Chapter 1
Introduction

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1.1 The challenge: living on a changing, dynamic planet

Earth is a restless planet (Solomon & the Solid Earth Science Working Group, 2002). With its atmosphere, oceans, ice cover, land surfaces and its interior, it is subject to a large variety of dynamic processes operating on a wide range of spatial and temporal scales, driven by large interior as well as exterior forces. Many areas of the Earth's surface are exposed to natural hazards caused by dynamic processes in the solid Earth, the atmosphere and the oceans. Earthquakes, tsunamis, volcano eruptions, tectonic deformations, landslides, deglaciation, sea level rise, floods, desertification, storms, storm surges, global warming and many more are well known phenomena that are expressions of the dynamics of our restless planet. In modern times these processes are influenced, as well, by anthropogenic effects; to what extent is still largely unknown.

Earth is a finite planet. Resources such as clean water, arable land, flora and fauna, minerals, and energy are limited. Probably even more importantly, the capacity of the Earth system to maintain a delicate equilibrium under increasing anthropogenic pressure is limited.

A growing population has to cope with this restless, and finite, planet. On the one hand, settlements are encroaching into areas of high risks from natural hazards with major infrastructure being built in locations with high risks of large earthquakes, volcanic eruptions, storm surges, tsunamis, landslides and flooding, thus increasing the vulnerability of society. Increasingly, critical infrastructure is destroyed in natural disasters, affecting the economy on national and global levels, and displacing large populations, with severe social implications. On the other hand, the growing demands for access to food, water, materials, and space put stress on the finite resources of the planet. The anthroposphere has grown into a powerful force rapidly transforming the Earth's surface layers (as documented, e.g., by Turner II et al., 1990) and capable of changing major processes, including those of the climate system. However, humanity has not reached the necessary understanding to actually

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wield this power. Earth system processes, whether natural or modified by humans, affect our lives and the lives of future generations: decisions made today will influence the well-being of future generations. In order to minimize the anthropogenic impact on Earth system processes and in order to preserve resources for future generations, a better understanding of Earth system processes is required.

Reaching a condition of "sustainable development" has been recognized as a necessary (albeit not sufficient) prerequisite for living on a restless planet with finite resources, and with a limited capacity to accommodate the impact of the increasingly powerful anthropogenic factor. A number of World Summits have acknowledged that a sustainable development is mandatory for realizing a stable and prosperous future for the anthroposphere. Although there are many other influential factors, understanding the Earth system, its major processes and its trends, is one of the prerequisites for the success of the quest for sustainable development. Major decisions determining our future will have to be based on a much deeper understanding of this complex system.

A deeper understanding of the Earth system cannot be achieved without sufficient observations of a large set of quantities characteristic of Earth system processes. As emphasized by the Earth Observation Summits (EOSs), there is an urgent need for comprehensive Earth observations (see the documents in the Appendices of GEO, 2005b). Earth observations are not only necessary for a scientific understanding of the Earth, they are fundamental for most societal areas ranging from disaster prevention and mitigation, the provision of resources (such as energy, water and food), improving our understanding of climate change, the protection of the biosphere, environment, and human health, and ultimately to the building and management of a prosperous global society.

1.2 The potential: geodesy's contribution to a global society

Geodesy is the discipline that deals with the measurement and representation (geometry, physics, temporal variations) of the Earth and other celestial bodies (Sideris, 2007). The "three pillars" of geodesy are the Earth's time-dependent geometric shape, gravitational field, and rotation (Figure 1.1). Today, along with these pillars a number of related quantities are observed with terrestrial and space-geodetic techniques using a combination of spaceborne and airborne sensors and *in situ* networks (see Chapter 2). With its observational means, geodesy has the potential to determine, unambiguously and with utmost precision, the geometric shape of land, ice, and ocean surfaces as a global function of space and time. Since the dense web of microwave radiation used for geodetic positioning passes through the atmosphere, its interaction with the atmosphere yields important weather parameter information. The geometric methods when combined with global gravity information and the geoid, allow us to infer mass anomalies, mass transport phenomena and mass exchange in the Earth's system. Finally, the variations in Earth rotation reflect mass transport in the Earth system and the exchange of angular momentum among its components.

