperature of the measurement environment and the change of instrument constant Δ_1.

I have established that the standard deviation of instrument constant Δ_1 and instrument constant Δ_2 of the MOM Gi-B3 gyrotheodolite is not temperature dependent in the examined air temperature range.

By eliminating the examined air-temperature-change-based error effects I have managed to increase the accuracy of the azimuth determination and orientation transfer by means of MOM Gi-B3 gyrotheodolite.

(Szabó and Égető, 2007a), (Szabó and Égető, 2007b)

Thesis 2

Based on the experiences gained from the examination of the temperature dependence of the instrument constants Δ_1 and Δ_2 I have refined the procedure of azimuth determination performed by the MOM Gi-B3 gyrotheodolite, issuing a measurement directive defining a mandatory determination of the theodolite's instrument constant Δ_1 for each independent determination of the North direction. As the subject of the determination of the instrument constant I defined the

[4] After each thesis the related scientific publications are referenced in brackets.

determination of the instrument constant Δ_2 instead of the determination of the instrument constant Δ and refined the equations for the determination of the instrument constant and azimuth determination performed by the MOM Gi-B3 gyrotheodolite.

(Szabó and Égető, 2007a), (Szabó and Égető, 2007b)

Thesis 3

I have examined the effect of the centering eccentricity on the accuracy of the azimuth determined by the MOM Gi-B3 gyrotheodolite. I have established that centering eccentricity is a significant source of error of azimuth determination in tunnel surveying.

I have elaborated a new solution for centering the MOM Gi-B3 gyrotheodolite on a pillar and thus, I have improved the accuracy of centering performed by the MOM Gi-B3 gyrotheodolite with one order of magnitude.

I have elaborated a new solution and new measurement procedure to integrate the azimuth determination measurements performed by the MOM Gi-B3 in an engineering surveying network based on direction and distance measurements and thus, eliminated centering eccentricity.

With these improvements I have increased the accuracy of the orientation transfer by means of the MOM Gi-B3 gyrotheodolite.

(Szabó and Égető, 2007a), (Szabó and Égető, 2007b), (Szabó, 2016)

Thesis 4

I have investigated the homogeneity in the geodetic network orientation in an engineering surveying network by means of specially distributed experimental measurements carried out by the MOM Gi-B3 gyrotheodolite. Based on the analysis of measurements I have established that within the precision of the measurements, the examined parts of the geodetic network have identical orientation. Subsequently, based on the experimental measurements, I have determined an instrument constant and azimuths of calibration base lines, which ensure the homogenous orientation of the new undergound subnetworks if used in precise orientation transfer procedures.

(Szabó, 2005b), (Szabó and Égető, 2007a), (Szabó and Égető, 2007b)

Thesis 5

I have elaborated an estimation method to process the laser gyro time series of orientation transfer by inertial navigation and autocollimation. I have simplified the basic equation of the orientation transfer given by Neuhierl and Wunderlich. By applying the estimation method processing the measurement data of fewer sensors compared to the previously known calculation method, I have improved the precision and accuracy parameters of the orientation transfer by inertial navigation and autocollimation.

I have optimised the orientation transfer by inertial navigation and autocollimation described by Neuhierl and Wunderlich in publications (Wunderlich et al., 2005; Neuhierl, 2005; Neuhierl et al., 2006). I have equipped the measuring system by an inclinometer and an autocollimation theodolite and improved the layout of the measurement. By using the measured inclination values I have extended my previously mentioned estimation method to consider the measuring system's deviations from the regular positions and thereby I have eliminated the previously disregarded effect of systematic errors affecting the orientation transfer.

(Szabó, 2007), (Szabó et al., 2015a), (Szabó et al., 2015b)

Thesis 6

I have demonstrated the suitability of the optimised orientation transfer by inertial navigation and autocollimation and the enhanced estimation method for orientation transfer along a horizontal measurement trajectory and, therefore, the general suitability of the measurement and estimation methods for orientation transfer.[5]

By analysing the results of simultaneous comparison measurements, I have verified the equivalence of the optimised orientation transfer by inertial navigation and autocollimation and the orientation transfer by gyrotheodolite in terms of precision and accuracy.

(Szabó, 2007), (Szabó et al., 2015a), (Szabó et al., 2015b)

[5] Neuhierl and Wunderlich applied the method along a vertical trajectory.

5 Potential applications of the results of the dissertation

Generally:

- orientation transfer in engineering surveying applications;
- orientation measurements performed by gyrotheodolite and using the procedure of inertial navigation and autocollimation primarily in respect of underground surveying networks, facilities and equipment;
- other specific control measurements.

Construction engineering related applications performed by MOM Gi-B3 gyrotheodolite:

- orientation transfer as independent orientation-control measurement performed by gyrotheodolite in the course of the construction of the Gotthard Base Tunnel in Switzerland;
- azimuth determinations by gyrotheodolite in the course of the construction of the Budapest Metro Line 4 (from 2004 to 2009);
- other underground orientation measurements performed for engineering surveying purposes.

Additional application suggested:

- orientation transfer by inertial navigation and autocollimation instead of classical traversing through the portal zones of tunnels and galleries affected by atmospheric refraction.

6 List of publications related to the dissertation

Reviewed papers published in a journal in foreign language

[1] Szabó, G., Égető, Cs., Wasmeier, P., Ackermann, Ch., Wunderlich, Th., Ingensand, H. (2015a): Richtungsübertragungen entlang horizontaler und vertikaler Trajektorien – Ein Simultanvergleich der INS-Autokollimation-Methode und der Kreiselrichtungsübertragung.
In: Allgemeine Vermessungs-Nachrichten (AVN) 122 (2015), Nr. 4, S. 131–139.

