MONITORING SYSTEM EARTH WITH THE RECENT AND FORTHCOMING GRAVITY-FIELD DEDICATED SATELLITE MISSIONS

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Abstract

During the last decade a number of revolutionary satellite missions have either been planned, set to orbit and are in the final stages of preparation by the European Space Agency and NASA, aiming all to measure Earth's gravity field at an unprecedented detail. The missions of CHAMP and GRACE have set the ground to understand the variations of the Earth's gravity field with a spatial resolution of ~200 km and a temporal resolution of 10 days. Their accomplishments will be continued by GOCE, which being the first satellite gravity gradiometry mission promises to determine Earth's gravity field with an accuracy of ±1cm to 50 km half wavelength. These great accomplishments offer the opportunity to study the temporal variations of the gravity field, which are associated with mass transport and redistributions within and on the Earth's surface. Therefore they can provide a continuous series of the water cycle, polar ice melt, seasonal and annual sea level rise, abrupt changes in the Earth's crust due to earthquakes, etc. The present work aims to provide an outline of the concepts, measurement principles, goals, accomplishments and applications of recent and future gravity-field dedicated satellite missions in monitoring system Earth, studying global environmental changes, managing natural disasters, as well as the opportunity for synergy between various branches of geosciences like geodesy, geophysics, oceanography, hydrology, environmental sciences, social sciences, etc.

Keywords: gravity field dedicated satellite missions, earth, temporal changes, geoid, sea level

1. Introduction – Geosciences and the Gravity Field

The study of the Earth's gravity field has been relying for many decades on the combination of terrestrial measurements of gravity field functionals, like land and marine gravity anomalies, gravity disturbances, geoid heights and deflections of the vertical, with satellite measurements of the instantaneous sea surface height from altimetric satellites and digital terrain, bathymetry and digital density models (Sansò and Sideris 1997). This data provided very useful and accurate information for the medium to high frequency spectrum of the gravity field, while the determination of the low frequencies, i.e., the long wavelengths of the gravity spectrum was relying on few observations to orbiting satellites. The latter refers to the determination of the gravitational potential through perturbation theory from the monitoring of the orbit of revolving satellites. This situation resulted in significant errors in the determination of the long and medium wavelengths and a subsequent cumulative geoid error of the order of ±46 cm for wavelengths up to 100 km in a global scale (Lemoine *et al.* 1998). But, the needs of geodesy, oceanography, geophysics, geology, hydrology and earth sciences in general demand the determination of the gravity field and the geoid with an accuracy of the order of ±1 cm for wavelength of ~10 km. This accuracy is absolutely needed in order to detect, study and monitor the natural processes that take place in the Earth's interior, the dynamics of the ocean masses variations and their seasonal cycle, the interaction and changes of tectonic plates, the balance of freeboard and captured ice in the oceans, the variations of the sea level, the balance and variations of mass on the Earth's surface from all kinds of dynamic phenomena, and the connection of height systems in local, regional and global scale. All aforementioned areas of research benefit greatly from an accurately and rigorously determined model of the Earth's gravity field and the geoid. Changes and variations in the Earth's gravity field are the natural response of our planet to processes taking place in its interior, surface and atmosphere, while the geoid forms the natural reference surface for the determination of heights and height differences. The interaction and interrelation between Earth's gravity field and the geosciences is presented schematically in Figure 1. From that Figure it can be seen that all processes inside the Earth, such as tectonic plate movement, orogeny, sedimentation, rifting, the formation of oceanic ridges and trenches and the eruption of hot spots have a response in its gravity field. Equivalently, processes on the Earth's surface, such as post glacial rebound, rifting, exchange of mass balance, polar ice melt, sea level change and mass/heat flux have a

response on the geoid, which is the natural reference surface to study land, ice, ocean and climate changes.