Observations of the Earth's variable shape, gravity field, and rotation provide the basis for the realization of the reference systems that are required in order to assign (time-dependent) coordinates to points and objects, and to describe the motion of the Earth in space (Figure 1.1). For this purpose, two reference systems are intrinsic in geodesy, namely the celestial reference system and the terrestrial reference system, which are dynamically linked to each other by the Earth's rotation. The two most accurate reference systems currently available are the International Celestial Reference System (ICRS) and the International Terrestrial Reference System (ITRS)(see Section 2.2 for more details), which are defined by the International Earth Rotation and Reference Systems Service (IERS). These systems are conventional coordinate systems that include all conventions for the orientation and origin of the axes, the scale, and the physical constants, models, and processes to be used in their realization. Based on observations, these systems can be realized through their corresponding "reference frames". The frame corresponding to the ICRS is the International Celestial Reference Frame (ICRF), which is a set of estimated positions of extragalactic reference radio sources. The frame corresponding to the ITRS is the International Terrestrial Reference Frame (ITRF), which is a set of estimated positions and velocities of globally distributed reference marks on the solid Earth's surface. These two frames are linked to each other by estimates of the Earth Orientation Parameterss (EOPs). ICRS, ITRF and the EOPs are provided by IERS.

Today, the internationally coordinated geodetic observations of the global geodetic station networks provide a continuous monitoring of the ITRF. This well-defined, long-term stable, highly-accurate, and easily accessible reference frame is the basis for all precise positioning on and near the Earth's surface. It is the indispensable foundation for all sustainable Earth observations, *in situ*, as well as airborne and spaceborne. Furthermore the ITRF underpins all geo-referenced data used by society for so many uses. At the most foundational level the ITRF rigorously supports the Spatial Data Infrastructure (SDI). The SDI is a model of all geo-referenced data that consists of many layers, all connected to the geodesy layer which is the realization of the ITRF at national and regional (and increasingly the international) scale. The other layers of the SDI are like elements of a "house", built on strong foundations, and include map and image data of the physical surface of the Earth, its terrain, waterways, forests, vegetation and habitats; transport and built infrastructure such as roads, railways, and other structures; cadastral land boundaries; political boundaries; and many others. These layers of digital geo-referenced data are crucial for many activities, ranging from mapping, construction, land development, natural resource management and conservation, navigation - in fact all decision-making that has a geo-related component.

Historically, geodesy was limited to determining the shape of the Earth, its gravity field, and its rotation including their changes over time. With modern instrumentation and analytical techniques, the scope of geodesy has extended to include the causes of the observed changes, i.e., the dynamics of and mass transport within the Earth system. With this broader scope, new pathways emerge in which geodesy can

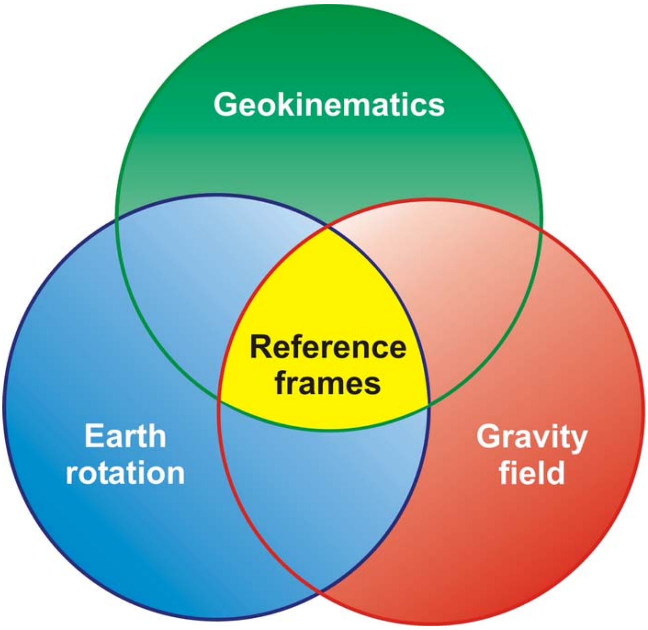

Fig. 1.1. Constituents of an integrated geodetic monitoring system. The “three pillars” of geodesy provide the conceptual and observational basis for the reference frames required for Earth observation. These three pillars are intrinsically linked to each other as they provide different observation related to the same Earth system processes.

contribute to the scientific understanding of the Earth system as well as the development, functioning, and security of society in general.

