The Global Geodetic Observing System – Part 2, the System

by Hans-Peter Plag, Markus Rothacher, and Michael Pearlman

In the first part of this article (*GW* Jan/Feb 2009), we introduced GGOS as the organisation that provides a coordination structure for the activities of the international geodetic community. In this second part, the authors introduce GGOS as an observing system and illustrate its versatility by describing examples of applications.

GGOS observes Earth's shape, gravity field and rotation and their changes in time. The variations in these "three pillars" of geodesy are inherently related to the dynamics of the Earth system, including the interior and surface of the solid Earth and its fluid envelope. Mass transport in the Earth system, particularly in the fluid envelope of the solid Earth, is associated with specific fingerprints in the geodetic quantities. Studies of geohazards, climate change, sea level variations, and resource management are just a few examples of areas that benefit or even depend on geodetic observations.

The ultimate goal of GGOS is to provide observations and products that meet the requirements of science and applications in many fields, including geodynamics, tectonics, hydrology, meteorology, oceanography, glaciology, geohazards, and early warning for impending natural hazards. The observing system appropriate to meet the demanding requirements of these fields in terms of accuracy, spatial and temporal resolution, and latency of the observations is based on a very complex combination of many different sensors and instruments, on the Earth, in the air and in space, that need to be integrated into a comprehensive and consistent "geodetic tool" for the monitoring of the Earth system as a whole.

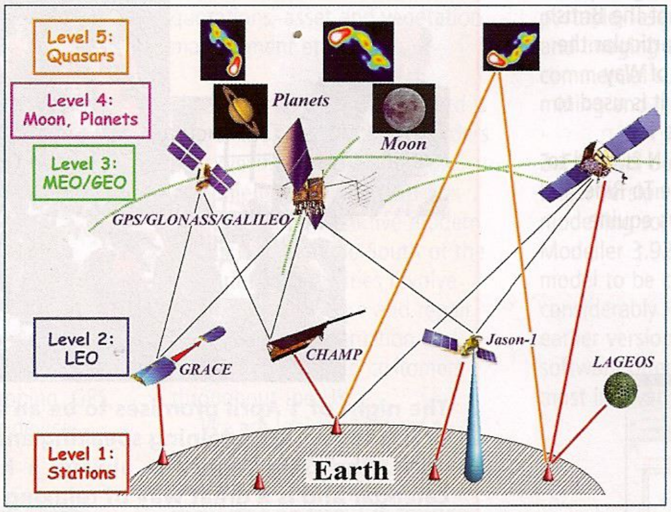

Figure 1: The five levels of GGOS and their interactions with observations of various types. *The infrastructure of GGOS consists of five distinct levels, depending on the distance from the Earth's surface. Level 1 at the Earth's surface consists of the ground networks of in situ instruments and space-geodetic tracking stations, as well as the data and analysis centres. Level 2 includes the LEO satellites, for which highly accurate orbits are determined with the help of the ground-based level as well as Level 3, which includes the GNSS. The ground networks and the GNSS are crucial for positioning. Level 4 comprises the Moon and the planets; this level is particularly important for the dynamic reference frame. Finally, Level 5 includes the stable quasars, which provide the inertial reference frame fixed in space.*

A value chain from observations to products

GGOS provides products that are pivotal for Earth observation, Earth science, geo-information systems, and terrestrial and planetary navigation. In order to do so, from a value-chain point of view, GGOS comprises four main components:

1. The instrumentation includes global terrestrial networks of geodetic stations and observatories, Earth observing satellites and satellite navigation systems, and planetary missions.
2. The data infrastructure comprises the infrastructure for data transfer, data management and archiving, and data and product dissemination.
3. The data analysis covers the complete and consistent data processing chain from the initial acquisition and the processing of large amounts of observations, to the consistent integrated analysis and combination of products, and the assimilation of the observations into complex models of the Earth system.
4. The GGOS Portal provides a unique access point for users to all GGOS products, including relevant metadata and documentation.

A multi-layered, yet integrated system

From a vertical point of view, looking from the Earth's surface upward, the observing system can be viewed as five major levels of instrumentation and objects that actively perform observations, are passively observed, or both. These are shown in Figure 1.

These five levels of instrumentation and objects – independent of whether they are active or passive, receivers or emitters or both – are connected in various ways. First, the geodetic techniques are affected by and 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. For example, Earth surface displacements are observed with several independent geometric and imaging techniques; Earth rotation variations are derived from independent techniques; and changes in surface mass storage are extracted from observations of the time-variable gravity field, Earth rotation, and surface displacements.

Thus, the different parts of the overall system are cross-linked through observations of the same geometric and physical quantities, and, to a certain extent, they are inter-dependent. The observations are linked through geometry and physics of the Earth system and the same models. Therefore, consistency of data processing, modelling, and conventions across the techniques and across the "three pillars" is mandatory for exploitation of the full potential of the observing system.

