THE GLOBAL GEODETIC OBSERVING SYSTEM

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The Global Geodetic Observing System (GGOS) was established by the International Association of Geodesy (IAG) in July 2003. In April 2004 the IAG, represented by GGOS, became a participating organization of the Group on Earth Observation (GEO) and in May 2006 GGOS was accepted as a member of the Integrated Global Observation Strategy Partnership (IGOS-P).

GGOS is the contribution of geodesy to the Global Earth Observation System of Systems (GEOSS). It provides the reference systems and frames, which are crucial for Earth observing systems. GGOS is built on the IAG Services (IGS, IVS, ILRS, IDS, IERS, IGFS, etc.) and the products they derive on an operational basis for Earth monitoring, making use of space- and ground-based geodetic techniques such as Very Long Baseline Interferometry (VLBI), Satellite and Lunar Laser Ranging (SLR/LLR), Global Navigation Satellite Systems (GNSS), Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), altimetry, InSAR (Interferometric Synthetic Aperture Radar), gravity satellite missions, and gravimetry, etc. All these observation techniques are considered integral parts of GGOS, allowing the monitoring of the Earth's shape and deformation (including water surface), the Earth's orientation and rotation, and the Earth's gravity field and its temporal variations with an unprecedented accuracy. The observed parameters give direct evidence of many global processes that have a crucial impact on human society such as earthquakes, volcanism, floods, sea level change, climate change, groundwater redistribution, mass balance of the polar ice sheets, etc.

GGOS relies on the observing systems and analysis capabilities already in place in the IAG Services and envisions the continued development of innovative technologies, methods and models to improve our understanding of global change processes. GGOS provides a framework that ranges from the acquisition, transfer and processing of a tremendous amount of observational data

to its consistent integration and assimilation into complex numerical models of the Earth system (including solid Earth, oceans, atmosphere, hydrosphere, cryosphere and the interactions thereof). This is being achieved by an international effort and a close, multidisciplinary cooperation with groups working in related fields such as geodynamics, geophysics, oceanography, hydrology, glaciology, meteorology, and climatology. In summary, GGOS provides essential contributions to an integrated Earth monitoring system to help us better understand global change and its impact on environment and society.

Keywords: IAG, GGOS, ILRS, IVS, IDS, IGS, GNSS, VLBI, SLR, LLR, space geodesy, reference frames, gravity field, IERS, GEO.

1. Introduction

Earth is a restless planet [1]. With its atmosphere, oceans, ice covers, land surfaces and its interior, it is subject to a large variety of dynamic processes operating on a wide range of spatial and temporal scales, and driven by large interior as well as exterior forces. Many areas of the Earth's surface are exposed to natural hazards caused by dynamic processes in the solid Earth, the atmosphere and the ocean. Earthquakes, tsunamis, volcano eruptions, tectonic deformations, land slides, deglaciation, sea level rise, floods, desertification, storms, storm surges, global warming and many more are typical and well known phenomena that are expressions of the dynamics of our restless planet. In modern times these processes are influenced, as well, by anthropogenic effects; to what extent is still largely unknown. Some of the many examples of anthropogenic effects are carbon and methane emissions, changes in soil composition and erosion rates, regulations and diversions of rivers, deforestation, and extinction of species (see e.g. [2] for an overview of the anthropogenic impact on the Earth system over the last 300 years).

A growing population has to cope with this restless, and finite, planet. Settlements are encroaching into areas of high risks from natural hazards with major infrastructure being built in potentially hazardous locations, thus increasing the vulnerability of society. Increasingly, valuable and crucial infrastructure is lost in natural disasters, affecting the economy on national and global levels, and displacing large populations, with severe social implications. The growing demands for access to food, water, materials, and space put stress on the finite resources of the planet. Earth system processes, whether natural or modified by humans, affect our lives and the lives of future generations. Decisions made today will influence the well-being of future generations. In order to minimize the anthropogenic impact on Earth system processes and to preserve resources for future generations, a better understanding of Earth system processes and an efficient and conservative organization of anthropogenic processes is required. Responsible stewardship of the planet is not possible without a profound understanding of the processes that shape the planet. Examples are mitigation of the potential impact of climate change on ecosystems, sustainable management of the oceans, preservation of water resources for humans and the biosphere, and preparing for a potentially devastating impact of sea level rise on coastal communities.

