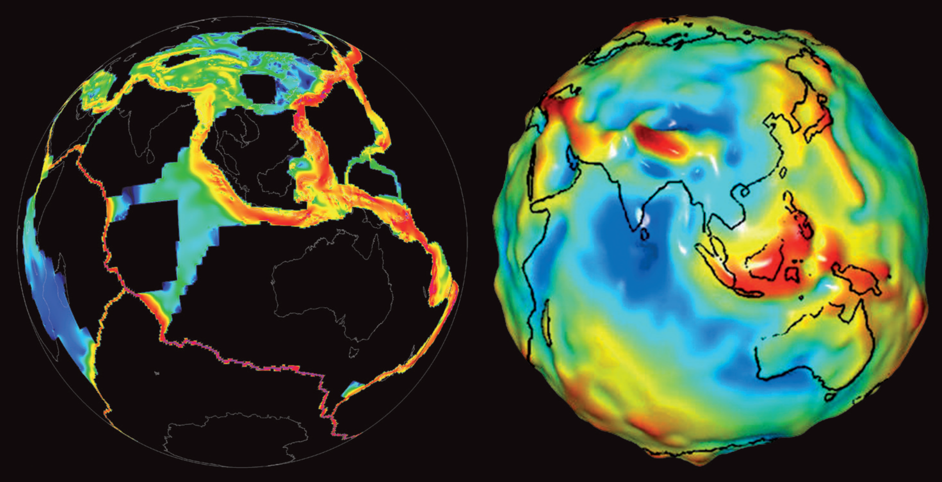
Global Geodetic Observing System for geohazards and global change

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.



Left picture: Global strain rate map.
Courtesy C. Kreemer.
Right picture: Global gravity model.
Courtesy University of Texas Center for Space Resarch and NASA.

Image de gauche : carte du taux de déformation du globe.
Avec la permission de C. Kreemer.
Image de droite : modèle de la gravité terrestre.
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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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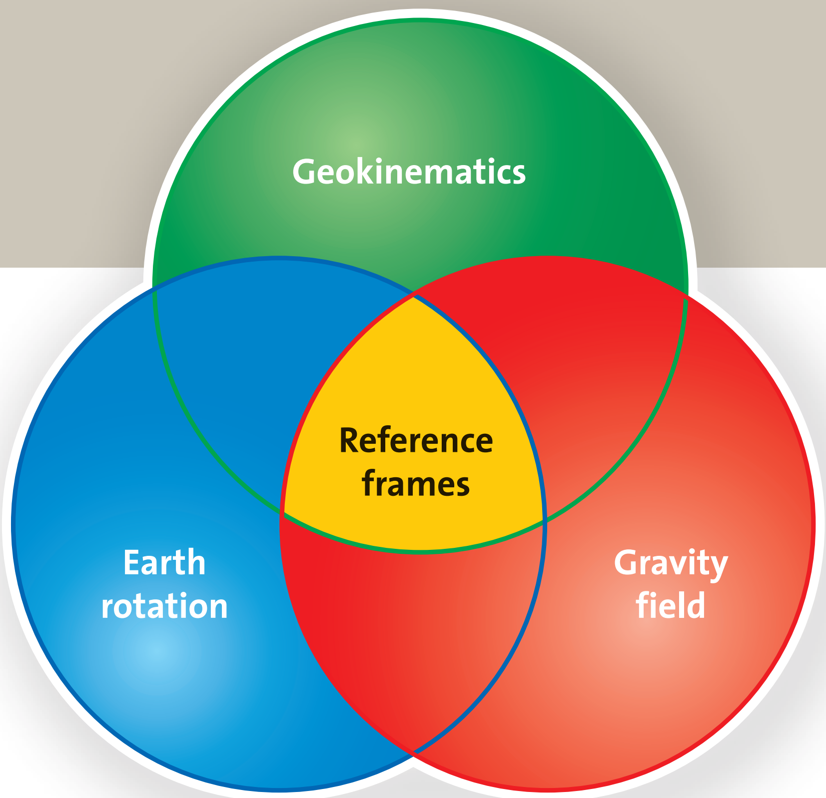


Fig. 1: The observations in the so-called "three pillars" of geodesy, Earth's geometry, gravity field and rotation, are intrinsically interlinked and affected by the same unique Earth system processes. Together, these observations provide the basis to maintain the geodetic reference frames with high accuracy, spatial resolution and temporal stability.

