THE GOCE DEDICATED GRAVITY MISSION EXPECTATION AND PREPARATION

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Abstract:
The knowledge of the gravity field of the Earth and of an associated reference surface of the altitudes (the geoid) is necessary for geodesy, for improving theories of the physics of the planet interior and for modeling the ocean circulation in absolute. This knowledge comes from several observing techniques but, although it benefited from the artificial satellite approach, it remains incomplete and erroneous in places. Within a reasonable future, a substantial improvement can only come from new space techniques. Thanks to the intense lobbying by the concerned geoscientists, the coming decade is seeing the advent of three techniques already proposed in the seventies and to be implemented by different space agencies; these are the CHAMP, GRACE and GOCE missions. This paper presents the GOCE project in the context of the two others and what the geoscience community is expecting from it.
Key-words: gravity field, geodesy, geophysics, oceanography, satellite tracking, gradiometer.

1. INTRODUCTION

Geodesy is a science which major goal is to define and study the shape of the Earth, its deformations (from relative movements of points on its surface), its gravitational field (or its gravity field if one includes the rotational effects. The use of artificial satellites yielded a global and continuous view of our planet, and geodesy, too, benefited from this revolution. It became a science at the crossroads of others, and it is used daily for navigating satellites with high precision for oceanography and geophysics. To-day, we are entering a new era of this science which will see the deciphering of our planet's gravity with unprecedented resolution and accuracy.

2. THE SCIENTIFIC OBJECTIVES

For a better understanding of both surface and deep phenomena which are related to the interior structure of the Earth and its temporal evolution, for studying the dynamics of the oceans and their interaction with meteorological and climate changes, for modeling the ice caps-oceans-continents relationships and for predicting the long term evolution of the mean sea level, also for unifying vertical reference systems and for the precise determination of satellite orbits in space, it is necessary to significantly improve the current models of the Earth's gravitational potential, both in resolution and precision - if not its temporal variations induced by the afore mentionned phenomena. The gravity field plays a dual role in Earth sciences.
On the one hand, by comparing the real field with the field of an idealized body (e.g. an ellipsoid in hydrostatic equilibrium) one defines gravity anomalies which characterize deviations from a state of internal equilibrium (that is non radial density variations), which constitutes one method of sounding our planet's interior. The magnitude of gravity anomalies

[1] Groupe de Recherches de Géodésie Spatiale: *http://www.omp.obs-mip.fr/grgs/*

is in the range -1000/+1000 milligals (where 1 mgal=10^{-5} ms^{-2}). As a matter of fact this is one of four ways of "looking" inside, the other three being seismology, magnetic field studies and the analysis of the Earth's rotation. However the gravity analysis approach is unique in providing direct information on the density field (although this is integrated and cannot be univocaly inverted). When one strips the Earth from its topographic blocks (with assumed, or known density) one is left with residual gravity anomalies which magnitude is not much different from the magnitude of the original ones; this examplifies the phenomenon of isotasy, which is the concept of mechanisms of support of the topographic masses. Therefore the residual field mirrors mass excesses or deficits in depth which inform us on the lateral structure of the lithosphere and upper mantle. A significant part of this information is to-day provided by seismology -by tomographic analysis, but still suffers from uncertainties due to hypothesis on which such inversions are based. The combination of both types of data (seismic velocities and gravity anomalies) is a powerful tool to get a better picture of the interior and to make progress in the understanding of several phenomena for instance the accumulation of stresses and triggering of earthquakes.

On the other hand a surface which is intimately related to gravity, the geoid, is used as the reference for defining and measuring the altitudes on the continents but also under the oceans or over the ice caps. The geoid is a particular equipotential surface of the gravity potential (the sum of the gravitational and centrifugal potentials) which may be viewed, in oceanic areas, as the surface of an ocean at rest. The Earth's rotation being sufficiently well known and its effects being smooth at the surface (they essentially decrease with increasing latitudes), the irregularities of the geoid (in the ±100 meter range, as measured with respect to an ellipsoid of revolution which approximates the Earth's shape) characterize the density field variations in a way similar to the gravity anomalies. In addition, on the topographic surface water naturally flows along the geoid slope; over the oceans sea water circulates (under the forcings of winds and density-salinity fluctuations) and these movements (different from the vertical displacements of water due to tides) and associated amounts of transported water (and heat, chemicals, nutrients,…) can be quantified with respect to the geoid: these are the ocean currents. One distinguishes between the mean and the variable parts of the circulation: the latter can nowadays be monitored by satellite altimetry, whereas the former (which is needed in the modeling of the climate by quantifying the long term absolute transports of heat - especially in the shallow parts of the oceans) requires the precise knowledge of the difference between the mean sea surface and the geoid (the so-called sea surface topography); the mean sea surface itself can be deduced from long series of altimeter measurements but it is demanded that the geoid be independently determined.

