Global Geodetic Observing System

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Editors

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Meeting the Requirements of a Global Society on a Changing Planet in 2020

Springer

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Foreword

The Global Geodetic Observing System (GGOS) has been established by the International Association of Geodesy (IAG) in order to integrate the three fundamental areas of geodesy, so as to monitor geodetic parameters and their temporal variations, in a global reference frame with a target relative accuracy of 10^{-9} or better. These areas, often called 'pillars', deal with the determination and evolution of (a) the Earth's geometry (topography, bathymetry, ice surface, sea level), (b) the Earth's rotation and orientation (polar motion, rotation rate, nutation, etc.), and (c) the Earth's gravity field (gravity, geoid). Therefore, Earth Observation on a global scale is at the heart of GGOS's activities, which contributes to Global Change research through the monitoring, as well as the modeling, of dynamic Earth processes such as, for example, mass and angular momentum exchanges, mass transport and ocean circulation, and changes in sea, land and ice surfaces. To achieve such an ambitious goal, GGOS relies on an integrated network of current and future terrestrial, airborne and satellite systems and technologies. These include: various positioning, navigation, remote sensing and dedicated gravity and altimetry satellite missions; global ground networks of VLBI, SLR, DORIS, GNSS and absolute and relative gravity stations; and airborne gravity, mapping and remote sensing systems. The optimal assimilation of such heterogeneous observations into models of geodynamics, oceanography, hydrology, glaciology, and weather and climate, will be done by interdisciplinary teams of researchers from geodesy and other sciences, and through the coordinated work of all IAG Services and Commissions. Naturally, addressing problems of such large scale and complexity requires international effort and commitment. Such initiatives are already underway (GEO, GEOSS), and GGOS represents IAG, and geodesy in general, in all of them, and provides the scientific and infrastructure contribution of geodesy to the Earth sciences.

The science and applications that GGOS addresses have important implications for the well-being of the global society. In an era of economic uncertainty and rapid environmental change it is imperative that action be taken to minimize risks from natural hazards, climate change, sea level rise, etc., to develop forecasting models for oceans and weather, and early warning systems for severe storms, tsunamis, and other hazards, and to manage our natural resources and our environment in a sustainable manner. To understand the Earth processes responsible for the aforementioned hazards requires continuous monitoring campaigns over long periods of time, as well as novel modeling of the observed changes with time. In other words, we can no longer speak of geodesy in three dimensions; we have entered a new and exciting era of four-dimensional geodesy, in which modern geodesy has become an indispensible contributor to the understanding of System-Earth and its evolution in time. IAG is well-positioned and proud to be able to contribute to this international effort through the work of GGOS, and therefore considers GGOS as its flagship Component.

The GGOS 2020 document describes the challenges, science, technology, applications, strategies, future plans and expected contributions of IAG and GGOS to the Earth sciences through the next decade. It contains the collective work over a period of several years of many individuals and organizations too many to list here without whom this volume would not have been possible. The IAG, and I personally, express our sincere gratitude to each one of them. Many thanks are due to the authors of the various chapters and the editors of this volume, and in particular to Hans-Peter Plag, for the countless hours he has devoted to writing, editing and coordinating, and his enthusiastic dedication to the project.

Calgary, February 2009

Prof. Michael G. Sideris
President, International Association of Geodesy

Preface

About this book

Background

This book describes the scientific rationale and the specifications for the Global Geodetic Observing System (GGOS) of the International Association of Geodesy (IAG) in terms of concepts, conventions, infrastructure and services, that would meet future requirements of a global community facing increasingly challenges on a changing planet. With this in mind, the document provides the basis for the further development of GGOS over the next decade and beyond. GGOS is built upon the basis provided by the existing Services and Commissions of IAG and is one of the major IAG components. In order to maximize the benefits to users of the considerable infrastructure and resources available to these Services, the concept for GGOS and the strategy for its development and implementation require careful considerations of the future needs of society for geodetic observations and services.

Improvements to the International Terrestrial Reference Frame (ITRF) and the availability of geodetic observations of changes in Earth's shape, gravity field and rotation over the last few decades have been a major driver of scientific discovery. Further improvement can be expected to lead to more exciting discoveries, particularly in combination with emerging new observation technologies for monitoring the variability of the Earth's gravity field and surface deformations. In a broader sense, the geodetic reference frames and observations have contributed to a transition of many processes in society and are expected to continue to do so. This great potential for scientific progress in support of societal needs associated with an improved geodetic observing system motivated the process that led to this book.

The context for this book is the increasing societal and scientific need for Earth observations, and their dependence on an appropriate geodetic foundation as well as a continuous series of geodetic observations. There is a growing awareness that sustainable development, which is the agreed-upon leading principle and goal of the global community, cannot be achieved without sufficient knowledge about the state, trends and processes in the Earth system. This is manifested in the establishment of the Group on Earth Observations (GEO) with currently about 75 member countries. The main purpose of GEO is to facilitate the implementation of the Global Earth Observation System of Systems (GEOSS), with the vision for this system *to realize a future wherein decisions and actions for the benefit of humankind are informed by coordinated, comprehensive and sustained Earth observations and information* (GEO, 2005a).

