GGOS provides a basis on which advances in geoscience can be built. By considering the Earth system as a whole (including the geosphere, hydrosphere, cryosphere, atmosphere and biosphere), monitoring Earth system components and their interactions by geodetic techniques and studying them from the geodetic point of view, the geodetic community provides the geoscience community with a powerful tool consisting mainly of highly accurate observations, high-quality services, standards and references, and theoretical and observational innovations.

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The paramount importance of sustainable development for a prosperous future of the anthroposphere has been widely acknowledged. Understanding of the major processes in the Earth system and its changes over time is one of the many prerequisites of sustainability and cannot be achieved without comprehensive monitoring of the Earth system. The recent Earth Observation Summits (EOS) have underlined the urgent need for a coordinated and sustained program of Earth observation and tasked the intergovernmental Group on Earth Observations (GEO) with the implementation of the Global Earth Observation System of Systems (GEOSS). Geodesy provides the foundation on which most Earth observation systems are built. Therefore, the geodetic observing system is essential for Earth observation and GEOSS.

Responding to the international development in Earth observation and the scientific challenges associated with rapidly increasing requirements for geodetic observations, the International Association of Geodesy (IAG) has organized all its observation activities under the umbrella of the Global Geodetic Observing System (GGOS), the observing system of IAG. In this paper, we give an overview of the major contributions of geodesy to Earth sciences and observations, introduce GGOS, and summarize the challenges and the potential future developments.
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Geodesy’s contribution to Earth science and Earth observations

Geodesy is the science of determining the geometry, gravity field, and rotation of the Earth (the “three pillars” of geodesy) and their temporal evolution. The recent advent of space geodesy has improved geodetic accuracy by more than three orders of magnitude over the last three decades. Combined with the rapid growth of communication techniques, this has led to a revolution in applied and global geodesy, and geodesy has developed into a science making unique contributions to the understanding of the Earth system, its inherent dynamics, and its response to climate change.

Today, space-geodetic techniques allow the determination of positions with respect to a global reference frame with unprecedented accuracy (e.g. detecting millimeter-level changes in the geometry of the Earth’s surface over several thousand km). Moreover, geodetic imaging techniques increasingly gain importance, particularly when integrated with the traditional point-based approach of geodesy. Based on these techniques, temporal changes in the “three pillars” are provided with increasing accuracy and spatial and temporal resolution. These observations record the “fingerprints” of mass movements in ocean, atmosphere, ice sheets and terrestrial water storage; they scale mass and volume changes in the ocean; they allow the determination of the displacement field associated with earthquakes and the velocity and strain fields of the Earth’s surface; they measure the water content in the atmosphere; and they provide crucial constraints for all models of mechanical processes in the Earth system. With modern instrumentation and analytical techniques, the scope of geodesy is rapidly extending from a mere monitoring of the changes to the modeling and understanding of the sources of the observed changes. With this broader scope, geodesy contributes to the scientific understanding of the Earth system as well as the development, functioning, and security of society in general.

Observations of the “three pillars” provide the basis for the realization of the reference systems required to assign time-dependent coordinates to points and objects, and to describe the Earth’s motion in space (Figure 1). The two most accurate reference frames available are the International Celestial Reference Frame (ICRF) and the International Terrestrial Reference Frame (ITRF), which are realizations of the corresponding conventional coordinate systems. These two frames are linked to each other by estimates of the Earth Orientation Parameters (EOPs). ICRF, ITRF and EOPs are provided by the IERS.

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The global geodetic networks provide 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. The ITRF underpins all geo-referenced data serving society in many ways. The GNSS provide access to precise point coordinates in the ITRF anytime and anywhere on the Earth’s surface, with centimeter-level accuracy and without 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.

In support of scientific applications the observations of the global geodetic networks of the last ~15 years have been used to determine improved models of the secular horizontal velocity and strain fields (Figure 2), to derive seasonal variations in the terrestrial hydrosphere, to study seasonal loading, to invert for mass motion, to improve the modeling of the seasonal term in polar motion and to detect surface deformations associated with volcanoes, earthquakes, fault motion, or subsidence caused by anthropogenic activities such as groundwater extraction (see Plag & Pearlman, 2009).