To a large extent, geodesy is a “service science”. In the past, the main “customers” of geodesy came from the surveying and mapping profession, while today geodesy serves all Earth science, including the geophysical, oceanographic, atmospheric, and environmental science communities. Consequently, today the development of the geodetic observing system is guided by the user requirements of a much broader “customer” base.

With the “three pillars”, geodesy precisely observes and consistently monitors mass movement in the Earth system and its associated dynamics:

- **Geokinematics:** measuring the geometric shape of the Earth’s surface (solid Earth, ice and oceans) and its kinematics and variations, on global to local spatial scales, and at time scales from rapid to secular;
- **Earth rotation:** monitoring the variations of the Earth’s rotation as an indicator of all angular momentum exchange inside, on or above the solid Earth, as well as of the torques acting on the solid Earth (including those due to the Sun and Moon); and
- **Gravity field:** determining and monitoring the Earth’s gravity field and inferring the underlying mass redistributions in the solid Earth, liquid core, atmosphere, oceans, hydrosphere, and cryosphere.

Ultimately, all geodetic observations are affected by the same physical Earth system processes. Thus, geodesy provides a unique framework for monitoring and ultimately understanding the Earth system as a whole. Modern space-geodetic techniques are well suited for observing phenomena on global to regional scales, and thus are an important complement to traditional *in situ* observation systems.

The rapid development of space-geodetic techniques (see Chapter 2) also enables auxiliary applications that utilize the atmospheric disturbance of geodetic measurements (ionosphere, troposphere, magnetic field) for non-geodetic applications. Atmospheric disturbances formerly were the natural factor limiting the accuracy of geodetic measurements. Now this "noise" is increasingly being recognized as "signal", and the distortions of microwave signals propagating through the atmosphere can be "inverted" for atmospheric parameters and utilized for numerical weather prediction (e.g., Jerrett & Nash, 2001; Elgered et al., 2005), climate studies, and studies in atmospheric physics.

A major driver for the development of the geodetic observing system is the progress of science. In addition, technological advances with improved sensors, networks, and communications, the impact of nanotechnology, and the development of new and improved observing systems (for example, Interferometric Synthetic Aperture Radar (InSAR), LIght Detection And Ranging (LIDAR) and all remote sensing missions, including Gravity Recovery and Climate Experiment (GRACE), Gravity field and steady-state Ocean Circulation Explorer (GOCE), and future satellite missions) are key drivers. As pointed out above, the mounting pressure of environmental changes and the associated societal needs demand improved Earth observations which in turn put increasing demands on the geodetic observing system. Issue such as hazards monitoring and understanding of global change, the exponential growth of, and need for, geo-spatial information, and the complexity and scale of the global problems that cannot be solved by a single science require a well developed geodetic observing system. Geodetic expertise is therefore increasingly needed, and valued, by other sciences (Sideris, 2007).

With this development, geodesy faces several challenges (Sideris, 2007), namely: (1) inter-disciplinarity is required in order to contribute to collaborative solutions to problems, to allow for an optimal assimilation of a wide spectrum of observations into inter-disciplinary models, and to enable to interpretation and separability of the various signals; (2) development of a framework for a four-dimensional geodesy is required, in which temporal variations in the shape of the Earth and its gravity field are fully accounted for, long-term observation campaigns and archiving are planned with the 4-D nature of the system in mind, and an accuracy level for geometric and gravimetric quantities of much better than 10^{-9} (approaching 10^{-12}) is achieved; and (3) the recognition of what geodesy is and who benefits from needs to be communicated through appropriate outreach, and geodesy, in particular the International Association of Geodesy (IAG), faces the challenge of how best to promote the geodetic contributions to science and society at large.