Geodesy provides the foundation for most Earth observations as well as crucial observations of changes in the Earth's geometry, gravity field, and rotation, which are all related to mass transport in the Earth system and the system dynamics. Therefore, geodesy is crucial for meeting many of the requirements for observations of global change and observations supporting studies of the Earth system. Providing the basis for precise positioning and navigation, geodesy is also crucially supporting or enabling many activities and processes in a modern society.

Realizing the importance of the geodetic reference frame and the contribution of geodesy to Earth observations, GEO has included a specific Task AR-07-03 "Global geodetic reference frames" in its Work Plan 2007-2009 and and as Sub-Task DA-09-2c in the Work Plan 2009-2011. Understanding the requirements for GGOS is a central goal of this task. The present book provides this input to the GEO Task.

The development of Earth observations takes place in a context where a considerable fraction of the funding for Earth observation infrastructure and research is allocated in response to major natural and anthropogenic disasters without a sufficiently well developed core infrastructure stable over time. Many satellite missions are research-oriented, whereas operational monitoring of many key indicators of the Earth system is insufficiently implemented (GEO, 2005b).

In geodesy, this situation is not much different. Current limitations in funding, often with a lack of appreciation of decision makers of the importance of the geodetic observing system for Earth observations and society at large, has led to the global geodetic community seeking yo provide better products and services based on incremental improvements to the system in an overall framework that severely limits the options for such improvements.

Scope

The advent of the space-geodetic techniques, and the rapid improvement and growth of communication techniques and capacities, has launched a revolution in the field of applied and global geodesy. Moreover, geodetic imaging increasingly gains importance, and the integration of the new techniques and methods into the traditional point-based approach of geodesy poses a major challenge. Therefore, it is timely to assess thoroughly the user requirements for the geodetic observations and products, and based on these requirements to design an optimal future system, which makes use of the maturing space-geodetic techniques as well as emerging imaging techniques. In order to do so, the authors for the contributions collected in this book had to take a fresh approach to the problem, not only with respect to the infrastructure but even more so concerning the underlying concepts, including the conventional approach to geodetic reference frames. Some of the concepts described or proposed here contradict current "best practices" and time will tell whether these new concepts will facilitate significant progress or whether they will have to be modified.

The authors of the contributions collected in the book do not attempt to assess current systems, concepts, products and services, but rather take a new look at the problem of building a geodetic observing system. The starting point is a rigorous review of the societal and scientific problems that require geodetic observations for their solution. This analysis leads to a set of general user requirements. These requirements are then, in a second step, used to derive functional system specifications. A third step focuses on the design of a system that would meet these specifications.

Collectively, the chapters of this book provide:

(1) a description of the scientific and societal problems, as well as practical applications that benefit from geodetic observations, services and products;
(2) a comprehensive overview of the user requirements for geodetic observations and products as derived from a broad range of societal benefit areas and scientific requirements;
(3) the functional specifications for a geodetic observing system capable of meeting the user requirements;
(4) a concept for future realizations of a (terrestrial) reference system able to meet the user requirements;
(5) the design of a system capable of addressing the functional specifications, in terms of conventions, techniques, infrastructure, and data analysis; and
(6) considerations and recommendations for the system implementation.

The anticipated audience

This book is a comprehensive document describing the background rationale for GGOS. It was written by a team of Chapter Lead Authors, each supported by Chapter Writing Teams. Besides including geodetic experts in all relevant fields, the chapter teams also include experts from other fields of Earth sciences and Earth observations. This book serves two purposes: (1) to inform users of Earth observations (in particular, GEO) of the potential of GGOS, and (2) to ensure that the GGOS community is aware of the users' needs and requirements so as to integrate GGOS into GEOSS for maximum mutual benefit. Thus, this book seeks to facilitate communication across several sectoral and discipline boundaries, including those between geodesy and other Earth sciences, between scientists and operational agencies, and between GGOS and GEOSS.

Documents consulted

Geodesy has a long tradition of assessing the requirements of society and of projecting these into future developments of the geodetic techniques and observing systems. This book continues this tradition, and it therefore benefited from a number of reports made available over the last four decades. These reports include, but are not limited to, the "Williamstown Report" (Kaula, 1970), the "Erice Report" (Mueller & Zerbini, 1989), the report on geodesy in 2000 prepared by the U.S. National Research Council in 1990 (Commission on Physical Sciences, Mathematics, and Applications, 1990), the "Coolfont Reports" (NASA, 1991a,b,c), the gravity report by the U.S. National Research Council (Commission on Geosciences & Resources, 1997), the *Living on a Restless Planet* report of the Solid Earth Science Working Group of NASA (Solomon & the Solid Earth Science Working Group, 2002), the report of an InSAR Workshop (Zebker, 2005), and the recent ESA document *The Changing Earth* (Battrick, 2006).

