The Global Geodetic Observing System (GGOS): observing the dynamics of the Earth system

Background and rationale for a GGOS membership in IGOS-P

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1 Introduction

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 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, that is the Earth's figure (geometry), its gravity field and its rotation.

Modern geodetic observations of these three geodetic quantities allow the detection of mass movements in the Earth's subsystems with unprecedented accuracy and with high temporal resolution. Thus, these observations link the subsystems together and provide 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, volcanos, tsunamies, natural and man-made subsidence, landslides, and other potential hazards.

2 Contribution of geodesy to Earth observation

The three fundamental 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). 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.

With the three main geodetic quantities (Figure 1), geodesy precisely observes and consistently monitors the mass movements in the Earth system and the associated dynamics by

- observing and providing the geometric shape of the Earth's surface (solid Earth, ice and oceans), globally and regionally, as well as its temporal variations: horizontally and vertically, and at time scales from rapid to secular;

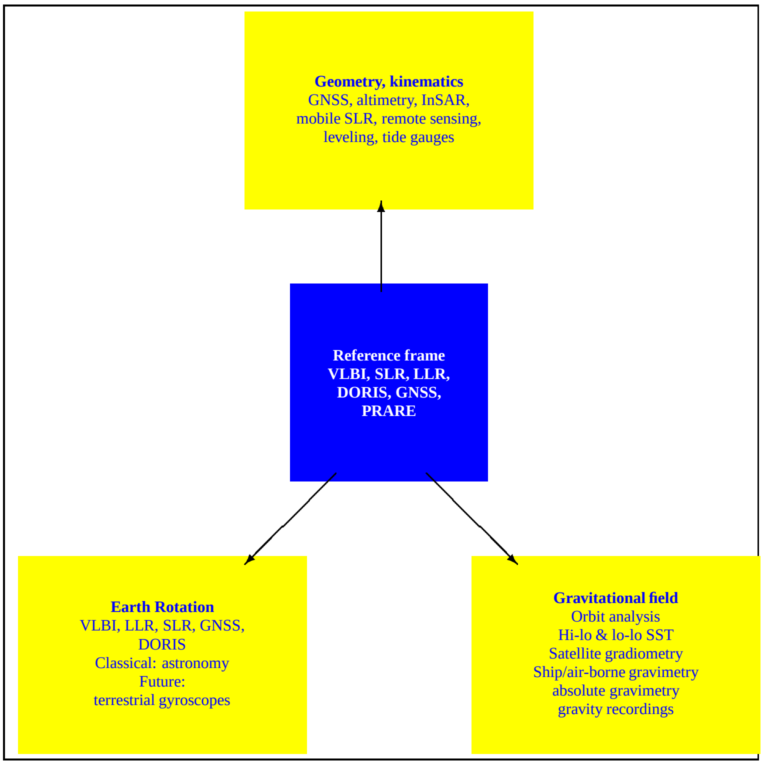

Figure 1: Contribution of geodesy to Earth observation and other societal applications
The fundamental geodetic quantities are the Earth's figure, gravitational field, and rotation, which all are based on the global terrestrial and celestial reference frames. The space-geodetic techniques are crucial in the determination and monitoring of the quantities and their temporal variations and the reference frames. Modified from Rummel (2000).

- monitoring 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;
- exploring 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, cryosphere;
- monitoring the atmosphere, oceans and cryosphere with space geodetic remote sensing techniques.

In summary, geodesy provides a unique frame for the monitoring, understanding and prognosis of the Earth system as a whole. Modern space-geodetic techniques are inherently strong on global to regional scales and thus constitute an important complement to traditional *in situ* observation systems.

3 The Global Geodetic Observing System (GGOS)

Over the last decade, the *International Association of Geodesy* (IAG) has established a system of services (see Appendix A for an overview), which provide a number of products to a wide range of scientific and non-scientifc users. These services have established considerable observing infrastructure, comprising global ground-based networks of observing sites, dedicated satellite missions, data and analysis centers and web sites giving access to the products. Organisationally, 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 IAG is currently integrating all existing global geodetic observation infras-