Living on a restless planet with finite resources and a limited capacity to accommodate the impact of the increasingly powerful anthropogenic factor requires careful governance. A number of World summits have acknowledged that finding a way to ensure sustainable development is mandatory for realizing a stable and prosperous future for the anthroposphere. Although there are many other influential factors, understanding the Earth system and its major processes and its trends, is one of the prerequisites for success in this quest for sustainable development. A deeper understanding of the Earth system cannot be achieved without sufficient observations of a large set of parameters characteristic of Earth system processes. As emphasized by the *Earth Observation Summits* (EOS), there is an urgent need for comprehensive Earth observations (see the documents in the Appendices of [3]). Earth observations are not only necessary for a scientific understanding of the Earth, they are fundamental for most societal areas ranging from disaster prevention and mitigation, the provision of resources such as energy, water and food, gaining an understanding of climate change, the protection of the biosphere, the environment, and human health, to the building and management of a prosperous global society.

Geodesy provides mandatory reference frames as a foundation for Earth observation. Moreover, geodesy observes parameters related to the mass transport in the Earth system and the system dynamics. With this, geodesy is a cornerstone in Earth observation.

2. Geodesy's contribution to Earth observations and society at large

The "three pillars" of geodesy are the Earth's time-dependent geometric shape, gravitational field, and rotation (Figure 1). With its observational means (Table 1), geodesy has the potential to determine and monitor with utmost precision the geometric shape of land, ice, and ocean surfaces as a global function of space and time. The geometric methods, when combined with global gravity information and the geoid, allow us to infer mass anomalies, mass transport phenomena and mass exchange in the Earth's system. The variations in Earth rotation reflect mass transport in the Earth system and the exchange of angular momentum among its components.

The geodetic observations of the "three pillars" provide the basis for the realization of the reference systems that are required in order to assign (time-dependent) coordinates to points and objects, and to describe the motion of the Earth in space (Figure 1). For this purpose, two reference systems are basic in geodesy, namely the celestial reference system and the terrestrial reference system, which are dynamically linked to each other by the Earth's rotation. The two most accurate reference systems currently available are the *International Celestial Reference System* (ICRS) and the *International Terrestrial Reference System* (ITRS), which are defined by the *International Earth Rotation and Reference Systems Service* (IERS). These systems are conventional coordinate systems that include all conventions for the orientation and origin of the axes, the scale, and the physical constants, models, and processes to be used in their realization. Based on observations, these systems can be realized through their corresponding "reference frames". The frame corresponding to the ICRS is the *International Celestial Reference Frame* (ICRF), which is a set of estimated positions of extragalactic reference radio sources. The frame corresponding to the ITRS is the *International Terrestrial Reference Frame* (ITRF), which is a set of estimated positions and velocities of globally distributed reference marks on the solid Earth's surface. These two frames are linked to each other by estimates of the Earth rotation parameters. ICRS, ITRF and the Earth rotation parameters are provided by IERS.

Today, the internationally coordinated geodetic observations collected and made available by the global geodetic station networks provide a continuous monitoring of the ITRF. This well-defined, long-term stable, highly accurate and easily accessible reference frame is the basis for all precise positioning on and near the Earth's surface. It is the indispensable foundation for all sustainable Earth observations, *in situ*, as well as airborne and space-borne. Furthermore the ITRF underpins all geo-referenced data used by society for many uses. All these digital geo-referenced data are crucial for many activities, including mapping, construction, land development, natural resource management and conservation, navigation - in fact all decision-making that has a geo-related component.

Historically, geodesy was limited to determining the Earth's shape, gravity field, and rotation including their changes over time. With modern instrumentation and analytical techniques, the scope of geodesy can be extended to include the sources of the observed changes, that is, the dynamics

Table 1. Observing the "three pillars" of geodesy and maintaining the global geodetic reference frames. GGOS utilizes a large set of space-geodetic, airborne and in-situ techniques. For acronyms, see text and Table 2.

