CHAPTER 1

Introduction

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Measurement of gravity acceleration (together with estimation of the gravitational constant) was among the first physical experiments, and until today it retains high importance—in areas of theoretical physics to physical geodesy and applied geophysics. As it is typical in most physical experiments, the final result is dependent on two fundamental aspects—on the measurement itself and the results after generally accepted processing of the acquired experimental data. From the viewpoint of applied geophysics (which we define as the study of the subsurface structure of the Earth using physical measurements), the processing of gravity data plays a very important role. The reason for that is that gravity acceleration values themselves are strongly dependent on various nongeological phenomena (latitude, height, influence of topography), which mask the manifestation of subsurface density inhomogeneities in the measured gravity field. Therefore the main output from gravity data processing, in our efforts to make the data suitable for geophysical interpretation, is always a "gravity anomaly." "The gravity anomaly is defined as the difference between the observed and the theoretical or predicted vertical acceleration of gravity" (Hinze et al., 2013, p. 143). We find a very similar definition (even more concrete) in LaFehr and Nabighian (2012, p. 90): "A gravity anomaly is defined as the difference between measured gravity and theoretical gravity based on a defined earth model." Through this process of elimination of unwanted, nongeological, gravity effects we are able to interpret anomalous gravity with the aim to recognize and describe the geological sources of this field. At this point it is good to emphasize that the removal of these unwanted nongeological effects is accomplished using a mathematical description of the synthetic gravity field for the defined Earth model.

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Several different definitions exist for describing various gravity anomalies. The most important are the so-called free-air and Bouguer gravity anomalies. Free-air anomalies are, in general, not suitable for geological interpretations, owing to their strong correlation with topography. Several authors use the term Faye anomaly as a synonym for free-air gravity anomaly (e.g., Pick et al., 1973; Telford et al., 1990), while many others distinguish among these two kinds of anomalies (for details, see Table 1.1). The Bouguer anomaly (BA) is a very important tool for geological interpretation. It was named after Pierre Bouguer (1698–1758), a well-known French astronomer, geodesist, and physicist, who was one of the pioneers in gravimetry. This publication is focused on several selected topics from the area of BA evaluation. A general definition of BA can be written in the form of a simple equation (e.g., LaFehr, 1991):

$$\mathrm{BA} = g_{\mathrm{obs}} - (g_0 + g_{\mathrm{f}} + g_{\mathrm{B}})$$

where g_0 is the latitude-dependent theoretical value of gravity at the vertical reference datum, g_{f} is the elevation-dependent free-air term, and g_{B} is the elevation- and topography-dependent Bouguer term (later in the book we will discuss more precise equations, see Chapter 2: The Physical Meaning of Bouguer Anomalies—General Aspects Revisited and Chapter 7: National Gravimetric Database of the Slovak Republic). It is important to mention here that during the removal of the g_0 term, the effect of centrifugal acceleration (due to the rotation of the Earth) is removed from the processed gravity acceleration value and the final BA value is consequently understood as a component of gravitational acceleration.

When discussing the various aspects of the BA evaluation in the past, readers can come across numerous discrepancies in its definition expressed either in textbooks or monographs (sometimes even including modern texts), which have been published within the last 25 years. In almost all contributions to this topic it is clearly stated that measured gravity has to be processed in the way that unwanted non-geological influences on gravity acceleration must be removed, but the way it is done and mainly understood is, in general, not unified. Discrepancies are mainly in the area of:

1. the understanding of the position of BA evaluation (the problem of a possible relocation of processed gravity values to some different reference height datum),

Table 1.1 Summary of Basic Terms and Aspects of Bouguer Anomaly Definition in Various Textbooks and Monographs