In the frame of the Integrated Global Observing Strategy - Partnership (IGOS-P) and GEO, several reports documented the needs for Earth observations in several societally relevant fields. Examples are the documents of GEO, such as GEO (2005a,b), the IGOS-P Theme reports (e.g., IGOS-P Ocean Theme Team, 2001; Lawford & the Water Theme Team, 2004; Marsh & the Geohazards Theme Team, 2004; Townshend & the IGOL Writing Team, 2004; Key & the IGOS-Cryo Writing Team, 2004), as well as reports produced by the various United Nations (UN) Agencies and programs. The latter include in particular the recent UN Water report (United Nations, 2006).

In a number of recent reports, user requirements for geodetic observations have been considered. Some of these reports are focused on national developments (e.g., Williams et al., 2005), improvements to the current situations (e.g., Plag, 2006a), or single technological aspects (such as Niell et al., 2006). Of direct importance for this book are the documents and publications produced by IAG scientists and teams focusing on GGOS, namely the papers in Rummel et al. (2000) and the GGOS Implementation Plan (Beutler et al., 2005). A considerable number of recent studies concerning relevant Earth system processes and the geodetic observations required to study these processes have been produced. Examples are the UNAVCO report on solid Earth science (UNAVCO, 1998), the German report on mass movements (Ilk et al., 2005), and the U.S. report on InSAR (InSAR Working Group, 2005). In addition to these report, a number of science reports from related fields have been consulted, such as the report on earthquake science by the National Research Council (Board on Earth Sciences and Resources, 2003), the NASA study on a global earthquake satellite system (Raymond et al., 2003), and the National Research Council Decadal Survey (National Research Council, 2007).

Reno, Boston,
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The book has gone through several rounds of reviews. Individual reviews of an early draft were provided by Chris Hughes, Norman Miller, Ivan Mueller, Chris Reigber, Fernando Sanos, and Christian Tscherning. An open review in the IAG community resulted in more than 300 individual comments. A final review of parts of the book was carried out by an IAG Panel consisting of Hermann Drewes, Chris Rizos, and Michael Sideris. The Editors extend their sincere thanks to all who invested time and effort into turning this book into a valuable basis for the further development of GGOS.

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Executive Summary

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Preamble: Geodesy is the science of determining the geometry, gravity field, and rotation of the Earth, and their evolution in time. Traditionally, geodesy has been serving other sciences and many societal applications, including mapping. With the advent of satellite geodesy and an accuracy improvement of more than three orders of magnitude over the last three decades, geodesy has developed into a science making unique contributions to the study of the Earth system, its inherent dynamics, and its response to climate change, as well as a tool underpinning a wide variety of other remote sensing techniques. Facilitated by the Global Navigation Satellite Systems such as the Global Positioning System, a wide and growing variety of applications associated with positioning and navigation are being developed, particularly in combination with products derived from global geodetic observations. This book describes the requirements for a global observing system to provide products and services with the geodetic accuracy necessary to address important geophysical questions and societal needs, and to provide the robustness and continuity of service which will be required of this system in order to meet future needs.

(Chapter 1) **Living on a dynamic planet – the challenge:** A growing population is living on a dynamic planet, endowed with finite resources and limited capacity to accommodate the impact of the increasingly powerful anthropogenic factor. Sustainable development is crucial for realizing a stable and prosperous future for the anthroposphere, as has been acknowledged by a number of World summits. Although there are many influential factors, a detailed understanding of the Earth system with its major processes and its trends is one of the prerequisites for sustainable development. A deeper understanding cannot be reached without sufficient observations of a large set of quantities of the Earth system. As emphasized by the Earth Observation Summits (EOSs), there is an urgent need for a comprehensive, coordinated and sustained program of Earth observation. Earth observations are not only necessary for a scientific understanding of the Earth, they are fundamental for most societal activities, ranging from disaster prevention and mitigation, the adequate provision of resources such as energy, water and food, the understanding of climate change, the protection of the biosphere, environment, and human health, to the building and management of a prosperous and sustainable global society.

(Chapter 1) **Geodesy is fundamental in meeting this global challenge:** Geodesy provides the foundation on which all Earth observation systems are built. In this function, geodesy is essential for Earth observation just like the foundation and frame of a house are necessary to keep it stable over time. But modern geodesy does more: it also provides comprehensive observations of changes in the Earth's shape, gravity field and rotation, the so-called "three pillars of geodesy." The principal geodetic quantities associated with these "pillars" are intimately related to mass transport in the fluid envelope of the solid Earth and its interior, as well as the dynamics of the Earth system. Therefore, the geodetic observing system provides essential observation of Earth system processes. It turns out, not surprisingly, that the geodetic observing system is similarly essential for exploring the planets, the solar system, and beyond.