Component	Objective	Techniques	Responsible
I. Geokinematics (size, shape, kinematics, deformation)	Shape and temporal variations of land-ice-ocean surface (plates, intra-plates, volcanos, earthquakes, glaciers, ocean variability, sea level)	Altimetry, InSAR, GNSS cluster, VLBI, SLR, DORIS, imaging techniques, leveling, tide gauges	International and national projects, space missions, IGS, IAS, future InSAR service
II. Earth Rotation (nutation, precession, polar motion, variations in LOD)	Integrated effect of changes in angular momentum (mass changes in atmosphere, cryosphere, oceans, solid Earth, core/mantle; momentum exchange between Earth system components)	classical astronomy, VLBI, LLR, SLR, GNSS, DORIS; under development: terrestrial gyroscopes	International geodetic and astronomical community (IERS, IGS, IVS, ILRS, IDS)
III. Gravity field	Geoid, Earth's static gravitational potential, temporal variations induced by solid Earth processes and mass transport in the global water cycle.	Terrestrial gravimetry (absolute and relative), airborne gravimetry, satellite orbits, dedicated satellite missions (CHAMP, GRACE, GOCE)	International geophysical and geodetic community (GGP, IGFS, IGeS, BGI)
IV. Terrestrial Frames	Global cluster of fiducial points, determined at mm to cm level	VLBI, GNSS, SLR, LLR, DORIS, time keeping/transfer, absolute gravimetry, gravity recording	International geodetic community (IERS with support of IVS, ILRS, IGS, and IDS; BGI)

of and mass transport within the Earth system [4]. With this broader scope new pathways emerge in which geodesy can contribute to the scientific understanding of the Earth system as well as the development, functioning, and security of society in general. Ultimately, the observations in these "three pillars" are affected by the same unique Earth system processes: all of them relate to mass redistribution and dynamics (Figure 2). Thus, geodesy provides a unique framework for monitoring and ultimately understanding the Earth system. Modern space-geodetic techniques are well suited for observing phenomena on global to regional scales, and thus are an important complement to traditional *in situ* observation systems.

Many scientific applications depend on detailed knowledge of the Earth's shape, its gravity field and rotation. In the past geodesy has with ever-

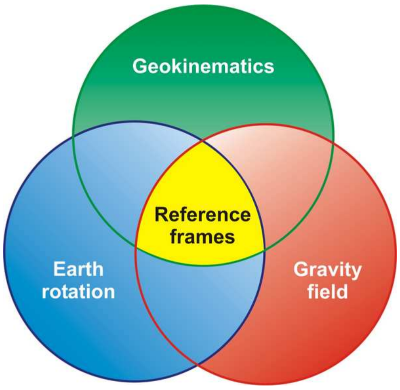

Fig. 1. Constituents of an integrated geodetic monitoring system. The "three pillars" of geodesy provide the conceptual and observational basis for the reference frames required for Earth observation. Moreover, these "three pillars" are intrinsically linked to each other as they relate to the same unique Earth system processes. Today, the space-geodetic techniques and dedicated satellite missions are crucial in the determination and monitoring of geokinematics, Earth's rotation and the gravity field. Together, these observations provide the basis to determine the geodetic reference frames with high accuracy, spatial resolution and temporal stability. From [5], modified from [6].

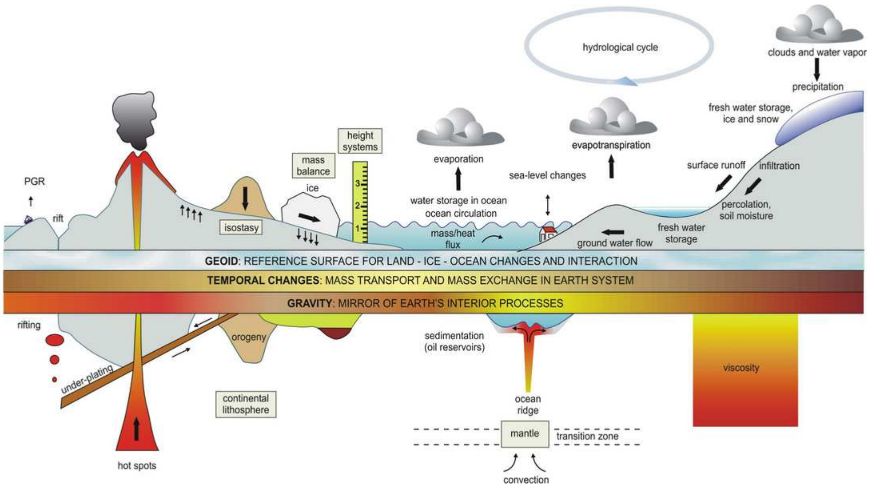

Fig. 2. Mass redistribution in the Earth system. All geophysical processes are associated with mass redistribution and changes in the dynamics, thus affecting commonly the Earth's gravity field, geometry, and rotation. Consequently, geodesy with observations of the "three pillars" contributes to an observing system that allows the monitoring of mass transport in the Earth system. From [7].

increasing accuracy provided the necessary observations, although with many limitations in accuracy and spatial coverage. The fairly recent advent of space-geodetic techniques has brought about a rapid development in global geodesy, particularly during the last decade or so. The relative precision of the measurements is approaching the very impressive level of 1 *part-per-billion* (ppb) or even better. Today, geodetic techniques permit the measurement of changes in the geometry of the Earth's surface with an accuracy of millimeters over distances of several 1000 km.