Fig. 1 : Observations sur les "trois piliers" de la géodésie – la géométrie, le champ gravitationnel et la rotation de la Terre – reliés entre eux de façon intrinsèque et sujets aux influences des mêmes processus uniques du système Terre. L'ensemble de ces observations fournit la base qui maintient les systèmes de référence géodésiques avec précision, une bonne résolution spatiale et une stabilité temporelle.

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.

The scope of geodesy is rapidly extending from a mere monitoring to the modeling and understanding of the sources of the observed changes.

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.

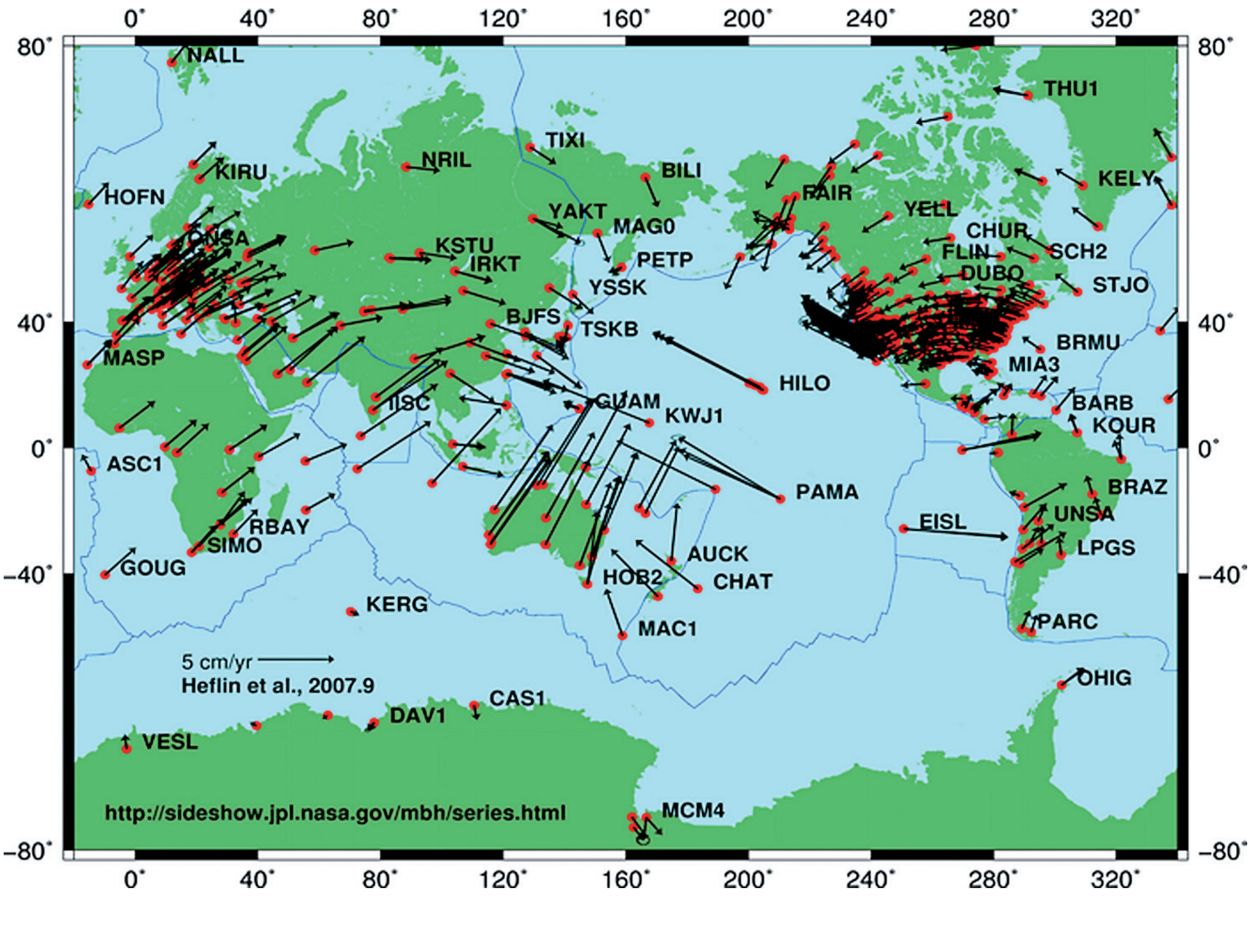
In support of scientific applications the observations of the global geodetic networks of the last ~15 years have been used to determine improved models of the secular horizontal velocity and strain fields (*Figure 2*), to derive seasonal variations in the terrestrial hydrosphere, to study seasonal loading, 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.