(Chapter 1) **Geodesy is in transition:** The advent of space-geodetic techniques and the rapid improvement of communication technologies and capacities have fundamentally changed, if not revolutionized, geodesy and its methods. While previously point coordinates were given with respect to local or regional reference frames, positions can now be observed with respect to a global reference frame with unprecedented accuracy. Based on these techniques, changes in the Earth's shape, rotation and gravity field are determined with increasing spatial and temporal resolution, increasing accuracy, and with decreasing latency. These observations capture the "fingerprints" of mass movements in the oceans, atmosphere, ice sheets and terrestrial water storage; they provide the "scales" to weigh changes in the mass in the ocean; they allow the determination of the kinematics and strain field of the Earth's surface and the displacement field associated with earthquakes; they provide information on the water content in the atmosphere; and they constitute crucial constraints for all models of mechanical processes in the Earth system.

With the development of the space-geodetic techniques, the scope of the geodetic observing system is rapidly extending from a provider of the reference frame, and the tools for the determination of accurate positions, to a system monitoring the mass transport and the dynamics of the solid Earth and its fluid envelope with unprecedented spatial and temporal resolution and accuracy. Thus, this observing system is in transition from a utility for other geoscientists, to a provider of a consistent set of Earth observations relevant for nearly all societal benefit areas of Earth observations.

Geodesy is a "service science". In the past the "customers" of geodesy mainly came from the surveying and mapping profession; today, however, geodesy also serves the geophysical, oceanographic, atmospheric, and environmental science communities. Thus, it is their user requirements that also influence the development of the geodetic observing system.

(Chapter 2) **International cooperation is essential for geodesy:** Over many years, the international scientific community has managed in a major cooperative effort the establishment and maintenance of a global infrastructure that provides the observational basis for the determination of highly accurate positions anywhere on Earth and in space. This achievement has been facilitated by the International Association of Geodesy (IAG) and is based on the voluntary commitment of national geodetic authorities, space agencies, research institutes, universities, and individuals. Two reference systems are basic in geodesy, namely the celestial reference system and the terrestrial reference system. The International Earth Rotation and Reference Systems Service (IERS) has the responsibility for defining these geometric reference systems, and to realize them through appropriate frames. The International Celestial Reference System (ICRS) is the fundamental basis for the definition of celestial positions, and the International Terrestrial Reference System (ITRS) is the fundamental basis for describing terrestrial positions. These systems are conventional coordinate systems including all conventions for the orientation and origin of the axes, the scale, physical constants, models, and processes to be used in their realization.

The ICRS is realized through the International Celestial Reference Frame (ICRF), which is a set of estimated coordinate positions of extragalactic reference radio sources distributed over the sky. The ITRS, in turn, is realized through the International Terrestrial Reference Frame (ITRF), which is a set of globally distributed points on the solid Earth's surface, for which estimates of coordinate positions and (currently constant) velocities are derived from space-geodetic observations at these points.

Conceptually, the link between ITRS and ICRS is provided by the Earth rotation. Consequently, the ITRF and ICRF are connected through estimates of the Earth rotation parameters, which are also derived and made available through the IERS as so-called Earth Orientation Parameters (EOP) as determined by space-geodetic techniques.

Currently, the ICRF is determined by the technique of Very Long Baseline Interferometry (VLBI). For the determination of the ITRF, a combination of several independent space-geodetic techniques, including VLBI, Satellite Laser Ranging (SLR), Lunar Laser Ranging (LLR), Global Navigation Satellite System (GNSS), and Doppler Orbitography and Radiopositioning Integrated by Satellites (DORIS) is employed. Similarly, the EOPs are derived from a combination of these techniques. For each of these techniques, a technique-specific IAG Service maintains a global network of tracking stations (based on voluntary efforts of many contributors). Each of these techniques has unique advantages as well as disadvantages, and only the combination of the techniques guarantees an accurate and stable reference frame. Therefore, the most important elements for the determination and maintenance of the ITRF are the so-called "core stations", which have at least three of the independent space-geodetic techniques co-located (in addition to absolute and relative gravity observations and tide gauges, where possible). However, globally, there are currently only about 15 of these core stations, while about 40 stations are considered necessary in order to meet the most demanding user requirements.

The GNSSs have developed into the most widely applied technique for positioning (and navigation). The dramatic development of the Global Positioning System (GPS) over the last ten years into an accurate and highly efficient technology for positioning has been facilitated by the work of the International GNSS Service (IGS).

The Global Geodetic Observing System (GGOS) of the IAG is the proposed unifying umbrella for the IAG Services, which integrates the observing systems for changes in the Earth's shape, gravity field, and rotation and improves internal consistency. It links the geodetic services into the global Earth observation systems in order to provide a consistent service to the users. In particular, GGOS aims to ensure that the geodetic products and tools respond to increasingly more demanding user requirements.

Much of the international cooperation originates from regional and national organizations, which not only facilitate the dissemination of the global developments into the regions, but also are influential in motivating national bodies to contribute to international geodetic activities. Today, the ITRF, and the products and services that give access to the ITRF anywhere and anytime, are crucial for many economic and scientific applications. They have become so integrated in many applications that they are often taken for granted, as an integral part of the societal infrastructure freely available to everybody. However, without the international cooperation in geodesy, this global reference frame could not be maintained at its current level of accuracy and accessibility. Considering the nature of the voluntary commitment of many contributors on which GGOS is based, the incomplete spatial coverage of the ground-based networks, and the complementarity of the geodetic techniques, national decisions to discontinue geodetic infrastructure such as the operation of ground stations, or to withdraw support for specific techniques, can have severe consequences for GGOS and its products, in particular the ITRF.