For both solid Earth physics and oceanography, the requirements are for a 100 km resolution geoid (and gravity field) with a cumulated error - i.e. up to that resolution, of 1 cm (and 1 mgal) or better. Clearly the classical domains of geodesy (unification of vertical reference systems, inertial navigation, accurate satellite orbits for monitoring the Earth's deformations, the sea surface, the Earth's kinematics, etc.) will greatly benefit from such knowledge.

In addition to this, there is a growing interest, in relationship with environmental studies and prediction capabilities, in measuring the time variations of the gravity field. Some of them (e.g. the oceanic and solid tides) are deduced from the measurements or modeling of phenomena which are responsible for them, with satisfactory precision and resolution - or close to be satisfactory. In the contrary others can only be determined from direct observations, from which the responsible phenomena are then modeled. These are: the post-glacial rebound of the lithosphere (therefore of the planet surface); the variations of the ice caps, of the sea level, of the large continental aquifers; the distribution of precipitations (rain, snow), the soil moisture, the evapo-transpiration… that is the water cycle in general.

3. THE PRESENT SITUATION

To-day three types of information are used to describe or model, at local, regional or/and global scales, the Earth's gravitational potential and various functionals:

- surface measurements of gravity, on land, at sea (with ships and submarines), by plane. These measurements are often reduced to gravity anomalies, then gridded and made available at a variable resolution which depends on the area, on the actual density of observations, also on restrictions still exerted by many countries for protecting national economic and military interests. The resolution of such grids varies from a few to hundreds of kilometres, and the precision ranges from about one to ten milligals - the accuracy may be worse due to systematic errors in many data sets (such as the marine surveys). The data are archived at world level, mainly at the National Imaging and Mapping Administration (NIMA) in the USA, and at the Bureau Gravimetrique International (BGI) in France. Airborne measurements are slowly expanding but the precision at ground level (after downward continuation) is still insufficient;
- satellite altimetry over the oceans: as said above, it provides the sea surface which time average is close to the geoid but differs from it (up to about one meter in areas of strong currents such as the Gulf Stream, the Arctic Circum-polar Current, the Kuro-Shio). For several applications in marine geodesy and geophysics, it is sufficient to correct for the mean circulation with the present (approximate) models, though coastal currents, uncertainties in tidal models and larger error measurements close to the shore limit the usage of the information to the off-shore and open ocean areas. Such restriction being understood, satellite altimetry data have had an important contribution to global Earth's gravity models in increasing their resolution over the oceans - but without providing the true geoid;
- the analysis of satellite orbit perturbations: for several decades a few groups in the world have determined global gravity field models from the inversion (via the law of the dynamics) of satellite orbit perturbations -which reflect the forces acting on a satellite. Most used satellites were indeed never designed for such purpose: the space geodesists simply took benefit of the more or less accurate measurements made from ground stations on these satellites for orbit knowledge. Various techniques were exploited, essentially the Doppler effect on the signal transmitted from a stable oscillator on board a spacecraft to ground stations - or the reverse (case of the DORIS system), and roundtrip ground to satellite distances measured by laser systems. The main limitations of these models come from the altitude of the observed satellites (due to the quasi-exponential decay of the perturbations with altitude), from the observation coverage (limited by the ground station pass duration) and from uncertainties in modeling the surface forces (atmospheric drag, solar radiation pressure and Earth albedo). If the data coverage has improved for some satellites thanks to the development of denser station networks (e.g. the DORIS system), or by starting to track satellites from "above" that is by the GPS (Global Positioning System) constellation, the other limitations remain and prevent from making significant progress. To-day, solutions derived from satellite only data cover spatial scales from 500 to 40000 km, but they are reliable (say at the centimetre level on the geoid knowledge) only down to a resolution of about 1000 to 1500 km. That is why they are combined with surface gravimetric and altimetric data which bring higher resolution if not precision - depending on the area. Such combined models globally reach 50 km resolution though they represent the field with such details solely over areas with enough surface data; and again the surface represented over the oceans is not the geoid: for the study of the absolute ocean circulation, satellite only models have to be used with their present drawback of much too limited resolution.

