How to validate satellite-derived gravity observations with gravimeters at the ground?

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1. Introduction

There is a major international effort in the present decade to measure variations in the Earth's global gravity field using low orbit satellites. The first satellite CHAMP (Challenging Mini-satellite Payload) was launched in 2000 and was followed two years later by GRACE (Gravity Recovery and Climate Experiment). In the near future, there will be a third mission called GOCE (Gravity field and steady-state Ocean Circulation Explorer) that will orbit even closer to the ground and hence be even more sensitive to smaller scale gravity changes. The primary goal of these missions is to use the temporal changes of the Earth's gravity field to infer changes in regional and continental water storage, and ocean circulation (see Tapley et al. 2004; Wahr et al. 2004; Svenson et al. 2003).
In addition to satellite-derived gravity observations there is since 1997 a ground network of about 20 superconducting gravimeters (SG) within the frame of the GGP (Global Geodynamics Project). These instruments are able to study time variations in surface gravity over a very wide spectrum ranging from second to several year periods (see e.g. Hinderer & Crossley 2004).

	GRACE	Superconducting gravimeter
Gravity resolution (expected)	0.1 2 microgal	1-10 nanogal
Spatial resolution Half wavelength	500 250 km (nominal) ***1300 km (real)***	Point measurement
Spherical harmonic Expansion degree	40 80 (nominal) ***15 (real)***	
Temporal resolution	1 month	10 sec
Long term stability	No drift	Small drift < 3 microgal/year

Table 1. A comparison between satellite-derived and surface gravity performances.

Table 1 gives an overview of the similarities and differences between satellite and ground gravity measurements in terms of amplitude sensitivity (in µGal), space and time resolution and long term stability. Of course the highest resolution in time and amplitude is obtained with the SG at the Earth's surface but the SG measurements are point observations on the contrary to satellite-derived gravity which acts as a spatial integrator filter. Moreover these two types of data are not sensitive to the same gravity contributions as we will see in section 2.

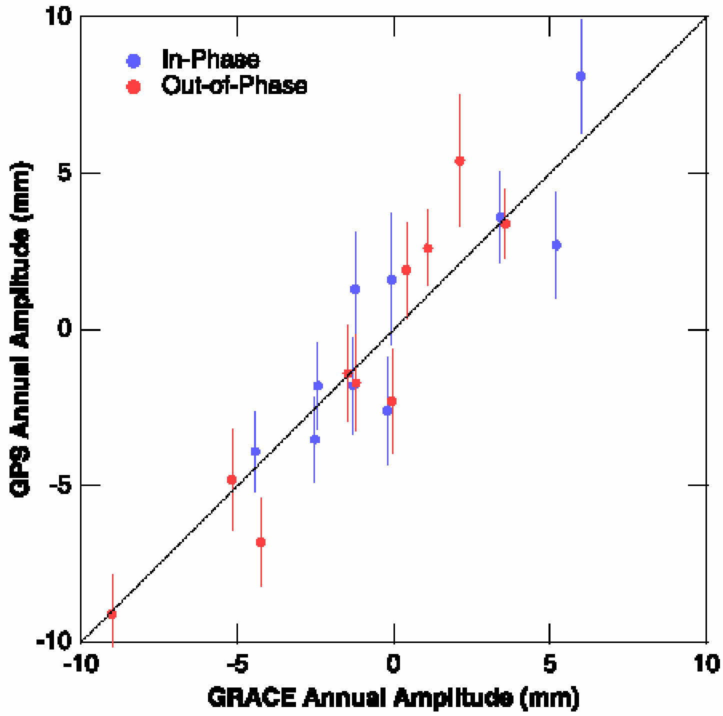

Figure 1. GPS versus GRACE derived observations of the annual hydrological signal in vertical displacement (mm) in the Amazon basin (from Davis et al. 2004).