(Chapter 3) **The development of the geodetic observing system needs research:** Maintaining a terrestrial reference frame at the level that allows, for example, the determination of global sea level changes at the sub-millimeter per year level, pre-, co- and postseismic displacement fields associated with large earthquakes at the sub-centimeter level, timely early warnings for earthquakes, tsunamis, landslides, and volcanic eruptions, as well as the monitoring of mass transport in the Earth system at the few gigatons level, requires a comprehensive Earth system approach.

Currently, geodesy is facing an increasing demand from science, the Earth observation community, and society at large for improved services, observations and products. Most of these requirements are in terms of improved accuracy (in particular, instantaneous accuracy), better reliability (including addressing the issue of liability), and improved access to the reference frame. The IAG and GGOS are aware of the enormous challenges implied by the demand to improve the accuracy from an average level of close to 10^{-9} (i.e., 1 ppb of the Earth's radius) to an instantaneous level (with daily or higher temporal resolution) of 10^{-10}, as required in order to meet emerging user requirements. In fact, GGOS faces two types of scientific and technological challenges, namely an "internal" challenge and an "external" challenge. The "internal" challenge to geodesy is concerned with developing GGOS and the geodetic technologies in order to meet the demanding requirements in terms of reference frame accuracy and availability, as well as the spatial and temporal resolution and accuracy of the observations. In many cases, it is not so much the measurements from a single technique that ultimately limits accuracy, but rather the ability to attribute signals to specific sources, and to model these. Therefore, meeting this challenge requires integration of techniques and models. This challenge is a central theme for research and development inside IAG for the future. The "external" challenge is related to geodesy's contribution to Earth system monitoring and science. The signals induced by global change in the Earth's shape, gravity field and rotation are small (on the order of parts-per-billion of the quantities) and embedded in often larger variations not caused by global change. Besides measuring the geodetic quantities with an accuracy considerably better than the signals, identifying and extracting the global change signals also requires the modeling of all known processes in an Earth system model taking into account the interactions between the various Earth system components. This challenge requires geodesy to interact with all Earth sciences and to accommodate the terrestrial processes in data processing and modeling.

(Chapter 4) **The benefits of the global and national geodetic infrastructure are enormous:** A very accurate and stable global geodetic reference frame, such as the ITRF, is indispensable for Earth observation, science and the functioning of a modern society. In such a frame, coordinates can be attached to points and objects (e.g., an airplane, a measuring sensor, a mark in the ground) and their movements over time can be described (e.g., the position of a point on the Earth's surface before, during, and after an earthquake). The benefits of the ITRF and the global geodetic infrastructure are wide-ranging. GGOS and, in particular, the key product ITRF:

- contribute substantially, directly or indirectly, to many economic activities and to the global wealth;
- allow for the exploitation of the space-geodetic technologies for a wide range of practical and scientific applications;
- provide a foundation on which today's national and regional reference frames are built and link these frames to each other;
- allow the interrelation of all geo-referenced data to be described in the same frame, thus facilitating full interoperability of geo-related databases and services;
- support governmental and intergovernmental priorities and international activities, such as sustainable development, climate change, the Global Earth Observation System of Systems (GEOSS), the Intergovernmental Panel on Climate Change (IPCC), and the United Nations (UN);
- provide a mechanism in many countries, including developing ones, for national participation in important global programs aimed at a better understanding of the Earth system, its climate, global geodynamics, geohazards, etc., and the mitigation of the impact of natural and anthropogenic hazards on society; and

- provide a mechanism for participation of the private sector and research institutes in international projects and activities, particularly in the field of technology development.

(Chapter 4) **The societal prospects of space geodesy:** The technological development facilitated through the new space-geodetic techniques for navigation and positioning poses challenges by creating new requirements for accessibility, accuracy and long-term stability. The rapid development of satellite-based precise point positioning techniques, which allow the determination of very accurate position anytime and anywhere on the planet, enables a wide range of position-related applications. The new geodetic technologies are leading to fundamental changes not only in all areas of navigation and transport, but also for application in process control (e.g., farming, construction, mining, resource management), construction and monitoring of infrastructure (e.g., off-shore platforms, reservoirs dams, bridges, and other large civil structures), surveying and mapping (including off-shore), and Earth observation. Geodetic techniques are crucial for the assessment of geohazards and anthropogenic hazards, and they will play a pivotal role in early warning systems of such hazards and disasters. The outcomes include increased security, a better use of resources, and progress towards sustainable development.