Over the last one and a half decades, the global geodetic networks have provided an increasingly detailed picture of the kinematics of points on the Earth's surface and the temporal variations in the Earth's shape. Among other applications, the observations have been used to determine improved models of the secular horizontal velocity field (e.g., [8–10]), to derive seasonal variations in the terrestrial hydrosphere (e.g., [11]), to study seasonal loading (e.g., [12]), to invert for mass motion (e.g., [13]), and to improve the modeling of the seasonal term in polar motion (e.g., [14]). Geodetic techniques provide the means to observe surface deformations on volcanoes (e.g., [15–17]), in unstable areas (e.g., [18]), associated with earthquakes and fault motion (e.g., [19–21]), or subsidence caused by anthropogenic activities such as groundwater extraction (e.g., [22]). Current developments indicate that geodetic observing techniques will be able to determine the magnitude of great earthquakes in near-real time and thus help mitigate the problem of low initial magnitudes estimated by seismic techniques [23].

The space-geodetic techniques and methods also enable auxiliary applications that utilize the atmospheric disturbance of geodetic measurements (ionosphere, troposphere, magnetic field) for non-geodetic applications. The distortions of geodetic microwave signals propagating through the atmosphere can be inverted and used for weather prediction (e.g., [24–26]), climate studies, and studies in atmospheric physics. Air temperatures retrieved from GNSS radio occultation technique provide new and near-complete coverage of the Earth's atmospheric mass field in the upper troposphere and stratosphere, complementing passive measurements from existing infra-red and micro-wave sounders. Water vapor in the lower troposphere is relevant for forecasts of precipitation, while water vapor in the upper-troposphere is the largest contributor to the atmospheric greenhouse effect. Thus, the geodetic techniques provide observations relevant for numerical weather forecast as well as climate studies.

To a large extent, geodesy is a "service science", and as such, the development of the geodetic observing system should be guided by the requirements of its users [27]. In the past, the main "customers" of geodesy came from the surveying and mapping profession, while today geodesy serves all Earth science, including the geophysical, oceanographic, atmospheric, and environmental science communities. Geodesy is also indispensable for the maintenance of many activities in a modern society. Traditionally, geodesy has served society by providing reference frames for a wide range of practical applications from regional to global navigation on land, sea, and in air, construction of infrastructure, to the determination of reliable boundaries of real estate properties. Reference frames were, however, national or regional in scope, and they were suited for the determination of coordinates relative to a network of reference points. Thus, determination of precise point coordinates required simultaneous measurements at several points. Today, the *Global Navigation Satellite Systems* (GNSS) provide access to precise point coordinates in a global reference frame anytime and anywhere on the Earth's surface with centimeter-level accuracy and without requiring additional measurements on nearby reference points.

On the user side, this technological development has stimulated new applications demanding even greater accuracy and better access to geodetically determined positions. On local to regional scales, applications such as land surveying, monitoring of infrastructure, prevention and mitigation of impacts of environmental hazards, and numerous technical applications require more or less instantaneous access to geodetic positions in a reliable reference frame with centimeter-level accuracy or better [27]. New developments and application will lead to increasing dependence on the geodetic foundation, that is, the terrestrial geodetic reference frame including easy access to this frame in the form of accurate positions.