Variations in Earth’s rotation reflect mass transport in the Earth system and the exchange of angular momentum among its components. Earth rotation observations have provided insight into many global-scale dynamic phenomena such as the El Niño/Southern Oscillation (ENSO), the most prominent feature of the climate system on inter-annual time scales. During an ENSO event, the tropical easterlies collapse causing

Fig. 2: Horizontal velocity fields at the Earth’s surface derived from geodetic observations.

Fig. 2: Champs de vitesse horizontale à la surface de la Terre obtenus à partir d’observations géodésiques.

the atmospheric angular momentum to increase, which, by conservation of angular momentum, leads to a decrease in the solid Earth’s angular momentum and an increase in length-of-day of up to 0.5 milliseconds for particularly strong ENSO events.

Data from many space missions and other geodetic observations have contributed to the determination of Earth’s gravity field models, with a significant step forward due to the satellite missions CHAMP and GRACE, in orbit since 2000 and 2002, respectively. GRACE in particular has pushed our knowledge of the static gravity field to centimeter-level accuracy in geoid determination (Figure 3), as well as providing a direct measure and unprecedented insight in the mass flux in the water cycle down to spatial scales of about 500 km and sub-monthly time scales. The upcoming European GOCE mission will further hone precision and resolution of the static part of the gravity field to an unprecedented level (cf. Plag & Pearlman, 2009).

The Global Geodetic Observing System (GGOS)

Over the last fifteen years, technological development and increasingly demanding scientific requirements have led to the establishment of a number of techniques and product-specific IAG Services utilized by the scientific and non-scientific communities. As an umbrella for these services, the IAG initiated GGOS as an IAG Project in 2003 and as its permanent observing system in 2007.
The acronym “GGOS” has two very distinct aspects: (1) the “organization GGOS”, consisting of committees, panels, working groups, and bureaus, and (2) the “observation system GGOS”, comprising the infrastructure of a wide range of instrument types, satellite missions, and data and analysis centers. While the structure of GGOS as an organization was established essentially from new entities, the observational infrastructure for GGOS as a system largely stems from pre-existent IAG Services.

GGOS as an organization (Figure 4) facilitates networking among IAG Services and Commissions and other stakeholders in the Earth Science and Earth Observation communities. It provides coordination, scientific advice, and research activities to the IAG Services in support of the development of accessible products with higher accuracy and consistency catering to the needs of global change research.

**Fig. 4:** GGOS is being built on scientific support from the IAG Commissions and the infrastructure of the IAG Services. GGOS coordinates the work of the Services across technique boundaries through three Bureaus and provides an overarching strategy for the development of GGOS through its Committees, Science Panel, and Working Groups.

From Plag & Pearlman (2009).

**Fig. 4 :** GGOS se construit grâce aux apports des commissions IAG et de l’infrastructure des Services IAG. GGOS coordonne les travaux des Services de manière pluridisciplinaire par l’intermédiaire de trois bureaux et définit une stratégie intégrale pour le développement du GGOS à travers ses comités, sa commission scientifique et ses groupes de travail.


**Definitions:**
- **IERS:** International Earth Rotation and Reference Systems Service
- **IGFS:** International Gravity Field Service
- **IVS:** International VLBI Service for Geodesy and Astrometry
- **VLBI:** Very Long Baseline Interferometry
- **IGS:** International GNSS Service
- **GNSS:** Global Navigation Satellite Systems
- **ILRS:** International Laser Ranging Service
As an observing system, GGOS utilizes the infrastructure of the IAG Services, providing consistent observations of the three pillars. In particular, GGOS delivers a global picture of the Earth’s surface kinematics and estimates mass anomalies, mass transport and mass exchange in the Earth system. Moreover, it provides the observations required to maintain a terrestrial reference frame with an ever increasing accuracy and temporal stability. GGOS exploits and aims to extend the unique constellation of relevant satellite missions that are in orbit now, and planned for the next two decades, by integrating them into a single measurement system (Figure 5). The backbone of this integration is the existing global ground network of tracking stations for the geodetic space techniques (Table 1, next page), currently being integrated with terrestrial gravity networks as well as airborne and terrestrial campaigns. 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. The analysis of the dense web of microwave radiation connecting the GNSS satellites with Low Earth Orbiters (LEO) and with the Earth’s surface is a powerful emerging new technique for probing the atmosphere’s composition.