4. HIGH RESOLUTION GRAVITY MAPPING FROM SPACE: THE NEW MISSIONS

New progress can only come from a space approach for this only can satisfy the scientific needs (homogeneous data, full coverage, higher resolution and precision) within reasonable time and cost. Basic principles were found years ago; technological advances to-day allow for their implementation.
To get rid of the limitations of past systems, a new satellite approach should satisfy as many of the following criteria as possible: quasi-polar orbit (for the coverage), 3-D uninterrupted measurements (for recovering the gravity signals with an isotropic error), mean altitude as low as possible (for higher resolution), counteract the effects of signal attenuation with altitude by a differencing measurement method, isolate the gravitational signals by measuring or/and compensating the surface forces (which involves ultra-sensitive accelerometers). The missions under development satisfy more or less these criteria. Working at low altitude is the constraint which has received most attention and all missions will fly at or below 450 km (compared to the altitudes of satellites used so far: 800 km or larger). Surface forces are measured by micro-accelerometers (and even compensated in the case of the most advanced mission). The other criteria have been considered differently according to the type of mission and the used technology.
The first dedicated satellite mission, launched on July 15, 2000, is **CHAMP** (Challenging Mini-Satellite Payload for Geophysical Research and Application) **[1]** ; its two main objectives are the mapping of the magnetic field and of the gravity field of the Earth. It was developped by Germany, with an important French contribution: provision of magnetometers, and of the tri-axial electrostatic micro-accelerometer STAR designed and build by ONERA (Office National d'Etudes et de Recherches Aérospatiales). The CHAMP spacecraft is tracked by the GPS constellation (the GPS receiver was provided by the USA) which should ultimately yield an orbit accuracy of one to three centimeters. The expected life time is five years and its altitude (from 450 km to about 300 km toward the end) is such that it should bring a significant gain in resolution (about a factor of two) and in precision (factor of two to four depending of the wavelength) over our current knowledge.
CHAMP appears as the precursor of the second gravity mission **GRACE** (Gravity Recovery and Climate Experiment), which is an USA mission **[2]** conducted in cooperation with Germany. It consists in flying two satellites separated by 150 to 300 km from each other, on the same mean orbit ; the satellites are each tracked by the GPS (like CHAMP) and besides measure their relative distance and velocity with a micrometric accuracy - this observable may be viewed as an extremely fine measurement of the gravitational potential difference at the satellites. Each spacecraft is equipped with a micro-accelerometer: Super-STAR, which is also made by ONERA and of a class superior to STAR. The mission, launched on March 17, 2002, should remain in orbit during three to five years at an altitude starting at 470 km and finishing at about 320 km. The mean orbit is very close to polar (89.8 degrees, compared to 87 degrees for CHAMP). The mission concept is especially adapted to the monitoring of the time variations (from monthly to biennial) of the gravity field over the 300-5000 km spatial scale, with a corresponding contribution to the mean (static) field where an order of magnitude gain over the present knowledge is expected at such scales.
The third mission, which was selected in November 1999 as the first core mission of the Earth Explorer programme of ESA (European Space Agency) is **GOCE** (Gravity field and steady-state Ocean Circulation Explorer) **[3]**. It has the heritage of twenty years of studies of previous projects: Gradio (studied by the French Centre National d'Etudes Spatiales, CNES, between 1981 and 1986), Aristoteles (studied at ESA from 1986 to 1993). For the first time, a gradiometer will be flown on board a satellite (*fig. 1*) on a very low altitude orbit (between

230 and 250 km) of 96.5 degree inclination, with drag-free control. The gradiometer instrument, designed by ONERA with a new class of six ultra-sensitive micro-accelerometers (capable of measuring accelerations of 5.10^{-13} ms^{-2}), will deliver gravity gradients (second derivatives of the gravitational potential) in spacecraft axes with an accuracy of a few milli-Eötvös (1 E= 10^{-9} s^{-2}) per $Hz^{1/2}$ in the 0.005-0.1 Hz measurement bandwidth. The satellite is to be also tracked by the GPS (and by ground laser stations, actually like CHAMP and GRACE - for control and safety), and the combination of these trajectory observations and of the gradiometer measurements should yield a global gravity model with a resolution of 100 km at least (65 km at most) with a total uncertainty (i.e. up to the 100 km resolution) of 2.5 millimeters on the geoid and 0.08 milligal on the gravity. This will therefore be an extraordinary jump in knowledge for the concerned disciplines: geodesy, solid Earth physics and oceanography. GOCE should be launched early 2006.

