Linking the Global Geodetic Observing System (GGOS) to the Integrated Global Observing Strategy Partnership (IGOS-P) through the Theme 'Earth System Dynamics'

H.-P. Plag, Nevada Bureau of Mines and Geology and Seismological Laboratory, University of Nevada, Reno, Mailstop 178, Reno, NV 89557, USA, email: hpplag@unr.edu.

G. Beutler, Astronomical Institute, University of Bern, Bern, Switzerland, email: gerhard.beutler@aiub.unibe.ch

R. Forsberg, Danish National Space Center, Copenhagen, Denmark, email: rf@spacecenter.dk

C. Ma, Goddard Space Flight Center, Greenbelt, MD, USA, email: cma@gemini.gsfc.nasa.gov

R. Neilan, Jet Propulsion Laboratory, Pasadena, CA, USA, email: rneilan@jpl.nasa.gov

M. Pearlman, Harvard-Smithonian Center for Astrophysics, Cambridge, MA, USA, email: mpearlman@cfa.harvard.edu

B. Richter, Bundesamt für Kartographie und Geodäsie, Frankfurt a.M., Germany, email: bernd.richter@bkg.bund.de

S. Zerbini, Department of Physics, University of Bologna, Bologna, Italy, email: zerbini@df.unibo.it

Abstract

When setting up GGOS as a project, the IAG Executive Committee asked the GGOS Steering Committee to establish a relationship with IGOS-P. IGOS-P addresses a number of problems and components of Earth observing systems in the frame of specific Themes. The IGOS-P Theme process will also be an important mechanism for the development of the components of the Global Earth Observation System of Systems (GEOSS).

Many of the burning questions related to the water cycle, the climate, global change, and geohazards cannot be solved without sufficient knowledge of mass transports throughout the Earth system and the associated dynamics. All these processes affect the three fundamental geodetic quantities, namely the Earth's figure (geometry), its gravity field and its rotation. Thus, GGOS is an unique contribution to Earth observation in its capability to provide detailed information on the dynamics of the solid Earth and its fluid envelop on all relevant spatial and temporal scales.

Focusing on the observing system for the mass transports within the Earth system the suggested 'Earth System Dynamics' Theme has the goal to develop the science basis for and to facilitate the implementation of GGOS. The Theme will define the role of GGOS, the underlying strategy and its interface to the other components of GEOSS. The interaction of GGOS with the other IGOS-P Themes will facilitate the full exploitation of the geodetic contribution by all other global observing systems. The Theme will ensure that GGOS meets the user requirements both from the IGOS-P Themes and the nine societal benefit areas identified by the Earth Observation Summit II.

Keywords: *Global Geodetic Observing System, Integrated Global Observing Strategy, Earth Observation, Earth System Dynamics*

1 Introduction

The need for information on the current state of the Earth System and its processes is today greater than ever before. The increasingly visible effects of a growing population and economic development on the environment has raised the public and political awareness of the significance of the changes in the Earth environment. The ability to detect and understand the various processes in the Earth system, including those causing climate change is fundamental in the quest for sustainable development and in order to reduce uncertainties, assess impacts, and predict changes.

Long-term monitoring of the Earth system provides the indispensable data base for these studies and tasks. Over the last decade, the recognition of the fundamental role of Earth observation in managing the planet in a sustainable way has led to a number of initiatives and programs aiming at a better coordination, better coverage in terms of observed parameters, domains and spatial and temporal scales, more user-orientation and less duplication, which recently culminated in the plan for a *Global Earth Observation System of Systems* (GEOSS).

In the frame of the *International Association of Geodesy* (IAG), the *Global Geodetic Observing System* (GGOS) is under implementation and GGOS will contribute to GEOSS. When setting up GGOS as a project, the IAG Executive Committee asked the GGOS Steering Committee to establish also a relationship with the *Integrated Global Observing Strategy Partnership* (IGOS-P). IGOS-P addresses a number of problems and components of Earth observation systems in the frame of specific Themes. The IGOS-P Theme process is also expected to be an important mechanism for the development of the components of the GEOSS.

