

Preface

Gravity interpretation involves inversion of data into models, but it is more. Gravity *interpretation* is used in a “holistic” sense going beyond “inversion”. Inversion is like optimization within certain a priori assumptions, i.e., all anticipated models lie in a limited domain of the a priori errors. No source should exist outside the anticipated model volume, but that is never literally true. Interpretation goes beyond by taking “outside” possibilities into account in the widest sense. Any neglected possibility carries the danger of seriously affecting the interpretation.

Gravity *interpretation* pertains to wider questions such as the shape of the Earth, the nature of the continental and oceanic crust, isostasy, forces and stresses, geological structure, finding useful resources, climate change, etc. Interpretation is often used synonymously with modelling and inversion of observations toward models. Interpretation places the inversion results into the wider geological or economic context and into the framework of science and humanity. Models play a central role in science. They are images of phenomena of the physical world, for example, scale images or metaphors, enabling the human mind to describe observations and relationships by abstract mathematical means. Models served orientation and survival in a complex, partly invisible physical and social environment.

Inversion of gravity anomalies is the mathematical derivation of density distributions and their confidence limits. This is a notoriously non-unique problem, while the so called forward problem of finding the gravity effects of given mass distributions is perfectly unique. The ambiguity of inversion simply results from the fact that knowledge of a sum does not imply knowledge of the addends. If you know $c = a + b$, but nothing about a and b , c reveals neither a nor b . There is always an infinite model space; the infinity of answers can be reduced only by invoking a priori information. It can be of any nature and depends on the problem at hand. If for example $b = 2a$, you get $a = c/3$ and $b = 2c/3$.

This treatise attempts to give a perspective of the problem and to prepare readers for finding their way to solutions. A priori information is central to gravity inversion. It ranges from “hard” geological and geophysical data, such as seismic results, to general ideas based on experience and to models of processes which would produce gravity signals. Generally the additional knowledge will be limited, but often very important aspects will be revealed. If the a priori information were complete, there would be no problem left to be solved.

This touches the question: what does gravity tell and what not? To endeavour along these lines is the exciting business of approaching the truth, but one can never be absolutely sure. Nature has built in too many obstacles. If gravity is measured on or above the Earth's surface, one cannot truly look inside. The signals come largely from within, though. There is a philosophical extension of these ideas about gravity interpretation: in our general intellectual human condition we are in a very similar situation concerning our world views including that of ourselves. We observe and receive signals from within and without, and we communicate. We build our virtual worlds that should be consistent. This aim feeds back into our approach to gravity interpretation.

Texts of Applied Geophysics generally have an "exploration outlook"; the present book has also a strong geodynamic "inclination". Gravity is active and passive: a *force* doing work toward equilibrium from a disturbed state and generating a *field* with observable signals to be interpreted. In many geological situations gravity has done work and we try to find out what happened. For example, a valley has been excavated and refilled by lower-density sediments, giving a negative gravity anomaly. Or hot, low-density mass has risen or is rising, and cold, high-density mass has sunk or is sinking and working against viscous forces and deflecting density surfaces from their equilibrium level. The density distributions generated give gravity signals which can be interpreted only in view of such model ideas. Without them, models of a totally different nature can "explain" the anomalies.

This situation causes confusion. Is it worth at all to interpret gravity? Some seem to think: not. This view is definitively wrong. Gravity plays two fundamentally useful roles in the earth sciences: it helps to inexpensively detect "anomalies" worth studying, and it falsifies and eliminates models by forward computations. The methodological side is the theory and practice of data gathering, forward modelling and of Bayesian inversion, including the various preliminary steps of measurement and data preparation. The practical side is the presentation of applications and case histories. The philosophical side is that it wants to teach general aspects of applying observations to science and to life.

Presentation of observational techniques is kept to a minimum, but some discussion is unavoidable. Gravity or geoid observations are affected by errors or confidence limits. Errors have an important effect on what can be learnt from gravity, so their discussion is carried through all chapters. With the development of new methods of terrestrial, marine, airborne and satellite-based observational methods, and with increasing accuracy of the observations the scope of interpretation widens. Many methods of forward calculation of gravity effects are well known and reference is given to other texts; but some aspects of the basic approach in this treatise are novel.

