

The gravity field and GGOS

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Abstract

The gravity field of the earth is a natural element of the Global Geodetic Observing System (GGOS). Gravity field quantities are like spatial geodetic observations of potential very high accuracy, with measurements, currently at part-per-billion (ppb) accuracy, but gravity field quantities are also unique as they can be globally represented by harmonic functions (long-wavelength geopotential model primarily from satellite gravity field missions), or based on point sampling (airborne and in situ absolute and superconducting gravimetry). From a GGOS global perspective, one of the main challenges is to ensure the consistency of the global and regional geopotential and geoid models, and the temporal changes of the gravity field at large spatial scales. The International Gravity Field Service, an umbrella “level-2” IAG service (incorporating the International Gravity Bureau, International Geoid Service, International Center for Earth Tides, International Center for Global Earth models, and other future new services for, e.g., digital terrain models), would be a natural key element contributing to GGOS. Major parts of the work of the services would, however, remain complementary to the GGOS contributions, which focus on the long-wavelength components of the geopotential and its temporal variations, the consistent procedures for regional data processing in a unified vertical datum and Terrestrial Reference Frame, and the ensuring validations of long-wavelength gravity field data products.

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1. Introduction

The earth's gravity field is a natural key element of Global Geodetic Observing System (GGOS), the International Association of Geodesy's first global project, attempting at unifying all contemporary geodetic observation techniques at the highest accuracy ($\sim 10^{-9}$ level) to provide a uniform global reference system, and to understand the earth system dynamics and the complex interactions between the cryosphere, hydrosphere, atmosphere, and ocean at spatial scales from a few meters to continental and global scales, and temporal scales from an hour to geological time.

With recent advances in determination of the earth gravitational field, the gravity field is a natural basic element of GGOS. The static gravity field through the geoid is a fundamental requirement for a consistent global geodetic reference system, including a common global vertical reference system. Similarly, the monitoring of changes of the gravity field has direct implications for the study of earth dynamics, and gravitational field changes may help in

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detecting mass shifts in the earth's interior, which might be associated with point movements on the earth's surface, providing the rationale for a close coupling between geometric and gravity field change observation points. Also, change of the geophysical fluids provides gravitational signals, which are measurable both locally and on global scales, and may provide significant new information on, e.g., the changes in global ocean circulation ("ocean bottom pressure change").

The long-wavelength parts of the gravity field are these years being determined with unprecedented precision. The traditional geodetic representation of the earth gravitational field in spherical harmonics is of form:

$$V(r, \varphi, \lambda) = \frac{GM}{a} \left[1 + \sum_{n=2}^N \sum_{m=0}^n (J_{nm} \cos m\lambda + K_{nm} \sin m\lambda) \bar{P}_{nm}(\sin \varphi) \right]$$

where G is the gravitational constant, M the mass of the earth, a the mean semi-major axis of the earth and J_{nm} and K_{nm} are the fully normalized spherical harmonic coefficients. Already now, the lowest harmonics are determined from space geodesy with unprecedented accuracy (relative error in $J_{20} \sim 10^{-12}$), with changes in the lowest harmonics due primarily to postglacial rebound since the last Ice Age. With the new satellite gravity field missions, the coefficients determined at "GGOS-level" accuracy will be pushed to higher degrees, and the changes in these coefficients will give new constraints on global and continental-change in hydrology, ocean circulation, continental and mountain glaciers, solid earth, etc.

2. Gravimetry and GGOS

Advances in the measurement of the gravity acceleration have reached accuracies of 10^{-9} g (≈ 1 μ Gal or 10 nm/s²), allowing the measurement of effects of mass changes in the earth interior or the geophysical fluids (ocean and atmosphere loading), as well as the measurement of height changes at ≈ 3 mm relative to the earth center of mass. This makes repeated absolute (and superconducting) gravimetry observations a natural element of a fundamental GGOS geodynamics observatory station, a co-located site with permanent GPS and possible additional geodetic technologies including DORIS, VLBI, SLR, tide gauges, etc.