In order to ensure that the implementation of GGOS is in agreement with the *Integrated Global Observing Strategy* (IGOS), and that GGOS optimally serves the needs of GEOSS and the different IGOS-P Themes, GGOS has applied for membership in IGOS-P. Moreover, GGOS has suggested a new 'Earth System Dynamics' Theme, focusing on the observation system for mass transport and dynamics of the Earth system in the frame of a 'whole system' approach.

In the following, we first give a brief overview of geodesy's contribution to Earth observations, and then in Section 3 describe briefly the background, goals, and current status of GGOS. Then, in Section 4 we provide background information on IGOS and IGOS-P and summarize in Section 5 the currently established and proposed Themes with focus on those with direct links to geodesy. The development towards a GGOS membership in IGOS-P and a 'Earth System Dynamics' Theme is reported in Section 6.

2 Geodesy's Contribution to Earth Observation

The Earth is a dynamic system. Dynamic processes in the Earth's interior and the associated mass displacements lead to plate tectonics, volcanism, and earthquakes. Mass movements in the atmosphere, terrestrial hydrosphere, oceans and cryosphere associated with weather, climate and global change are caused by dynamic processes in the atmosphere and oceans. To study these processes is important for the understanding of atmospheric and oceanic circulation, transport of water in the hydrological cycle and the mass balance in the terrestrial and oceanic hydrosphere, volcanic processes, generation of earthquakes, glacial isostatic processes, mantle convection, and processes in the core. Many of the burning questions related to these processes cannot be solved without sufficient knowledge of mass transports throughout the Earth system and the associated dynamics.

Mass transport and changes in the dynamics all affect the three fundamental geodetic quantities, that is the Earth's figure (geometry), its gravity field and its rotation. These geodetic quantities and their temporal variations are observed with space-geodetic techniques using a combination of space-borne and air-borne sensors and *in-situ* networks (Figure 1). These observations allow the detection of mass movements in the Earth's subsystems with unprecedented accuracy and with high temporal resolution, thus linking the subsystems together and providing a truly global monitoring of mass movements and the associated Earth system dynamics. Observations of the displacements of the Earth's surface furnish records of the movements and deformations associated with atmosphere and ocean dynamics as well as earthquakes, volcanoes, tsunamis, natural and man-made subsidence, landslides, and other potential hazards. Geodesy monitors the variations of the Earth rotation as an indicator of all angular momentum exchange inside, on or above the Earth, as well as of the interaction between the Earth and the Sun and Moon. Geodesy explores the Earth's gravity field, both the stationary field and the time variable fields due to changes of mass distribution in the Earth system as a whole including the solid Earth, liquid core, atmosphere, oceans, hydrosphere, and cryosphere. Moreover, geodesy monitors the atmosphere, oceans and cryosphere with space geodetic remote sensing techniques. The internationally coordinated geodetic observations result in a global terrestrial reference frame, which is determined and monitored on the basis of observations provided continuously by the geodetic station networks. 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 air-borne and space-borne.

In summary, geodesy provides a unique frame for the monitoring, understanding and prognosis of the Earth system as a whole. Modern space-geodetic

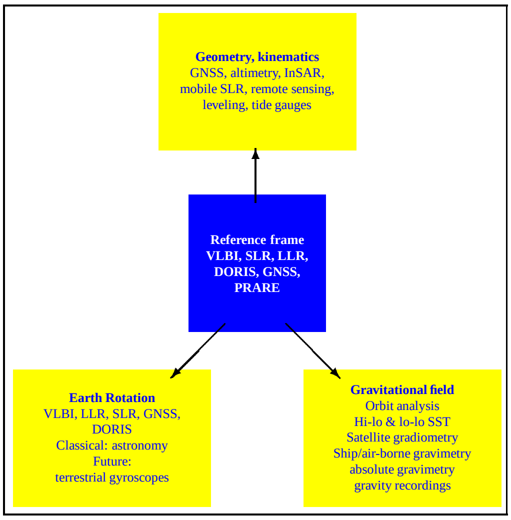

Fig. 1: Contribution of geodesy to Earth observation and other societal applications. Modified from Rummel (2000).

techniques are inherently strong on global to regional scales and thus constitute an important complement to traditional *in situ* observation systems. Thus, GGOS is an unique contribution to Earth observation in its capability to provide detailed information on the dynamics of the solid Earth and its fluid envelop on all relevant spatial and temporal scales.