[2] Szabó, G., Égető, Cs., Wasmeier, P., Ackermann, Ch., Wunderlich, Th., Ingensand, H. (2015b): Richtungsübertragungen entlang horizontaler und vertikaler Trajektorien – Ein Simultanvergleich der INS-Autokollimation-Methode und der Kreiselrichtungsübertragung.
In: Allgemeine Vermessungs-Nachrichten (AVN) 122 (2015), Nr. 6–7, S. 223–232.

[3] Szabó G. (2016): On the centering eccentricity of the MOM Gi-B3 gyrotheodolite. In: Periodica Polytechnica, Vol. 60 (2015), 12 pages, accepted for publication on 6 January 2016

Reviewed papers published in a journal in Hungarian

[4] Szabó G. (2005b): Giroteodolitok használata a budapesti 4-es metró alapponthálózatában. Geodézia és Kartográfia, 57. évf. (2005), 8. sz., 15–21. old.

[5] Szabó G., Égető Cs. (2007b): Irányátvitel MOM Gi-B3 giroteodolittal a svájci Gotthárd-Bázisalagút építésén. Geomatikai Közlemények X., MTA GGKI, Sopron, 2007, 273–280. old.

Reviewed paper published in the proceedings of an international conference and oral presentation, both in foreign language

[6] Szabó, G. (2007): Inertialmesstechnische Richtungsübertragung in einem Vertikalschacht mit der Hilfe von Laserkreisel-Zeitreihenanalyse. In: Brunner F. K., (Hrsg.): Beiträge zum 15. Internationalen Ingenieurvermessungskurs Graz, 2007. Heidelberg: Herbert Wichmann Verlag, 2007, S. 383–394.

Papers published in the proceedings of an international conference in foreign language

[7] Szabó, G., Égető, Cs. (2007a): Kreiselmessungen mit dem MOM Gi-B3 im Gotthard-Basis-tunnel. In: Brunner F. K., (Hrsg.): Beiträge zum 15. Internationalen Ingenieurvermessungskurs Graz, 2007. Heidelberg: Herbert Wichmann Verlag, 2007, S. 207–212.

[8] Szabó, G., Glaus, R., Müller, U. (2007): Kinematisches Laserscanning mit dem Gleismess-wagen swiss trolley. In: Brunner F. K., (Hrsg.): Beiträge zum 15. Internationalen Ingenieur-vermessungskurs Graz, 2007. Heidelberg: Herbert Wichmann Verlag, 2007, S. 201–206.

Reviewed paper published in the proceedings of a conference and oral presentation, both in Hungarian

[9] Szabó G. (2005a): Giroteodolitok gyakorlati alkalmazásának lehetőségei a budapesti 4-es metró építésekor. Barna Zs., Józsa Zs. (Szerk.): Doktori Kutatások a BME Építőmérnöki Karán, Műegyetemi Kiadó, Budapest, 2005, 7–15. old.

Further works not considered as publications

Further oral presentations

[10] Szabó G. (2004): Giroteodolitos mérések a budapesti 4-es metró építéséhez. Rédey István Geodéziai Szeminárium, BME Általános- és Felsőgeodézia Tanszék, Budapest, 2004. október 20.

[11] Szabó G., Égető Cs. (2006): MOM Gi-B3 giroteodolit alkalmazása a svájci Gotthard-bázisalagút építésén. V. Geomatika Továbbképző Szeminárium, MTA GGKI, Sopron, 2006. október 26–27.

[12] Szabó G. (2010): Irányátvitel inerciális technológiával, lézergiró-idősorok feldolgozása alapján. VII. Geomatika Szeminárium, MTA GGKI, Sopron, 2010. november 4–5.

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[14] Szabó, G. (2006): Bericht der MOM Kreiselmessungen im Gotthard-Basistunnel an Ostern 2006, Sedrun. 51 Seiten, ETH Zürich, Institut für Geodäsie und Photogrammetrie, Zürich, 2006.

[15] Szabó G., Szerdahelyi A., Égető Cs., Dede K., Kis Papp L. (2008): Giroteodolitos mérési és kutatási beszámoló I. 12 oldal, Hungeod-BME Földmérési Konzorcium, Budapesti Műszaki és Gazdaságtudományi Egyetem, Általános- és Felsőgeodézia Tanszék, Budapest, 2008.

Diploma thesis, scientific student association's papers

[16] Szabó G. (2004): Giroteodolitok használata a budapesti 4-es metró alapponthálózatában. Diplomamunka, 152 oldal, BME Általános- és Felsőgeodézia Tanszék, Budapest, 2004.

[17] Szabó G. (2003): Steuerleitsystem im maschinellen Tunnelvortrieb beim Bau des neuen Gotthard-Eisenbahntunnels – Alagútfúró gépsor geodéziai irányítása az épülő Gotthard vasúti alagút példáján. Tudományos Diákköri dolgozat, 33 oldal, BME Általános- és Felsőgeodézia Tanszék. Budapest, 2003.

[18] Égető Cs., Szabó G. (2001): Szabadálláspont koordinátáinak változása a meghatározáshoz felhasznált irányok függvényében. Tudományos Diákköri dolgozat, 65 oldal, BME Általános- és Felsőgeodézia Tanszék, Budapest, 2001.

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Neuhierl, T. (2005): Eine neue Methode zur Richtungsübertragung durch Koppelung von Inertialmeßtechnik und Autokollimation. Dissertation, Fakultät für Bauingenieur- und Vermessungswesen der Technische Universität München, München 2005.

Neuhierl, T., Schnädelbach K., Wunderlich, T., Ingensand, H., Ryf, A. (2006): How to Transfer Geodetic Network Orientation through Deep Vertical Shafts – An Inertial Approach. In: Shaping the Change XXIII FIG Congress Munich, Germany, Oct. 8–13 2006.

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