Detlef Angermann · Roland Pail
Florian Seitz · Urs Hugentobler

Mission Earth

Geodynamics and Climate Change Observed Through Satellite Geodesy

Springer

Mission Earth

Detlef Angermann • Roland Pail
Florian Seitz • Urs Hugentobler

Mission Earth

Geodynamics and Climate Change Observed Through Satellite Geodesy

With interview contributions by
Günter W. Hein, Harald Lesch, and
Stefan Rahmstorf

Springer

Detlef Angermann
Deutsches Geodätisches Forschungsinstitut
Technical University of Munich
Munich, Germany

Florian Seitz
Deutsches Geodätisches Forschungsinstitut
Technical University of Munich
Munich, Germany

Roland Pail
Astronomical & Physical Geodesy
Technical University of Munich
Munich, Germany

Urs Hugentobler
Satellite Geodesy
Technical University of Munich
Munich, Germany

ISBN 978-3-662-64105-7 ISBN 978-3-662-64106-4 (eBook)
https://doi.org/10.1007/978-3-662-64106-4

© Springer-Verlag GmbH Germany, part of Springer Nature 2022

This book is a translation of the original German edition „Mission Erde" by Detlef Angermann et al., published by Springer-Verlag GmbH, DE in 2021. The translation was done with the help of artificial intelligence (machine translation by the service DeepL.com). Contents and language were subsequently revised by the authors. Springer Nature works continuously to further the development of tools for the production of books and on the related technologies to support the authors.

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer-Verlag GmbH, DE part of Springer Nature.
The registered company address is: Heidelberger Platz 3, 14197 Berlin, Germany

Preface

Dear Reader!

Have you always wanted to know how your mobile phone knows where you are? Are you interested in how geodynamic processes and ongoing climate change are constantly changing our planet and how we can gain reliable information about its state and changes?

Especially in times of “fake news” and a literally hot climate debate, we think it is important to write down what we know for sure because we have measured it directly. We show how geodetic satellite observations provide a wealth of information about the state of and changes in our Earth, and how this information can be fed into ever better models for describing our complex Earth system—but also where we come up against limits with our measurements. And there is another aspect that is frequently overlooked. We geodesists are often accused, tongue in cheek, of preferring to deal with measurement errors rather than with the measurement itself. In fact, however, the awareness of inaccuracies is crucial in order to be able to judge how reliable the results and models derived from the measurements are in the first place. Only on the basis of this knowledge can the reliability of predictions about future developments be assessed. You will see: With highly accurate satellite data, modern geodesy provides reliable statements about geodynamic processes in the Earth system and about the effects of climate change. By implementing global reference systems of the highest accuracy, it also creates the necessary prerequisite for reliably detecting the smallest changes over periods of years and decades.

Geodesy is one of the oldest sciences in the world and its data and findings have always been highly relevant to society. With the advent of the satellite age, however, its character and range of applications have developed almost explosively. Today, it plays an important role in many areas of daily life and as a basis of information for political decision-makers.

Yes, we know: This book is written with great courage to even greater gaps—and with the perspective "from above", which may be unfamiliar to many. We ask for the indulgence of colleagues from other geodetic disciplines that we have only touched on their hobbyhorses, such as engineering geodesy, geoinformation, land management, photogrammetry, or cartography, although they achieve just as much social relevance with their results.

This book is written for the curious! Are you looking for formulas and mathematical derivations? Sorry, you won't find any. Do you expect to be able to program those comprehensive algorithms based on this book that are needed to reproduce the results described here? Forgive us, in this case the book is a dead loss. We also do not claim to have written a textbook, although the contents will be of equal interest to students in the natural, Earth, and engineering sciences.

Finally, a note for linguists: As trained engineers, we use the expedient approach of the generic masculine in this book. This saves us, and you, from gender-language contortions. So, dear reader, we do so with the explicit statement that we are at least as happy about great interest from female readers. Yes, that's right, women and girls, we desperately need you in the natural and technical sciences, too!

And now we invite you to accompany us on our "Mission Earth". We hope you enjoy and are keen on exploring and measuring what is probably the most exciting planet in our universe!

Munich, Germany

Detlef Angermann
Roland Pail
Florian Seitz
Urs Hugentobler

Contents

About the Authors

Detlef Angermann (*1958) holds a doctorate in Geodesy and is head of the Focus Area Reference Systems at the Deutsches Geodätisches Forschungsinstitut (DGFI-TUM) of the Technical University of Munich. His research focuses on the analysis of geodetic space observations for the realization of reference systems and the determination of Earth system parameters. He is Director of the Office of Products and Standards of the Global Geodetic Observing System of the International Association of Geodesy.

Contact: www.dgfi.tum.de

Roland Pail (*1972) is Professor of Astronomical and Physical Geodesy at the Technical University of Munich. His research activities cover topics in physical and numerical geodesy, with a focus on global and regional modelling of the Earth's gravity field, satellite missions for Earth observation, and applications in components of the Earth system (oceans, water cycle, ice masses, and geophysics).