Several methods have been proposed to calibrate/validate (CAL/VAL experiment) space-derived gravity observations:

- use of **models** for the atmosphere, oceans, hydrology, tides, or post-glacial rebound but this method does not appear very satisfactory from the conceptual point of view since satellite data are supposed to enhance these models;

- use of man-made '**controlled**' experiment like water impoundment of the Three-Gorges Reservoir in China (with detailed monitoring of water level + ground geodesy) (Boy & Chao 2002); it is however difficult because of the small spatial extension (40 km^3, 600 km x 1-2 km) and unknown underground contribution;

- use of in-situ Ocean Bottom Pressure (**OBP**) like the MOVE (Meridional Overturning Variability Experiment)) project in tropical northwest Atlantic (Kanzow et al. 2005) or the Japanese project linked to the Kuroshio current in Western Pacific Ocean; this method is based on the capability of space-borne gravity measurements to detect the time variation of the oceanic mass redistribution and its currents; it is also difficult because of the small number of pressure sensors available;

- use of **GPS** observations of ground motion like in the study of hydrology-driven vertical deformation in the Amazon River Basin (Davis et al. 2004); this method is indirect (one compares displacement to gravity) but GPS has indeed the similar spatial sensitivity as GRACE data and the results are promising (see Fig. 1);

- use of **ground based gravity** data mainly with SG but also with repeated measurements using Absolute Gravimeter (AG) (Niebauer et al. 1995) in specific zones of interest (together with collocated GPS measurements); this will be the approach described in this paper.

2. Ground and satellite gravity transfer functions

There are three different contributions to ground gravity resulting from a surface loading process (Hinderer & Legros 1989):

1. the Newtonian attraction
2. the elastic term due to vertical motion in existing field (term depending on Love number h'_n of degree n)
3. the elastic term due to mass redistribution (term depending on Love number k'_n of degree n).

For instance the ratio of satellite-derived versus ground gravity transfer function for a hydrological surface load (due to soil moisture or snow coverage or underground aquifer) of degree n becomes:

$$\frac{\Delta g_{sat}}{\Delta g_{ground}} = \frac{(n+1)(1+k'_n)}{(n+1) - 2h'_n + (n+1)k'_n} \quad (1)$$

Figure 2 shows the variation of this ratio as a function of the degree n of the spherical harmonic decomposition of the hydrological load. This ratio tends to unity for large n because the elastic deformational part in h'_n vanishes but is significantly different from unity for low degrees.

Notice that ground changes are always predicted to be larger than satellite changes for all degrees (ratio < 1). The reason is due to elasticity that systematically enhances the pure Newtonian attraction effect. When there is more water below the surface, gravity is increased and, at the same time, the crust is subsiding which again increases gravity.

3. A review of previous studies involving surface gravity

The ‘ground truth’ project based on GGP data was initiated some years ago to fulfil several goals among them the calibration, validation, or inter-comparison of ground gravity changes with satellite measurements (Crossley & Hinderer 2002). One goal was to provide an independent method different from other approaches and to investigate a common reference signal which is the gravity variation driven by the seasonal changes in continental hydrology (see Wahr et al. 1998; Andersen et al. 2005a; Boy & Hinderer 2006).

A first study directly comparing CHAMP data to 6 SG ground observations was done by Neumeyer et al. (2004) and has led to satisfactory results for all the stations in the one year analysis period (from December 2000 to December 2001). The superposition of the monthly gravity mean values from the SG residuals (after correction for solid tides, ocean and atmospheric loadings, and polar motion) with the CHAMP reconstructed values at the SG sites is rather good. Neumeyer et al. (2006) recently extended this study to GRACE data pointing out again the partial agreement between surface and satellite-derived gravity at specific locations.
Before a detailed comparison can be made, however, one has to remember that ground gravity measurements include necessarily a contribution from the vertical motion of the instrument through the ambient gravity field as shown in part 2 (h'_n term).This signal does not affect the orbiting satellite and hence there is a difference in the gravity changes as seen at (moving) ground level and by the satellite (Hinderer et al. 2006).