Many scientific applications depend on a detailed knowledge of the Earth's shape, its gravity field and rotation (see Chapter 3), and in the past geodesy has (with ever-increasing accuracy) provided the necessary observations. The relatively recent advent of space-geodetic techniques has brought about a rapid development in global geodesy. The relative precision of the measurements is approaching the very impressive level of 1 parts per billion (ppb) or even better. Today, geodetic techniques permit the measurement of changes in the geometry of the Earth's surface with an accuracy of millimeters over distances of several thousand km.

Over the last one and a half decades, the global geodetic networks have provided an increasingly detailed picture of the kinematics of points on the Earth's surface and the temporal variations in the Earth's shape. Among other applications, the observations have been used to determine improved models of the secular horizontal velocity field (e.g., Kreemer & Holt, 2001; Kierulf et al., 2002; Kreemer et al., 2003), to derive seasonal variations in the terrestrial hydrosphere (e.g., Blewitt et al., 2001), to study seasonal loading (e.g., Dong et al., 2002), to invert for mass motion (e.g., Wu et al., 2003), and to improve the modeling of the seasonal term in polar motion (Gross et al., 2004). Geodetic techniques provide the means to observe surface deformations on volcanoes (e.g., Lu et al., 2000; Lanari et al., 2002; Bonforte & Puglisi, 2003), in unstable areas (e.g., Ferretti et al., 2004), associated with earthquakes and fault motion (e.g., Banerjee et al., 2005; Vigny et al., 2005; Kreemer et al., 2006b), or subsidence caused by anthropogenic activities such as groundwater extraction (e.g., Strozzi et al., 2002). Current developments indicate that geodetic observing techniques will be able to determine the magnitude of large earthquakes in near-real time and thus help mitigate the problem of low initial magnitudes estimated by seismic techniques (Blewitt et al., 2006b).

Spaceborne sensor systems play an important role in Global Change studies. With satellites it is feasible to observe Earth system processes globally, uniformly and with relatively rapid repetition rates. Nevertheless, the results are still inconclusive, as evidenced by the ongoing debate about global warming (see, e.g., Hogan, 2005, and the references therein).

If the geodetic observations and products can be provided on a global scale with a precision at or below the 1 ppb level, consistently, and with sufficient stability over decades, geodesy can make very important contributions to our understanding of the state and dynamics of System Earth (see Chapter 5). A prerequisite for exploiting the full potential of geodesy for Earth observation, Earth system monitoring, and many practical applications, is a sophisticated integration of all geodetic techniques (spaceborne, airborne, marine and terrestrial), processing models and geophysical background models into one system model. This integration will permit – as part of global change research – the assessment of surface deformation processes and the quantification of mass anomalies and mass transport inside the individual components, and mass exchange between the components of the Earth's system. These quantities serve as input to the study of the physics of the solid Earth, ice sheets and glaciers, hydrosphere and atmosphere. They are of particular value for the study of complex phenomena such as glacial isostatic adjustment, the evolution of tectonic stress patterns, sea level rise (and fall), the hydrological cycle, transport processes in the oceans, and the dynamics and physics of the atmosphere (troposphere and ionosphere).

Geodesy is crucial not only for Earth observation and science, but today it is also indispensable for many activities in a modern society. Traditionally, geodesy has served society by providing reference frames for a wide range of practical applications from regional to global navigation on land, sea, and in the air, construction of infrastructure, to the determination of reliable boundaries of real estate properties. Reference frames were, however, national or regional in scope, adequate for the determination of coordinates relative to a network of reference points. Thus, determination of precise coordinates required simultaneous measurements at several points. Today, the Global Navigation Satellite System (GNSS) also provides access to precise point coordinates in a global reference frame anytime and anywhere on the Earth's surface with centimeter-level accuracy, without requiring additional measurements on nearby reference points.

On the user side, such technological developments have stimulated new applications demanding even greater accuracy and improved access to geodetically-determined positions. On local to regional scales, applications such as land surveying, monitoring of critical infrastructure, prevention and mitigation of impacts of environmental hazards, and numerous technical applications require more or less instantaneous access to a reliable reference frame with centimeter-level accuracy or better. Already today, the economic benefit of the geodetic reference frame is enormous (see, e.g., Williams et al., 2005), and as more and more societal applications become depended on precise positioning this is very likely going to increase. In particular, the emerging combination of broadband communications, geo-databases and easily accessible accurate positioning can be expected to facilitate the development of many new applications and services (see Chapter 4), which will transform society and lead to an increasing dependence on the geodetic foundation, i.e., the terrestrial geodetic reference frame and tools for easy access to this frame.