Source : http://sideshow.jpl.nasa.gov/mbh/series.html



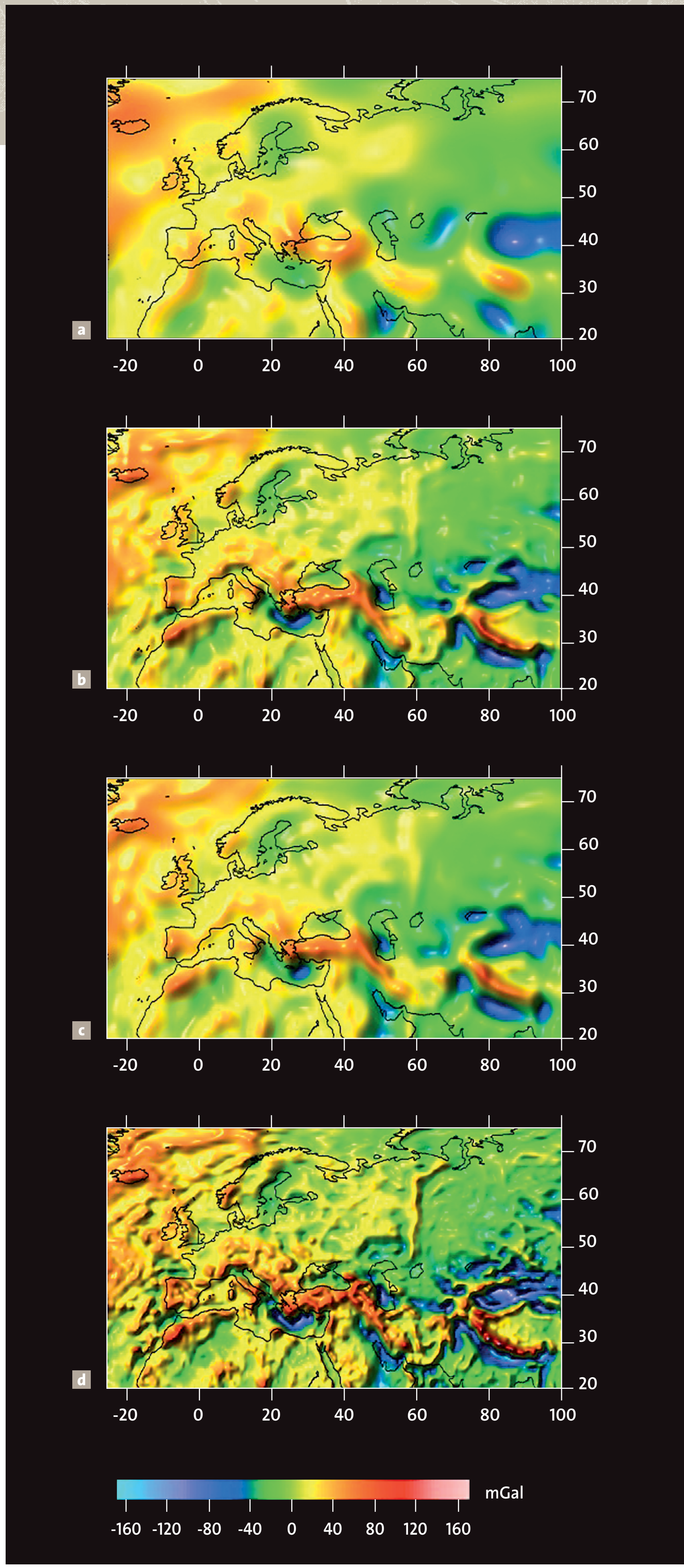


Fig. 3: Improvement of the Earth's gravity field models. These are (from top to bottom):
a) GRIM-5S1 (best gravity field model before CHAMP and GRACE, computed from SLR data only);
b) EIGEN-CHAMP03S (gravity field from CHAMP);
c) EIGEN-GRACE03S (gravity field from GRACE);
d) EIGEN-CG03C (gravity field from GRACE combined with terrestrial data).
Modified from Reigber *et al.*, 2005.

Fig. 3 : Amélioration des modèles des champs gravitationnels terrestres. Les modèles (de haut en bas) sont :
a) GRIM-5S1 (le meilleur modèle de champ gravitationnel d'avant CHAMP et GRACE, calculé à partir des seules données SLR) ;