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

3. The Global Geodetic Observing System: the organization and the system

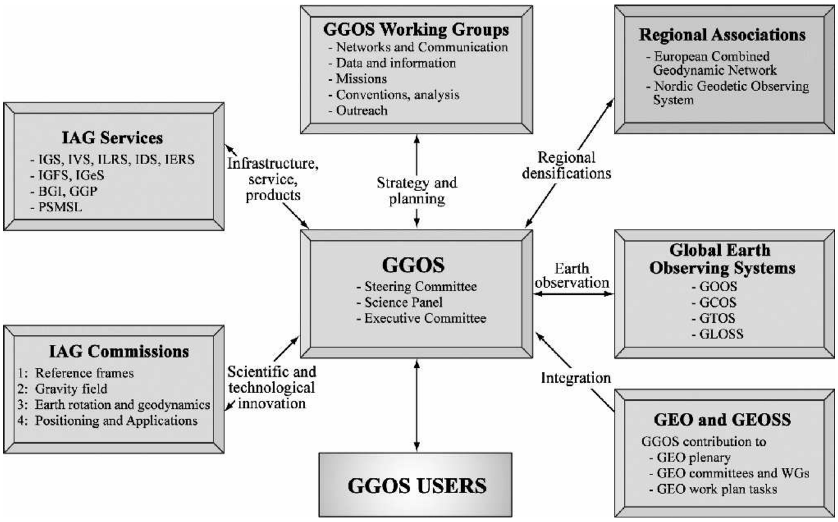

Fig. 3. Organizational links and relationships of GGOS. GGOS is being built on the scientific support from the IAG Commissions and the infrastructure of the IAG Services. GGOS integrates the work of the Services through a number of GGOS Working Groups and provides coordination and advice through its Committees. GGOS links these entities to the main programs in Earth observations, and provides an unique interface for GGOS users to the geodetic services. Modified from [5].

The international cooperation fostered by the IAG has led to the establishment of the IAG Services that provide increasingly valuable observations and products not only to scientists but also for a wide range of non-scientific applications (Table 2). With the recent developments in geodesy, Earth observations, and societal needs in mind, the IAG has established the *Global Geodetic Observing System* (GGOS) as the observing system of IAG. After a preparatory phase which included the IAG Symposium on *Integrated Global Geodetic and Geodynamic Observing System* in Munich in 1998 [28], GGOS was initially created as an IAG Project during the IUGG meeting in 2003 in Sapporo, Japan. After the first two years devoted to the definition

Table 2. The IAG Services. The IAG Services are the backbone of GGOS, providing the infrastructure for observations, data archiving and processing, and generation of products.

Pillar	Acronym	Service	Technique(s)
Systems, Frames, Rotation	IERS	International Earth Rotation and Reference Systems Service	Combination of all geometric techniques
Geometry Solid Earth	IGS	International GNSS Service	Global Navigation Satellite Systems (GNSS), particularly Global Positioning System (GPS), Global Navigation Satellite System (GLONASS), and in future Galileo
	IVS	International VLBI Service for Geodesy and Astrometry	Very Long Baseline Interferometry (VLBI)
	ILRS	International Laser Ranging Service	Satellite Laser Ranging (SLR), Lunar Laser Ranging (LLR)
	IDS	International Doris Service	Doppler Orbitography and Radiopositioning Integrated by Satellites
Geometry Ocean and Ice	PSMSL	Permanent Service of Mean Sea Level	Tide gauges
	IAS	*Internatonal altimetry Service (in preparation)*	Satellite altimetry
Gravimetry	IGFS	International Gravity Field Service	gravimetric *in situ* (absolute and relative), airborne, and spaceborne techniques
	BGI	Bureau Gravimetric International	gravimetric techniques
	IGeS	International Geoid Service	gravimetric techniques
	ICET	International Center for Earth Tide	Earth tide gravimeters
Standards	BIPM	Bureau International des Poids et Measures	
	IBS	IAG Bibliographic Service	

of the internal organizational structure of GGOS and its relationship with external organizations (the "Design Phase"), the Executive Committee of the IAG at its meetings in August 2005 in Cairns, Australia, decided to continue the Project. In the "Implementation Phase" from 2005 to 2007, the GGOS Steering Committee, Executive Committee, Science Panel, Working Groups, and Web Pages were established, and the Terms of Reference were revised. Finally, at the IUGG meeting in 2007 in Perugia, Italy, IAG elevated GGOS to the status of a full component of IAG as the permanent observing system of IAG.

It is important to note here that "GGOS" has two very distinct aspects, which should not be confused: (1) the "organization GGOS" consisting of components such as committees, panels, working groups, etc., and (2) the "observation system GGOS" comprising the infrastructure of many different instrument types, satellite missions, and data and analysis centers. While GGOS as an organization has established and is extending its structure from essentially new entities, the observational infrastructure for GGOS as the system is being largely provided by the IAG Services.