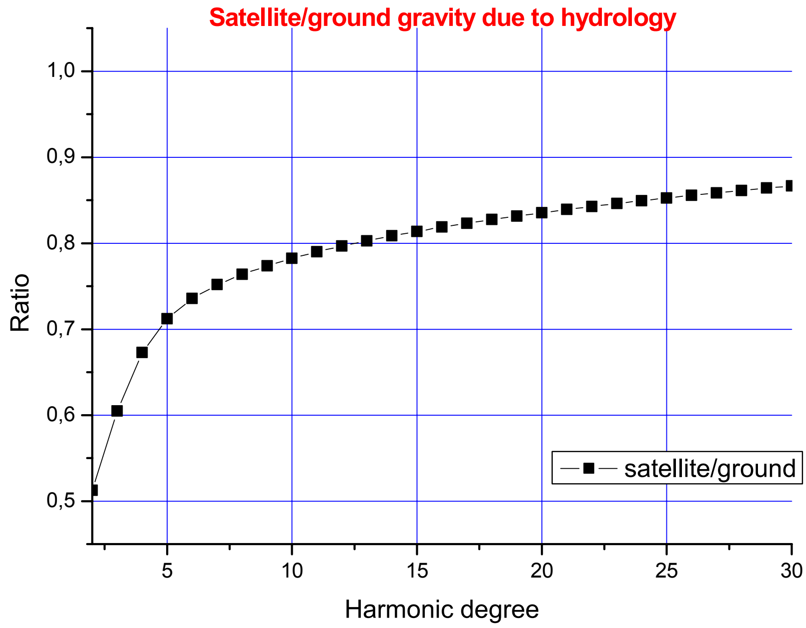

Figure 2. Ratio of the satellite versus ground gravity transfer function due to a hydrological load as a function of the degree n of the spherical harmonic decomposition.

We note in these studies that the comparison of single station results with the large-scale satellite solutions is problematic due to the completely different error budgets involved. GRACE data for example are good to 1 μGal only over length scales longer than 500- 1000 km, whereas SGs are good to the same accuracy (or better) at a single point. In order to average SG measurements and reduce local effects, there have been attempts to assemble a network solution from nearby SG stations rather than doing the above single station comparison; one way is for instance to do an Empirical Orthogonal Function (EOF) decomposition of the SG signals and to compare it to the same decomposition of the GRACE field (Crossley et al. 2004). Within the existing rather sparse GGP network, Europe is obviously the best place to try such an approach.

The approach was first initiated using 1 year of SG data by Crossley and Hinderer (2002) and Crossley et al. (2003) and extended to longer data sets by Crossley et al. (2004, 2005). This approach was further extended to a 21 month time interval to inter-compare surface data (GGP European sub-network), satellite data from GRACE, and theoretical predictions for two global scale hydrology models (Andersen et al. 2005a; Hinderer et al. 2006).
The results show the existence of an annual signal that is coherent over Europe with an amplitude of a few µGal mostly due to the seasonal loading from continental hydrology (soil moisture + snow) according to recent models such as LaD (Milly & Shmakin 2002) or GLDAS (Rodell et al. 2004). There is even a possibility to detect in GRACE data inter-annual signals (Andersen & Hinderer 2005) and, in particular, there is a clear evidence that GRACE has been affected by the heat wave that occurred in summer 2003 in Europe (Andersen et al. 2005b). The Wettzell (Germany) and the Medicina (Italy) SG data seem to confirm this point as shown by Figure 3.