Contact: https://www.asg.ed.tum.de/iapg/mitarbeiter/pail

Florian Seitz (*1976) is Professor of Geodetic Geodynamics and heads the Deutsches Geodätisches Forschungsinstitut (DGFI-TUM) at the Technical University of Munich. His research interests are the combination of geodetic space observation techniques, geodetic reference systems and Earth rotation, the determination of temporal changes of the sea surface, and the investigation of dynamic processes and interactions in the Earth system.

Contact: www.dgfi.tum.de

Urs Hugentobler (*1959) is Professor of Satellite Geodesy and heads the Satellite Geodesy Research Facility of the Technical University of Munich, which operates the Geodetic Observatory Wettzell in the Bavarian Forest together with the Federal Agency for Cartography and Geodesy. His research topics focus on high-precision positioning by means of the global navigation satellite systems as well as the precise modelling of satellite orbits.

Contact: https://www.asg.ed.tum.de/iapg/mitarbeiter/hugentobler

Prologue

Sadly, she looks out to sea. A gentle breeze comes in from the ocean and cradles her long, flowing hair. Lost in thought, she lets her eyes wander over the horizon. They linger on the last rays of the setting Sun, which the great ocean swallows anew every day—again and again. The sea had been her friend until now. For many generations, it has provided food for her family and served as her primary playground throughout her childhood. Countless stories have been told by her parents and grandparents about this paradise. Now, however, something crucial has changed. Almost imperceptibly, but steadily, the sea is encroaching deeper and deeper inland during the tidal surge, swallowing more and more of the snow-white sandy beach, and eating its way further and further towards her village. It has not yet begun to wash out her house. She does not know that modern satellite techniques measure the progress of sea level rise with high accuracy from space every day. She has never dealt with that before, just as modern technology has never been a central element of her life until now. But she can see what the satellites measure with her own eyes, and guess that the rising sea is not just a problem for her small world. She knows she will have to leave soon, even before the aquatic behemoth reaches the doorstep of her home. The rising saltwater from the sea has contaminated the groundwater and made the soil infertile. For as long as her family can remember, their village has been self-sufficient. From the treasures that the abundant soil and the even more abundant sea had to offer them. That has now changed—insidiously, yet inexorably. They will move away from here to the nearest major city on the mainland. At least for a few generations, until it too is threatened by rising sea level. She will have to leave, but she knows that her heart will stay here forever …

Pouring rain lashes down on her, soaking her hair and clothes. She buries herself deep in her jacket and tries to find shelter at the nearest grocery store awning. She awkwardly digs her new cell phone out of her pocket. With the move, she was confronted with a whole new world in one fell swoop. Huge houses, busy streets, dirty air, and countless people. Nothing is like it used to be, and something grave has changed: Modern technology dominates the new life in the vibrant city. In the meantime, she has become accustomed to the mobile phone and has learned to use it for her personal use. It is no bigger than the conch shell that is in her other jacket pocket and is meant to remind her of her old life, to connect her to her old life. This little high-tech gadget has become her indispensable companion for finding her way around this jungle of houses, cars, and streets, while her parents and grandparents can't seem to warm to it at all. She has been here for a good five weeks now, but many things are still foreign to her, such as the opaque bureaucracy with which she has never had anything to do before. She has to go to the registration office to sort out personal matters and present important documents. She has never been to this part of the city, which looks so different from the one where she moved into a small, simple apartment with her family. She lost her bearings in the pouring rain and got lost. To protect her mobile phone from the deluge pouring from the sky, she presses herself tightly against the wall. The screen lights up brightly as she presses the activation button. Unnoticed, her cell phone makes contact with all the positioning satellites visible from her location, quickly determining her current position and displaying it on the electronic map. Other information pops up: The positions of banks, post offices, restaurants, and supermarkets in her vicinity. All what a sophisticated system behind it has interpreted as "important places". Now that the rain is slowly losing intensity, she starts moving, guided by a small blue dot and an arrow on a tiny screen …

1

Introduction

1.1 The Earth: A Dynamic Planet

We live on a highly dynamic planet, on and in which processes of change are constantly taking place. Many of these changes are linked to the immediate habitat of us humans, and some of them are subtle indicators of potential climate change.

Figure 1.1 shows the most important components of the Earth system as well as various geodynamic processes that take place in the interior, on the surface or in the exterior of the Earth. In the Earth's interior, processes of change occur on very long time scales of millions of years, for example convective motion in the mantle, which ultimately drive processes in the lithosphere such as plate tectonics and are thus responsible for mountain building, earthquakes and volcanism. In the oceans, large transports of heat and energy take place via ocean currents. Here, large amounts of energy irradiated by the Sun are transferred from the equatorial regions towards the poles. The hydrological cycle reflects seasonal periodic processes as well as trends in precipitation, evaporation and runoff, which ultimately lead to variable amounts of water storage in a given region. In addition to liquid water, there are also long-term variations such as secular melting processes of large ice sheets (Greenland, Antarctica) and smaller inland glaciers. All these subsystems are very closely coupled with each other, but also with the atmosphere. This close interaction is also what makes understanding this complex Earth system so difficult, because any change in one subsystem can trigger massive consequences in another. So if you pull a thread in one subsystem, it is not unlikely that the woolly jumper in the neighboring subsystem will unravel.