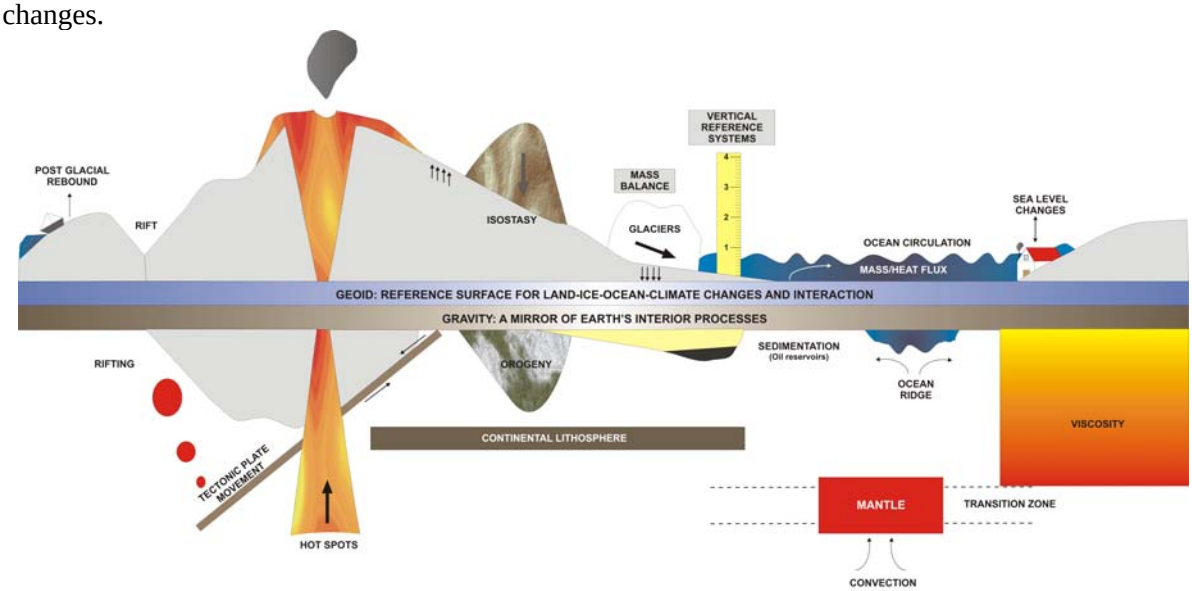


Figure 1. Contribution of the Earth's gravity field to geosciences.

In order to achieve the accuracy needed in the determination of the gravity field and of the geoid for the aforementioned studies to be feasible in a global scale, terrestrial gravity measurements over extended regions would have to be performed. Unfortunately, this is a very time consuming and expensive operation. Therefore, the only feasible method that could guarantee homogeneity, accuracy and global coverage, is the collection of observables related to the Earth's gravity field from space. The main problem of observing Earth's gravity field from space is related to the attenuation of the gravity signal with height, due to the orbiting altitude of artificial satellites revolving Earth. On the other hand, low orbiting altitude means larger drift and drag effects due to the influence of the Earth's atmosphere and shorter satellite life spans. Given these circumstances, during the last decade a triplet of revolutionary and novel gravity-field dedicated satellites have been launched or are in the final stage of preparation, all aiming at the determination of the Earth's global gravity field in order to understand and monitor climate change and variations in the Earth's mass. The satellite missions of CHAMP, GRACE and GOCE aim all at the accurate determination of the Earth's gravity field and its temporal variations in a global scale, therefore their orbiting altitude is set to 454 km for CHAMP, 485-500 km for GRACE and 250 km for GOCE, which is low compared to the orbiting altitude of altimetric (~1360 km) and GPS satellites (~20000 km). The orbiting altitude of these satellites is dictated from the methods employed to measure gravity functionals from space. These are: a) The high-low satellite to satellite tracking method (SST-hl) used by all missions, b) the low-low satellite to satellite tracking method (SST-ll) used by GRACE, and c) the method of satellite gravity gradiometry (SGG) used by GOCE.

This work presents the main characteristics of the recent gravity-field dedicated satellite missions, their goals and fields of applications and the results acquired so far. It should be beard in mind that accurate knowledge of the Earth's gravity field is highly important for all geosciences and an invaluable tool to monitor changes in system Earth, due to both anthropogenic intervention and natural phenomena. Nowadays, this is of utmost significance, especially in view of the increasing rates of the deterioration of our natural environment and the risk that this has to both nature and humanity.