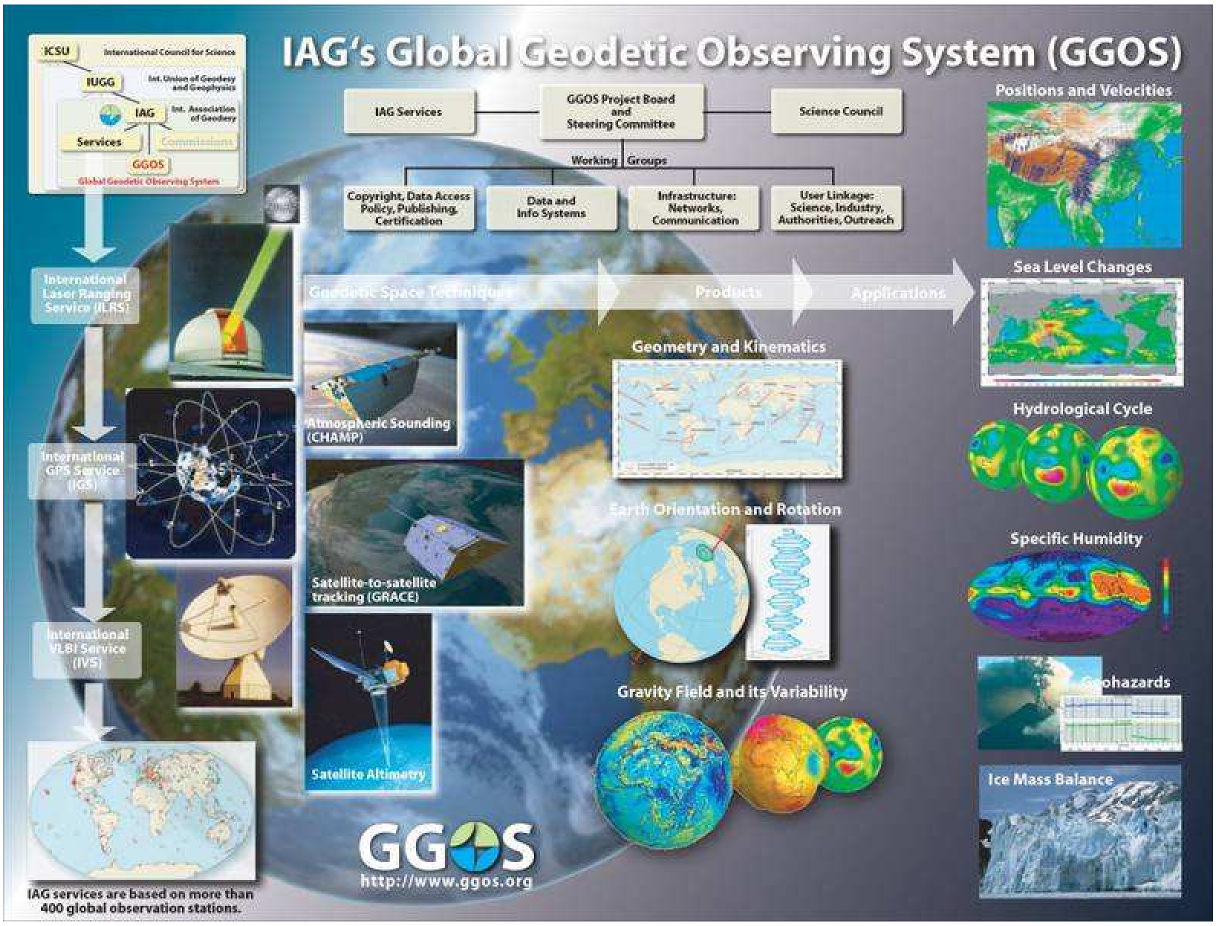

Figure 2: Overview of organisation, tasks and contributions of GGOS.
Poster available at http://www.ggos.org.

tructure into the *Global Geodetic Observing System* (GGOS, see Figure 2). GGOS will integrate the existing ground-based geodetic networks, the geodetic and navigational satellite systems, and the satellite missions into a coherent observation system (see Figure 3).

The GGOS as proposed by Rummel (2000), Rummel et al. (2002), and further developed by Beutler et al. (2003) "*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*". This system will provide on a global scale the spatial and temporal changes of the three pillars (geometry and kinematics, Earth orientation and rotation, and gravity field and its variability; see Figure 1). The system will allow to determine and maintain a terrestrial reference frame with higher accuracy and much improved temporal stability. On the basis of the observations provided by GGOS, it will be possible to determine mass movements in the atmosphere, the ocean, and the terrestrial hydrosphere as well as in the Earth's interior. In addition to the geodetic variables, the space-geodetic infrastructure is also capable of providing additional information such as soundings of the atmosphere and ionosphere with the electromagnetic waves of the GNSS.