3 The GGOS

Over the last decade, IAG has established a system of services, which provide a number of products to a wide range of scientific and non-scientific users. The organizational development within international space geodesy has been inspired by the success of the *International GNSS Service* (IGS), which was established by IAG in 1994. Since then, the IGS has facilitated the creation of a global network of GPS tracking stations which today consists of more than 300 stations. These stations provide observations on an hourly or daily basis to data centers, from where the data are freely available. A number of IGS Analysis Centers (AC) determine satellite orbits and clocks as well as Earth Rotation Parameters (ERP) on a routine basis with a variety of latency and accuracy (Ray et al., 2004), which are widely used in scientific and, increasingly, also non-scientific applications.

The success of the IGS stimulated the establishment of other technique-specific space-geodetic services by IAG, such as the *International VLBI Service* (IVS), the *International Laser Ranging Service* (ILRS), and the *International DORIS Service* (IDS). These services provide continuously observations from their ground-based tracking networks, which are also used to determine station displacements, deformations of the solid Earth, geocenter motion, and ERPs. Both, observations and products, are made available to a wide range of users, though mainly in scientific fields.

The products of the technique-specific services are the basis on which the *International Earth Rotation and Reference Systems Service* (IERS) determines and monitors the *International Terrestrial Reference Frame* (ITRF) as the most accurate frame realization of the *International Terrestrial Reference System* (ITRS). For that purpose, a number of ITRF ACs submit single and multi-technique solutions, which are then combined to provide the so-called regularized station coordinates and secular velocities (McCarthy & Petit, 2003) of a given ITRF version. The latest version is ITRF2000, which is considered to be the most accurate realization of the ITRS so far (Altamimi et al., 2002). It is based on a network of more than 400 stations, many of them co-located by two or more techniques.

The IERS includes also the *Global Geophysical Fluid Center* (GGFC), which was established in 1998. The GGFC and the associated seven Special Bureaus (SB) for Atmosphere, Oceans, Tides, Hydrology, Mantle, Core, Gravity/Geocenter, and Loading have the responsibility of supporting, facilitating, and providing services to the worldwide research community, in areas related to the variations in earth rotation, gravitational field and geocenter that are caused by mass transport in the geophysical fluids. The GGFC provides a general frame for research related to the further development of the products delivered by the IERS and the IAG services.

Following the example of the IGS and the other space-geodetic services (IVS, ILRS, IDS), very recently services related to the gravitational field have been initiated. In particular, the *International Gravity Field Service* (IGFS) takes the responsibility for all aspects of the Earth's gravitational field. In addition, the establishment of an *International Altimetry Service* (IAS) is contemplated. Such a service was pointed out as missing and an evident complement of the IAG system of services. The increasingly important role of *Interferometric Synthetic Aperture Radar* (InSAR) for many applications, ranging from the monitoring of small scale surface displacements to changes in the biosphere, has brought up the idea of setting up an international InSAR service (LaBrecque, 2004, personal communication). InSAR observations are relevant to geodetic applications and therefore should be studied and developed under the umbrella of IAG. The organizational model of the IAG services has also been applied to interdisciplinary fields, e.g. to the *European Sea Level Service* (ESEAS), which integrates geodetic and hydrographic techniques into a sea level observing system for the European coasts (Plag, 2002).

These services have established considerable observing infrastructure, comprising global ground-based networks of observing sites, data and analysis centers, and web sites giving access to the products. They utilize signals and data from operational satellite systems and dedicated satellite missions. Organizationally, most of these geodetic services are based on the 'best effort' principle and depend on the contributions of globally distributed institutes.