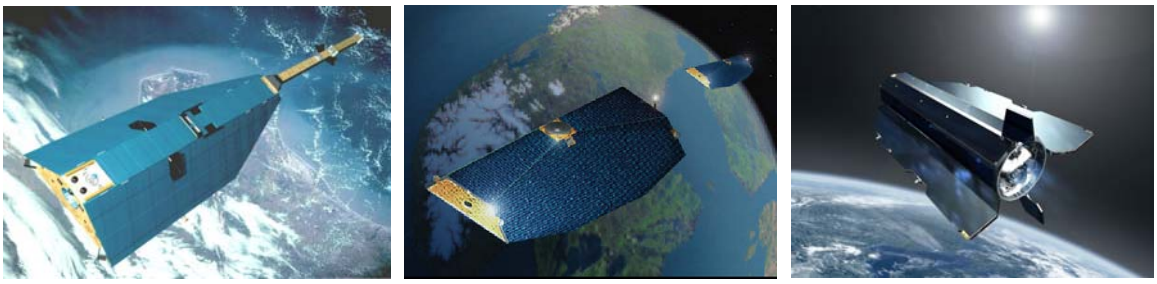
2. Gravity-field dedicated satellite missions

The new era in Earth's gravity field observation from space originates in July 2000, when the first gravity-field dedicated satellite mission of CHAMP (Challenging Mini-satellite Payload) was set to orbit. This concluded a decade of scientific planning and work and almost half a century of envisioning to measure gravity potential from a space shuttle. CHAMP (see Figure 2a), launched by the GeoForschungsZentrum (GFZ) residing in Potsdam, Germany follows a near-circular (*eccentricity* $e=0.004001$) and near-polar (*inclination* $i=87.3^o$) orbit with an initial orbiting altitude of 454 km. Even though it was designed to provide measurements of the gravity field for a five-year time span, it

has exceeded even the most optimistic expectations since it continuues to be in healthy state (February 2008) and is anticipated to work until mid 2009 (Reigber *et al.* 2005a, b). As it will discussed below the satellite uses the technique of SST-hl in combination with an onboard accelerometer to measure gravitational and non-gravitational forces acting on the satellite and measure the gravitational potential. The main focus of CHAMP is put in the determination of the low-degree harmonics, i.e., the very long wavelengths of the Earth's gravity field.

The satellite mission of GRACE (Gravity Recovery and Climate Experiment) (see Figure 2b), which is composed by two satellites in pair, is the natural continuation of CHAMP, since it has its main focus on the accurate determination of the long to medium wavelength of the Earth's gravity field and its temporal variations. GRACE is a joint project by the national space agencies of the USA (National Aeronautics and Space Administration – NASA) and Germany (Deutsches Zentrum für Luft- und Raumfahrt – DLR), while the Center for Space Research (CSR, University of Texas) and GFZ are responsible for data collection, archiving, processing and validation. As mentioned above the GRACE mission is composed by two identical satellites, GRACE-A and GRACE-B, which measure Earth's gravity field with the SST-ll technique, i.e., they measure changes in their inter-satellite distance and interpret that as changes in gravity attraction. The satellites were set to orbit in March 17, 2002 in a near-circular ($e=0.0019994$) and near-polar ($i=89.03^o$) orbit, at an initial altitude of 475 km with their distance being 211.4687 km. Their expected lifespan of 5 years has already been exceeded, while the satellites are sill in a healthy status and they are expected to provide measurements until 20010-2011 (Tapley *et al.* 2003, 2004b).

The satellite mission of GOCE (Gravity field and steady Ocean Circulation Explorer) (see Figure 2c) is the final one in this series of gravity-field dedicated satellite missions and is scheduled for launch in spring 2008 under the auspices of the European Space Agency (ESA). GOCE will be the first satellite to measure the gravity field from space with the technique of space gravity gradiometry (SGG) and is anticipated to provide new data and information for the high frequencies of the gravity field spectrum with an accuracy of ±1 cm up to harmonic degrees $n=250$ (~80 km half wavelength). The satellite will be set to a sun-synchronous dawn-dusk orbit, which will be near-circular ($e\leq 0.0045$) and with an inclination of $i=96.5^o$ (Drinkwater *et al.* 2003). Its altitude will be very low, compared to other satellites, set to 250 km and will have a life span of two years only. GOCE observables are expected to increase the accuracy of the medium and higher order harmonics (n>50-60), while they will also contribute significantly in increasing the spatial resolution with which we observe Earth's gravity field. As usual, global gravity field models are represented in a spherical harmonic expansion of the gravity potential. The Global Geopotential Models (GGMs) that will result from the GOCE mission data are expected to have a cumulative geoid error of ±1 cm for degrees of expansion n=250-260 which translates to ~80-76 km (half wavelength) (Förste et *al.* 2007). This is a tremendous improvement compared to the present state geoid height accuracy of ±46 cm for n=360. The combination of GOCE-generated GGMs with current terrestrial and space data will result in an unprecedented representation of the Earth's gravity both in terms of accuracy and resolution (Rummel *et al.* 2000, 2002).