A well-defined and accessible reference frame, together with high-speed communications and advanced data processing, enables modern societies to operate in a very cost efficient manner, and hence create a basis for higher standards of living. National studies have shown that a number of major areas in national economies depend to a large part (up to 40%) on their geodetic infrastructure and services. Taking into account the fact that most national reference frames are fully dependent on the global infrastructure and frames, any degradation of the global infrastructure may have serious consequences for national economies.

The availability of a global geodetic reference frame such as ITRF and the tools to determine precise point coordinates anytime and anywhere on Earth have a profound effect on almost all areas of society. Since the ITRF is accessible anywhere on the planet, it improves access to an important technological resource, particularly in developing countries. Therefore, it is an important contribution compatible with the principle of sustainable development demanding equal access to resources for all.

(Chapter 5) **Towards a geodetic Earth system service:** Changes in the Earth's shape, gravity field, and rotation are inherently related to the dynamics of and mass transport in the Earth system. With the rapid progress of the geodetic observation techniques, an integrated GGOS constitutes the basis for an Earth system service that provides information on the state of and trends in the Earth system with respect to relocation of mass, deformations of the Earth's surface, and changes in the Earth's dynamics.

Mass transport on time scales up to decades takes place mainly in the fluid envelope of the solid Earth, where water transport is three orders of magnitudes larger than any other type of mass transport. Thus, information on the fluxes in the global water cycle, including the ice sheets and glaciers, oceans, and terrestrial hydrosphere can be provided with unprecedented spatial and temporal resolution and accuracy, particularly for global and regional scale changes. This information is crucial to understanding the impact of global change on the water cycle, in particular the ice sheets, sea level, and large terrestrial water catchments,

Surface displacements are related to both mass relocations on and above the solid Earth's surface and geodynamic processes within the solid Earth. Surface displacements are caused, for example, by earthquakes, tectonic processes, magma flow in the crust, and anthropogenic ground water changes. Thus, information on surface displacement provides a basis for, for example, scientific studies of geohazards, hazard assessment, early warning, and resource management.

For times scales of up to decades, changes in the dynamics of the Earth system, particularly its rotational dynamics, are brought about to a large extent by changes in the climate system. The solid Earth, oceans, and atmosphere continuously exchange angular momentum, and changes in the mean circulation of the atmosphere and ocean affect the rotation of the solid Earth. Mass redistribution on the Earth's surface, for example, through melting of ice sheets, deform the solid Earth and, as a result, also change the rotation. Earth rotation is affected by these processes in an integral way, and thus is an ideal parameter to assess the overall state of the system.

(Chapter 5) **Geodetic observations and products are crucial for maximizing the benefits of Earth observation:** Geodesy provides the foundation for a global geodetic reference frame such as the ITRF that can be used by all Earth observing systems to monitor atmosphere, ocean, and other resources, and which relates the measurements to a globally consistent reference frame. Without a sufficiently accurate and stable ITRF, the benefit of Earth observations for most of the nine Societal Benefit Areas (SBAs) identified by the EOSs would be significantly reduced. Monitoring quantities relevant to geohazards, the global water cycle, climate, weather, energy, and even health, depends on a ready and reliable access to an accurate global geodetic reference frame. Today, only the ITRF meets these requirements of most applications. Therefore, a the ITRF is crucial for realizing GEO's vision for GEOSS, i.e. *a future wherein decisions can be based on sufficient information for the benefit of humankind.*

Geodesy supports Earth system observation, modeling, interpretation, and prediction in general. Some of the tools of geodesy, in particular GNSS, already yield routine observations of the atmosphere, such as the water vapor fields in the lower troposphere, the mass fields in the stratosphere, and the electron content fields in the ionosphere. The raw GNSS measurements are inherently calibrated with respect to atomic clocks. There are no other observations of the Earth's global atmosphere that can claim such a recurrent, atomic calibration. In that respect, geodesy could further help track climate change. On the modeling and prediction issues, geodesy could support the development of Earth system circulation models for the fluid envelope of the Earth with space- and time-varying gravity fields.

Despite considerable progress over the last two decades, mainly due to technological improvements, the quality of the reference frame has been hampered by fluctuations in institutional support and contributions. In particular, infrastructure central to the long-term stability of the reference frame, such as SLR stations and VLBI antennas, have been retired without replacements; a development potentially leading to a degradation of the ITRF accuracy. In the near future, satellite missions central for monitoring ice sheets, sea level, and the global water cycle will cease to operate, and follow-on operational missions must be planned now.

Unanticipated impacts of global change can be very costly in terms of life and property. However, unnecessary mitigation can be costly, too. A good example is provided by the anticipated sea level changes widely acknowledged as a slowly developing hazard with potentially disastrous consequences. Mitigation of the sea level rise impact is a long-term process which requires a planning and implementation time scale of the order of decades. Mitigation of sea level rise impact is extremely expensive and risky: too little will cause severe impact, too much will put unnecessary demands on national and regional economies. Therefore, decisions must be based on solidly founded sea level scenarios in order to minimize the risk associated with misjudgment (in either direction). Considering the typical life time of coastal infrastructure of 100 to 200 years, the sea level scenarios have to cover at least one hundred years. Crucial information required to improve the understanding of sea level and ice sheet changes, and to set up future sea level scenarios comes from Earth observation systems. Satellite altimeters, satellite gravity missions, GNSS satellites, tide gauges and other *in situ* techniques are all necessary components of the "sea level observing system". However, with all these components in place, the observations cannot provide the required fidelity if not linked to a stable global reference frame. Without this frame, past and present changes in ice sheets and sea level cannot be sufficiently quantified and understood, and plausible future scenarios of regional and local sea level cannot be provided to society as a basis for informed planning.