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 consistent system and to analyse 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.

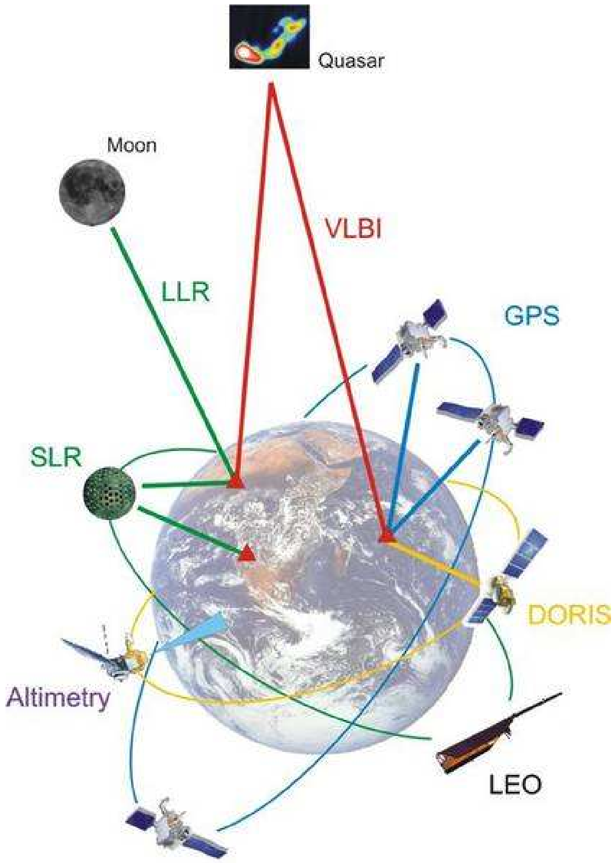

Figure 3: Space components of GGOS.
GGOS will integrate the space-based geodetic infrastructure with global ground-based networks into a consistent global observing system. From http://www.ggos.org.

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.

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, we get the list compiled in Table 1. From this list it is clear that geodesy will be a major contributor to GEOSS. Moreover, a geodetic reference frame, which is not explicitly mentioned in any of these requirements, is indispensable for GEOSS to reach its goals.

Thus, from an organisational point of view, GGOS is particularly needed as the unique interface between GEOSS and other users on the one side and the IAG Services on the other side.

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

4 GGOS and IGOS-P

GGOS was established through the decision of the IAG Executive Committee at the 23-rd IUGG General Assembly, 2003 in Sapporo, Japan. This decision was supported through an IUGG Resolution of the same assembly[1]. It is expected that the Executive Committee of IAG at its next meetings in August 2005 in Cairns, Australia, will decide to transform the current GGOS project into a permanent observing system.

Already when setting up GGOS as a project, the IAG Executive Committee asked the GGOS Steering Committee to establish a relationship with IGOS-P with the goal to become an official member. The membership of GGOS in IGOS-P would support the development of GGOS in line with the IGOS and facilitate a proper linkage between GGOS and other existing and developing Earth observation systems.

The scientific basis for GGOS is summarised in Rummel (2000) and Rummel et al. (2005). 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. 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*

[1]Resolution 3: Integrated Global Geodetic Observing System (IGGOS):
IUGG Recognizing,
1. The great progress made in the use of space and terrestrial techniques for monitoring the phenomena and processes in the System Earth during the last decades; and
2. The efforts made towards the integration of space techniques in the management of observations, data processing, evaluation, and modelling of the observable parameters, in particular by the different international services; and
3. The urgent need to further develop and strengthen the scientific and organizational collaboration of geodesy within the geosciences; and
4. The necessity of generation and accessibility of consistent products for users in Earth sciences, neighbouring disciplines and society in general.
Considering,
That the International Association of Geodesy (IAG) has taken an initiative towards the realization of IUGG Resolution no.1 adopted at the 22nd General Assembly in Birmingham 1999 by installing the integrated Global Geodetic Observing System (IGGOS).
Strongly supports the establishment of the IGGOS Project within the new IAG structure as geodesy's contribution to the wider field of geosciences and as the metrological basis for the Earth observation programs within IUGG and the international organizations mentioned in the 1999 Resolution no.1.
and Urges,
That Associations cooperate with the new project by providing data, models, products, and know-how useful for IGGOS and the benefit of geosciences; and
The participating in the IGGOS project by joining the relevant components in its structure and assisting its symposia and meetings.

demonstrate that the idea of launching a Dynamic Earth Theme could be realised without repetition or overlap.