**Fig. 5**: The five-level infrastructure contributing to GGOS:
(1) terrestrial geodetic infrastructure; (2) LEO satellite missions; (3) GNSS and Lageos-type SLR satellites; (4) planetary missions and geodetic infrastructure on Moon and planets and (5) extragalactic objects. Ground networks and navigation satellites are crucial for maintaining the reference frame and they allow, for example, 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 mainly originating from regional and global mass transport in the hydrological cycle.

**Fig. 5** : L’infrastructure à cinq niveaux qui contribue au GGOS : (1) infrastructure géodésique terrestre ; (2) missions satellitaires LEO ; (3) satellites GNSS et SLR (télémétrie laser par satellite de type Lageos) ; (4) missions planétaires et infrastructure géodésique sur la Lune et sur les planètes de notre système solaire et (5) objets extragalactiques. Les réseaux in-situ et les satellites de navigation sont essentiels pour maintenir le système de référence, permettant en outre de surveiller les volcans, les séismes, les régions actives sur le plan tectonique et les zones sujettes aux glissements de terrain. Les satellites LEO (à orbite terrestre basse) surveillent le niveau de la mer, les calottes de glace, les réserves d’eau continentales, la teneur en eau de l’atmosphère, les mouvements de surface à haute résolution et les variations du champ gravitationnel terrestre dus principalement aux transports de masse régionaux et globaux dans le cycle hydrologique.
Challenges and future development

GGOS is embedded in an institutional and organizational environment undergoing rapid changes in response to urgent needs of decision-makers and humanity at large. The world of Earth observations has changed dramatically over the last decade, and more changes are to come. A major challenge for GGOS is the integration as organization and observing system into GEO and GEOSS, respectively. In order to facilitate this integration, IAG is a Participating Organization in GEO. Currently GGOS is based on the voluntary commitment of many contributors, which leads to large fluctuations in available resources and calls for a high degree of redundancy in order to ensure a stable geodetic infrastructure. In the future, more formal intergovernmental agreements may be necessary to guarantee stability of this core element of GEOSS. GGOS also needs to establish firm links to major user groups. The GEO Communities of Practice (CoP) appear to be appropriate points of contact to main user groups, particularly those related to disasters and geohazards, water, and climate change.

GGOS faces the challenge of demanding user requirements (cf. Plag & Pearlman, 2009). 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 latency, is a very demanding task, complicated by the transition to new technologies as they evolve in parallel while maintaining an operational system. Exploitation of the full potential of geodesy for Earth observation requires a sophisticated integration of all geodetic

A “whole Earth” approach allows for an optimal assimilation of a wide spectrum of observations in inter-disciplinary, four-dimensional models.
techniques, processing, and geophysical background models into one system capable of providing the best possible information on surface deformation, mass transport, and dynamics of the Earth. Addressing this challenge requires a “whole Earth” approach allowing for an optimal assimilation of a wide spectrum of observations in inter-disciplinary, four-dimensional models.

With respect to system implementation, the continuous sequence of key satellites, such as altimetry missions for sea and ice surface and dedicated gravity missions for mass transport in the water cycle, are key challenges. GGOS does not “own” these satellites, and depends on support from space agencies and research institutes in order to have access to this part of the infrastructure. To this end, awareness must be enhanced as to what geodesy is and who benefits from it, procured through appropriate outreach.