Most importantly, for the integration of the elements into an observing system, the different techniques are connected through co-location of sensors both on Earth and in space. The co-location of different and often complementary techniques is crucial in order to separate technique-dependent effects from the fingerprints of the Earth-system processes in the geodetic observations. Co-location of different techniques at the same location on Earth has proven pivotal for the stability of the International Terrestrial Reference Frame (ITRF). For example, at Ny-Ålesund, Svalbard, the VLBI antenna is co-located with several GPS and GLONASS receivers, a DORIS beacon, a superconducting gravimeter, frequent absolute gravity measurements, and a tide gauge. All these instruments are connected through site surveys.

Today, the uneven geographical distribution of so-called core stations with three or more techniques, as shown in Figure 2, is a limiting factor for the accuracy of the ITRF, and GGOS works towards a more even distribution.

The emerging co-location of different sensors and observation types on board a satellite is extremely important in establishing connections between the different observation techniques; it complements the co-location of stations on the Earth. An example of the recent development is the rapid progress achieved in orbit determination with the tracking data of the TOPEX/Poseidon satellite using DORIS, GPS, SLR and altimetry crossovers. GGOS urges future satellite missions to establish links between different observation and tracking techniques. It is of particular importance that all GNSS satellites be equipped with laser retro-reflector arrays.

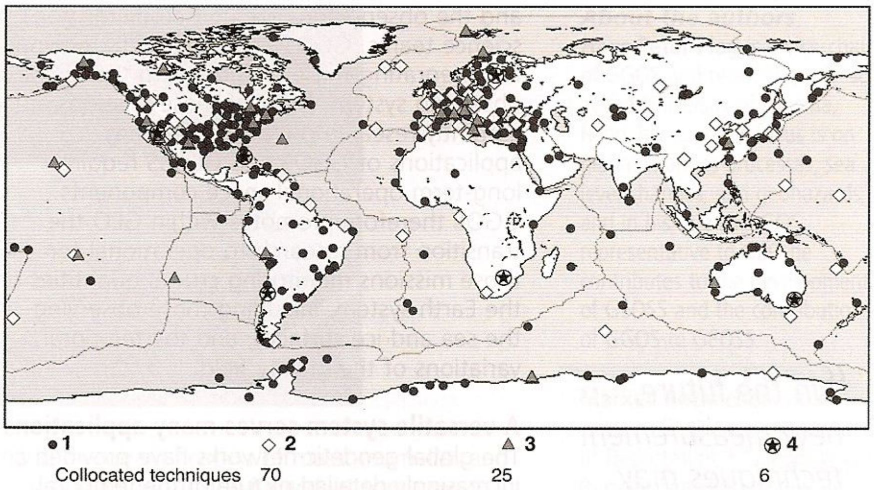

Figure 2: Network of core geodetic stations. *The stations are those used in the determination of ITRF2000, which include 25 stations with three co-located techniques.*

Figure 3: Retro-reflector arrays on satellites, such as those on the GPS-35 and -36 satellites, provide a link between the GNSS and the SLR station network, with SLR in return providing independent control of the GNSS satellite orbits.

A system that senses atmosphere, ocean, ice and solid Earth

Facilitated by the links of the various techniques through physics, models and co-location, the five layers of the global geodetic infrastructure form the complex, integrated GGOS observing system. At present, the major observation types acquired by this system are:

1. observations of the microwave signals emitted by GNSS satellites at the ground stations and at the LEO satellites;
2. laser ranging to LEOs, dedicated laser ranging satellites, GNSS satellites and the Moon;
3. observation of the microwaves emitted by quasars with the antennas in the Very Long Baseline Interferometry (VLBI) network;
4. onboard measurements by LEO satellites of accelerations, gravity gradients, satellite orientation, etc;
5. radar and optical observations of the Earth's surface (land, ice, glaciers, sea level, etc.) from remote sensing satellites;
6. distance measurements between satellites (K-band, optical, interferometry, etc);
7. ground-based measurements of other quantities related to variations in gravity (with absolute and relative gravimeters), Earth rotation (for example, with ring lasers), sea level (for example, with tide gauges), and water storage (for example, lake and groundwater levels).

For many of these observations, in particular, the space-geodetic observations, time measurements are crucial and, ultimately, the accuracy of the geodetic observations depends on the accuracy of time measurements.

A system with many shareholders, built upon technique-specific services

Much of the instrumental infrastructure of the GGOS observing system is provided by other organisations, some of which are not or only loosely affiliated with the International Association of Geodesy (IAG). The GNSS, for example, are implemented, operated, and maintained by national or regional authorities or consortia, and influence of GGOS on these systems is by providing expert advice to these organisations. The GNSS signals are crucial for GGOS, and in combination with products provided, for example, by the IGS, these signals can be utilised for scientific applications. Space missions such as satellite altimetry, satellite gravimetry, and InSAR are implemented and operated by space agencies,

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and the observations are utilised by mission science teams. GGOS provides the framework for integrating these missions into the global observing system. Most of these missions are currently research-driven, while many applications of GGOS and GEOSS require long-term operational space components. GGOS therefore promotes within GEO the transition from research to operational for those missions monitoring crucial quantities of the Earth system, including those observing the sea and ice surfaces, and the temporal variations of the gravity field.