1.3 The observing system: the current development of the Global Geodetic Observing System

The international cooperation fostered by the IAG has led to the establishment of the IAG Services, which provide increasingly valuable observations and products not only to the scientific community but also for a wide range of non-scientific applications. The IAG has therefore taken the first steps towards the implementation of the Global Geodetic Observing System (GGOS). GGOS was created as an IAG Project during the IUGG meeting in 2003 in Sapporo, Japan. After the first two years devoted to the definition of the internal organizational structure of GGOS and its relationship with external organizations, the Executive Committee of the IAG at its meetings in August 2005 in Cairns, Australia, decided to progress the Project into the implementation phase. Finally, at the IUGG meeting in 2007 in Perugia, Italy, the IAG elevated GGOS to the status of a full Component of IAG as the Observing System of IAG.

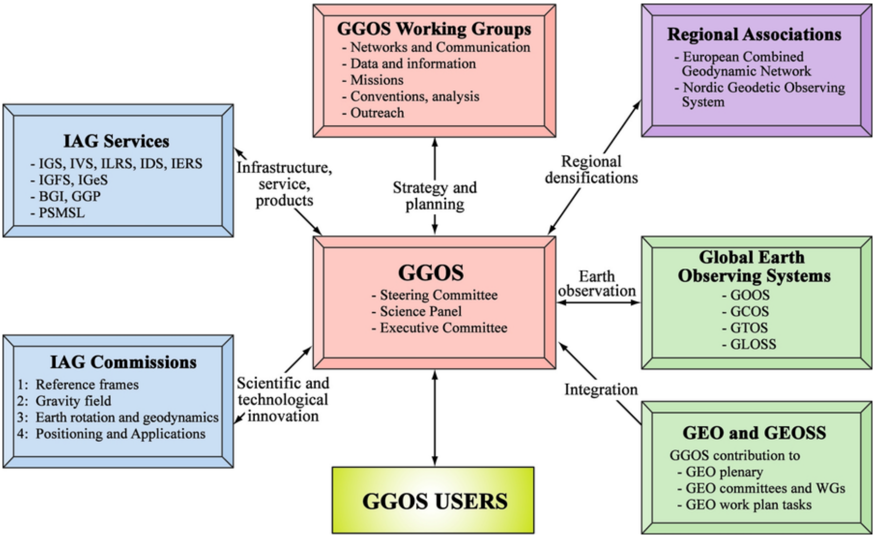

Fig. 1.2. Organizational links and relationships of GGOS. GGOS is being built on the scientific support from the IAG Commissions and the infrastructure of the IAG Services. GGOS integrates the work of the Services through a number of GGOS Working Groups and provides coordination and advice through its Committees. GGOS links these entities to the main programs in Earth observations, and provides a unique interface for GGOS users to the geodetic services. Modified from Plag (2006a).

GGOS as an organization is being built on the existing IAG Services as a unifying umbrella. Figure 1.2 shows the current organizational structure of GGOS with its Committees, Panels and Working Groups, the links to the IAG Services and Commissions, regional organizations, and to the outside world. In particular, the large international programs such as the Group on Earth Observations (GEO), which is implementing the Global Earth Observation System of Systems (GEOSS), and the relevant United Nations programs (see Chapter 5 for more details of these programs). GGOS provides the links between the IAG Services and the main programs in Earth observations and Earth science. It constitutes a unique interface for many (although not all) users of the geodetic services. GGOS adds a new quality and dimension to Earth system research by combining the geodetic techniques into one observing system of highest accuracy in a well-defined and reproducible global terrestrial frame. The observing system, in order to meet its objectives, has to combine the highest measurement precision with spatial and temporal consistency that is maintained over decades. The research needed to achieve these goals will influence the agenda of the IAG Commissions and the GGOS Working Groups.