The interval of absolute gravimetry remeasurements should typically, be a few years, depending on the understanding of seasonal and local hydrological and meteorological signatures in the measurements. The absolute gravimetry may be supplemented by relative gravimetry by carefully calibrated gravimeters and well-planned survey layouts, but generally such relative measurements on anything but the very local scale is not sufficiently accurate (at best $\sim 10^{-8}$) to match the current status of absolute gravimetry.

Developments in superconducting gravimetry at observatory sites are routinely giving several orders of magnitude better accuracy (10^{-12} g) in terms of short-term temporal changes of gravity, and highlight the limiting effects of local effects (e.g., ground-water levels) in the use of repeated absolute gravity measurements in monitoring overall height and mass changes of the earth system. A global network of stations, such as done under the Global Geodynamics Project (GGP), but possibly with more sites, would be a natural element of a global system of fundamental GGOS observatories, albeit even a global network – by nature with a sparse coverage of superconducting gravimeters – will still be significantly affected by aggregated local aliasing effects, making comparisons to global satellite gravity field change measurements uncertain.

It should be pointed out that the present generation of superconducting gravimeters require the occasional calibration by absolute gravimetry to model minute offsets and residual drifts. Therefore, absolute and superconducting gravity are complementary measurements. Technological developments in the field are ongoing, and with developments of smaller sensors – and new measuring concepts such as the cold-atom interferometer – promise to make the availability of especially absolute gravimeters more widespread.

With these general remarks, the role of the GGOS project in terms of gravimetry could be:

- To actively promote the use of repeated absolute gravity measurements at globally distributed fundamental GGOS satellite stations, and especially take actions to make sure such measurements are done, e.g., at sites in developing countries.
- To similarly make sure that a network of superconducting gravimeters operate at a global sub-network of the GGOS fundamental station network.

- To make standards and recommendations for the establishment of absolute gravimetry stations (e.g., monumentation, possible auxiliary observations including ground-water level, remeasuring intervals, vertical gradient corrections).
- To make standards for computations of gravity change measurements (e.g., consistent and standardized corrections including solid earth tides, ocean tides, polar motion, atmosphere/tidal/ocean loading).

The ongoing co-operations within the Global Geodynamics Project (superconducting gravimetry network; Crossley et al., 1999) is an example of a successful coordination project, and similarly the International Absolute Base Gravimetric Network (IABGN initiative; cf. Boedecker, 1991) could serve as national starting points for a more comprehensive global GGOS gravimetric fundamental station distribution.

3. Gravity field satellite missions and GGOS

With the launch of dedicated gravity field missions (CHAMP, 2001; GRACE, 2002; GOCE, planned for 2006), the global gravity field will be determined with unprecedented accuracy, with gravity temporal changes determined at relative accuracies of from 10^{-2} to 10^{-10} depending on wavelength, with the low-low satellite tracking methodology of GRACE (the high-low tracking CHAMP and the gravity gradiometry GOCE missions are primarily aimed at determining the static gravity field, and thus, the precise determination of the geoid, cf. Section 4). The gravity field temporal change observations will potentially generate completely new data on global and continental scale hydrology and glaciological changes, as well as changes due to geodynamics and ocean circulation (Figs. 1–3).

Fig. 4 shows the accuracy of GRACE monthly gravity field signal (left, prelaunch and current, Tapley et al., 2004) and projected GOCE gravity field accuracy (right) compared with various geophysical signals (Han et al., 2004a,b) and the EGM96 geoid signal (denoted as earth geopotential, Lemoine et al., 1996). Selected geophysical signals or errors shown include the atmosphere error (modeled by ECMWF–NCEP), ocean tides (modeled by CSR4.0–NAO99 for GRACE and CSR4.0 total signal for GOCE), hydrology (NOAA CPC model), oceanography (ECCO model),



Fig. 1. Absolute gravimeter (FG-5), capable of 10^{-9} accuracy during a 1–2-day measurement. Local environmental effects are the main limitation in accuracy of such measurements.