References	Used Terms in BA Evaluation	Form of BA Evaluation	Title of BA	Comments
Nettleton (1940, pp. 16–22, 51–62, 133–134)	Corrections (but gravity is reduced)	Equation in a symbolic form (equation in p. 133)	Bouguer anomaly	(1) Bouguer gravity is the theoretical gravity (normal field with following corrections) and (2) terrain effect term T is finally added in BA evaluation
Grant and West (1965, pp. 235–243)	Corrections (but gravity is reduced)	Do not give a final equation in a symbolic form, only partial steps are given	Bouguer gravity or Bouguer gravity anomaly	(1) Bouguer gravity is the title for the final anomalous field and (2) authors mention "free-air anomaly" or "free-air disturbance"
Torge (1989, p. 100)	Reductions	Equation in a symbolic form (Eq. 4.36)	Bouguer anomaly Δg_B	Topographic reduction term δg_{Top} is subtracted from free-air anomalies
Telford et al. (1990, pp. 11–15)	Corrections (but gravity is reduced)	Equation in a symbolic form (Eq. 2.28)	Bouguer anomaly g_B	They explicitly define the Bouguer anomaly value for the station
Blakely (1996, pp. 136–150)	Corrections	Equation in a symbolic form (Eq. 7.17)	Bouguer anomaly Δg_{SB} and $\Delta g c_B$	Distinguishes between simple and complete BA
Jacoby and Smilde (2009, pp. 151–166)	Reductions (authors avoid the term correction)	Equation in a symbolic form (equations in p. 165)	Bouguer anomaly BA or δBA	(1) Distinguish between free-air and Faye anomaly (2) distinguish between simple and complete BA
LaFehr and Nabighian (2012, pp. 81–100)	Corrections (but gravity is reduced)	Equation in a symbolic form (equation in p. 91)	Bouguer anomaly g_b	Distinguish between simple and complete BA
Hinze et al. (2013, pp. 122–155)	Corrections	Equation in a symbolic form (Eqs. 6.37 and 6.38)	Bouguer anomaly g_{SBA} and g_{CBA}	Distinguish between simple and complete BA
Long and Kaufmann (2013, pp. 17–39)	Corrections (but gravity is reduced)	Equation in a symbolic form (Eq. 2.40)	Bouguer anomaly Δg_B	(1) Distinguish between simple and complete BA (2) distinguish between free-air and Faye anomaly
Fairhead (2016)	Corrections	Equation in a symbolic form (in various modifications) (Chapter 2.1.3)	Bouguer anomaly	Distinguishes between simple and complete BA

2. technical aspects (e.g., different height systems—use of ellipsoidal vs orthometric heights) and selection of all evaluated corrections (e.g., atmospheric correction),
3. improper, or at least, inconsistent use of terminology and notation in BA evaluation (corrections vs reductions, anomaly vs disturbance, mathematical expression of BA equation).

Thanks to important discussions among US experts in the beginning of this millennium (Hinze et al., 2005; Li et al., 2006; Keller et al., 2006; together with other important papers—e.g., LaFehr, 1991; Chapin, 1996; Talwani, 1998; LaFehr, 1998; Li and Götze, 2001), which have been connected with the setting of new BA calculation standards in North America, many aspects have been made clearer and defined in a more correct way—from the scope of applied geophysics. Textbooks and monographs, published during the last several years (e.g., Jacoby and Smilde, 2009; LaFehr and Nabighian, 2012; Hinze et al., 2013; Long and Kaufmann, 2013; Fairhead, 2016) were written from these aspects in a much better way and BA evaluation is defined correctly from the viewpoint of applied gravimetry. In Hinze et al. (2013, pp. 145–151) readers can find several modifications of BA evaluation for different acquisition situations (a good overview for a planar approximation is also given in the NGA Report, 2008, p. 4).