According to the IAG By-Laws, GGOS *works with the IAG Services and Commissions to provide the geodetic infrastructure necessary for the monitoring of the Earth system and global change research.* The vision for GGOS implicit in this statement is to empower Earth science to extend our knowledge and understanding of Earth system processes, to monitor ongoing changes, and to increase our capability to predict the future behavior of the Earth system. The mission of GGOS embedded in the statement is to facilitate collaboration of the IAG Services and Commissions, and other stakeholders in the Earth science and Earth observation communities, to provide scientific advice and coordination that will enable the IAG Services to develop products that can meet the requirements of global change research, and to improve the accessibility of geodetic observations and products for a wide range of users. The IAG Services benefit from GGOS as a framework for communication, coordination, and scientific advice necessary to develop improved or new products with increased accuracy, consistency, resolution, and stability. IAG benefits from GGOS as an agent for improved visibility of geodesy's contribution to the Earth sciences and to society in general. The users benefit from GGOS as a single interface to the global geodetic observation system not only for access to products but also to voice their needs. Society benefits from GGOS as a utility supporting Earth science and global Earth observation systems as a basis for informed decisions.

GGOS as an observing system utilizes the existing and future infrastructure provided by the IAG Services. It will provide consistent observations of the spatial and temporal changes in the shape and gravity field of the Earth, as well as the temporal variations of the Earth's rotation (Figure 1.1). In particular, GGOS will provide on a global scale and in relation to one reference system a means to determine the spatial and temporal changes in the shape of the solid Earth, oceans, ice cover and land surfaces. In other words, it will provide a global picture of the surface kinematics of our planet. It will provide, in addition, estimates of mass anomalies, mass transport and mass exchange within the Earth system. Surface kinematics and mass transport together are the key to the determination of global mass balance, and an important contribution to the understanding of the energy budget of our planet (e.g., Rummel et al., 2002, 2005; Drewes, 2006). Moreover, the system will provide the observations that are needed to determine and maintain a terrestrial reference frame of higher accuracy and greater temporal stability than what is available today (Beutler et al., 2005).

GGOS as a system will exploit (and try to extend) the current constellation of satellite missions relevant to this goal, and missions planned for the next two decades, by integrating them into one observing system. The foundation for this integration are the existing global ground networks of tracking stations for the space-geodetic techniques: Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Lunar Laser Ranging (LLR), GNSS, and Doppler Orbitography and Radiopositioning Integrated by Satellites (DORIS). GGOS will integrate these tracking networks with terrestrial gravity networks. GGOS will complement the space segment and global ground network with airborne and terrestrial campaigns that serve the purpose of calibration and validation, regional densification, and refinement. Assimilation of these observations into models of weather, climate, oceans, hydrology, ice and solid Earth processes will fundamentally enhance the understanding of the role of surface changes and in the dynamics of our planet. Furthermore, through the analysis of the dense web of microwave radiation connecting the GNSS satellites with Low Earth Orbiters (LEO) and with the Earth's surface a powerful new technique emerges for probing the atmosphere's composition.

It is clear that GGOS has two very distinct aspects: (1) the "organization GGOS" consisting of components such as the Steering Committee, Science Panel, Bureaus, Working Groups, etc., and (2) the "observating system GGOS" comprising the infrastructure of many different instrument types, satellite missions, and data and analysis centers. While GGOS as an organization is establishing its structure from essentially new entities, the observational infrastructure for GGOS as the observing system is being largely provided by the IAG Services. Most of this book addresses issues related to the observing system aspect of GGOS, while the organizational aspect is considered mainly in Chapter 10.

The challenge for geodesy in terms of Earth system monitoring is well summarized by Chao (2003), who states: "*After three decades and three orders of magnitude of advances, space geodesy is poised for prime time in observing the integrated mass transports that take place in the Earth system, from high atmosphere to the deep interior of the core. As such space geodesy has become a new remote sensing tool, in monitoring climatic and geophysical changes with ever increasing sensitivity and resolution.*

The transport of mass and energy are key processes that determine the dynamics of our Earth system. The Earth system can be conveniently viewed through its components, so-called geophysical fluids – the atmosphere, hydrosphere, cryosphere, biosphere, lithosphere, and the deep interior of mantle and cores. All geophysical fluids undergo a host of mass transports for various reasons, external as well as internal. Studying these processes is undoubtedly one of the most interdisciplinary field in all of Earth sciences. However, mass transport has not received due attentions." Meeting the challenge of developing the geodetic observing system into a mass transport and dynamics observing system is a primary motivation for this book.