b) EIGEN-CHAMP03S (champ gravitationnel à partir de CHAMP) ;
c) EIGEN-GRACE03S (champ gravitationnel à partir de GRACE) ;
d) EIGEN-CG03C (champ gravitationnel à partir de GRACE cumulé avec des donnés terrestres).
Modifié d'après Reigber *et al.*, 2005.

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.

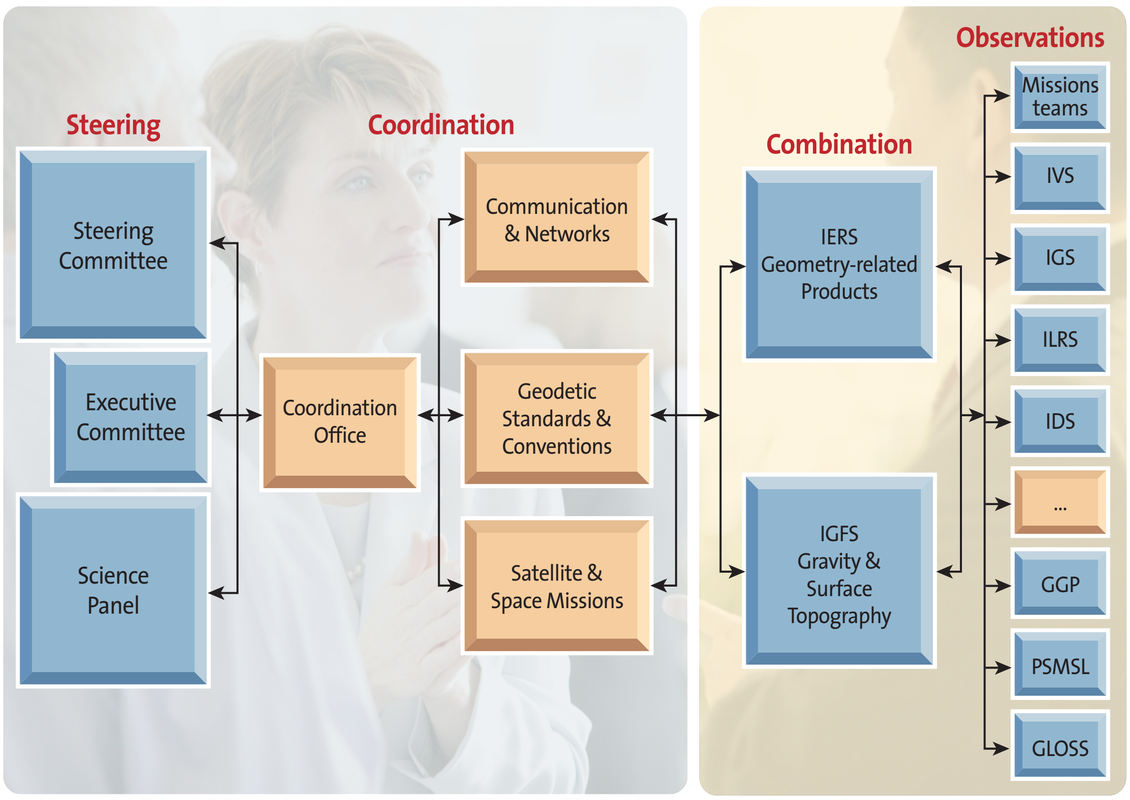
GGOS as an organization (*Figure 4*) facilitates networking among IAG Services and Commissions and other stakeholders in the Earth Science and Earth Observation communities. It provides coordination, scientific advice, and research activities to the IAG Services in support of the development of accessible 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.

