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Global Gravity Field Modeling from Satellite-to-Satellite Tracking Data

Springer

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Foreword

The satellite gravimetry mission GRACE marks the beginning of a new level of engagement of geodesy in climate research. Since its launch in 2002, GRACE is delivering uninterrupted series of rather detailed maps of temporal variations of the Earth's gravity field. They reflect changes in the continental water cycle, quantify mass losses and gains of glaciers and the ice shields of Greenland and Antarctica, and allow to discriminate the steric from the mass component of global sea level rise and determine postglacial land uplift. Important statements on sea level rise and global ice mass balance in the IPCC report 2013 [62] are based on GRACE data.

The measurement principle of GRACE is high-precision intersatellite tracking between its two low-orbiting satellites. GRACE is now in its final mission phase and will hopefully be followed in 2017 or 2018 by an almost identical mission. This is a necessity, for time series of thirty years and more are required to unambiguously identify climate-related signals. Therefore, in order to ensure continuity of such data, preparations have started toward concepts for a mission thereafter. Very likely, it will again be based on the principle of 'satellite-to-satellite tracking between low-orbiting satellites (SST low-low).' In addition, the goal will be to make it a mission superior to GRACE in terms of spatial and temporal resolution and measurement precision. This will ask for improved concepts in terms of technology, data analysis, and interpretation.

In order to get young scientists interested and prepared for such a mission, Prof. Jakob Flury, the speaker of the Collaborative Research Center 1128, together with Dr. Majid Naeimi took the initiative for the autumn school 'Global Gravity Field Modeling from Satellite-to-Satellite Tracking Data.' The aim of Collaborative Research Center 1128 'Relativistic Geodesy and Gravimetry with Quantum Sensors' funded by the Deutsche Forschungsgemeinschaft (DFG) is to explore new frontiers of the determination of the Earth's gravitational field and of monitoring the global and regional mass redistribution. Thus, the autumn school fits perfectly to its agenda.

But why exactly 'satellite-to-satellite tracking'? Let me say a few words about the history of this so successful technique. Since Newton, it is well known that the orbit of any artificial satellite orbiting the Earth is perfectly analogous to the free fall of an apple from a tree or a prism in a vacuum tube of an absolute gravimeter. Tracking the orbital motion of a satellite is therefore analogous to the measurement of the free fall of a test mass in the laboratory. Both types of experiments, tracking of satellites and as free-fall experiments in the laboratory, are applied in practice in order to determine the attraction of the Earth. However, the satellite experiment is confronted with two fundamental obstacles: First, while it is relatively easy in a laboratory to follow the complete free fall of a prism using, e.g., laser interferometry, it is almost impossible to get a long and evenly distributed sequence of tracking data to a satellite from an observatory on Earth, the limitations being visibility and weather conditions. Thus, only in a complicated patchwork of observations collected from many tracking stations, data taken from several satellites, and using various types of tracking techniques, it became possible, step by step, to derive comprehensive gravity models. The development in the USA is described in two fascinating volumes, edited by Henriksen [58]. The situation changed with the advent of GPS in the nineties. From then on, any low-orbiting satellite could be tracked from the configuration of GPS satellites at high altitude, uninterruptedly, and even three dimensional. Second, as expressed by Newton's inverse-squared distance law, the signal strength of gravity gets rapidly weaker with the square of the distance from the Earth. As a consequence, at satellite altitude, only a highly damped version of the Earth's gravity field can be observed. This is and was an intrinsic limitation of any type of satellite gravimetry. Therefore to obtain the Earth's gravity field with high accuracy and high spatial resolution, this damping issue should be resolved. One measure is, of course, to use satellites orbiting the Earth at lowest possible orbits, just to be as close to the attracting Earth's masses as possible. A second countermeasure is 'differentiation,' i.e.. either satellite gradiometry or satellite-to-satellite tracking.