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'. 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 social 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' would help to ensure full exploitation of synergies. Moreover, GGOS provides the unique reference frame for all of the spatial data collected and is thus an indispensable utility for the existing themes and GEOSS.

GGOS is currently preparing a reference document for the implementation plan for GGOS. This document will summarize the contribution of GGOS to Earth observations and describe the present and planned developments under the umbrella of IAG towards GGOS. The document also addresses the contribution of GGOS to the nine benefit areas considered by GEOSS and the existing and planned IGOS-P Themes. Moreover, the objectives of and rationales for a 'Earth System Dynamics' Theme are fully developed.

GGOS will provide the global geodetic observations and, more importantly, a consistent set of well defined products derived thereof, with the spatial and temporal resolution required (and further interpreted/analyzed) by the entire community of Earth sciences. GGOS should 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 community. This statement is false. In order to understand the necessity to establish GGOS and the necessity for the establishment for 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, 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.

With these facts in mind we believe that only an IGOS-P theme can be considered to be the appropriate frame to develop the necessary scientific and operational frame for the implementation of GGOS.

It is the objective of the suggested ’Earth System Dynamics’ Theme to provide the science basis for the implementation of GGOS and to ensure that GGOS can be fully integrated in the frame of IGOS. Moreover, through interaction of such a Theme and/or the GGOS with the other IGOS themes, particularly the Ocean, Global Water Cycle, Geohazards, and Coastal Themes, the full exploitation of the geodetic contribution to all other global observation systems will be facilitated. Most importantly, the theme will ensure that GGOS meets the user requirements both from the other IGOS-P Themes and the nine social benefit areas identified by the EOS-II.

The need for such a theme is mutual, both from the IAG/GGOS side as well as from the user side. These users are at different levels from other IGOS-P themes to the nine social benefit areas guiding GEOSS. On the one hand, GGOS will not be able to exploit the full potential of the observations without taking a comprehensive system approach considering all mechanical interactions between the different system components. Thus, without considering Earth system dynamics in a consistent frame, GGOS will not be able to serve the users appropriately. On the other hand, existing and planned IGOS-P Themes such as the Geohazard, Water, Ocean, Cryosphere and Coastal Zone themes, will benefit considerably from a better monitoring of mass transport in the Earth system, particularly on global to regional scales. The accuracy and long-term stablility of the reference frame resulting from observations provided by GGOS is crucial for most of the observing systems implemented through the existing or planned Themes, and long-term stability of the reference frame on the level required to monitor, e.g., sea level and changes in ice sheets requires to take into account the Earth system dynamics fully. Monitoring displacements of the Earth surface on local to regional and global scale is crucial for understanding and mitigating the impact of geohazards. Most of the societal benefit areas depend also on improved knowledge of mass transport in the Earth system. Consequently, most of these areas identify a need for geodetic observations. Moreover, most observing systems will depend heavily on having access to a stable reference frame. GEOSS focuses on long-term, georeferenced databases, and for these, the stability of the reference frame is crucial, too.

GGOS is an unique contribution to the monitoring system in its capability to provide sufficient information on the dynamics of the solid Earth and its fluid envelop on all relevant spatial and temporal scales. The suggested ’Earth System Dynamics’ Theme is intended to define the role of GGOS, the underlying strategy, its interface to the other components of the Earth observing systems, and its linkage to the users.

5 Conclusions and recommendations

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, the global geodetic observing system 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.

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 truely a whole system theme, comparable in this whole-system aspect only to the Global Water Cycle Theme.

The suggested 'Earth System Dynamics' Theme aims at establishing the overall strategy, requirements, and background for the full implementation of GGOS. The theme would thus contribute to a number of the existing and planned themes. It would, in fact, provide a basis for some of them and foster the exploitation of links between them. The 'Earth System Dynamics' Theme would have the task to ensure that the integrated observing system for the dynamic Earth system focusing on mass movements and dynamics would be built in a cost-effective way to serve most of the existing themes 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.