5. THE EXPECTED PERFORMANCE OF GOCE

A great number of studies and of end-to-end numerical simulations were performed. All characteristics of the measuring instruments, of the satellite systems (attitude, drag-free compensation, …) were taken into account. These yielded performance figures in terms of errors on the spherical harmonics of a global Earth's gravity model (see *fig. 2*, where the performances of the other dedicated missions are also shown for comparison), and on the geoid and gravity field themselves (table 1). From these, it is obvious that GOCE should deliver even better results than the requirements presently formulated by the geoscientists and therefore serve the needs of this community for many years.

Fig. 2

Table 1

6. PREPARATION OF THE GEODETIC COMMUNITY IN EUROPE

Deriving a global gravity model with the resolution and precision allowed by the GOCE mission is to be a formidable task : tens of millions of measurements will be processed, and over 100 000 parameters will have to be determined simultaneously ! This is a typical activity of the satellite geodesists, but at a scale never encountered before. Subsequently the model will be used by the solid Earth physicists, the oceanographers, etc.
Therefore, the geodesists in Europe decided to put their expertise and efforts in common and proposed to ESA to join forces for the computation of a global gravity model from the GOCE data. The European GOCE Gravity Consortium (EGGC) was formed in the fall of 2000 and it comprises ten teams in different European organisations (Institutes, Universities, Space Centers). The proposal also includes work on preprocessing refinements, parallel development and running of different methods, solution validation, interface to science, etc. **[4]**.

7. CONCLUSION

The GOCE mission, dedicated to the high resolution mapping of the mean Earth's gravity field, should be launched in 2006. It will be a breakthrough in space geodesy and for the benefit of all geosciences. It will bring for the first time the global knowledge of the geoid and gravity anomaly field with a resolution better than 100 km and with errors smaller than one centimeter and one milligal, respectively. The challenges are numerous : construction of the gradiometer at a prescribed fantastic sensitivity, of a very fine drag-free system, of a high-class spacecraft attitude measurement and control system, orbit control at 250 km altitude over two years at least, „,and the computation of a global gravity model with more than 100 000 parameters. For this last task, a consortium of European expert satellite geodesy teams has been established.

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Table 1. Simulated GOCE performance

Spatial resolution D (half-wavelength)	Maximum degree L (corresponds to D)	Geoid height error in mm (cumulated to L)	Gravity anomaly error in mgal (cumulated to L)
1000 km	20	0.4	0.0006
400 km	50	0.5	0.001
200 km	100	0.6	0.03
100 km	200	2.5	0.08
65 km	300	45.0	2.0