D. Angermann et al., *Mission Earth*, https://doi.org/10.1007/978-3-662-64106-4_1

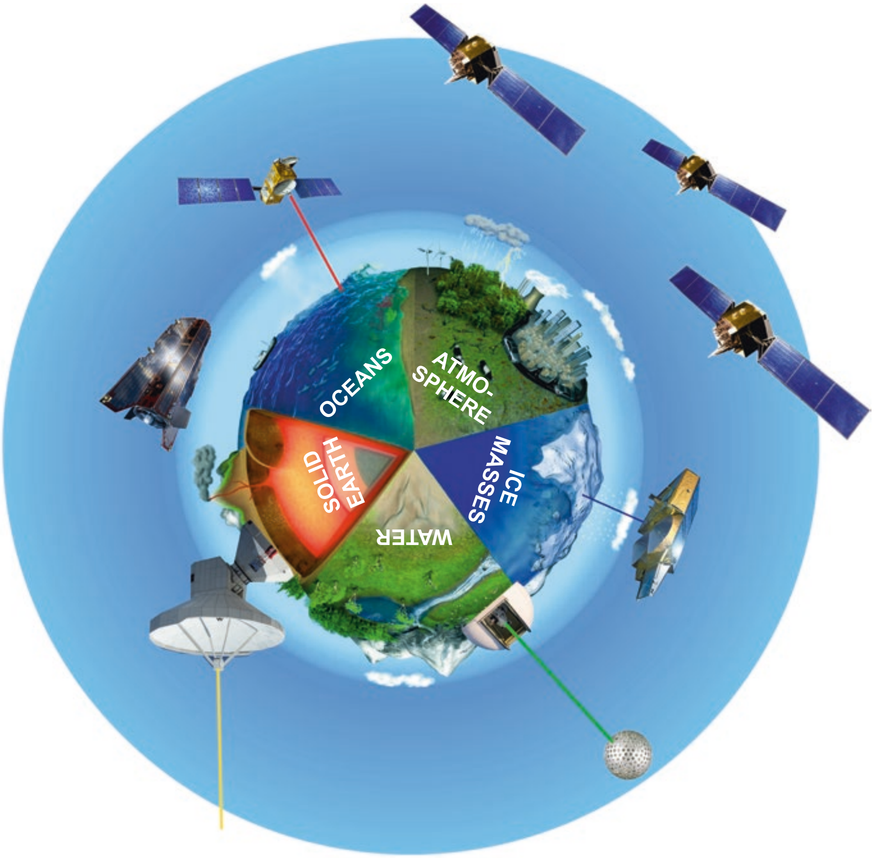

Fig. 1.1 Components of the Earth system and geodetic observation techniques

From the point of view of system understanding and modelling, however, this also results in important boundary conditions in the form of so-called conservation variables. If two or more subsystems communicate with each other like vessels connected by pipes, the same amount of water mass must arrive in one vessel as flows out of the other. Something similar to the (water) mass also applies to energy and, somewhat more abstractly, angular momentum. Of particular importance to us, of course, is the interaction of the individual subsystems and ultimately of the entire Earth system with the biosphere living on it, of which we as humans are a central part.

1.2 Earth System, Climate Change and Society

In this interplay, processes of change in the subsystems are also indicators of a changing global climate. Here, the following question increasingly plays a central role: Which of the observed change processes are part of a natural cycle and which are caused or at least influenced by humans?

One example of trends in the Earth system is the change in the Earth's global average temperature. Since the beginning of the industrial revolution at the start of the last century, the global mean surface temperature has risen by more than one degree Celsius, and the carbon dioxide content of the atmosphere has increased by almost 50 percent during this period. With the aid of computationally highly sophisticated climate models, which are run on the world's largest scientific computer systems, it is also possible to make forecasts for the future. Figure 1.2 shows the course of global mean temperatures over the past 120 years as well as forecasts for global temperature development over the next century. Depending on the scenario assumed, in particular which countermeasures are taken politically at the global level in the next few years,