One of the most important aspects of BA evaluation is the fact that the goal of the applied processing steps (reductions/corrections) is not to "reduce" measured gravity values (as explained in several older textbooks, e.g., Grant and West, 1965; Telford et al., 1990), but rather, they are used during "tuning" or improvement of the theoretical gravity field. The goal of this tuning is to obtain precise theoretical values of gravity acceleration of a reference Earth model, which are then removed from the measured (observed) values, producing an anomaly field. In the classical work of Hayford and Bowie (1912) we can find on pages 72 and 73 the following statement: "Usually corrections are applied to the observed values of the intensity of gravity to reduce them to sea level and to correct for the supposed influence of topography. In this publication the corrections are applied to the theoretical value of the intensity of gravity at the sea level to obtain the theoretical value at the station, a value which is directly comparable with the observed value. This seems to the authors to be more logical method and more conductive to clear thinking than the usual method."

This concept was also very well understood by Nettleton (1940)—who entitled the evaluated and subtracted theoretical fields as *Bouguer gravity* and the final received anomalous field as *Bouguer anomaly* (see also Table 1.1). Unfortunately, many authors later on have understood these two quantities as synonyms. Fortunately, in the actual textbooks mentioned about, this aspect is presented in the correct way from the viewpoint of applied gravimetry.

The next most important aspect of BA evaluation is the fact that in applied gravimetry we do not move or relocate the processed gravity value to some reference datum (we can find this incorrect explanation in several older textbooks and papers, e.g., Jung, 1961, pp. 82, 83; Dobrin, 1976, p. 417), but, instead, the positions of the BA values "reside" at the acquisition points. This is well explained in Jacoby and Smilde (2009, p. 155): "Note that reductions do not physically move the observations to another level – as incorrectly expressed frequently. Reductions compare the observation with normal values by estimating the latter at observation locations ... Anomalies are determined at the observation points, not at the reference level." Another clear statement to this point can be found in LaFehr and Nabighian (2012, pp. 86, 87): "Let us be clear that by making this reduction, we are not reducing the data to a datum, i.e., obtaining at a fictitious station on the datum what we would have measured if we had been able to do so." Here it is important to mention the short note from Ervin (1977), where he point to the absurdity of such kind of fictive relocation of processed values. On the other hand, we can still find in actual geophysical monographs (e.g., Mallick et al., 2012), this typical old-fashioned interpretation coming from physical geodesy (where experts need to know the gravity acceleration at the geoid datum), but in the majority of up-to-date geophysical textbooks this aspect is explained correctly.

The terminology used in BA evaluation belongs also to the problems discussed, especially the meaning of the terms reduction and correction. These two terms express the same steps in the processing of gravity data, but sometimes they can be understood in different ways. For example, Nettleton (1940) used these terms as synonyms, while some other authors write about reduction of gravity values—but the partial steps are titled as corrections (for an overview, see Table 1.1, second column). The majority of authors of this monograph chapters prefer the use of the term correction, because the term reduction can indicate the sense that something could be moved in the downward direction (reduced), which could contribute to misunderstanding the physical location of BA values (as discussed earlier). It would be very helpful to have a unification of such important terms in gravimetry, but also here the most important principle is to understand the real content of the used terms.

The final comment to the terminology in this introduction is focused on the problem of "anomaly" versus "disturbance." In physical geodesy experts are distinguishing between these two terms—an anomaly is a difference between quantities known at different points, whereas a disturbance is valid for this kind of calculation at the same point. So, from this viewpoint, BA, as we understand it in applied gravimetry, should be called a "disturbance" (see more details in Chapter 2: The Physical Meaning of Bouguer Anomalies—General Aspects Revisited), when the vertical datum for the used heights is the ellipsoid. But we agree (i.e., the majority of editors of this book) with the statement by Hinze et al. (2005, p. J31) that "The geophysical community is largely unaware of the term disturbance as used by geodesists, which will add further confusion if the term is used." So, we suggest to continue using the term "anomaly" in the case of BA definition.