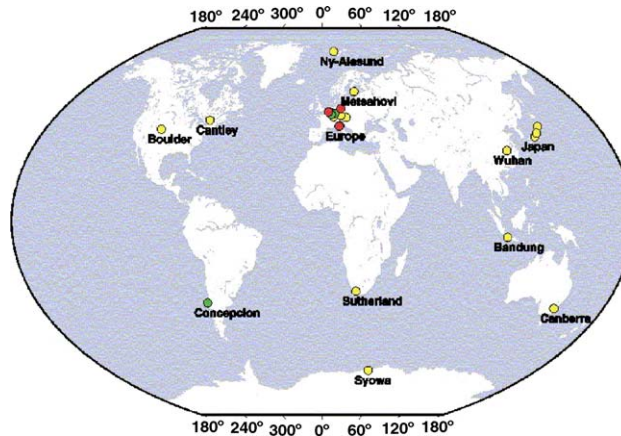


Fig. 2. Current network of coordinated superconducting gravimeter observatories (GGP project, 1997–2003).

post-glacial rebound (Mitrovica–Milne model yearly signal instead of monthly), and geoid change due to the Chilean 1960 earthquake (Han et al., 2004a,b).

The challenge of GGOS with respect to the results to the gravity field satellite missions could be to:

- Influence space agencies responsible for the satellite missions for timely release of data.
- Recommend standards for reference systems (e.g., for combination of satellite missions) and geophysical corrections to be applied (e.g., ocean tide and atmosphere de-aliasing for temporal gravity models, consistent treatment of the permanent tides, etc.).
- Actively promote future gravity field satellite missions (e.g., GRACE-style follow-on missions) for the long-term monitoring of earth system changes.

4. Challenge of the mm-geoid

When referring to the earth radius, a geoid accurate to 10^{-9} would be a geoid of 6 mm accuracy. To obtain the geoid at global scales at the level of a few millimeters would be a major challenge, but a challenge which at the longer wavelength is to be essentially fulfilled by the results of gravity field satellite missions, with demonstrated geoid accuracy of GRACE at 2–3 mm rms to spherical harmonic degree 50, and ~10 cm rms to degree 120 (Tapley et al., 2004), and GOCE at 1 cm rms to degree 200 (ESA, 1999).

It should be noted, however, that the local variations of the geoid at wavelengths higher than resolved from the satellite missions are large, and at the order of 20–50 cm rms or larger depending of the local roughness of the gravity field. To resolve these wavelengths only terrestrial and airborne gravimetry/gradiometry and ocean satellite altimetry can provide additional information. Even with the most dense terrestrial data coverage, getting geoid models at the

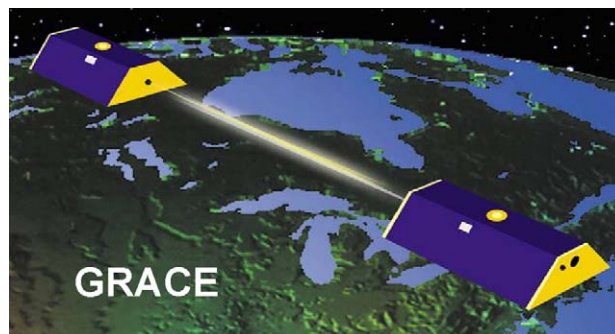


Fig. 3. Low–low satellite-to-satellite tracking missions like the US–German GRACE mission promise to deliver the temporal variations of the earth gravity field on a monthly basis to spherical harmonic degrees around 100.