A versatile system serves many applications

The global geodetic networks have provided an increasingly detailed picture of the temporal variations in the Earth's shape and of the kinematics of points on the Earth's surface, including the ocean, ice cover and land surfaces. Among other applications, the observations have been used to determine improved models of the secular horizontal velocity field, to study seasonal loading and derive seasonal variations in the terrestrial hydrosphere, to invert for mass changes in ocean, ice sheets and land water storage, to improve the modelling of the seasonal term in polar motion, and to study transient surface deformations prior to and after earthquakes. Geodetic techniques provide the means to observe surface deformations on volcanoes, in unstable land-slide prone areas, associated with earthquakes and fault motion, or subsidence caused by anthropogenic activities such as groundwater and oil extraction. In the near future, geodetic observing techniques will be able to determine the magnitude and displacement field of great earthquakes in near-real time as support for early warning systems.

Variations in Earth's rotation result from mass transport in the Earth system and the exchange of angular momentum among its components (atmosphere, oceans, solid Earth, etc). Observations of these variations have provided insight into many global-scale dynamic phenomena. An example is the El Niño/Southern Oscillation (ENSO). ENSO events are associated with a collapse of the tropical easterlies and an increase of atmospheric angular momentum, which is compensated by a decrease in the solid Earth's angular momentum and an increase in the length of day of up to 0.5 milliseconds for particularly strong ENSO events.

The CHAMP and GRACE satellite missions, in orbit since 2000 and 2002, respectively, have significantly improved the resolution and precision of our gravity field models, pushing our knowledge of the static gravity field to centimetre level accuracy in geoid determination. The upcoming European GOCE mission will provide further improvement. The integration of various satellite missions with the geometric techniques such as GPS, SLR and DORIS, has created new opportunities for the study of mass transport in the Earth system in a globally consistent way. The GRACE mission monitors changes in Earth's gravity field and provides unprecedented insight in water storage changes at sub-continental scales in land water storage, ice sheets and oceans.

Oceanographic applications illustrate the unique way in which the combined geodetic observations provide accurate and quantitative constraints on the ocean mass budget, tidal dissipation, near-surface ocean flow and its variability, and large-scale ocean mass variations. The observations are invaluable for understanding the causes of sea level rise and the dynamics of ocean mass redistribution.

Geodesy is crucial not only for Earth observation and science, but also for providing reference frames for a wide range of practical applications including land, sea and air navigation and position-fixing to centimetre-level accuracy.

An evolving system with great potential

In the future, new measurement techniques may evolve and be included into the system. One example for such innovative technologies is GNSS reflectometry, a technique based on recording ocean and ice-surface reflected GNSS signals with LEO satellites. Considering that by 2013 more than 120 GNSS satellites will provide signals, this concept has a huge potential to measure ocean and ice surface topography and roughness at high spatial resolution and rapid temporal coverage to support ocean and ice monitoring and for global tsunami early warning systems.

Another emerging concept is the co-location of space geodetic techniques on special micro-satellites. Such micro-satellites could be equipped with GNSS antennas for

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, levelling, 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)

Techniques and Services of GGOS. *For acronyms, see text. VLBI: Very Long Baseline Interferometry; SLR: Satellite Laser Ranging; LLR: Lunar Laser Ranging (LLR); 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 System Service.*

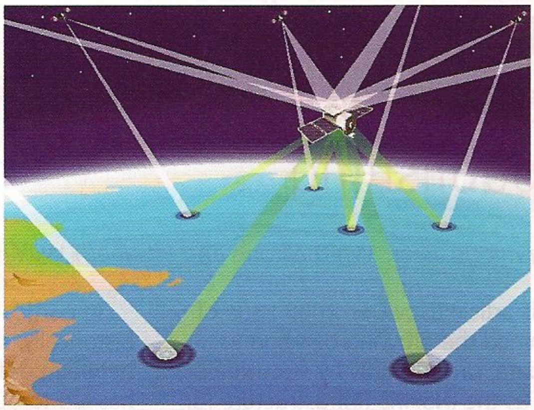

Figure 4: Use of reflected GNSS signals for altimetry. *An Earth orbiting instrument uses direct GNSS signals for precise positioning, but also receives reflected signals to make several simultaneous bistatic altimetry measurements.*

precise orbit determination and for radio occultations, star sensors for attitude, an SLR retro-reflector and a VLBI microwave source. As the satellite (or satellite constellation) orbits the Earth it will connect all the global core sites and improve co-location from space.

A prerequisite for exploiting now and in the future 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. This integration 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, and mass exchange between the components of the Earth's system. GGOS is pivotal in facilitating this integration.

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