In order to ensure effective communication and coordination between the new theme and those already existing, explicit links would have to be established. These links would have to be bi-directional in order to ensure, on one hand, that GGOS is developed to meet the needs of the other themes. The strategies developed in the other themes should, on the other hand, fully account for the potential contributions from GGOS.

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 neglection of other parts, that do not directly serve a specific theme but are crucial for the overall performance of GGOS.

We therefore recommended that

(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.

A Recent developments in global geodesy

Over the last decade, the organisational development within international space geodesy has been inspired by the success of the *International GNSS Service* (IGS, formerly called International GPS Service), which was established by the *International Association of Geodesy* (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 (Figure 4). 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),

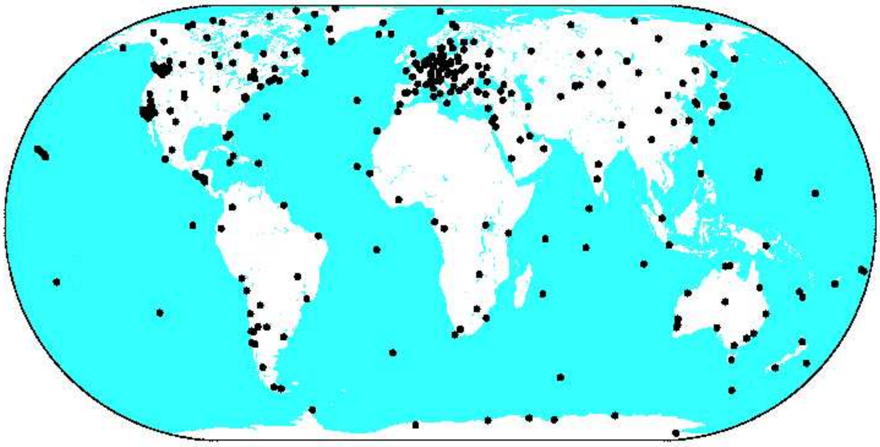

Figure 4: Global network of IGS GPS tracking stations.

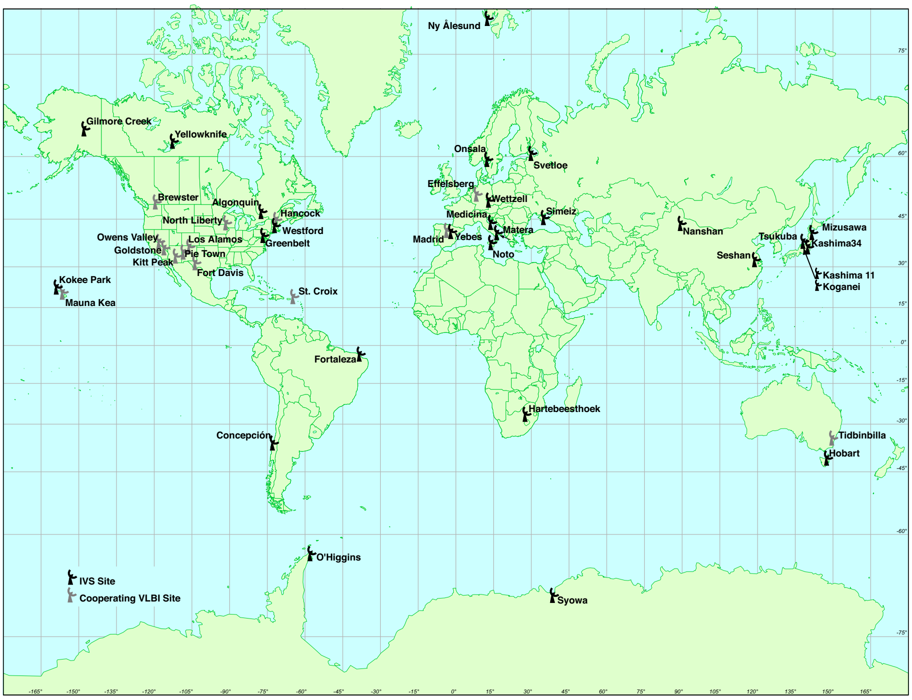

Figure 5: Global network of IVS tracking stations.

and the *International DORIS Service* (IDS). These services provide continuously observations from their ground-based tracking networks (see Figures 5 to 6), 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 realisation of the *International Terrestrial Reference System* (ITRS). For that purpose, a number of ITRF ACs provide 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 realisation 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 (Figure 7).