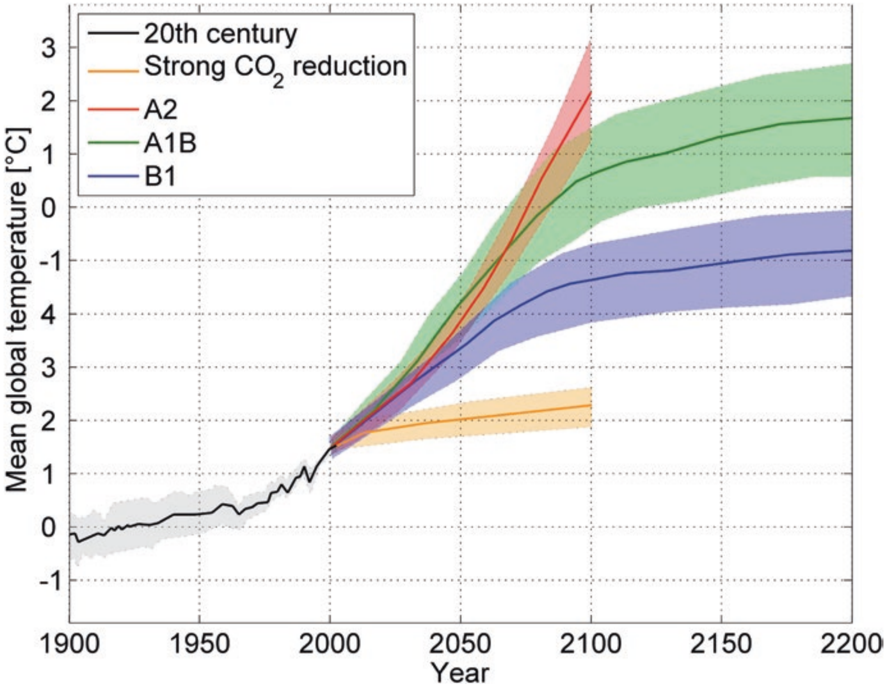

Fig. 1.2 Forecast for temperature development until 2100 (after IPCC, 2007, modified). Curves B1, A1B and A2 refer to different scenarios for future greenhouse gas emissions

a temperature increase of approximately 1.5 to 4.5 degrees Celsius is predicted as the global mean. Achieving the “two-degree Celsius target” familiar from the media (according to the Paris Climate Treaty of 2015, the target is even 1.5 degrees Celsius), which was agreed upon after hard wrangling at the past world climate conferences, seems extremely questionable or at least very ambitious from the perspective of what has been achieved so far.

In addition, due to the complexity of the Earth system and the different behavior of continents and oceans with regard to temperature changes, there are very large regional differences. The continents warm much more easily and quickly than the oceans. Figure 1.3 demonstrates the irregular geographic distribution of the predicted temperature increase. For this purpose, predicted temperatures for the years 2081 to 2100 were averaged and compared with a mean temperature for the period 1986 to 2005. The regional temperature development is shown for an optimistic climate scenario (Fig. 1.3a), which assumes a massive reduction in carbon dioxide (CO_2) emissions, and a pessimistic scenario (Fig. 1.3b), which is based on a further increase in greenhouse gases. Obviously, the regions of the Northern Hemisphere close to the poles will be particularly affected, while other areas—especially ocean areas—will warm only to a lesser extent. Since ocean areas, which occupy about 70 percent of the Earth’s surface and are therefore strongly included in the averaging, a global mean temperature increase of two degree Celsius means that within a century it will be four to five degrees Celsius warmer in continental regions, and as much as six to seven degrees Celsius warmer in polar regions.

Due to these temperature changes, there are a number of other temporal variations in the Earth system. For example, melting processes of the large ice sheets such as Greenland and Antarctica can be detected today (Sect. 4.5). This is coupled with a rise in global sea level, which has risen by about 20 centimeters in the past century (Sect. 4.4).

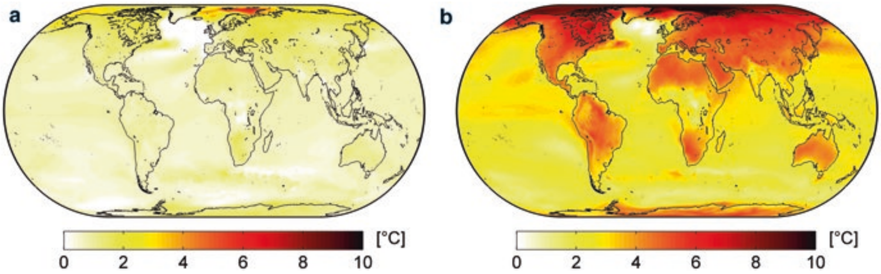

Fig. 1.3 Geographical distribution of temperature changes in 2081 to 2100 compared with 1986 to 2005 for an (**a**) optimistic and a (**b**) pessimistic climate scenario (after IPCC, 2014, modified)

However, understanding the processes of change in our Earth system is not only of scientific interest, because they also have a socio-economic impact. Natural disasters such as earthquakes, volcanic eruptions, floods, landslides and storms not only claim tens of thousands of lives every year, but also cause high costs due to the large damage of infrastructure. Furthermore, the Earth is a finite planet with limited resources of raw materials, fossil energy, drinking and process water availability and cultivable soils. This contrasts with a steadily growing world population. In 2050, the population is expected to reach 8.5 billion people. The finite nature of the available resources can lead to mass migrations, political and military conflicts.