(a) (b) (c)

Figure 2. The gravity field dedicated satellite missions of CHAMP (a), GRACE (b) and GOCE (c).

The three measurement techniques of the gravity field from space, namely SST-hl, SST-ll and SGG, are based on a combination of on-board accelerometer(s) and satellite to satellite tracking both between the satellites themselves and the GPS satellites as well. The necessary conditions that every space-borne gravity measurement technique has to fulfil are: *a) Allow continuous and uninterrupted monitoring of the satellites in the three-dimensional space, b) give the capability of measuring and/or reducing the effects of non-gravitational forces, so that the gravity potential signal can be measured*

or isolated, and c) the flight altitude should be as low as possible and close to the Earth's attracting masses so that the attenuation of the gravity signal due to height will be as little as possible. All three criteria are fulfilled by the SST-hl technique (see Figure 3). According to this method, a low Earth orbiting satellite is equipped with a high-end Global Positioning System (GPS) receiver and a three-axis accelerometer. The receiver tracks at each single instance at least twelve GPS and GLONASS satellites and based on their ephemerides, which are computed with a very high accuracy from the global observing network of the International GPS Service (IGS), and the carrier phase and code measurements that it makes, it can compute the 3-dimensional position vector of the satellite with a 1 cm accuracy. Moreover, the satellite accelerometer, positioned in its center of mass, measures the non-gravitational forces acting on the satellite (atmospheric drag, solar radiation, etc.), so that these forces can be removed at a later stage. CHAMP was the first satellite using this technique to measure the Earth's gravity field (Reigber *et al.* 1996). This measuring technique enables the determination of the long-wavelengths of the gravity field spectrum with a high accuracy, but it does not allow the acquisition of data for the medium to high frequencies due to the attenuation of the gravity signal with height (even though the satellite is orbiting the Earth at an already low altitude compared to other artificial satellites). This is due to the fact that the measuring system configuration does not completely fulfill condition *b)* listed above.

The classic geodetic practice followed to measure small-scale signal in the gravity spectrum is to measure potential differences, instead of the potential itself, or its second-order derivatives. In this way, two different possibilities arise for the reduction of the attenuation effects, i.e., satellite to satellite tracking low-low mode (SST-ll) and satellite gravity gradiometry (SGG) which are combined always with the SST-hl technique. In the SST-ll technique (see Figure 3) two identical satellites are set in the same orbit with a distance from 100 to 400 km separating them. This peculiar hunting between the satellites is translated in increasing or decreasing distance between them, which is measured with a very high accuracy. The change in distance is an effect of the ever-changing forces acting on the satellites, where among them lays the gravitational force. The satellites using this technique are equipped with accelerometers in order to separate non-gravitation forces and compute changes in gravity due to the effects of underlying disturbing mass on Earth. Furthermore, their precise position vector is computed with the on-board GPS receivers. This technique is used by the GRACE pair of satellites, which successfully measure the medium frequencies of the gravity field spectrum with high accuracy, while they also provide time-varying models of gravity variations on the Earth's surface. The latter are linked to the cycle of water on Earth, polar ice melt, precipitation changes and ocean circulation.

The third and final technique, to be used by GOCE, is that of SGG, which will bridge the gap in gravity exploration from space by determining with very high accuracy the high frequencies of the gravity field spectrum, signaling in this way the synergy and complementarity between the three missions (the low, medium and high frequencies of the gravity field spectrum are measured with high-accuracy from CHAMP, GRACE and GOCE, respectively). The SGG method refers to the measurement of acceleration differences, in all three spatial dimensions, between the test masses and the three on-board accelerometers (see Figure 3). The resulting observable is the difference in gravity acceleration in the positions of the test masses within the satellite body. These differences are caused from all attracting masses on Earth, which act differently on each of the three accelerometers of the satellite. Since the distances separating the accelerometers and the test masses in the satellite are small, small gravity differences can be detected and a high-resolution representation of the gravity field can be acquired (Jekeli 1999, Rummel *et al.* 2002, Schrama 1990).