Gravity field determination from space is as old as space age itself. It started with the first missions Sputnik 1 and Sputnik 2 in 1957. Taking their radio Doppler signal, the Earth's oblateness could be deduced with an unprecedented accuracy making more than 100 years lasting effort of geodetic arc measurements and triangulation obsolete ([23] or [102], see also [63]). However, refined gravity recovery, i.e., the construction of models beyond solely the determination of J2, turned out to be a complicated and long journey, again [58]. The development of geopotential modeling is described in [118]. In 1960 [3], the idea was spelled out of using tracking between spacecraft for gravity field determination. It became more concrete in [160]. What does it help? Measuring the relative motion between satellites eliminates the major and well-known gravitational effect, that of the spherical, slightly flattened Earth, which is almost identical for the two spacecraft. This leads to a strong amplification of the short-wavelength signal part of the Earth's gravity field relative to the remaining long-wavelength features. In a mathematical sense, it is like differentiation or like measuring the gravity gradient along the line connecting the two satellites. From the point of view of Fourier series analysis, it is the well-known effect of differentiation resulting in a multiplication of the series elements by their wave number, e.g. [20]. On invitation of NASA, leading Earth scientists gathered in Williamstown in 1969 to formulate a vision for a future Earth science program from space [80]. Satellite-to-satellite tracking was an element of this report. It is still worthwhile to read this report because it is truly visionary both in terms of the identification of the Earth science objectives and the ideas of their realization using new satellite mission concepts. The ideas of the Williamstown report were the basis of concrete program elements in 1972 in NASA's EOPAP report [109]. There, dedicated satellite gravimetry took shape, the so-called GRAVSAT mission ideas of satellite-to-satellite tracking in the high–low and low–low mode and satellite gradiometry. Analyzing the tracking data from Earth to the Apollo lunar orbiters for the purpose of gravity field recovery can be regarded the first realization of a high–low satellite-to-satellite tracking experiment [108]. Other high–low tracking tests were between the relay satellite ATS-6 and Apollo/Soyuz [150] and between ATS-6 and Geos-3 [51, 94, 128, 134, 159]. A first, not quite successful attempt of low–low tracking was the gravimetric use of the data of the docking experiment between the Apollo and Soyuz spacecraft [156].

In Europe, the first initiative in this direction was a summer school on satellite geodynamics in Lannion in 1974 sponsored by the French space agency CNES, where leading European geodesists and geophysicists discussed ideas about dedicated satellite gravimetry missions and their theoretical background, [4]. In 1978, it followed a workshop on Space Oceanography, Navigation and Geodynamics (SONG) organized by the European Space Agency [37]; it was the first step toward an ESA Earth observation program, and satellite-to-satellite tracking and gradiometry were on its agenda [127]. In parallel, ESA ran a first study mission and system definition study of a low–low satellite-to-satellite tracking experiment for gravity field determination, called SLALOM [5]. The idea was laser tracking from the space shuttle to two passive compact cannon ball satellites.

A theoretical milestone was [100]: Meissl formulated a framework connecting the spectral representation of various gravity functionals, such a geoid heights, gravity anomalies, and gravity gradients at altitude and at the Earth's surface, in a systematic way in terms of spherical harmonics. Later, this framework was denoted Meissl scheme [126], see also [124, 125]. Other important theoretical contributions and simulation work on satellite-to-satellite tracking were [26, 27, 50, 74, 79, 107, 130, 135, 152].

However, the necessary technology was not yet mature enough to get a dedicated low–low SST gravity mission approved. An analysis of the state of the art took place in a workshop organized by the US National Research Council: applications of a dedicated gravitational satellite mission [113], followed by several mission proposals in the years thereafter. While the European side concentrated on satellite gradiometry, i.e., the measurement of the relative gravitational acceleration between several test masses inside one satellite, the US American side pursued the realization of a low–low satellite-to-satellite mission, from 1979 on as Gravity Research Mission (GRM). Of great importance were simulation studies showing the potential of such a mission for determining temporal variations of the gravity field, caused by mass transport processes in system Earth, such as ice melting, sea level rise, and glacial isostatic adjustment [32, 154]. In 2002, GRACE was launched, the first low–low satellite-to-satellite tracking mission, the beginning of an amazing success story [140]. In 2012, the NASA GRAIL mission employed the same mission and sensor concept to the determination of the lunar gravity field [166].

The autumn school, supported by the Wilhelm und Else Heraeus foundation, took place from October 4 to 9, 2015, at the Physikzentrum in Bad Honnef, Germany. The organizers succeeded to attract as teachers five of the leading experts in this field. In their lectures, the participants were introduced into the basic alternative approaches of data analysis as well as into the characteristics, strength, and limitations of these methods. Furthermore, in order to deepen insight, they together with coworkers prepared and supervised labs. In a series of evening talks, additional selected topics were presented, ranging from future technology via advanced methodology, relativistic modeling to Earth application. About fifty students from 16 countries participated in the autumn school. Their unanimous conclusion is well prepared, perfectly organized, good atmosphere, and very useful.

Special thanks go to Prof. Flury and Dr. Naeimi, to all lecturers and their coworkers, and to the Physikzentrum and Wilhelm und Else Heraeus foundation.