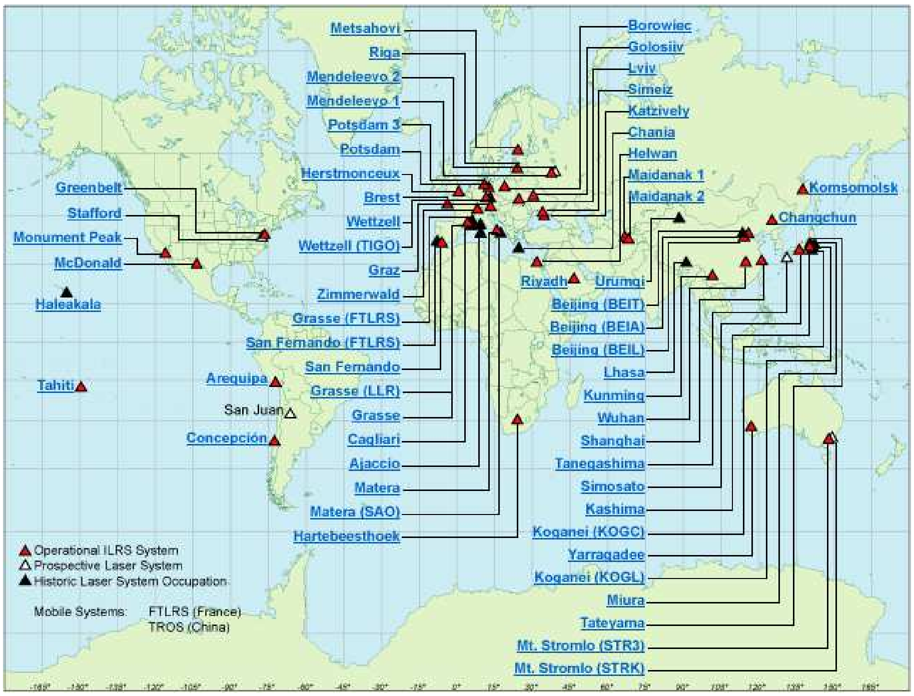

Figure 6: Global network of ILRS tracking stations.

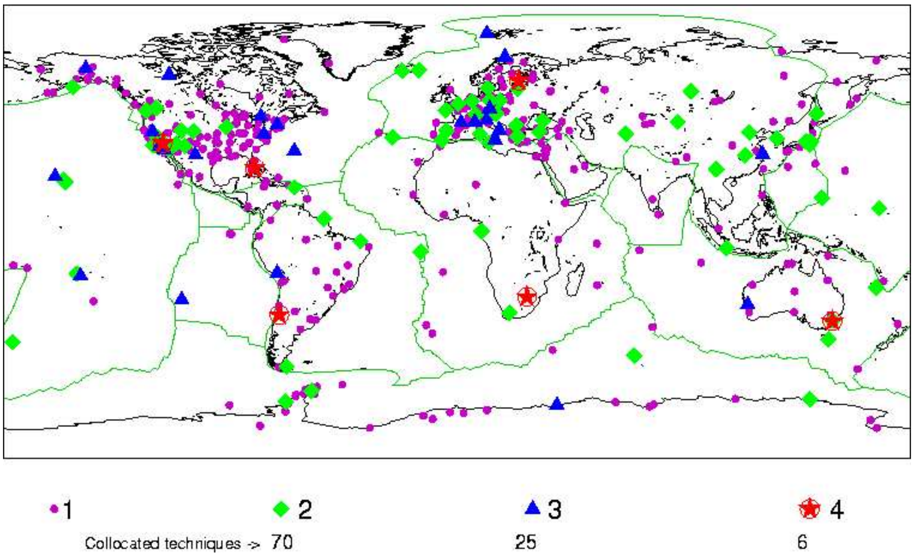

Figure 7: Global network of sites used in the determination of ITRF2000.

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 (Labreque, 2004, personal communication). InSAR observations are relevant to geodetic applications and therefore should be studied and developed under the umbrella of IAG. The organisational 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 (Plag, 2002).

The structure of IAG Services, which has been build up over the last decade is currently complemented by the GGOS, which will integrate the Services into an interacting system and form a new, unique, user-oriented interface for the geodetic observing systems. From an organisational 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.

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