GGOS as an organization is an unifying umbrella for the IAG Services and an interface between the Services and the "outside world" (Figure 3). Internally, the GGOS Committees, Science Panel and Working Groups focus on cross-cutting issues relevant for all Services. By combining the "three pillars" into one observing system having utmost accuracy and operating in a well-defined and reproducible global terrestrial frame, GGOS adds to these pillars a new quality and dimension in the context of Earth system research. The observing system, in order to meet its objectives, has to combine the highest measurement precision with spatial and temporal consistency and stability that are maintained over decades. The research needed to achieve these goals influences the agenda of the IAG Commissions and the GGOS Working Groups. Externally, GGOS provides the links between the IAG Services and the main programs in Earth observations and Earth science. It constitutes a unique interface for many (although not all) users to the geodetic Services. GGOS participates on behalf of IAG in large international programs focusing on Earth observations, in particular the *Group on Earth Observations* (GEO, see below).

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

As organization, GGOS is challenged by the recent developments in global Earth observation. The *Ten-Year Implementation Plan* (TYIP) for the *Global Earth Observation System of Systems* (GEOSS), which was prepared by the *Group on Earth Observation* (GEO) between 2003 and 2005, and endorsed by the *Earth Observation Summit III* (EOS-III) in 2005 (see [29]) is likely to guide the development of global Earth observation programs over the next decade. GGOS as an organization needs to be integrated appropriately into the context of Earth observation and society, and GGOS as an observing system has to be developed in accordance with the strategies and methodologies of the global observing systems for the mutual benefit of all. Earth observation and society at large will benefit from the availability of geodetic observations and products, and GGOS will benefit from an improved visibility and acknowledgment of the valuable service it provides.

In order to facilitate the integration of GGOS into GEOSS, IAG is a Participating Organization in GEO (since 2004) and is represented there by the GGOS organization. GGOS is also a contributing system to the GEOSS, which is implemented by GEO. In the frame of GEO, GGOS carried out a strategy process (denoted as GGOS 2020) with the goals (1) to establish the relevant user requirements across the nine *Societal Benefit Areas* (SBAs) of GEO (for a list of these SBAs, see [3]), and (2) to provide the basis for the implementation of a geodetic observing system that will meet the requirements of the society at large and the SBAs of GEO in particular [30].

Since 2006, GGOS is a member of the *Integrated Global Observing Strategy Partnership* (IGOS-P) [31] and is integrating its work into the *Integrated Global Observing Strategy* (IGOS) which is an initiative of IGOS-P. Moreover, GGOS contributes to a number of global observing systems, steps are being taken to strengthen joint initiatives with government organizations and international bodies, including relevant United Nations authorities. These initiatives have already and will continue to enhance the visibility of geodetic activities in the context of Earth sciences, Earth observation and practical applications [27].

GGOS as an observing system is built upon the existing and future infrastructure provided by the IAG Services. It aims to provide consistent observations of the spatial and temporal changes of the shape and gravitational field of the Earth, as well as the temporal variations of the Earth's rotation (see Figure 1 above). In other words, it aims to deliver a global picture of the surface kinematics of our planet, including the ocean, ice cover and land surfaces. In addition, it aims to deliver estimates of mass anomalies, mass transport and mass exchange in the Earth system. Surface kinematics and mass transport together are the key to global mass balance determination, and an important contribution to the understanding of the energy budget of our planet (e.g., [32–34]). Moreover, the system aims to provide the observations that are needed to determine and maintain a terrestrial reference frame of higher accuracy and greater temporal stability than what is available today [35].

GGOS as a system (Figure 4) exploits (and tries to extend) for this purpose the unique constellation of satellite missions relevant to this goal that are in orbit now and those planned for the next two decades, by integrating them into one measurement system. The backbone of this integration is the existing global ground network of tracking stations for the geodetic space techniques *Very Long Baseline Interferometry* (VLBI), *Satellite Laser Ranging* (SLR), *Lunar Laser Ranging* (LLR), GNSS and *Doppler orbitography and radio positioning integrated by satellite* (DORIS). GGOS integrates these tracking networks with terrestrial gravity networks. GGOS will complement the space segment and global ground network by airborne and terrestrial campaigns that serve the purpose of calibration and validation, regional densification, and refinement. Assimilation of these observations into models of weather, climate, oceans, hydrology, ice and solid Earth processes will fundamentally enhance the understanding of the role of surface changes and mass transport in the dynamics of our planet. Furthermore, through the analysis of the dense web of microwave radiation connecting the GNSS satellites with *Low Earth Orbiters* (LEO) and with the Earth's surface a powerful new technique emerges for probing the atmosphere's composition.