The motivation for preparing this book was the excellent experience which editors and authors of individual chapters have made during the 2-day workshop with the title "Bouguer anomaly - what kind of puzzle it is?," which was held in September 2014 in Bratislava. It was organized in the frame of a scientific project "Bouguer anomalies of new generation and the gravimetrical model of Western Carpathians." This project was supported by the Slovak Research and Development Agency and conducted by the Department of Applied Geophysics, Comenius University in Bratislava, together with the Geophysical Institute of the Slovak Academy of Sciences and the companies G-trend s.r.o. and Geocomplex Inc. (more information about the project outputs can be found in Chapter 7: National Gravimetric Database of the Slovak Republic). The workshop was attended by several well-known experts from the gravimetrical branch (in alphabetic order: Benedek, J., Bielik, M., Braitenberg, C., Čunderlík, R., Dérerová, J., Ebbing, J., Gabriel, G., Hronček, S., Karcol, R., Li, X., Meurers, B., Mikuška, J., Mrlina, J., Pánisová, J., Papp, G., Pašteka, R., Pohánka, V., Ruess, D., Scücs, E., Smilde, P., Szwillus, W., Švancara, J., Vajda, P., and Zahorec, P.). During the workshop we had excellent, thorough discussions on the topic of BA evaluation problems. This workshop can be understood also as a "continuator" of local gravimetrical conferences AGK ("Alpen-Gravimetrie-Kolloqium"), which had been organized mostly by colleagues from Austria, periodically from the mid-1980s until 2006, and have been hosted by several central European institutions and universities. After the end of the last mentioned Bratislava workshop in 2014, several presenters carried out an intensive discussion regarding the possibility of publishing several of the presented topics in the form of a widely accessible publication. This book is the result of this discussion.

It is organized logically in eight chapters, including Introduction and Conclusion, where the topics are ordered from aspects of BA definition, through history of BA evaluation, normal field (an alternative) evaluation and calculating terrain corrections, finishing with an example of the national gravity database organization and recalculation.

In the second chapter titled "The Physical Meaning of Bouguer Anomalies—General Aspects Revisited" Bruno Meurers picks up the approach of composing synthetically all gravitational effects contributing to the gravity observed at the Earth's surface. This concept enables us to precisely specify the physical meaning of Bouguer anomalies obtained under certain assumptions (e.g., reference surface). The chapter also tries to assess the errors, which inherently occur due to specific assumptions made in calculating the BA in practice. This is focused on the problem of the scalar representation, the geophysical indirect effect, the truncation of the mass correction area, and the normal gravity calculation in areas with negative ellipsoidal heights.

The third chapter titled "Some Remarks on the Early History of the Bouguer Anomaly" from Mikuška et al. investigates in detail the historical aspects of several important parts of the BA evaluation. For instance, one can find that the term "Bouguer reduction" is most likely accreditable to Helmert. This term was used in the context of the popular geodetic concept of reducing gravity from the Earth surface to sea level, although Bouguer himself had never reduced gravity values or pendulum lengths in such a manner. Authors confirm that the foundations of the so-called "Bouguer anomaly" and the procedures applied to the measured gravity, which are required by the gravity method of applied geophysics, can be tracked back to originate from the famous book of Pierre Bouguer published in 1749. Among others, various authors call attention especially to one specific historical artefact, namely the misunderstanding associated with the gravity data reductions to sea level in applied geophysics which, although geophysically unacceptable, has withstood the ravages of time and can be found in the literature even in the 21st century.