In order to establish a coherent geodetic observing systems and thus to meet the user requirements in a consistent and efficient way, the structure of IAG Services, which has been build up over the last decade, is currently complemented by the GGOS. GGOS was established through the decision of the IAG Execu-

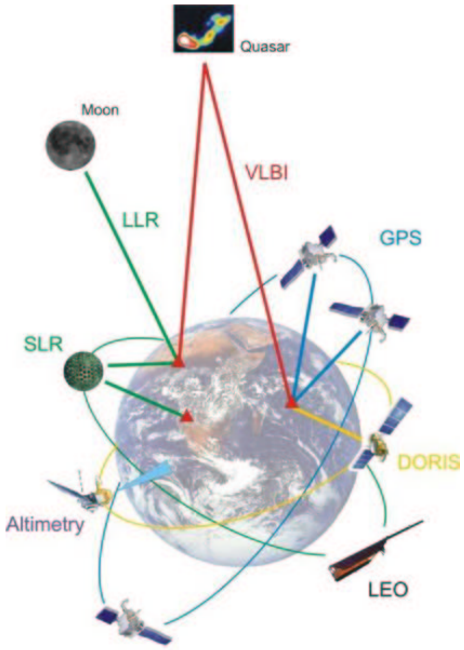

Fig. 2: Space components of GGOS. From http://www.ggos.org, courtesy M. Rothacher.

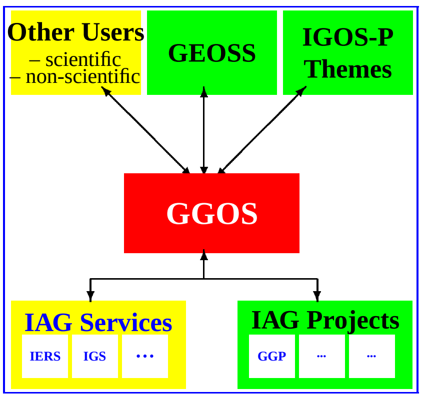

Fig. 3: The envisaged role of GGOS in Earth observation.

tive Committee at the 23-rd IUGG General Assembly, 2003 in Sapporo, Japan. This decision was supported through an IUGG Resolution of the same assembly. The Executive Committee of IAG at its meetings in August 2005 in Cairns, Australia, decided to transform the current GGOS project into a permanent observing system.

The scientific basis for GGOS is summarized in Rummel (2000) and Rummel et al. (2005). The GGOS "*aims at maintaining the stability of and providing the ready access to the existing time series of geometric and gravimetric reference frames by ensuring the generation of uninterrupted time series of state-of-the-art global observations related to the three pillars of geodesy*" (Beutler et al., 2003). The accuracy level targeted by GGOS for the three fundamental geodetic quantities (and their mutual consistency level) is 10^{-9} or better. At this level of accuracy, a big variety of mechanical interactions between the different Earth system components are relevant and need to be treated consistently. In this respect, modern geodesy requires a system approach to the dynamics of the Earth and involves expertise from all Earth sciences in the analysis and interpretation of the geodetic observations.

GGOS aims at integrating the different levels of the geodetic observing systems from ground-based stations as level (1), over Low Earth Observing satellites as well as gravity and altimetry missions as level (2), and navigation satellite systems as level (3), to quasars as level (4) into one coherent observation system (Figure 2) and to analyze and interpret the observations in a consistent Earth system frame. The way to achieve this goal is long and will require considerable developments, both in observational capabilities and physical modeling, including theoretical developments. In particular, the transition from a mainly research-based and science-driven system to an operational, user-driven system will deserve special attention.

From an organizational point of view, GGOS is particularly needed to create a unique interface between GEOSS and other users on the one side and the IAG Services on the other side (Figure 3). Externally, GGOS is envisaged as the unique interface between the observing systems maintained by IAG, which will provide geodetic observations and products to GEOSS, the IGOS-P themes, and other users outside of IAG. Internally, GGOS will facilitate steps towards fully consistent data processing, which will improve the quality and accuracy of the products made available internally and externally. Moreover, GGOS will advocate standardization of the products and ensure that the interface giving access to products is fully interoperable with the other systems contributing to GEOSS.