Due to the dynamic processes of the Earth system, global risks also arise. In addition to risks from natural disasters such as earthquakes, volcanism or hurricanes, slow processes such as sea level rise also have enormous threat potential. The associated loss of habitats can result in major migration movements and social conflicts.

1.3 Geodynamic Processes: Very Different Speed

The periods of geodynamic processes are very different. Plate tectonic processes (Sect. 4.2) take millions of years and lead to movements of lithospheric plates at a snail's pace of a few centimeters per year. Comparable to a crossbow that is stretched over long periods of time and then abruptly released, the tensions built up by plate tectonics are abruptly released in the form of earthquakes, often in just a few seconds (Sect. 4.2). This produces seismic waves that travel through the Earth's body at a speed of several kilometers per second.

Changes in the Earth's water masses also occur on completely different time scales. While we observe a global sea level rise of about three millimeters per year (Sect. 4.4), tsunamis have propagation speeds of several hundred meters per second (Sect. 4.3).

But what does it mean if we want to observe such processes of change? From the extreme examples given with regard to spatial and temporal scales, we can already derive requirements for observing systems to measure these phenomena. On the one hand, the goal is to record extremely small change processes that occur very slowly. This means that we need to observe with extremely high accuracy in order to detect, for example, plate motion rates of a few centimeters per year or sea level changes of a few millimeters per year. So here we are looking for a very small needle in a very large haystack. At the other end of the time scale, observations are needed almost in real-time if we want to use them for early warning systems, for example.

So we need to be able to measure with high precision, and do so as permanently and as globally as possible. This is exactly where geodesy comes into play …

1.4 Global Measurement of the Earth

The discipline of geodesy deals with the continuous measurement of the time-varying geometry of land and sea surfaces, the Earth's gravitational field, and its rotation and orientation in space. In addition to the classical surveying tasks, it thus also makes fundamental contributions to monitor processes in the Earth system in space and time and to analyze the dynamics between the system elements with very high accuracy. Therefore, geodesy is able to directly observe even very small and slow processes of change.

Today, the term geodesy or surveying is still often associated with the image of the rubber-booted civil servant who toils through the mud in the field in wind and almost any weather to measure property boundaries and roadways or to check whether the evil neighbor has possibly even absconded with a piece of land. However, at the latest since the beginning of the satellite era, but actually much earlier with the technical development of new measuring methods and sensors, this picture has changed and the range of applications of geodesy has expanded enormously. Today, for example, a geodesist measures car parts in industrial production with very high-precision, develops detailed models of buildings and even entire cities on the computer even before the first sod is turned, takes care of digital maps, provides the mathematical tools for vehicle navigation systems and also measures our dynamic planet on a global scale. In addition to pure data acquisition as the first part of the food chain, geodesy also deals with the analysis of data, their visualization, up to the royal league, the derivation of models and products and their interpretation.

In this sense, this book should not be misunderstood as a general overview of the geodetic portfolio, but rather focuses on the aspects of global Earth monitoring and the methods of satellite geodesy. Only satellites enable us to make global observations over short periods of time in order to record the changes of our dynamic planet with a high degree of accuracy. As Fig. 1.1 already suggests, there is an interdisciplinary exchange with many other geoscientific disciplines, such as geophysics, oceanography, glaciology, atmospheric physics, climate research, Earth system research and astronomy.

Modern geodesy contributes to geodetic Earth system research with three basic pillars. These are shown in Fig. 1.4. Associated measurement methods are symbolically indicated in Fig. 1.1 and discussed in detail in Chap. 3.

Geometry and Kinematics

Geodesy defines the geometric form of parts of the Earth's surface up to the planet as a whole in form elements or geometric objects. This includes point coordinates of stations on the Earth's surface, their changes as well as spatial deformations of the solid Earth. However, since more than two-thirds of the Earth's surface consists of oceans, we also care about the geometric changes of the ocean surface.

Orientation and Rotation

Geodesy determines the rotation of our planet and its orientation in space. It determines the position of the Earth's rotation axis relative to the fixed star sky and determines its variable rotation speed. This is necessary, for example, to link the orbit of a satellite with any position on the Earth's surface, so that our navigation system also indicates the correct location (Sect. 4.7).