In the fourth chapter titled "Normal Earth Gravity Field Versus Gravity Effect of Layered Ellipsoidal Model" Karcol et al. discuss the question of whether the present-day normal gravity field calculation is suitable from the aspect of applied gravimetry. Today the normal field or theoretical gravity is on a regular basis strictly related to a model of rotational biaxial ellipsoid with one important property—namely, the constant potential on its surface. This condition, however, would require a specific density distribution within the model. Treating the Earth atmosphere and topography is another issue. These masses are simply moved into the interior of such ellipsoid and "dissolved" there. In short, this approach does not fit the geophysical reality very well. Instead, in this chapter, the authors attempt to calculate the normal field as the gravity effect of a layered rotational ellipsoid, namely the gravitational effect of a suitable set of homeoid shells bounded by two similar ellipsoids having a constant ratio of axes, plus the centrifugal component. The authors believe that this approach will fit the structure and density distribution within the Earth much better than existing models. They analyze and present the primary differences between the two approaches, and also discuss the relation of the normal field to the free-air correction.

In the frame of the fifth chapter titled "Numerical Calculation of Terrain Correction Within the Bouguer Anomaly Evaluation" Zahorec et al. describe properties of numerical evaluation of the terrain corrections by means of a recently developed code Toposk (developed in order to recalculate the terrain corrections of the unified gravity database of the Slovak Republic). The program is designed primarily for calculating the gravitational effect of topographic masses. Terrain corrections are then derived from these effects. Its application is not restricted to the territory of Slovakia, but can be used worldwide. It allows using interpolated heights for the calculation points in order to reduce the errors resulting from the elevation model inaccuracy. The choice of arbitrary subzone divisions, as well as multiple options for coordinate systems, is allowed. By default the program uses the following zone divisions: inner zone T1 (to a distance of 250 m from the calculation point), intermediate zone T2 (250–5240 m), and outer zones T31 (5240–28,800 m) and T32 (28,800–166,730 m). The computing algorithm was tested on several synthetic models, giving satisfactory results when compared with analytically evaluated values.

In the sixth chapter titled "Efficient Mass Correction Using an Adaptive Method" Szwillus and Götze focus their attention on an effective way of numerical evaluation of topographic effects. These calculations are always very time-consuming. To increase the computational efficiency, the authors present an adaptive approach that enables users to perform large-scale or even globally complete correction. The central idea is to use only that part of the topography information that is actually relevant for the gravitational effects. Numerical analysis of the synthetic model shows that this adaptive approach is expected to perform well as long as its parameters are chosen according to the geostatistical properties of topography in the studied area. Real-world tests of a high-resolution topography dataset from the Himalayan Plateau demonstrate the reliability and efficiency of the adaptive approach.

In the seventh chapter "National Gravimetric Database of the Slovak Republic" Zahorec et al. present a case study of BA calculation for a large database (from the entire country). The results of the Slovak gravimetric database compilation, with actually more than 320,000 observation points, are presented (realized in the scope of the mentioned project "Bouguer anomalies of new generation and the gravimetrical model of Western Carpathians"). Gravity data were collected for more than 50 years, which yields a very heterogeneous dataset, with large variations in the station coverage and processing methods. The regional gravimetric database (more than 212,000 points) was resumed in 2001. The compilation discussed herein (with more than 107,000 detailed gravity measurements added to the original database) was made during the period 2011–14. A rigorous quality control process and complete recalculation of the Bouguer anomalies is presented. The primary focus of this project was on a proper recalculation of the terrain corrections. A new software solution for reconstruction of the gravity acceleration values from the BA map (program CBA2G_SK) was developed for geodetic applications.

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At the end of this introductory part, we would like to express our hope that this book will positively contribute to the scientific development in the area of BA evaluation, with the aim to improve further geological interpretation of gravimetrical datasets. We would like to express our grateful thanks to our colleagues, who helped us with the organization of the mentioned workshop, mainly to Barbora Šimonová, Martin Krajňák, and Marián Bošanský. We are also thankful to the companies who have supported our efforts from a technical point of view, mainly to Proxima R&D and G-trend s.r.o. Special thanks go to John Bain for his support and many suggestions, which have helped to improve the scientific content of the published material in this book. Finally, we would like to thank the support from the publishing house—especially to Marisa LaFleur, Hillary Carr, Stalin Viswanathan, and Rakesh Venkatesan.

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