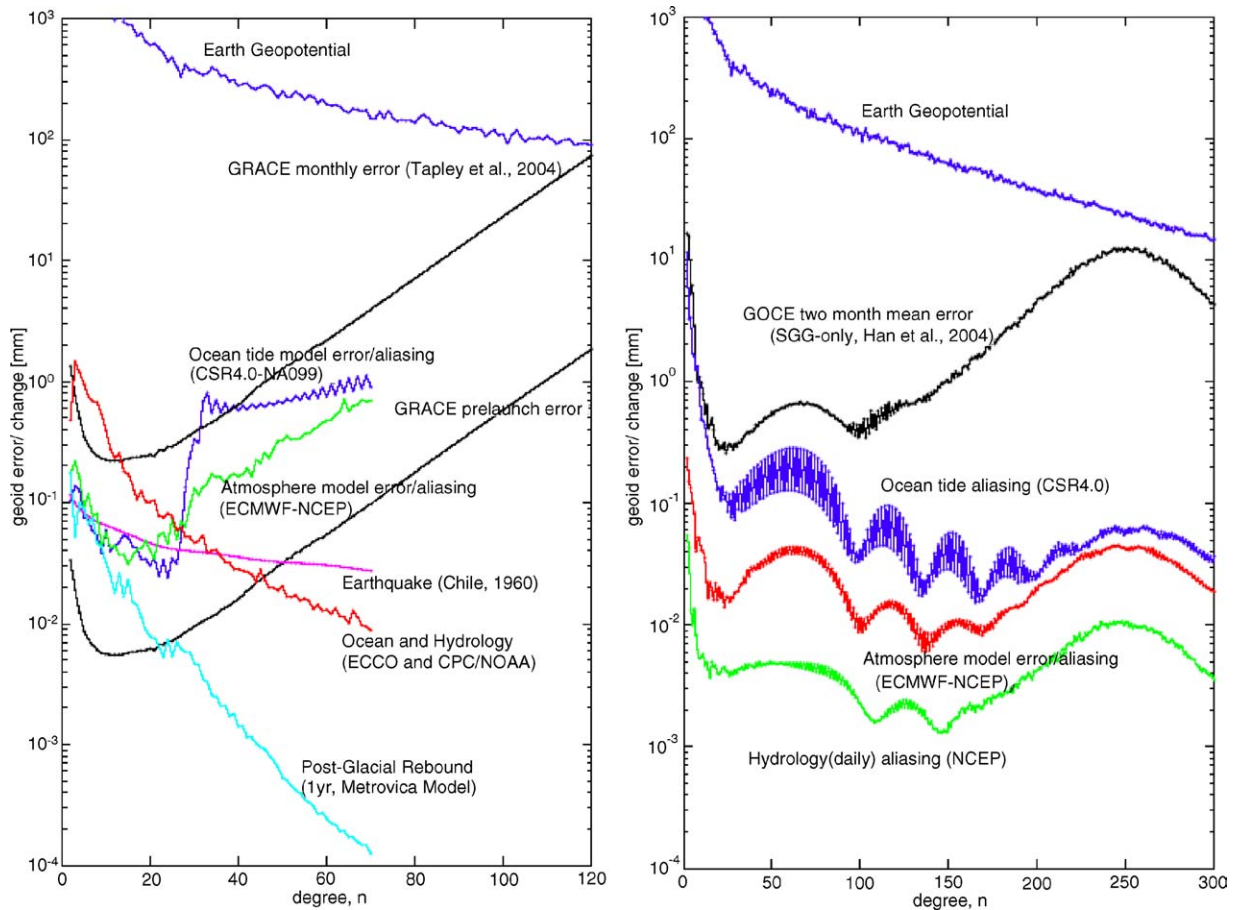


Fig. 4. The accuracy of GRACE monthly gravity field signal (left, prelaunch and current, Tapley et al., 2004) and projected GOCE gravity field accuracy (right) compared with various geophysical signals (Han et al., 2004a,b) and the EGM96 geoid signal (denoted as earth geopotential, Lemoine et al., 1996).

mm-level from local data is a true challenge. Local geoid modeling methods still are imperfect, both terrestrial and airborne data are prone to small systematic biases, and in mountainous areas systematic errors and aliasing from the use of DEM's is a potential source of introducing short-wavelength geoid errors. In practice, over much of the earth a realistic goal could only be the cm- or even dm-geoid (when regarding the full spectrum of the geoid).

A global, theoretically and practically well-defined geoid at the mm- or realistically cm-level accuracy would be a key element of GGOS (Fig. 5). It would serve as the reference for the monitoring of the earth's oceans by satellite altimetry, as the key to linking the vertical datum of the world, and thus, e.g., ensure that leveled heights of fundamental GGOS observatories can all be related to the same system, and GGOS tide gauges similarly used to monitor globally

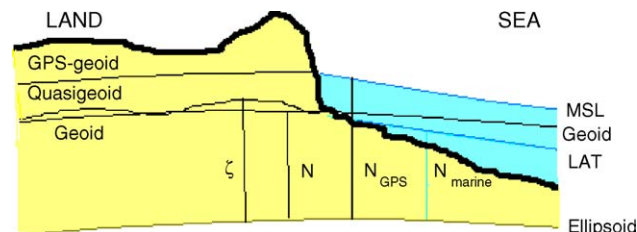


Fig. 5. Different "geoid" concepts in practical use. The geoid and quasi-geoid refer to different ways to treat topographic density; the "GPS-geoid" is the geoid-like surface GPS users need to transform GPS ellipsoid heights to a local vertical datum, and at sea, hydrography needs a "geoid" related to lowest astronomical tide (LAT). It is the challenge of GGOS to introduce a unified, global model, ideally at cm-accuracy.

reference sea-level heights. The GGOS global geoid would not be a static product; it would change with time, e.g., due to geodynamic effects such as land uplift and general mass shift in the earth's interior and the geophysical fluids.