3. Impact of dedicated gravity satellite missions in geosciences and results

From the aforementioned description of the dedicated gravity satellite missions and their measurement principles and goals, the impact that they have on all branches of geosciences becomes apparent. The main benefit is directed towards geophysics, oceanography and geodesy with implicit consequences to all other sciences using their data and products. In the field of geophysics, geology and seismology, even though the study of the Earth's gravity field seems of minor importance, the improvements already achieved by the gravity missions of CHAMP, GRACE and GOCE give a much clearer three-dimensional representation of mass distribution and density variations in the lithosphere and upper mantle. When the latter are combined with seismic tomography and geophysical prospecting they provide a much more accurate representation of the structures in Earth's interior. Moreover, density variations are closely related with the gravity field since gravity anomalies are a

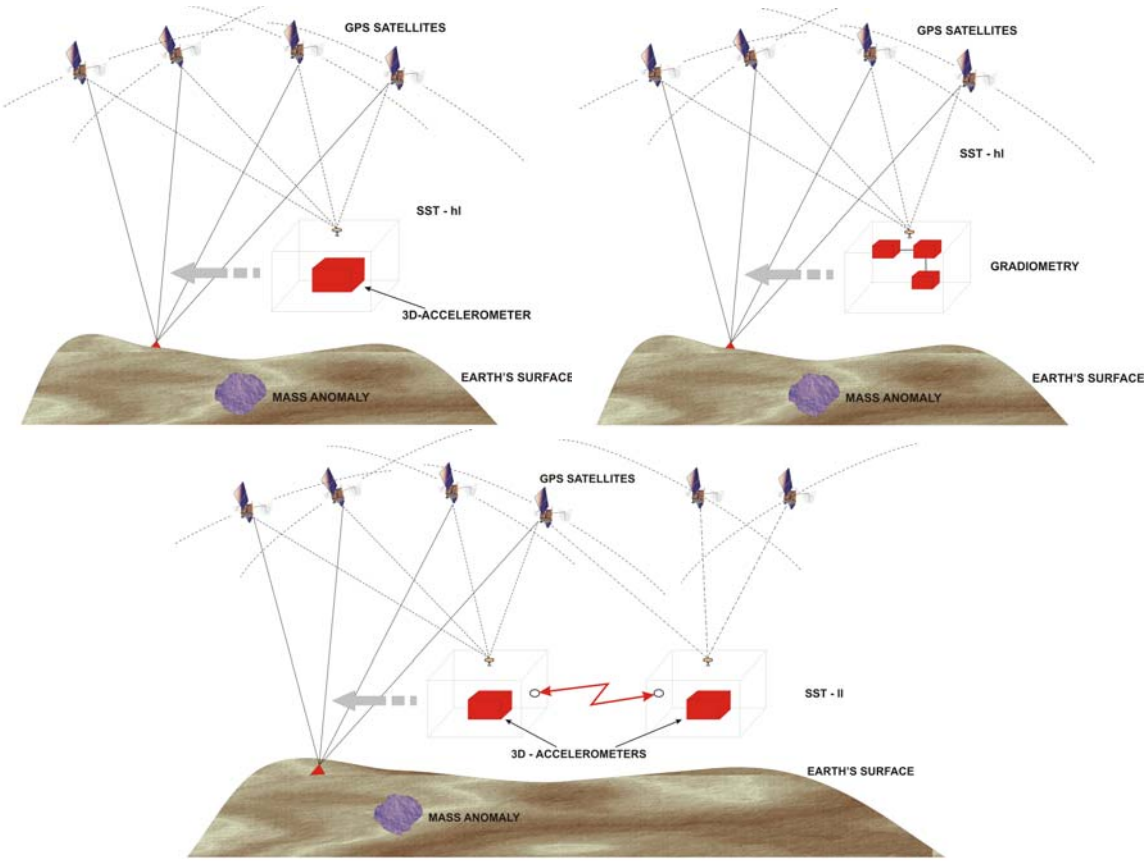


Figure 3. The techniques of SST-hl (top-left), SST-ll (top-right) and SGG (bottom) for the measurement of the gravity field from space.

result of variations in mass and density distribution. Therefore, better knowledge of mass and density variations can boost the study and determination of fracture zones, tectonic plate movement, sedimentation (closely related with oil and gas exploration), orogeny, rifting, while it is expected to contribute significantly in identifying the birth mechanisms of earthquakes. In Figure 4 the accuracy and horizontal resolution requirements for the study of various quantities in geophysics and geology are presented. From that figure it is evident that the prior to the dedicated gravity missions state was inadequate for the rigorous study of all aforementioned phenomena, something addressed to a great extend by the achievements of the recent gravity missions.