GGOS (the observing system) faces two types of scientific and technological challenges, namely an "internal" challenge and an "external" challenge (see Chapter 3). The "internal" challenge to geodesy is to develop GGOS and the geodetic technologies so that they meet the demanding user requirements in terms of reference frame accuracy and availability, as well as in terms of spatial and temporal resolution and accuracy of the geodetic observations. Developing an observing system capable of measuring variations in the Earth's shape, gravity field, and rotation with an accuracy and consistency of 0.1 to 1 ppb, with high spatial and temporal resolution, and increasingly low time latency, is a very demanding task. Accommodating the transition of new technologies as they evolve in parallel to maintaining an operational system is part of this challenge. The "external" challenge is associated with the integration of the "three pillars" into a system providing information on mass transport, surface deformations, and dynamics of the Earth. The Earth is a complex system with physical, chemical and biological processes interacting on spatial scales from micrometers to global and temporal scales from seconds to billions of years. Therefore, addressing the "external" challenge requires a "whole Earth" approach harnessing the expertise of all fields of Earth science.

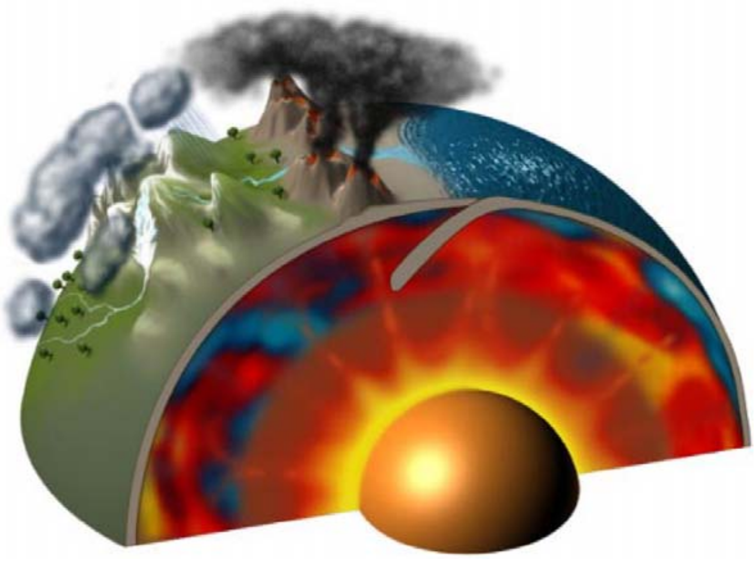

Fig. 1.3. The dynamic Earth. The interaction of solid Earth, hydrosphere, and atmosphere processes has created a highly complex system. From Solomon & the Solid Earth Science Working Group (2002).

The "internal" challenge provides GGOS with a central theme for research and development inside IAG. This book is a first step in sketching a roadmap for this central theme that will lead to a fully defined implementation plan.

The biggest challenge for geodesy, however, may arise from recent developments in global Earth observation. Stimulated by the international quest for sustainable development and the resulting demand for information on the current state and future evolution of the Earth system (GEO, 2005a), the need for comprehensive Earth observations is acknowledged in extensive programs of the United Nations, the European Union, and the international community, culminating in the establishment of the GEO at the EOS-III on 16 February 2005 in Brussels, Belgium. GEO has the task of implementing according to the Ten-Year Implementation Plan (TYIP) endorsed by EOS-III (GEO, 2005a, see also Section 5.1). This TYIP is likely to guide the development of global Earth observation programs over the next decade. The challenge is therefore to integrate GGOS as an organization into the context of Earth observation and society, and to develop GGOS as an observing system in accordance with the strategies and methodologies of the global observing systems for the mutual benefit of all. Earth observation and society at large will benefit from the availability of geodetic observations and products, and GGOS will benefit from an improved visibility and acknowledgment of the valuable service it provides.