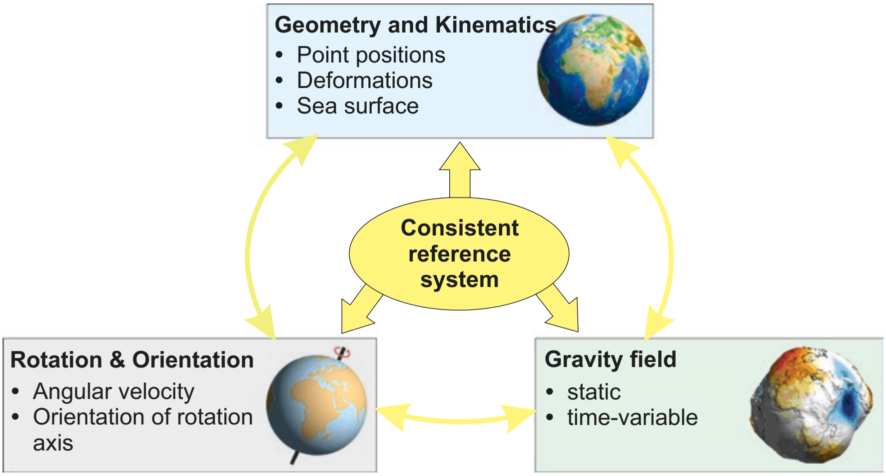

Fig. 1.4 The three pillars of geodesy

Gravity Field

Geodesy determines the gravitational field in the Earth's outer space generated by the irregular distribution of mass in the Earth's interior and on the surface, as well as its changes over time, which are related to mass transport processes in the Earth system (Sect. 3.7).

Highly accurate reference systems are of particular importance in this context (Sect. 3.2). If we want to record very small changes, such as a few millimeters of sea level change, we also need a reference state, a zero surface, so to speak, which must be known even more precisely so that we can make the right statements. Consistent reference systems are particularly important if we want to combine apples and oranges—in our case geometric and gravimetric observations—in joint models and then interpret the model behavior correctly.

Dear reader! Where do we go from here? Part 2 of this book presents the historical development of geodesy up to the satellite era. Part 3 deals in detail with the global observation methods of modern geodesy. Part 4 describes and discusses examples of important change processes in the Earth system, many of which are sensitive indicators of climate change. Finally, in Part 5, we place these applications and results in a societal context and discuss the relevance of geodetic observation techniques, findings, and products for the man and woman in the street. Have fun reading on!

2

The Measurement of the Earth Through Time

2.1 Introduction

The year 1957 marks an important milestone in the history of geodesy: The launch of the first artificial satellite virtually revolutionizes the surveying of the Earth. With the help of satellite observations, the Earth as a whole can now be measured with high accuracy for the first time and thus different continents can also be easily connected with the artificial measuring targets in the sky, which was previously unimaginable using terrestrial (earthbound) observations. Due to the rapid development of satellite observation methods and computer technology as well as the increase in accuracy in time measurement, the range of applications of geodesy has continuously expanded over the past decades to include the highly accurate recording of the effects of geodynamic processes or the consequences of climate change.

But what did it look like before the satellite age? Without the artificial objects in space, a global measurement of the Earth is not possible. Earth-based observation methods require a direct line of sight between the measurement points, making the vast oceans insurmountable in terms of measurement technology. Surveying larger areas, such as land surveying in the nineteenth century, involves enormous metrological efforts. Also the theory of the continental drift of the famous geoscientist Alfred Wegener from the year 1912 cannot be confirmed at that time by measurements. The already known methods of astronomical positioning only provide accuracies of a few meters, which is not nearly enough to prove the movements of the Earth's plates of a few centimeters per year.

D. Angermann et al., *Mission Earth*, https://doi.org/10.1007/978-3-662-64106-4_2

Wegener justifies his theory with the fact that the east coast of South America fits exactly to the west coast of Africa, as if they had been connected in former times. This finding goes back to the first map of a primeval continent published by the French naturalist Antonio Snider-Pellegrini in 1858. Wegener also detects that some geological formations on the coast of South America find their continuation on the African continent. Paleontologists also discover fossils of the same animal and plant species on both coasts. From these discoveries grows Wegener's idea that the land masses were once united in the supercontinent Pangaea and then drifted apart over millions of years. When he presented his theory of drifting continents at geological meetings, his colleagues laughed at him and mocked him as a "storyteller". The main criticisms are that he cannot explain what forces produce the drift of the continents, and furthermore, at that time no one is able to prove the drifting apart of the continents by suitable measurements. Wegener's theory is several decades ahead of its time, and so he is not granted the fame he deserves for his groundbreaking insight until his death. He died in 1930 during a Greenland expedition shortly after his 50th birthday and therefore unfortunately did not live to see the later triumph of his hypothesis. It was not until the 1950s and 1960s that Wegener's ideas were revived as a theory of plate tectonics, and in the 1990s the movements of the Earth's plates were successfully demonstrated for the first time using modern geodetic observation methods (Sect. 4.2).

But not only the entry into the space age has triggered an enormous change. Even before that, the history of the development of the surveying of the Earth over the millennia was extremely exciting. In addition to the social and technological framework conditions, the idea of the shape of the Earth and its position in space has also undergone serious changes. In ancient times, people still firmly believed in a disc-shaped Earth, in antiquity the Greeks proved its spherical shape, and in the seventeenth century the French and English argued over the question of whether the Earth was flattened at the poles. Even today, by the way, there are still advocates of the disc shape. The question of the correct world system also caused heated disputes in the sixteenth and seventeenth centuries.