On the other hand oceanography has already seen the great benefits of space observation from the altimetric satellite missions of GEOSAT, ERS1/2, T/P, JASON-1, GFO and ENVISAT. The recent gravity missions will provide further improvements in both accuracy and horizontal resolution (see Figure 4), so that processes which until today were kept secret, especially high-frequency ocean circulation, will be revealed. Oceanography is closely related to geodesy in marine areas, since geodesy needs accurate oceanographic models of the sea surface topography to derive the geoid, while oceanography needs geoid models with a ±1 cm accuracy to determine the ocean circulation and sea level variations (Gruberand and Steigenberger 2003). Given that the geoid models to be determined by CHAMP, GRACE and GOCE will have a better than ±1 cm accuracy for wavelengths of 150-160 km (full wavelength), their combination with the already available shipborne gravity and satellite altimetry data will lead to the accurate determination of the velocity and direction of big ocean currents like Kuroshio, Gulf Stream and the Antarctic Circumpolar Current. Moreover it will assist the determination of the weaker coastal and deep ocean currents, which up to now could be determined by in-situ observations only. Additionally, assimilation models, which have wide applications to oceanography as well as weather and climate monitoring and prediction (Fu and Cazenave 2000), will be benefited greatly, since an additional high-accuracy data source will be available.

Finally, geodesy, is probably the most benefited of all geosciences, since the dedicated gravity satellite missions signal the beginning of a new era due to the fulfillment of decade-long objectives (see Figure 4). First of all, in well-surveyed areas of the world like North America, Europe, Australia and Japan, where high-accuracy regional and local geoid models exist, the results acquired by the new

gravity missions will make leveling and the determination of heights by GPS measurements feasible and an everyday issue, will lead to the unification of vertical reference systems and enable inertial navigation. In poorly surveyed areas of the world, where no data or data with gross errors exist, the results from the gravity missions will contribute to geoid development of a higher resolution and accuracy (Vergos 2006). Significant contribution and improvement will be achieved in the estimation of satellite orbits, which will be determined with higher precision and accuracy since gravitational effects and errors associated with its accuracy will be reduced if not removed. Finally, the dedicated gravity missions will have a direct impact on monitoring temporal, seasonal and quasi-stationary sea level variations, determining the seasonal water cycle on our planet and the water balance on glaciers, lakes, oceans and rivers and will finally contribute to a more timely and accurate prognosis of large scale climate phenomena like El Niño and La Niña (Barzaghi *et al.* 2007, Vergos *et al.* 2006).