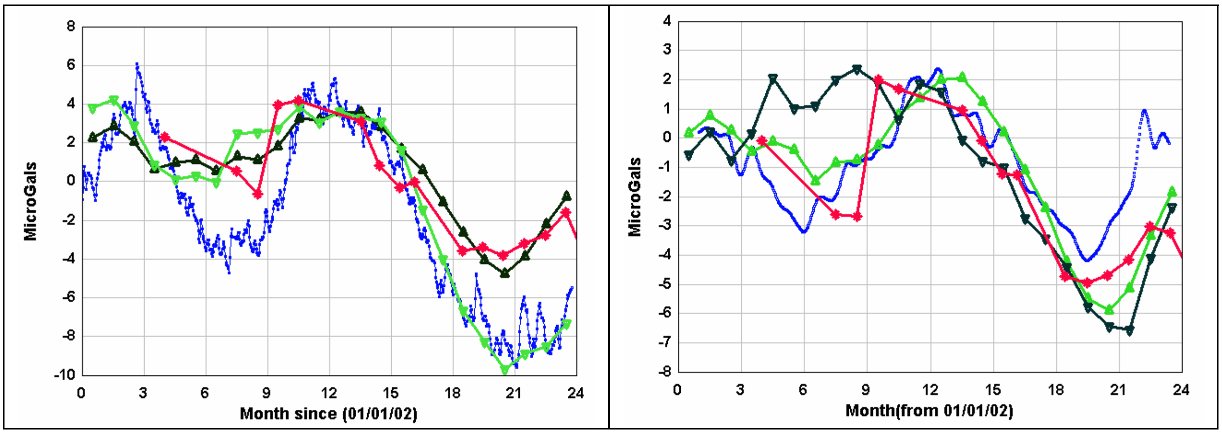

Figure 3. Direct observations of gravity field variations from two superconducting gravimeters located in Wettzell (Germany) and in Medicina (Italy). The SG gravity observations are shown in blue and the GRACE observations are shown in red. Predicted gravity changes from the GLDAS output are shown in green (triangles up) (raw, un-smoothed) and black (triangles down) (spatially smoothed to mimic GRACE observations) (from Andersen et al. 2005b).

4. A proposal for a pilot study: GHYRAF (Gravity, HYdRology in AFrica)

We have seen that continental hydrology changes are of limited amplitude in Europe where most of the ground based gravity validation experiments have been done. There are other regions where larger cyclic changes are expected and one is equatorial Africa. We propose hereafter a pilot study from the Sahara to the equatorial monsoon zone. The main target will be the comparison between models and multi-disciplinary observations (gravity, geodesy, hydrology, meteorology) of seasonal water storage changes in an arid region without any surface and underground water content variation and a very rainy region where we will be able to combine there a lack of hydrology in an arid region with a strong hydrology signal. The corollary is the ground validation of space-derived gravity (GRACE, GOCE).

Two types of ground-based measurement campaigns are involved (cf. figure 4):

• a repeated survey of 2 North-South absolute gravity profiles to assess the large soil moisture changes as predicted by recent hydrological models

• the installation of a high precision superconducting gravimeter (SG) at Nsimi (Cameroon) to act as a continuously monitored base station in a region of large water storage changes.

From the expression of the gravity transfer function (eqn. (1)) we know that it is important to determine the vertical motion at AG/SG points in order to correct for the free air gradient contribution which is not felt by the satellite.

Our project will include actual ground-based gravity measurements in a null zone (hydrologically) that will help constrain our observations for the other, high rainfall, zone in Central Africa. It will also enhance cooperation between various sub-disciplines (absolute and relative gravimetry, geodesy, hydrology, and satellite geodesy) and, finally, strengthen the activities of the AMMA (Multi Disciplinary Analysis of African Monsoon) international research program.