Munich, Germany
June 2016

Reiner Rummel

Preface

The present book collects the lecture notes of the international Wilhelm und Else Heraeus autumn school 'Global Gravity Field Modeling from Satellite-to-Satellite Tracking Data,' held from October 4 to 9, 2015, in Bad Honnef, Germany. The first ideas of the autumn school (the initial plan was a summer school) came up in November 2013 during an internal discussion in Hannover on the requirements for the GRACE/GRACE Follow-On Mock Data Challenge project[1] in the Collaborative Research Center (Sonderforschungsbereich) 1128 'Relativistic Geodesy and Gravimetry with Quantum Sensors (geo-Q)' of Leibniz Universität Hannover.[2] The idea soon attracted attention, and we received positive feedback from experts of the field.

In a rather short period of application time, we received many applications from around the world and we are pleased for hosting over fifty participants from Germany, USA, Switzerland, Austria, India, China, Iran, Russia, Bulgaria, Netherlands, Poland, Brazil, Luxembourg, Canada, and Sweden.

The main goal of the autumn school was to provide a basis to the interested students and geodesists for analyzing SST data from current and future satellite missions. The emphasis was put on different approaches for the recovery of the Earth's gravity field. These techniques are the acceleration approach, the energy balance approach, and the classical (variational) approach. In addition, the related subjects of orbit determination and parameter estimation were included.

The school started on Sunday 4 October with an opening talk by Prof. Reiner Rummel about the spherical harmonic analysis and gravity field determination and was followed by a 5-day intensive program. Core topic lectures on each morning

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[1] http://www.geoq.uni-hannover.de/mock.html

[2] http://www.geoq.uni-hannover.de

were complemented by more numerical and practical exercises in the afternoon. The chapters of this book are based on the core topic lectures given on each day as follows:

1. **Parameter Estimation for Satellite Gravity Field Modeling**, by Prof. Jürgen Kusche and Anne Springer, University of Bonn, Germany

This chapter gives first a general overview about Gauss–Markov models and their use in the presence of observation noise. Variance component estimation, regularization, and biased estimation are addressed. Exercises at the end of the chapter give more insight into the applications for gravity field determination from GRACE data.

2. **Precise Orbit Determination**, by Prof. Adrian Jäggi and Dr. Daniel Arnold, University of Bern, Switzerland

Here, the general issues of orbit modeling such as the treatment of tracking data, orbit representation techniques, and the orbit determination problem together with gravity field parameterization are considered. Two exercises for a deeper understanding of orbit determination are added.

3. **The Classical Variational Approach**, by Prof. Srinivas Bettadpour and Christopher McCullough, University of Texas at Austin, USA

The basic principles of the classical approach used by processing centers such as CSR and GFZ are discussed, followed by numerical exercises for more understanding.

4. **The Acceleration Approach**, by Dr. Matthias Weigelt, Institut für Erdmessung, Leibniz Universität Hannover, Hannover, Germany

A comprehensive overview about the acceleration approach including the strengths and drawbacks of this method is provided in this chapter. Approximate and rigorous solutions using this approach are discussed, with the exercises on the numerical aspects.

5. **The Energy Balance Approach**, by Prof. Christopher Jekeli, Ohio State University, USA

This chapter reviews the energy integral for the derivation of potential differences along the satellite orbit and for gravity field determination. Aspects of this approach including the separation of the temporal variations, the rotational potential, kinetic potential, and dissipative forces are described. Similar to other chapters, exercises provide more understanding about the numerical details of the method.

Acknowledgements

We would like to thank all the lecturers for contributing to the autumn school, for providing great lectures and exercises as well as for the fruitful discussions. Their great efforts to provide these lecture notes will certainly make this book as a long-lasting reference in satellite gravimetry. We also thank all attendees of the school who, with their enthusiasm, created a scientific and friendly atmosphere during the school.

A special thank goes to Wilhelm und Else Heraeus Foundation for generously hosting the school. We also acknowledge the support by Prof. Karsten Danzman from Albert Einstein Institute in Hannover who suggested the inspiring venue of Physikzentrum Bad Honnef, Germany. Finally, the support for typesetting by Richu Mary Shelly is gratefully acknowledged.

Data and Material for Exercises

All data and programs for the exercises as well as their solutions (if provided) are available at the following online repositories:

www.geoq.uni-hannover.de/autumnschool-data
http://extras.springer.com

For Chap. 2, the related files can be downloaded from:

http://aiuws.unibe.ch/WEHeraeusAS2015/Chapter2-OrbitDetermination.zip

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