The establishment of GGOS is an appropriate response to the emerging broad range of scientific and practical requirements with respect to geodesy. The Framework document resulting from the *Earth Observation Summit II* (EOS-II), which formed the basis for the 10-year Implementation Plan for the *Global Earth Observing System of Systems* (GEOSS) (GEO, 2005a) and the associated Reference Document (GEO, 2005b), identifies nine societal benefit areas for Earth Observations (see Appendix 2 in GEO, 2005b). For each of these areas the Reference Document provides an overview of the requirements in terms of observables and an assessment of the status of the observational capacity. Extracting the quantities potentially provided by geodesy (Table 1) demonstrates that geodesy will be a major contributor to GEOSS. More-

Table 1: Requirements for geodetic observables for the nine benefit areas. The status is indicated with the follow classes: 0: ok; 1: marginally acceptable accuracy and resolution; 2: could be ok within two years; 3: could be available in six years; 4: still in research.

Observable quantity	Status
Deformation monitoring, 3-D, over broad areas	3
Subsidence maps	3
Strain and creep monitoring, specific features or structures	2
Gravity, magnetic, electric fields - all scales	3
Gravity and magnetic field anomaly data	2/3
Groundwater level and pore pressure	4-1
Tides, coastal water levels	1
Sea level	2-1
Glacier and ice caps	2
Snow cover	2
Moisture content of atmosphere/water vapor	2
Extreme weather and climate event forecasts	3
Precipitation and soil moisture	3-1

over, a geodetic reference frame, which is not explicitly mentioned in any of these requirements, is indispensable for GEOSS to reach its goals.

4 IGOS and IGOS-P

”*The Integrated Global Observing Strategy (IGOS) seeks to provide a comprehensive framework to harmonize the common interests of the major space-based and in-situ systems for global observation of the Earth. It is being developed as an over-arching strategy for conducting observations relating to climate and atmosphere, oceans and coasts, the land surface and the Earth’s interior. IGOS strives to build upon the strategies of existing international global observing programs, and upon current achievements. It seeks to improve observing capacity and deliver observations in a cost-effective and timely fashion.*” (cite from http://www.igospartners.org).

IGOS is a strategic planning process, providing a structure that helps determine observation gaps and identify the resources to fill observation needs. IGOS is intended to cover all forms of data collection concerning the physical, chemical, biological and human environment including the associated impacts. Being user driven, it is expected that the results will increase scientific understanding and guide early warning, policy-setting and decision-making for sustainable development and environmental protection.

The IGOS-P was established in June 1998 by the 13 founding Partners for the definition, development and implementation of the IGOS. IGOS-P brings together a number of international bodies concerned with the observational component of global environmental issues, both from a research and a long-term operational programme perspective, with the principal objectives to address how well user requirements are being met by the existing mix of observations, and how they could be met in the future through better integration and optimization of remote sensing (especially space-based) and *in-situ* systems. IGOS-P serves as guidance to those responsible for defining and implementing individual observing systems (while the implementation of the Strategy, i.e. the establishment and maintenance of the components of an integrated global observing system, lies with those governments and organizations that have made relevant commitments). IGOS-P has adopted an incremental ”Themes” approach to aid the development of the strategy based on perceived priorities.

5 The IGOS-P Themes and Their Links to Geodesy

The goal of IGOS-P is a small number of Themes with strong linkages to critical social issues. The process of Theme selection is based on an assessment of the relevant scientific and operational priorities for overcoming deficiencies in information, as well as analysis of the state of development of relevant existing and planned observing systems. In general, all IGOS-P Themes address space-borne or air-borne observations that require highly accurate positioning of the sensors, and thus are linked to the global geodetic networks through their requirements for access to an accurate and stable reference frame.

In the following list of existing and planned Themes, we summarize the objectives (see http://www.igospartners.org for more details) and emphasize links to geodetic observations (besides the requirement to have access to a reference frame) where appropriate:

Atmospheric Chemistry Theme: ensure the long-term continuity and spatial comprehensiveness of the monitoring of atmospheric composition and to integrate ground-based and space-borne measurements using models and assimilation tools.

Carbon Observations Theme: enhance the scientific understanding of the global carbon cycle, provide for advanced Earth system observation capabilities, and deliver an improved knowledge base for better policy-making.

Geohazards Theme: integrate disparate, multi-disciplinary, applied research into global, operational systems, and through this improve the provision of timely, reliable and cost-effective information to those responsible for managing geohazards. Plate tectonics, pre-, co- and post-seismic strain, processes associated with volcanoes, early warning for tsunamis, subsidence, precarious rocks, landslides, and local and regional predictions of sea level rise are examples of topics that link this theme to geodetic observations.