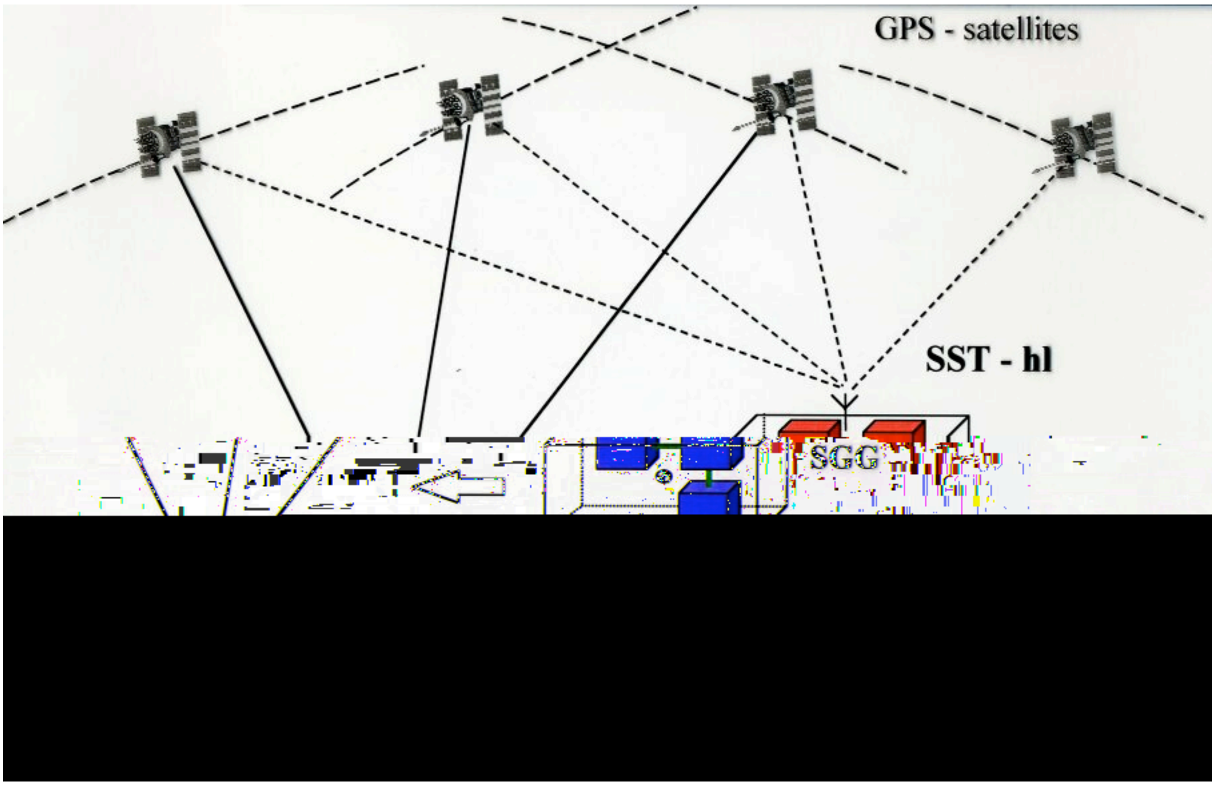

Fig.1 . Principle of the GOCE mission. The low orbiting spacecraft bears a gradiometer (made of micro-accelerometers arranged in pairs) : this is SGG (Satellite Gravity Gradiometry). It is also tracked by the GPS constellation : this is SST-hl (Satellite to Satellite Tracking in the high-low mode).

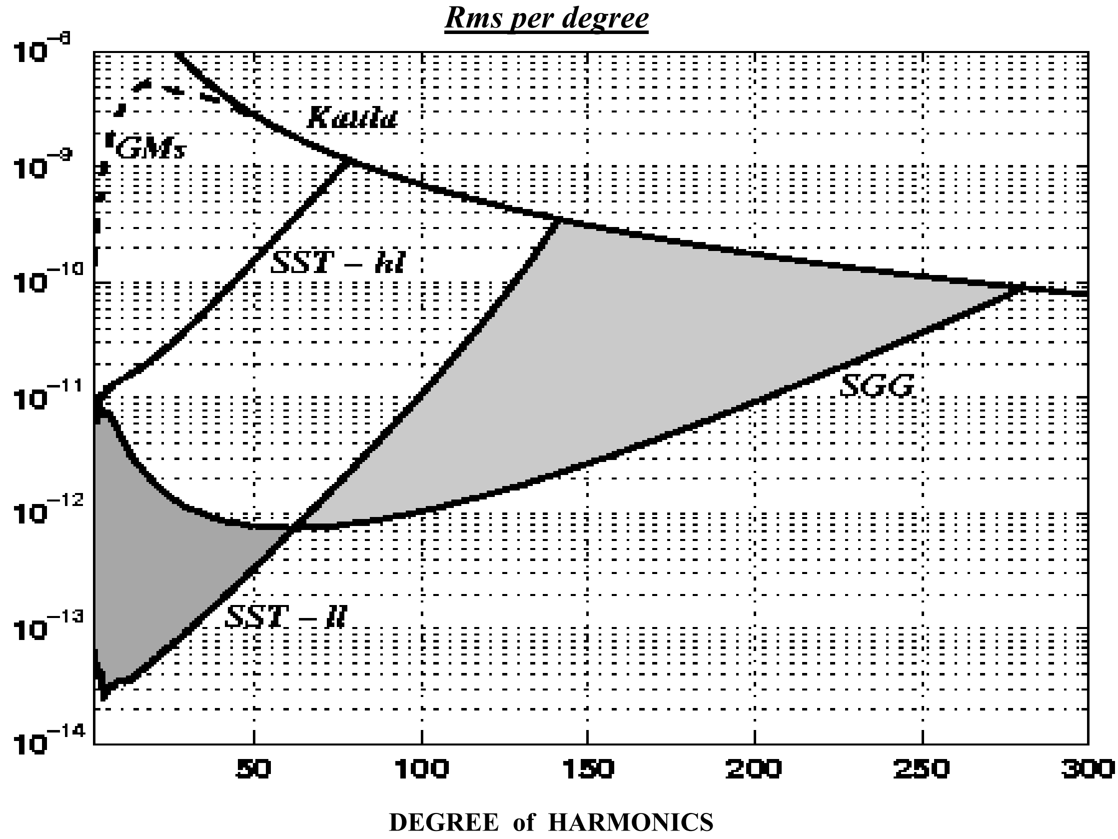

Fig.2. Expected (simulated) performances of the GOCE *(SGG)* mission, compared to those of the CHAMP (*SST-hl)* and GRACE *(SST-ll)* missions. The error spectra of the actual gravity models *(GMs)* and the signal spectra *(Kaula)* are also shown.