An integral part of the definition of a global geoid is related to the basic definition of the geoid. On land, the classical geoid is defined inside the topography, and thus dependent on density assumptions; for space geodesy applications, the introduction of such assumptions would be very impractical and a source of potential errors; therefore, either a Molodensky-style quasigeoid should be introduced, or a model “Helmert-style” geoid, assuming a uniform density of topography, should be adopted. In practice, the role of these fundamental definition problems is minor, though, as it is a straightforward task to transform between the different types of geoids (as long as actual density observations are not used). Other problems, such as the correct handling of the pole tide in the geoid is well-resolved theoretically, but the systematic application of the pole tide should be extended to the treatment of GGOS geometrical and earth rotation data as well (to date, this is not done fully consistent in all space geodetic observation data).

With this said, the role of GGOS in securing a “mm-geoid” could be:

- To make recommendations on standards for computations and corrections, as well as the final global geoid product.
- To utilize data and products from the International Gravity Field Services (BGI, IGeS, etc.) and satellite missions to coordinate the computation of a combined geoid product in a global reference system, optimally merging satellite and terrestrial gravity field data.
- Relate global geoid estimates at GGOS observatories to estimates from positioning, leveling and sea-level observations.
- To take initiatives to secure surveys of airborne and terrestrial gravity data in regions of insufficient data coverage (e.g., Antarctica), as well as improve the local gravity data coverage around key GGOS observatories.

5. Conclusions—the GGOS gravity field “master product”

Following the remarks in the previous chapters, the “master product” of the gravity field part of GGOS could then consist of:

- The word “mm-geoid” in a consistent definition and reference frame, with realistic standard deviations as a function of wavelength and geographical region.
- The implementation of a global vertical datum.
- Models of the temporal variation of the geoid, possibly with special focus on geodynamically active regions.
- Absolute and superconducting gravity observations at a globally distributed GGOS observation network, collocated with geometrical space geodesy sites, tied to sea-level by leveling, tide gauge and GPS observations.
- Standards and references for gravity-related data (“gravity RINEX”).

The GGOS gravity field “master product” would obviously be closely linked to other GGOS “products”; Geoid, sea-level observations and geometric positioning must obviously match – an inherent constraint on any global model; land uplift due to postglacial rebound (PGR) results have by nature the associated geoid changes; geoid changes are expressed in sea-level changes, like changes in ice sheets affects both the sea-level and the geoid through the shift of mass; on global scales changes in gravity field and figure of the earth impact on earth rotations estimates; earth rotation data enters in the correction of gravimetric observations.

In summary, the link between gravity field, geometry, geodynamics and earth rotation is strong, and the gravity field is a natural fundamental pillar in the GGOS project. The involvement in GGOS puts new demands on the existing IAG gravity field services – International Gravimetric Bureau (BGI), International Geoid Service (IGeS), International Center for Earth Tides (ICET), International Center for Global earth Models (ICGEM) – in terms of delivering products with well-described corrections and reliable global error estimates, and put demands on the geodetic and geophysical community at large to try and make existing gravity survey data available for, e.g., global geoid determination. Such utilization of existing data could be done without compromising national or commercial restrictions, if only long-wavelength filtered data are used, as already successfully done in several regional geoid determination projects.

The ongoing formation of a new umbrella International Gravity Field Service (IGFS), expanded with services/sub-projects making satellite altimetry and digital elevation data available at global scales, could be an important step forward

in coordinating the efforts necessary for the gravity part of GGOS, and also serve as catalyst to set up cooperative international data collection activities in the remaining parts of the earth with insufficient gravity field data coverage.

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