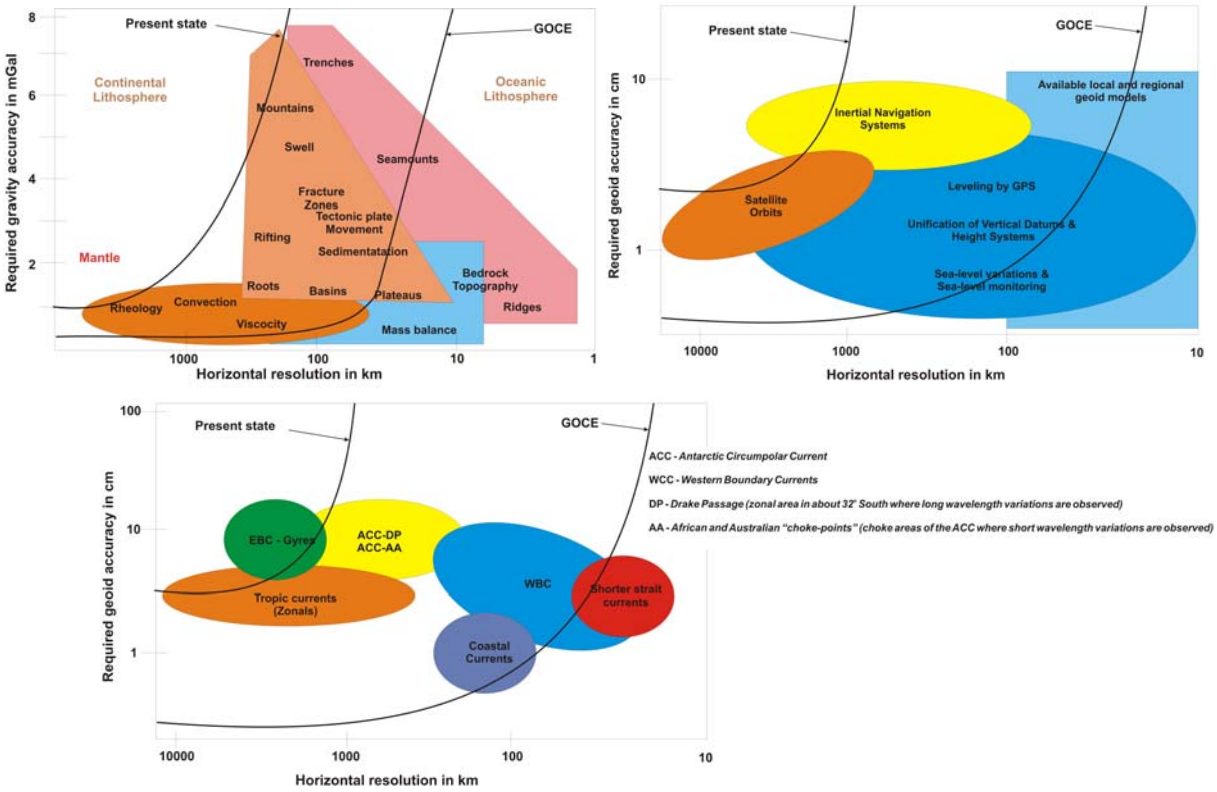


Figure 4. Impact of the gravity field dedicated satellite missions of CHAMP, GRACE and GOCE on geodynamics (top left), oceanography (top right) and geodesy (bottom).

Some of the early results acquired in earth sciences from the use of data from the dedicated gravity satellite missions can be viewed in terms of the improved accuracy in geoid determination. Figure 5 presents the cumulative geoid error for various global gravity models with increasing degree of harmonic expansion. The latest model coming from CHAMP and GRACE data is depicted with the green line, and it can be clearly seen that the accuracy improvement is almost ten times better compared to older models (Vergos 2006). It should be noted that this model does not include any GOCE data, since the satellite is not launched yet, therefore the medium to high frequencies lack accuracy. But, even in this case, by including only two years of data from the other satellite missions, the accuracy improvement is significant (two to three orders of magnitude compared to older models). Moreover, the outstanding contribution to geodynamics was proven even from the early results, since data from the GRACE mission led to the detection of the M9.3Sumatra earthquake that took place in 2004. Figure 5 (right image) shows the change in the gravity field caused by the earthquake and depicted by the GRACE satellites. The change in the gravity field was of the order of a few nanometres/s^2 which is one billionth of the acceleration that we experience everyday at the Earth's surface. Finally, another significant achievement of the dedicated gravity missions has been the monitoring of mass balance and mass exchange on the Earth's surface and the oceans. The results of the GRACE monthly gravity field models have a cumulative geoid accuracy of ±2-3 mm with a spatial resolution of ~400 km, thus allowing the determination of annual and seasonal geoid variations of up to 10 mm. Over large watershed areas, geoid variations can be attributed mainly to groundwater

changes. Such an example is observed in South America in the wider area of the Amazon River (see Figure 6), where geoid changes of the order of a few mm are evident in the monthly GRACE gravity models. This annual cycle in geoid variations show a clear separation between the large Amazon watershed and the smaller watersheds to the north, e.g., the Orinoco watershed (Tapley *et al.* 2004a) as well as the annual cycle of water balance in the area, since 1 mm in geoid height change is roughly translated in 2 mm water column change.