In the following chapters we would like to take you on a journey through time from the first surveys of earlier advanced civilizations to today's satellite age. You will learn how geodesy has changed over time and what great significance earlier discoveries still have today for modern geodetic observation methods and Earth surveying.

2.2 The Origins of Surveying

When, where and how did surveying originate and how did it develop? The end of the last ice age about 11,000 years ago and the accompanying rise in temperatures ushered in a change in the way people lived. In the course of the so-called Neolithic Revolution, the transition from hunter-gatherer culture to sedentarism takes place, associated with the construction of settlements, the cultivation of agricultural land and the raising of livestock. The beginnings of surveying start around 8000 BC, when people begin to become sedentary. Field surveyors are already necessary for the division of fields and the allocation of cultivable land among villagers.

In the fourth millennium BC, the first advanced civilizations emerged along rivers and in climatically favored regions of the Earth, such as the Egyptian Empire on the Nile and Mesopotamia in the fertile plains between the Euphrates and Tigris rivers in the southeast of present-day Iraq. The major social tasks of these advanced civilizations included the construction and maintenance of irrigation systems, the building of settlements and temples, and the division of usable agricultural land. In order to solve these tasks, practical knowledge of construction, mathematics and surveying techniques is essential.

The Nile plays a dominant role in the life of ancient Egyptian society, and its annual floods keep large parts of the country fertile due to the mud deposits. Elaborate irrigation systems channel the Nile waters to agricultural land, providing the basis for bountiful harvests. The annual flooding of the Nile requires extensive surveying work in order to re-establish ownership and the old property boundaries for the division of the fields. Egyptian tomb depictions document how measurements are taken with a rope made of hemp and divided into equal units of length by knots (Fig. 2.1). The Egyptians already used geometric knowledge for establishing right angles. For this purpose, they used either an angle hook or a measuring cord with the help of the 3:4:5 ratio (Egyptian triangle). In this respect, the famous theorem of Pythagoras was already known to the ancient Egyptians. With these tools, measuring ropes, leveling instruments and plumb bobs, the Egyptians succeeded in exact measurement when building the famous pyramids. Not only in position measurement, but also in height measurement, they already achieved amazing accuracies, for example in determining the flood heights of the Nile.

The Sumerians, the oldest inhabitants of the fertile Mesopotamia between the Euphrates and Tigris rivers, also set up a sophisticated irrigation system for their agricultural land. They practiced productive agriculture as early as the third millennium BC and invented the first potter's wheels, the first surviving writing system and the first legal systems. Field surveying skills develop,

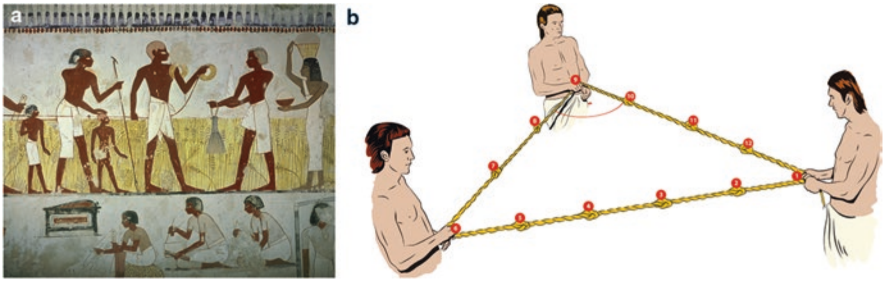

Fig. 2.1 Ancient Egyptian surveying: (**a**) Wall painting of Egyptian cordsman in a scene of stretching the cord from the tomb of Mennah, (**b**) Measuring rope made of hemp knotted at intervals (ratio 3:4:5, Egyptian triangle). (© Erich Lessing/akg-images/picture alliance), (© lukaves/Getty Images/iStock)

as in Egypt, from the practical needs of society such as field surveying, building settlements and irrigation systems. One document for the Sumerians' surveying work is the city plan of Nippur, the center of Sumerian culture on the Euphrates, found during excavations (Fig. 2.2).

In this period of the first advanced civilizations mankind believes that the Earth is a disc. For example, the ancient Egyptians imagine that people live in the middle of this disk, and the river Nile separates it into two large parts. According to their idea of the three planes, the people on the disk live in the upper world, below them are the deceased in the underworld, and above them is the heavenly place of the gods.

2.3 Ancient Greece: From the Disk to the Spherical Earth

Greek natural philosophy marks the beginning of European science in the sixth century BC. Astronomy and geometry become the supporting pillars of the gradually developing geodesy. Greek scholars pose the question of the figure and size of our planet. The natural philosopher Thales of Miletus, a great astronomer and mathematician of the time, searches for the origin of the Earth and its relationship to the sea. He holds that water is the origin of everything and that the Earth floats on the ocean. Thus, scholars in ancient Greece also consider the Earth to be a flat circular disc, washed by the ocean.