In order to facilitate the integration of GGOS into GEOSS, IAG is a Participating Organization in GEO and is represented there by the GGOS organization. GGOS is also a contributing system to the GEOSS, which is implemented by GEO. GGOS was a Partner of Integrated Global Observing Strategy Partnership (IGOS-P)

(Plag et al., 2006a) and continues to contribute to several of the GEO Community of Practices (COPs) that developed out of IGOS-P Themes. Moreover, steps are being taken to strengthen joint initiatives with government organizations and international bodies. These initiatives will enhance the visibility of geodetic activities in the context of Earth sciences, Earth observation and practical applications (Plag, 2006b).

1.4 The strategy: where to go from here

Identifying the requirements for observations and products of geodesy for a wide range of scientific and societal applications is an important prerequisite for defining a set of functional specifications of a geodetic observing system that would be able to serve some or all these applications. Compiling a comprehensive set of URs for geodetic observations and products and deriving functional specifications for a global geodetic observing system is one of the two major goals of this book. The other goal is to specify, based on the functional requirements, the system design of a future GGOS and to define the steps towards the implementation of this GGOS.

In Chapter 2 we first give an introduction to the "ways and means of geodesy" in general, and global geodesy in particular. Emphasis is on the introduction of modern geodetic techniques and methods, but the achievements and current contributions are briefly reported. This Chapter sets the stage for what is currently available and achievable.

Chapters 3 to 6 review the requirements for geodetic observation, products, and services for scientific investigations, monitoring the Earth system, maintaining a modern society, and exploring the planets and the solar system, respectively. In Chapter 3, the open scientific questions concerning the solid Earth, atmosphere, hydrosphere, and cryosphere and their interactions are reviewed with emphasis on how geodetic observations could contribute to providing answers to these fundamental questions. Chapter 4 looks at the many activities in a modern society that depend on or benefit from geodetic observations and products, such as navigation, surveying, mapping, construction, process control, and outdoor activities, and discusses the requirements particularly in terms of access to coordinates in a well-defined and well-maintained reference frame. Chapter 5 starts with the requirements of the key societal benefit areas of Earth observation (see Table 5.1 in Chapter 5 on page 155) as identified by the EOS-II, listed in the Reference Document for the TYIP for GEOSS (GEO, 2005b). These essentially qualitative requirements are then further developed into a set of quantitative requirements. Geodesy is not only essential for many applications on Earth but it also provides the basis for studying and exploring the planets and the solar system. These requirements are addressed in Chapter 6.

In Chapter 7 the results of the previous chapters are used to compile a comprehensive set of quantitative requirements linking the different requirements to applications and users. Based on this set, functional specifications for an observing system are derived.

Two global geodetic references systems, one rotating with the solid Earth, and the other one fixed in space, are fundamental concepts for geodetic theories, models and observations, and their realization through corresponding reference frames is a key task of global geodetic activities. Both the reference systems and the frames are governed by conventions not only concerning the axes and origin of the reference system but also the observations, constants, analysis methods, and models used in their realization. Chapter 8 reviews the current approach and develops it further so that future reference frames will meet the requirements defined in the previous chapters.

Chapter 9 addresses the design of the GGOS that is able to meet the functional specifications set out in Chapter 7. In this Chapter, use is made of the full set of available techniques including a consideration of the ground-based, airborne and spaceborne components.

The current GGOS is based on the voluntary commitment of many contributing countries, organizations, institutions and individuals. This situation leads to fluctuations in available resources, and therefore requires a high degree of redundancy in order to ensure a sufficient geodetic infrastructure. This infrastructure is central to the provision of a reference frame meeting the requirements of both scientific and non-scientific applications as well as for the contribution to international programs and activities directed towards global Earth observation. Chapter 10 describes steps necessary for the implementation of the system defined in Chapter 9 taking into account the available infrastructure as well as the current organizational and funding situation. With respect to the organizational background, the Chapter considers alternative approaches, including an intergovernmental one.

Finally, Chapter 11 provides recommendations for the development of GGOS, the implementation of its proposed components, and its future organization. Recommendations are given for improving the framework conditions, the infrastructure, the products, and the organizational background for global geodesy as a multinational endeavor.