D'après Plag & Pearlman (2009).



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
IDS: International DORIS Service
DORIS: Doppler Orbitography and Radio positioning Integrated by Satellite
GGP: Global Geodynamics Project
PSMSL: Permanent Service for Mean Sea Level
GLOSS: Global Sea Level Observing System

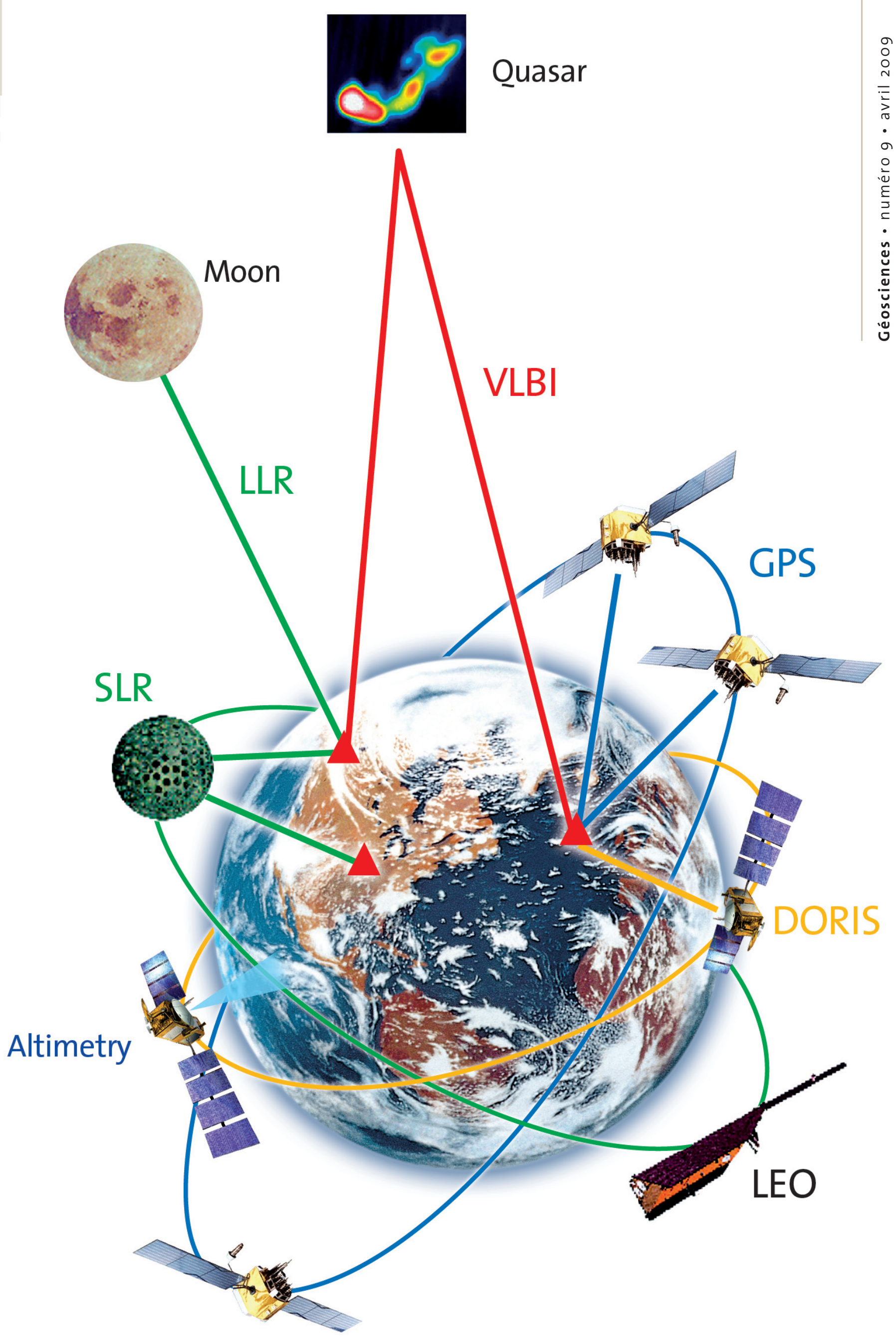


Fig. 5: The five-level infrastructure contributing to GGOS: (1) terrestrial geodetic infrastructure; (2) LEO satellite missions; (3) GNSS and Lageos-type SLR satellites; (4) planetary missions and geodetic infrastructure on Moon and planets and (5) extragalactic objects. Ground networks and navigation 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.*

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.

> *"Assimilation of geodetic observations into models of weather, climate, oceans, hydrology, ice and solid Earth processes will fundamentally enhance the understanding of the dynamics of our planet."*

Component	Objective	Techniques	Responsibility
I. Geokinematics (size, shape, kinematics, deformation)	*Shape and temporal variations of land/ice/ocean surface (plates, intra-plates, volcanoes, 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 length-of-day)	*Integrated effect of changes in angular momentum and inertia tensor (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, BGI)*
IV. Terrestrial Frame	*Global cluster of fiducial point, 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)*

Table 1: Components of GGOS. VLBI: Very Long Baseline Interferometry; SLR: Satellite Laser Ranging; LLR: Lunar Laser Ranging; GNSS: Global Navigation Satellite Systems; DORIS: Doppler Orbitography and Radio positioning Integrated by Satellite; InSAR: Interferometric Synthetic Aperture Radar; IGS: International GNSS Service; IAS: International Altimetry Service; IVS: International VLBI Service for Geodesy and Astrometry; ILRS: International Laser Ranging Service; IDS: International DORIS Service. GGP: Global Geodynamics Project; IGFS: International Gravity Field Service; BGI: International Gravimetric Bureau; IERS: International Earth Rotation and Reference Systems Service.

From Plag & Pearlman (2009).

Tab. 1 : Les différentes composantes de GGOS. VLBI (interférométrie à très longue ligne de base) ; SLR (télémétrie laser satellitaire) ; LLR (télémétrie laser lunaire) ; GNSS (système de positionnement par satellites) ; DORIS (orbitographie Doppler et radiopositionnement intégrés par satellite) ; InSAR (interférométrie radar à synthèse d'ouverture) ; IGS (service international de GNSS) ; IAS (service international d'altimétrie) ; IVS (service international de géodésie et d'astrométrie de VLBI) ; ILRS (service international de télémétrie laser) ; IDS (service international DORIS) ; GGP (projet global de géodynamique) ; IGFS (service international du champ de gravité) ; BGI (bureau international de gravimétrie) ; IERS (service international de la rotation terrestre et des systèmes de référence).

D'après Plag & Pearlman (2009).

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.

A "whole Earth" approach allows for an optimal assimilation of a wide spectrum of observations in inter-disciplinary, four-dimensional models.

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 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.

► Stockages souterrains : la mesure de la subsidence

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La surveillance de la déformation du sol en surface (ou subsidence) est un des moyens utilisés pour suivre le bon comportement des stockages souterrains [1]. Elle complète avantageusement les techniques de surveillance opérationnelle et sismique.