The Greek philosopher Pythagoras was the first to advocate the idea of the Earth as a sphere, which is supported by a wide variety of observations. One argument is based on observations on the ocean: If the Earth were indeed flat, a ship would have to be recognizable from the sail to the hull in its entire height, even at a greater distance. But this is not the case, because at first we

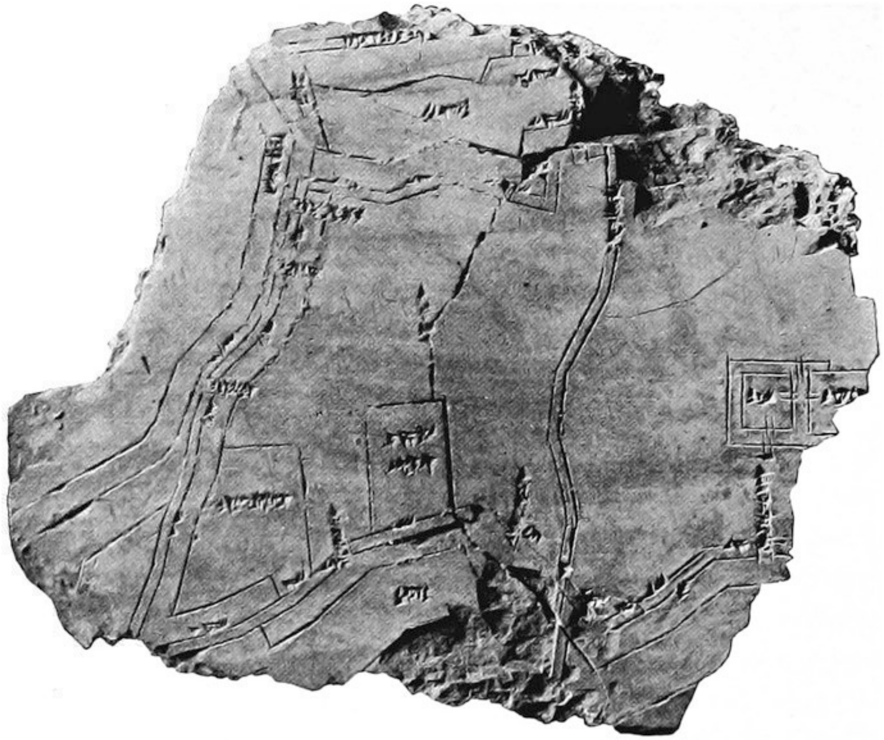

Fig. 2.2 Map of Nippur on an ancient clay tablet. (© Hermann Vollrat Hilprech, photo from 1903, Wikimedia Commons, public domain)

only see the sails of the ship in the distance. We only see the hull later, when the ship has already come closer to the shore. Conversely, sailors also notice that from a distance only the hills and treetops of an island are visible, and only as the ship approaches does the dazzling white beach come into view. The Greeks have another argument for the spherical shape of the Earth: The Sun's zenith changes as one travels further north or south. This can only be the case if one travels along a curved line, clearly disproving the Earth's disk shape. Aristotle provides a third argument: When observing a lunar eclipse, he noticed that the Earth always casts a round shadow on the Moon when the Earth steps between the Sun and the Moon. But this can only be so if the Earth is a sphere and not a flat disc. If it were a disk, the shadow could only be round if the Sun was directly below the center of the Earth's disk at the time of the eclipse, otherwise the shadow would always be elongated and have the shape of an ellipse.

Now that the spherical shape of the Earth is beyond doubt, the Greeks naturally ask themselves the question of the size of our planet. In the third century BC, the Greek scholar Eratosthenes, the head of the Royal Library of Alexandria, has an ingenious idea for determining the circumference of the

Earth. His method is explained in the box below. It is almost sensational that Eratosthenes, with his rather rough estimation and the limited measuring possibilities of that time, is already very close to today's value for the circumference of the Earth at the equator of 40,075 kilometers.

First Determination of the Circumference of the Earth by Eratosthenes

It is known to the Greeks that in the city of Syene (modern Aswan) on 21 June at the summer solstice the Sun's rays fall exactly perpendicularly into a well at noon and are thus directed towards the center of the Earth. It is also observed that in the northern city of Alexandria the Sun is not quite as high at the same time, rather a large obelisk casts a shadow whose angle can be easily calculated from the length of the shadow and the height of the obelisk. The result is a value of 7.2 degrees, exactly the fiftieth part of a circle. According to the schematic representation in the following figure, this angle is identical with the central angle at the center of the circle. Consequently, the distance between Alexandria and Syene is equal to the fiftieth part of the circumference of the Earth. It takes a camel caravan 50 days to travel between the two cities, covering about 100 stadia (ancient measure of length) per day, so Eratosthenes estimates the distance to be about 5000 stadia. One stadium corresponds to about 160 meters, so the distance is about 800 kilometers. Multiplying this distance by a factor of 50, this geometrically simple and at the same time ingenious method yields a circumference of the Earth of about 40,000 kilometers.