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

4. GGOS: an observing system of layered infrastructure

GGOS as an observing system has five major levels of instrumentation and objects (Figure 5) that actively perform observations, are passively observed, or both. These levels are: Level 1: the terrestrial geodetic infrastructure including the ground networks of *in situ* instruments and space-geodetic tracking stations, as well as the data and analysis centers; Level 2: the LEO satellite missions; Level 3: the *Middle/Geostationary Earth Orbiters* (MEO/GEO) that is, the GNSS and the Lageos-type SLR satellites; Level 4: the planetary missions and geodetic infrastructure on Moon and planets; Level 5: the extragalactic objects. The ground networks and the GNSS are crucial in positioning. Highly accurate orbits for the LEO satellites are determined with the help of the ground-based infrastructure as well as the GNSS satellites. Level 4 is particularly important for the dynamical reference frame. The stable quasars of Level 5 provide the inertial reference frame fixed in space.

These five levels of instrumentation and objects, independent of whether they are active or passive, receivers or emitters or both, are connected by many types of observations in a rather complex way to form the integrated GGOS observing system. In this system, the major observation types at

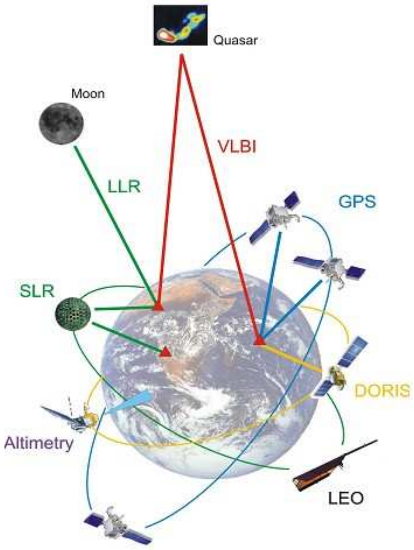

Fig. 4. Infrastructure contributing to GGOS. The combined infrastructure allows the determination and maintenance of the global geodetic reference frames, and the determination of Earth's gravity field and rotation. The ground networks and navigation satellites (currently in particular GPS) are crucial for maintaining the reference frame required for high accuracy positioning. In particular, they allow the monitoring of volcanoes, earthquakes, tectonically active regions and landslide-prone areas. The Low Earth Orbit (LEO) satellites monitor sea level, ice sheets, water storage on land, atmospheric water content, high-resolution surface motion, and variations in the Earth's gravity field. The latter are caused, to a large extent, by regional and global mass transport in the hydrological cycle.

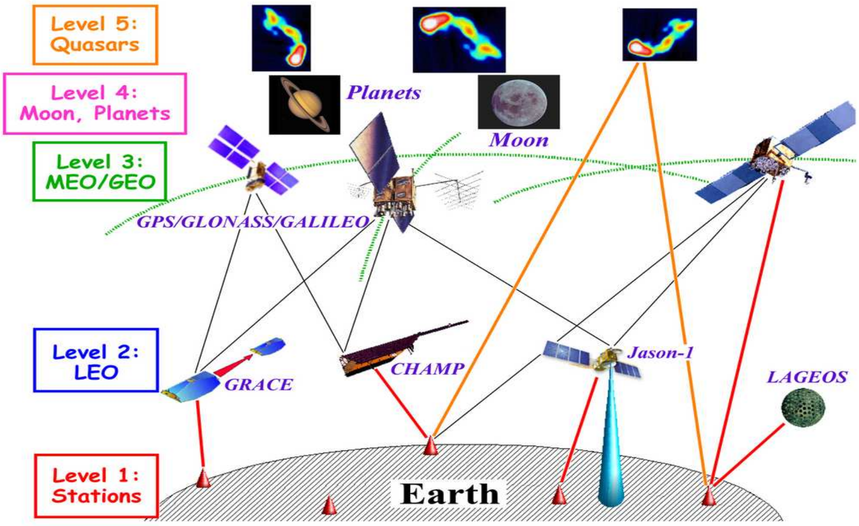

Fig. 5. The five levels of GGOS and their interactions with observations of various types. The infrastructure of GGOS consists of five distinct levels, depending on the distance to the Earth' surface. See tex for details.

present are: (1) observations of the microwaves emitted by GNSS satellites at the ground and at the LEO satellites; (2) laser ranging to LEOs, dedicated laser ranging satellites, GNSS satellites and the Moon; (3) microwave observation of extragalactical objects (quasars) by VLBI; (4) instrumentation onboard the LEO satellites measuring accelerations, gravity gradients, satellite orientation, etc.; (5) radar and optical observations of the Earth's surface (land, ice, glaciers, sea level, ect.) from remote sensing satellite; (6) distance measurements between satellites (K-band, optical, interferometry, etc.). In the future, new measurement techniques will evolve and be included into the system.