Ocean Theme: develop a strategy for an observing system for the oceans that serves the research and operational oceanographic communities and a wide range of scientific and non-scientific users. Ocean circulation, sea level rise, isostasy, and dynamic sea surface topography are linked to the three geodetic quantities, both for the monitoring and studies of the ocean's variability as well as model validation.

Water Cycle Theme: provide a framework for guiding decisions regarding the maintenance and enhancement of water cycle observations that support monitoring of climate, water management and water resource development, provision of initial conditions for numerical weather forecasts and climate predictions, and research related to the water cycle. The geodetic observations provide a unique tool to monitor the global to local scale movements of water through the Earth system and the Theme is strongly linked to geodesy.

Coast Observation Theme: coordinate and strengthen present and future coastal observational capabilities, both *in situ* and space-borne as a basis for a better understanding of the changes in the coastal zone and a service to the decision-making process (under development). Ocean circulation, sea level, and vertical land motion are relevant parameters influencing the dynamic processes in the coastal zone and linking this Theme to geodesy.

Coral Reef Sub-Theme: develop a strategy for the observation system of this particular ecosystem taking into account the unique characteristics of coral reefs requiring special observation techniques.

Cryosphere Theme: create a framework for improved coordination of cryospheric observations and the generation of data and information needed for both operational services and research (proposal in preparation). Ice mass balance, glacial isostasy, and induced sea level variations all are important parameters, that are directly observed by the geodetic observation techniques.

Land Theme: provide a global strategy for a land observations system focusing on globally needed observations for topics such as land cover and land use, human settlement and population, managed and natural ecosystems, soils, biogeochemical cycles, and elevation changes (under development). Changes in the elevation are directly observed by geodetic techniques.

6 Steps towards a 'Earth System Dynamics' Theme

In order to foster the implementation of GGOS and to further detail the science basis for GGOS, as well as to strengthen its linkage to existing and new Earth observing systems, such as GEOSS, the IAG has taken a first step to propose a specific IGOS-P Theme addressing the dynamics of the Earth system from a focus on mass movements. The proposal was presented and discussed at the 11-th Meeting of IGOS-P in June 2004 in Rome. In its response, the IGOS-P members requested that *IAG/GGOS should study the IGOS Process Paper as well as existing IGOS Theme reports to identify complementary or competing elements and to demonstrate that the idea of launching a Dynamic Earth Theme could be realized without repetition or overlap*.

In response to IGOS-P, a document was prepared (Plag et al., 2005) and submitted to IGOS-P for consideration at the 12-th meeting in May 2005 in Geneva. In that document, the following action plan was recommended:

(1) GGOS becomes a member of IGOS-P as a new Global Observing System;
(2) GGOS establishes links to the existing IGOS-P Themes, allowing GGOS to influence the development of the different theme-specific strategies and to determine the way in which GGOS can best serve the observing systems implemented under these strategies;
(3) GGOS together with relevant members of IGOS-P develops the 'Earth System Dynamics' Theme further and prepares a proposal for consideration by the IGOS-P members.

This action plan was accepted by IGOS-P at the 12-th meeting. Currently, a formal membership proposal is in preparation for the next IGOS-P meeting in November 2005.

The relevance of the contribution of GGOS to Earth observations in general and to most of the IGOS-P Themes in particular is obvious, and so is the relevance of the user-oriented issues addressed by a potential 'Earth System Dynamics'Theme. The fundamental contribution of GGOS is widely acknowledged. However, a major concern regarding the establishment of an 'Earth System Dynamics' Theme is the potentially considerable overlap between the suggested new theme and the existing or planned ones. A detailed survey of the requirements of the other themes, both existing, proposed, or in planning stage, and the nine societal benefit areas identified by EOS-II shows that these themes and benefit areas would greatly benefit from GGOS. Parts of their observing systems would overlap with GGOS and the 'Earth System Dynamics' Theme would help to ensure full exploitation of synergies. GGOS can be considered as the metrological basis for Earth sciences. Only a holistic, geodesy-driven approach to the entire Earth system, and its dynamics will ensure that geodesy will contribute in an optimum way to Earth sciences in the wider sense.