Le nivellement est une **mesure facilement répétitive et donc fiable**. Avec un matériel classique mais moderne de topographe il est facile d'atteindre le dixième de millimètre. Le nombre de mesures nécessaires et leur périodicité ont un impact fort sur l'usage que l'on peut en faire. Les techniques statistiques et de visualisation permettent d'interpréter, de localiser et de valider les résultats. D'autres techniques comme les mesures angulaires ou les méthodes satellitaires, telles l'interférométrie radar et spatiale ou la localisation GPS, donnent des mesures utiles qui, tout en les complétant, doivent souvent être validées par l'approche aujourd'hui classique du nivellement de précision.

(1) Pour les cavités salines la subsidence est un indicateur très direct de la convergence de parois liées au fluage (cf. article B. Feuga dans ce numéro).

Les principaux écueils sont liés aux réalités du sous-sol et parfois aux exigences excessives de donneurs d'ordre et de géomécaniciens qui ont une tendance naturelle à vouloir caler un modèle sur des mesures insuffisantes. En plus des difficultés numériques, les causes d'« échec » sont nombreuses : niveaux supérieurs trop peu reconnus car peu intéressants pour la conception des ouvrages ; variations climatiques négligées ; investigations menées sur une surface insuffisamment large (une prise en compte de la plasticité des géomatériaux hôtes, particulièrement pour le sel, est nécessaire) ; campagne initiale ou valeur zéro sans fiabilité ou timing ; système de repères peu ou mal entretenu ; recherche insuffisante ou trop difficile d'une zone réputée stable, etc.

Malgré toutes ces difficultés les mesures restent utiles et souvent interprétables. Même sans les coloriages sortis d'un modèle, une mesure inférieure à sa précision est déjà une information, et un modèle géomécanique, par nature incomplet, ne doit être regardé que comme un outil. **L'essentiel est toujours d'avoir mesuré à temps.**

L'observation géodésique du globe - Le réseau GGOS : une infrastructure polyvalente dédiée aux sciences de la Terre, aux géorisques et à l'étude des changements planétaires

Le Global Geodetic Observing System *(GGOS – réseau d'observation géodésique du globe) est issu des travaux de l'*International Association of Geodesy *(IAG – association internationale de géodésie). Il coordonne les actions de géodésie dans les domaines des sciences de la Terre et fournit l'infrastructure nécessaire à la surveillance globale et aux études sur le changement climatique (tout particulièrement pour l'élévation du niveau des mers). Avec ses systèmes de référence géodésique, GGOS constitue un support pour de multiples observations de la Terre. Les campagnes géodésiques portant sur les modifications de la géométrie, sur le champ gravitationnel et sur la rotation terrestre (les « trois piliers de la géodésie ») supportent une large gamme d'applications scientifiques et sociétales. Ainsi, les techniques géodésiques sont indispensables pour étudier, évaluer et surveiller les risques géologiques et les détecter précocement. Les modifications du niveau des mers et des calottes glaciaires sont observées depuis l'espace par altimétrie satellitaire, venant en appui des observations* in situ *des déformations et des modifications du champ gravitationnel qui sont associées. GGOS aide à la surveillance du transport de masse dans le cycle de l'eau à l'échelle globale. Les observations géodésiques permettent d'appréhender les évolutions dynamiques du système terrestre et aident entre autres à valider les modèles climatiques et océaniques. Pleinement déployé, GGOS contribue à l'amélioration des connaissances à l'échelle globale, à une gestion rationalisée des ressources pour un développement durable.*

References: **Plag, H.-P. & Pearlman, M., eds., 2009.** The Global Geodetic Observing System: Meeting the Requirements of a Global Society on a Changing Planet in 2020, Springer Verlag, Berlin. In Press.
Reigber, C., Schmidt, R., Flechtner, F., Konig, R., Meyer, U., Neumayer, K.-H., Schwintzer, P., & Zhu, S.Y., 2005. An Earth gravity field model complete to degree and order 150 from GRACE: EIGEN-GRACE02S, J. Geodynamics, 39, 1-10.