(Chapter 6) **Geodesy is essential for exploring the planets, solar system and beyond:** Planetary geodesy, radio science, interferometry (including imaging VLBI, astrometric VLBI, and Earth-space VLBI), and interplanetary navigation all require accurate terrestrial and celestial reference frames well linked together by Earth rotation observations for making and interpreting their measurements. The performance of the GGOS is not a limiting factor for these applications. However, in order to meet demanding future requirements, it will be important to develop GGOS such that the terrestrial and celestial reference frames and the Earth rotation parameters meet these requirements.

(Chapter 7) **User requirements for geodetic observations and products are demanding:** The current scientific and societal user requirements are demanding in terms of accuracy, resolution, latency and reliability, and the requirements are expected to increase in the future. The GGOS products must have sufficient accuracy, temporal and spatial resolution, and latency to meet these requirements. The most demanding users of the terrestrial reference frame in terms of accuracy and long-term stability are most likely the scientific studies of sea level change caused by climate change. In order to have a frame at least an order of magnitude more accurate than the signal to be monitored, the terrestrial reference frame should be accurate at a level of 1 mm and be stable at a level of 0.1 mm/yr. The most demanding applications of the geoid are likely to be the determination of the mean sea surface topography for oceanic general circulation models, and the GNSS determination of the height of surface points at the millimeter level. These applications require the static geoid to be accurate at a level of 1 mm and to be stable at a level of 0.1 mm/yr; consistent with the accuracy and stability of the terrestrial reference frame. The most demanding application in terms of accuracy and latency of EOPs and their consistency with the terrestrial and celestial reference frames is likely to be the tracking and navigation of interplanetary spacecraft. This application is capability-driven and requires the most accurate EOPs that can be determined, realizing that those determined in near real-time are somewhat less accurate than those determined with a delay of a couple of weeks. Quantitatively, an accuracy at a level of 1 mm for the EOPs should be achieved. For the time variable geoid, the monitoring of the water cycle at sub-regional to global scales appears to be the most demanding applications requiring the geoid variations to be monitored accurate to 1 mm, stable to 0.1 mm/yr, with a spatial resolution of 50 km and a time resolution of 10 days.

(Chapter 8) **Towards a modern geodetic reference frame:** A modern geodetic reference frame supporting precise point positioning consists of:

- a highly-accurate, global geodetic reference frame based on a sufficient number of multi-technique tracking stations;
- a service providing satellite orbits and clocks as well as Earth rotation parameters of high quality and long-term consistency in this global reference frame;
- a highly-accurate model of the gravity field (in particular, the geoid) and its changes;
- a well-determined tie between the geometric and gravimetric reference frames; and
- a velocity model that allows the determination of time-variable transformations between the global reference frame and national reference frames.

On a national level, the classical geodetic reference frames are still typically reliant on relative positioning. However, it is anticipated that increasingly for many applications a transition to precise point positioning will take place in many countries. A core element for this transition will be a reference frame service providing access to the reference frame anywhere on Earth, including the ocean surface, with a high instantaneous accuracy.

A deficiency of the current terrestrial reference frame is that it is only defined for relatively few points (of the order of 500) on the Earth's land surface. For all other points, no 'reference motion' is available hampering the identification of anomalous motion. Therefore, it is proposed to augment the current reference polyhedron with a dynamic Earth reference model. This model, in principle, will provide infinite spatial and temporal resolution for geometry and gravity, and thus establishes a reference frame accessible anywhere on Earth (and above) at any time. The dynamic Earth reference model will combine geometry, gravity and rotation into one consistent model. However, implementing this model poses significant scientific challenges, which will define a central theme for geodesy over the next decade.

(Chapter 9) **Infrastructure for geodetic Earth system monitoring:** GGOS is based on a combination of terrestrial, airborne, and spaceborne techniques, each with unique characteristics and contributions, and a layered infrastructure ranging for the ground-based networks to artificial satellites, infrastructure on the Moon, and quasars. Parts of the infrastructure are still in the form of research facilities, while other parts are fully operational.

The global ground-based infrastructure comprises not only the global *in situ* networks of several geometric and gravimetric techniques, but also the numerous data centers, analysis centers, and web-based services, that are required to determine and maintain the reference frames as well as to make them accessible for a wide range of users and their applications. Despite a large international effort, most networks are still characterized by spatially uneven distributions, and hence have large gaps in coverage. For some techniques, such as SLR, spatial gaps are large and place significant limitations on the achievable accuracy. Of particular importance are stations where several techniques are co-located, thus allowing the integration of the products of techniques into one coherent frame. Of the order of 40 evenly distributed core stations, i.e., stations with three or more space-geodetic techniques co-located, are required; however, currently there is a severe gap over the southern hemisphere. Without closing this gap, many of the most demanding user requirements will not be met.