Much of a textbook is concerned with the reader learning to work in geophysical "practice". Many today, especially science administrators on all levels, suggest that teaching is the main function of universities, and efforts in "pure science" and conveying in-depth understanding is not so important. This attitude is short-sighted. Only deep understanding will produce reliable results, also in limited exploration projects. Good self-critical judgement, for example of the probability and possibility

of errors in an interpretation, requires knowledge beyond technical skills. This our own experience we wish to share. Indeed, we endeavour to make readers wonder about problems.

Probably the best way of learning is from mistakes and from independent efforts in problem solving. We therefore include, as a CD, a collection of tasks or problems with some instructions for how to approach solutions. This will give readers the chance to make their own mistakes and to correct them. Answers are listed at the end, including discussion of the problems and solutions. Some of the tasks are applications of inversion (Chap. 7) to geological or theoretical modelling which add principal aspects discussed at some length.

One of our own examples serves as an illustration: when working out the solid-angle solution for a cube at one of its corners (see Sect. 2.9.6), the assumption that the gravitational vector effect points to the centre of mass led to the surprisingly beautiful result that the vertical gravity effect would be precisely $1/6$ of that of the infinite Bouguer slab of the same thickness and density. But beauty is no proof, and the result did not stand the test. The mistake was that, contrary to widespread belief, the gravitational vector does *not* generally point to the centre of mass, except in certain cases of special symmetry (see Sect. 2.9.1.2) which should have been immediately evident, for example, from the Earth's ellipsoid or the geoid. The misconception arose from a mix-up with mechanics where the action of a force on a body is described by action on its barycentre, i.e. centre of mass or balance point.

The authors have consulted other texts covering the subject, especially the classical book (in German) by Karl Jung (1961), *Schwerkraftverfahren in der Angewandten Geophysik* (Gravity methods in Applied Geophysics; it will be referred to as KJ61), and the book *Interpretation Theory in Applied Geophysics* by F.S. Grant and G.F. West (1965) (referred to as GW65). Many useful ideas have been taken up and partly expanded. In those early days of computing machines their possibilities had been clearly seen and the foundations had been laid down for their application.

One of the authors (WJ) studied physics, geophysics and more and more geology and considers himself a geophysically guided geologist, interested in how the Earth works and concerned about how mankind treats its home planet. The other author (PS) studied geodesy and became more and more involved in geophysics and geology when working with WJ on his PhD thesis on gravity inversion, developing the program package INVERT, of which an executable copy is attached to this book on a CD. The thesis is also the basis of the most important last chapter of the book on optimization and inversion. The cooperation led to a synthesis of the geological-geophysical approach to the problems of interpretation and the geodetic, more mathematically inclined approach. It is the combination of geological imagination and experience, on the one hand, and abstract geophysical-mathematical reasoning, on the other, that is the basis of Earth science. Experience-based intuition must be checked by mathematical validation. Indeed, science is suspended between the two extremes of freedom of thinking and rigorous checking. Scientists surely endeavour to approach the truth in such suspense.

Many colleagues and friends in various institutions, not only from our own study field, have participated in teaching us this lesson, from our parents, families

and some school teachers to our academic teachers, Karl Jung[†], Kiel, and Reiner Rummel, Delft, and to our later colleagues and students. Every one of them has chosen her/his own way and none is responsible for ours, but the – hopefully – mutual benefit has been immense. The intellectual challenges by colleagues and students are gratefully acknowledged. Geological teaching by Eugen Seybold, Kiel, and exchange with Richard Walcott, Richard Gibb, Alan Goodacre and Imre Nagy in Canada and with Gerhard Müller[†], Frankfurt (Main), were important. In Mainz, Georg Büchel, Evariste Sebazungu, Tanya Fedorova, Ina Müller, Chris Moos, Michaela Bock, Herbert Wallner, Hasan Çavşak, Tanya Smaglichenko and many others were influential on both of us.

Herbert Wallner helped intellectually by many discussions, with calculations and quite a number of figures. Tanya Fedorova provided some of the gravity inversion models. Evariste Sebazungu, in his own PhD thesis on potential field inversion, developed original ideas which entered into this treatise. Hasan Çavşak provided gravity calculations for various polyhedral bodies and helped discovering errors in some theoretical derivations. Pierre Keating provided information on some of the free modelling software. Discussions with Markus Krieger (Terrasys, Hamburg) led to several ideas and insights into the practical solution of interpretation problems.

All of them and many more contributed thought-provoking ideas and thus influenced the present treatise. Most importantly, the mutual discussions between the authors through the whole time of their cooperation were beneficial to both. Finally, lecturing on gravity (and magnetics) taught us more than anything else to endeavour to present the ideas clearly.

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