One might think that geodesy's contribution is already available to and trivial to understand for the Earth sciences and observation communities. This statement is false. In order to understand the necessity to establish GGOS and the necessity for the establishment of the 'Earth System Dynamics' Theme it is important to summarize the current status and the planned development of GGOS.

Thanks to continuous monitoring and analyzing activities using the space geodetic techniques VLBI, SLR/LLR, GNSS of the relevant IAG services IVS, ILRS, IGS, respectively, and thanks to the IERS, which analyzes the products of the technique-specific services, we have today a *mean* terrestrial and a celestial reference frame available, which are both accurate on the (or close to the) 10^{-9}-level. This essentially implies (sub-)cm and (sub-)0.1 mas accuracies, respectively. Thanks to the established reference frames it is "easily" possible (the IGS, IVS, ILRS, IERS would probably not agree with the attribute "easily") to derive the Earth rotation parameters (precession, nutation, length of day, UT1-UTC, polar motion) on the same accuracy (and time resolution) level. The two reference frames and the time series of Earth rotation parameters can and should now be made mutually consistent on the 10^{-9}-level. The mentioned accuracies and consistency only can be claimed in a mean sense for the terrestrial system (mean site coordinates and "velocities").

Thanks to more than thirty years of SLR/LLR and mainly thanks to the dedicated gravity missions CHAMP, GRACE, GOCE, we are approaching the 10^{-9}-level in gravity (with a spatial resolution of 50-100 km, half wavelength) within the next few years, as well. This accuracy implies that a global geoid (equipotential surface near sea level) with a 1-cm accuracy will become available. The accuracy-claim, on the other hand, is based (among other) on the availability of the above mentioned geometrical reference frames (needed to determine the orbits of the low-orbiting spacecrafts). Unfortunately, the accuracy is needed not in the "mean", but in the "instantaneous" sense: The short-period variations of station coordinates and gravity field (including ocean and atmosphere contributions) would need to be known or estimated (in principle) in one and the same parameter estimation process.

Without going into details one can therefore conclude that the generation and maintenance of the geometrical and gravitational reference frames on an accuracy- and mutual consistency-level of 10^{-9} with a temporal resolution down to the sub-daily domain will be *the* challenge for GGOS. It will also be the central issue of the proposed "Earth System Dynamics" Theme within IGOS-P.

The suggested 'Earth System Dynamics' Theme has the objective to establish the overall strategy, requirements, and background for a global observing system that consistently monitors the mass movements and dynamics of the Earth system at an accuracy level required in particular by the relevant IGOS-P Themes and the nine societal benefit areas identified by the EOS-II. Utilizing the full potential of the geodetic observations will not be possible without taking a comprehensive system approach considering all mechanical interactions between the different system components.

The need for such a theme is mutual, both from the IAG/GGOS side as well as from the user side, in particular the other IGOS-P Themes and the nine societal benefit areas guiding GEOSS. The Theme will provide the science basis for the implementation of GGOS and ensure that GGOS can be fully integrated in the frame of IGOS. The Theme takes into account the fundamental difference between GGOS and other observing systems in that GGOS requires an Earth system approach for its full development.

The 'Earth System Dynamics' Theme has the task to ensure that the integrated observing system for the dynamic Earth system focusing on mass movements and dynamics is built in a cost-effective way to serve most of the existing themes and GEOSS in two major areas: (1) provision of a stable and accurate global reference frame as well as tools to access this frame anywhere on the globe including air- and space-borne sensors, and (2) provision of long-term observations of the time-variable shape, gravity field and rotation of the Earth, which are related to mass transport and dynamics, both for research in the frame of the other themes as well as applications in the areas addressed by these themes.

7 Conclusions

A membership of GGOS in the IGOS Partnership and its active participation in the relevant IGOS-P Themes would, on the one hand, raise the awareness for the needs of these Themes inside the IAG and GGOS in terms of observations provided by GGOS and in terms of the reference frame. On the other hand, GGOS would provide to these Themes expert knowledge concerning the potential and the limitations of the geodetic observing systems.