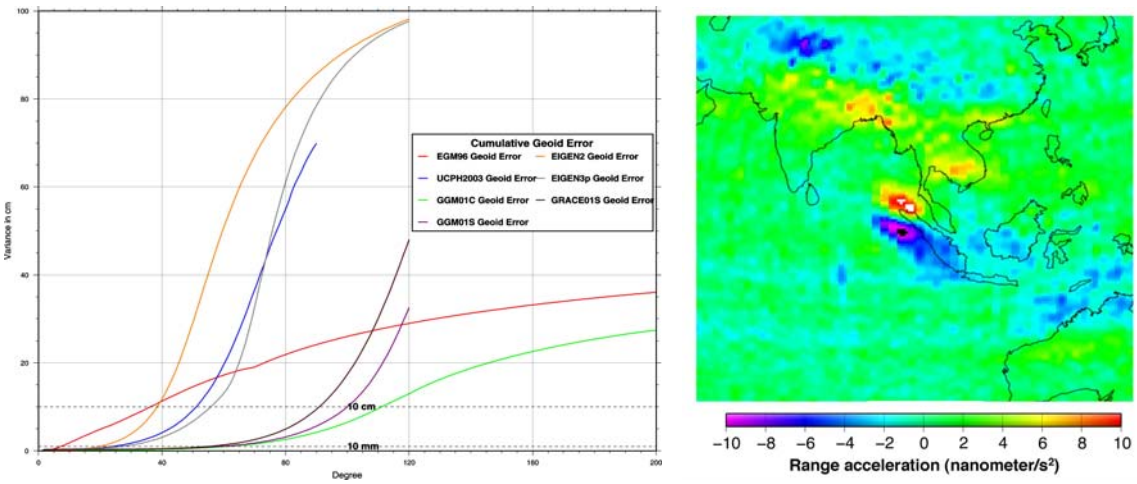


Figure 5. Accuracy improvement in geoid determination when using data from dedicated gravity missions (left) and detection of the Sumatra Earthquake by GRACE (right) [Image credit of NASA/JPL/University of Texas-CSR].

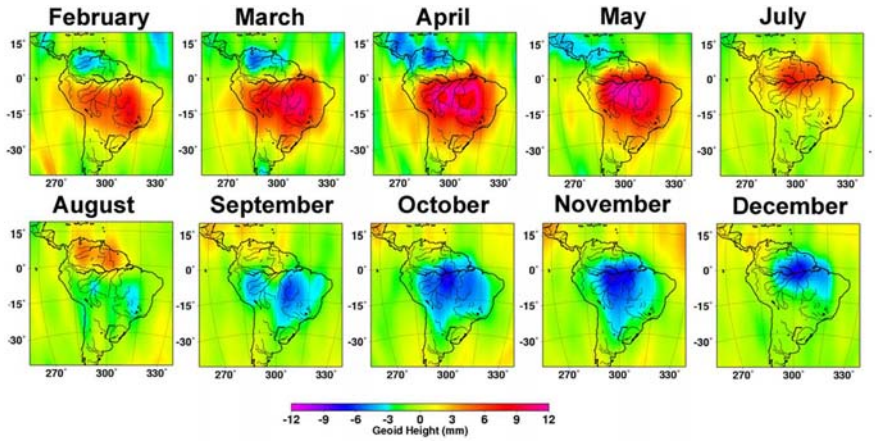


Figure 6. Annual (2004) geoid height variations in the Amazon basin from GRACE monthly solutions. [Image credit of Tapley et al. 2004a]

4. Conclusions

The recent and forthcoming dedicated gravity satellite missions have already a significant impact in geodesy and the geosciences in general. Their characteristics and measurement principles offer a unique and novel insight in the processes that take place in the Earth's interior, the variations of the oceans and mass redistribution on Earth. The gravity models that result from the CHAMP and GRACE data, and those to be acquired by the forthcoming GOCE mission, offer the opportunity for synergy between various fields in geosciences for sea level monitoring, large and small scale ocean circulation determination, water variations and ice melt estimation. Of utmost importance is their application for climate change observation and prediction, where in combination with other data sources in assimilation models they can lead to a better understanding of our changing planet and the development of more efficient tools for natural risk management towards the protection of our environment, infrastructure, economy and society. Finally, the dedicated gravity field satellite mission data have an increasing impact on geodesy, where unprecedented views of the Earth's gravity field have already been determined while the geoid at a global scale will be estimated with an accuracy of a few cm, thus allowing the connection of height systems, precise sea level monitoring, the introduction of a global vertical datum and the determination of orthometric heights by stand alone GPS.

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