Figure 5 also makes clear that different parts of the overall system are cross-linked through observations and inter-dependent. Moreover, all these techniques are affected by the same Earth system processes and they measure the "output" of the same unique Earth system, that is, the various geodetic fingerprints induced by mass redistribution and changes in the system's dynamics (see Figure 2 above). Therefore, consistency of data processing, modeling, and conventions across the techniques and across the "three pillars" is mandatory for maximum exploitation of the full potential of the system. In order to achieve this, GGOS pursues two main roads: (1) The individual parts (i.e., observation types) of the overall system are connected by co-location of different instruments at the same site on the Earth's surface or on the same satellite or object. This co-location of instruments and sensors is extremely important for the consistency and accuracy of the system and for the integration of the system to perform as one large "instrument". Moreover, each of the techniques has its own strength and weaknesses, and through co-location, the strengths can be exploited and the weaknesses can be mitigated. (2) The different parts of the Earth system are increasingly linked through consistent and comprehensive models, in order to capture all interactions and feedback between the various components of the Earth system as depicted in Figure 2, leading eventually to an integrated Earth system model predicting the geodetic fingerprints in the "three pillars" consistently as a basis for improved geodetic analyses. Enhanced modeling will also allow for more realistic estimates of the uncertainties of individual observations and products and thus improve the integrability of the different geodetic datasets.

GGOS is one of the systems contributing to GEOSS. This requires interoperability of those products and services provided by GGOS to GEOSS with the other systems of GEOSS. While there has been an increasing focus on interoperability between the various IAG Services, achieving interoperability with GEOSS components is still an emerging challenge with the extent not yet fully identified.

5. Conclusions

GGOS is IAG's Observing System. As an organization, it is the main interface for the IAG Services particularly to the major international Earth observation programs, including GEO. As an organization, GGOS enhances the visibility of geodesy in general and the work of the IAG Services in particular in society and specifically the relevant scientific organizations and Earth observation system. GGOS links the IAG Services to major user groups. The organization has the main tasks to: (1) identify a comprehensive set of geodetic products and establish the requirements concerning the products' accuracy, temporal and spatial resolution, latency and consistency; (2) develop the strategy for GGOS appropriate to meet these requirements; (3) identify the gaps in the system of IAG Services and develop strategies to close these gaps; (4) ensure the availability, consistency, reliability, accessibility, and interoperability of geodetic observations, products, and models.

As an observing system, GGOS builds on the infrastructure of the IAG Services and utilizes signals and observations from relevant infrastructure maintained by governmental authorities and space agencies (e.g., NASA and ESA). Based on this infrastructure, GGOS allow the monitoring of: (1) the deformation of the Earth surface (solid Earth, ocean, and ice) and Earth rotation with sub-millimeter accuracy; (2) the global gravity field and its time variations with unprecedented accuracy and resolution, particularly through dedicated gravity satellite missions; (3) the water vapor in the troposphere, tropopause height, and electron density in the ionosphere, thus the monitoring of atmospheric processes relevant for global warming; (4) many parameters related to natural hazards and disasters, increasingly providing observations relevant for early warning systems. Since GGOS depends to a degree on infrastructure (particularly the satellite missions) provided by others, GGOS has to interact with these providers (particularly the space agencies) in order to ensure continuity of the required infrastructure and to work with them to improve the infrastructure continuously.

In order to integrate the infrastructure of the IAG Services into a comprehensive and integrated geodetic Earth observation system of systems with highly accurate and consistent observations and products, GGOS faces main challenges in the combination and integration of all observation techniques into a consistent observing system, and in developing comprehensive modeling of the interactions in the Earth system across the "three pillars". Already today, geodesy and particularly GGOS has the documented potential to facilitate new insights into the geophysical processes in the Earth system. If the challenges can be met, GGOS will provide a basis for a deeper scientific understanding of the Earth System and the future of our changing Planet, as well as an improved basis for Earth observations and geodesy-dependent applications in society at large.

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