The satellite component contributing to GGOS includes low Earth orbiting satellites (e.g., dedicated gravity missions and altimeters), dedicated laser-ranging satellites (e.g., LAGEOS), and GNSS satellites. The former provide observations related to mass transport and displacements of the solid Earth, ice, and ocean surfaces. Mission continuity is a key infrastructure issue.

The dedicated laser-ranging satellites are crucial for the connection of the reference frame origin to the center of mass of the Earth system, a mandatory requirement for studies of global processes. These satellites have very long lifetimes, but their number is very small.

The signals from the GNSS satellites provide the basis for the "work horse" in GGOS. With currently about 400 tracking stations in more than 80 countries, this "work horse" allows for an accurate monitoring of the global reference frame and for access to the frame anytime and anywhere on Earth. Without the freely available signals of GPS, the impressive development of geodesy over the last two decades would have been impossible.

Today, infrastructure on the Moon consists of retro-reflectors for LLR.

VLBI utilizes radio signals emitted by quasars, and contributes unique observations that are especially important for the monitoring of Earth rotation, which provides the link between ICRF and ITRF. In fact, VLBI is the only space-geodetic technique capable of simultaneously monitoring ITRF, ICRS and Earth rotation. Furthermore, unlike the other space-geodetic techniques, VLBI provides a unique ITRF scale, traceable directly to the speed of light, which is essential to various long-term monitoring goals of GGOS, including changes in global hydrology and sea level rise.

Observations with terrestrial gravimeters, both absolute and relative, provide the basis for studies of many geophysical phenomena, including (but not limited to) free oscillations of the Earth, solid Earth and ocean tides, surface loading, changes in ice sheets, and sea level changes. Absolute gravimetry, combined with geometric techniques, is a terrestrial technique supporting SLR in constraining the tie between the reference frame origin and the center of mass of the Earth system.

In total, an estimated 500 person years per year are provided on the basis of voluntary commitment by national operational and research institutes to maintain the ground-based networks, the data centers, analysis centers and user interfaces. Not included in this estimate are the resources required to support the satellite missions and the GNSS satellites themselves.

(Chapter 9) **For a full exploitation of the potential, an operational core component is needed:** Currently, GGOS and the IAG Services are based on the voluntary commitments of many national authorities, institutions, and individuals. Moreover, GGOS, to a large extent, is still science-driven. As a consequence, the observing system keeps changing due to technological developments and scientific priorities, as well as national political decisions. The impact of fluctuations in the regional coverage of the terrestrial component can be severe, often dependent on national priorities or funding availability. A high redundancy is needed to compensate for these fluctuations. Technological progress leads to changes that are not always properly coordinated. Satellite missions are even more science-driven than the other components of GGOS, and discontinuation of important observation programs has happened in the past, and unfortunately are likely to continue to happen in the future. Funding for the global geodetic infrastructure depends on the national decisions and priorities in many countries, and this implies considerable volatility, sometimes threatening the proper maintenance of the reference frames and of the IAG Services themselves. All of these factors lead to temporal inhomogeneities in the system, its observations, and, most importantly, the geodetic reference frames. At the same time, as a consequence of the growing demands for geo-referencing in a wide range of applications, issues are raised concerning the reliability and continuity of the geodetic products, as well as liability of the service and data providers. Therefore, in order to fully exploit the potential of geodesy and to develop GGOS into an Earth system service, a fully operational core infrastructure is needed. Considering the scale of GGOS, such a core will require an approach based on intergovernmental agreements, implying firm commitments by the contributing nations. GGOS therefore has started a dialog at the international level, in particular within GEO, in order to develop an intergovernmental framework for these activities.

(Chapter 10) **Implementation of GGOS needs a multi-faceted organizational framework:** GGOS is based on the IAG Commissions, Inter-Commission Committees, and the Services of IAG. In order to maintain GGOS in the future, the technique-specific and the combination services must continue their work using state-of-the-art observational and analysis tools, with GGOS providing the overarching strategy and organizational framework. In particular, GGOS will have to ensure the coordination of the multi-technique network (including the data flow), it

will have to maintain the standards and conventions necessary to ensure consistency across the components contributing to GGOS, and it will have to develop a plan for an uninterrupted sequence of geodesy-related space missions. GGOS will need to be embedded within the framework of global Earth observation currently represented by GEO, the surveying and navigation communities, and the science community. GGOS will have to serve as an interface to all these stakeholders in GGOS as well as society at large. An on-going dialog of GGOS with its stakeholders, including the funding agencies, the space agencies, and relevant UN agencies, with the goal to ensure long-term stability of GGOS, and to secure long-term funding for GGOS, will be central for a successful implementation of GGOS.

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