Most of the existing and planned Themes require access to a stable and highly accurate reference frame that will allow us to monitor small changes in physical quantities. Most Themes need information related to mass transport, displacements of the Earth's surface, and variations in the dynamics. GGOS provides both, the basis for the reference frame and observations related to mass transport, surface displacements and Earth system dynamics. GGOS is thus relevant and in many cases indispensable for the observational systems considered in the themes.

A piecewise integration of the geodetic techniques into the existing themes would hinder the development of the integrated GGOS and thus of the global facility required by these Themes. Without the suggested 'Earth System Dynamics' Theme (or a similar approach outside the IGOS-P frame), the development in the different Themes might easily result in competing, theme-specific implementations of parts of the geodetic observing system, and the neglect of other parts, that do not directly serve a specific theme but are crucial for the overall performance of GGOS.

The establishment of an 'Earth System Dynamics' Theme as the frame for the implementation of GGOS would take into account the fundamental difference between GGOS and other observing systems in that GGOS requires an Earth system approach for its full development. While most of the existing Themes focus on sub-systems (like the Ocean Theme) or specific problem areas (like the Geohazards Theme), the 'Earth System Dynamics' Theme would be truly a whole system theme, comparable in this whole-system aspect only to the Global Water Cycle Theme.

References

Altamimi, Z., Sillard, P., & Boucher, C., 2002. A new release of the International Terrestrial Reference Frame for earth science applications, *J. Geophys. Res.*, **107**, 2214, doi: 10.1029/2001JB000561.

Beutler, G., Drewes, H., Reigber, C., & Rummel, R., 2003. Proposal to Establish the Integrated Global Geodetic Observing System (IGGOS) as IAG's First Project, distributed to IVS and IGS mailing lists on 21 August 2003.

GEO, 2005. The Global Earth Observing System of Systems (GEOSS) - 10-Year Implementation Plan, Distributed at and endorsed by the EOS-III Meeting, Brussels, 16 February 2005. Document prepared by the *Ad hoc* Group on Earth Observations (GEO) Impementation Plan Task Team IPTT. Avaliable at http://earthobservations.org.

GEO, 2005. Global Earth Observing System of Systems GEOSS - 10-Year Implementation Plan Reference Document - Draft, Tech. Rep. GEO 204/ESA SP 1284, ESA Publication Division, ESTEC, PO Box 299, 2200 AG Noordwijk, The Netherlands, Final Draft Document 204, prepared by the *Ad hoc* Group on Earth Observations (GEO) Impementation Plan Task Team IPTT. Avaliable at http://earthobservations.org.

McCarthy, D. D. & Petit, G., 2003. *IERS Conventions 2003*, IERS Technical Note 32, International Earth Rotation Service, Also available at http://www.iers.org.

Plag, H.-P., 2002. European Sea Level Service (ESEAS): Status and plans, in *Proceedings of the 14-th General Meeting of the Nordic Geodetic Commission, Espoo, Finland, 1-5 October 2002*, edited by M. Poutanen & H. Suurmüki, pp. 80–88, Nordiska Kommissionen för Geodesi.

Plag, H.-P., Beutler, G., Forsberg, R., Ma, C., Neilan, R., Pearlman, M., Richter, B., & Zerbini, S., 2005. The Global Geodetic Observing System (GGOS): observing the dynamics of the Earth system, Available at http://www.unep.org/dewa/igos.

Ray, J., Dong, D., & Altamimi, Z., 2004. IGS reference frames: Status and future improvements, *GPS Solutions*, pp. DOI:10.1007/s10291–004–0110–x.

Rummel, R., 2000. Global Integrated Geodetic and Geodynamic Observing System (GIGGOS), in *Towards an Integrated Global Geodetic Observing System*, edited by R. Rummel, H. Drewes, W. Bosch, & H. Hornik, vol. 120 of **International Association of Geodesy Symposia**, pp. 253–260, Springer, Berlin.

Rummel, R., Rothacher, M., & Beutler, G., 2005. Global Geodetic Observing System (GGOS): Science rationale, *J. Geodynamics*, **40**, 357–362.