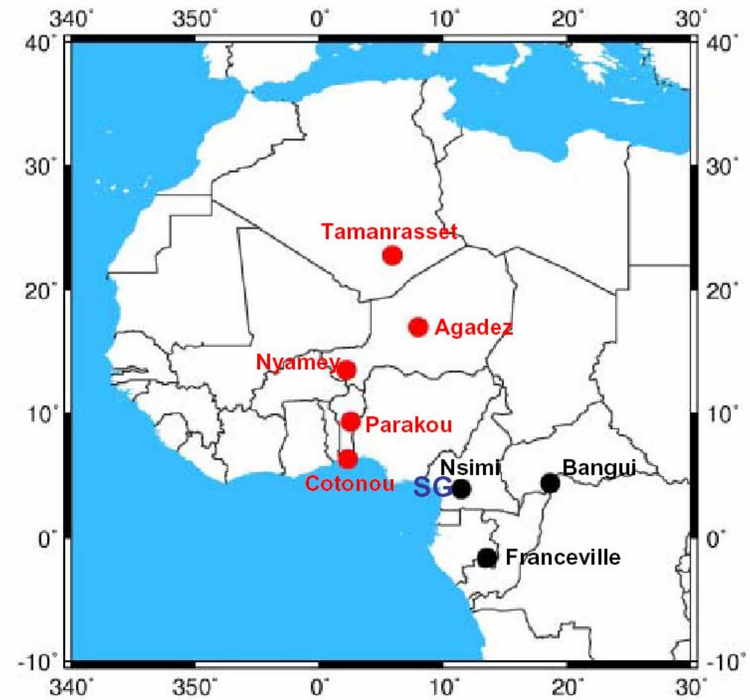

Figure 4. Location of the gravity measurement stations (Tamanrasset (Algeria), Agadez (Niger), Nyamey (Niger), Parakou (Benin), Cotonou (Benin), Franceville (Gabon), Nsimi (Cameroon), Bangui (Central African Republic)).

Our project will need a campaign of continuous precise GPS measurements along the profiles to assess the vertical deformation not seen by the GRACE satellites. Moreover in-situ measurements of hydrological parameters at each station are needed to assist us in modelling the local gravity effects at each station. Finally we also feel that new approaches to generating highly tuned data from the GRACE satellites to maximize the time and spatial resolution of the satellite data (see Rowlands et al. 2005) are necessary in this area.

The extreme predictions are for Tamanrasset (TAM) station in the Sahara where the lack of water in the underground leads to almost no change in gravity (less than 0.4 µGal) and to small vertical motions (less than 2 mm) and for the Nsimi station in Cameroon (near Yaoundé) where gravity changes as large as 20 µGal and displacement of the order of 10 mm can be reached during the monsoon period (see Figure 5 below).

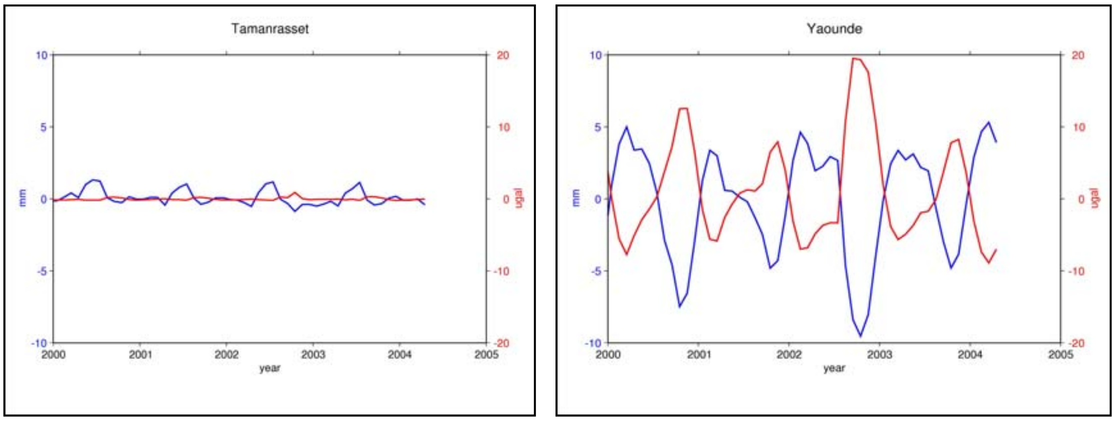

Figure 5. Hydrological predictions in gravity (in µGal) and in vertical displacement (in mm) in Tamanrasset (Algeria) and in Nsimi (Youndé) (Cameroon) stations.

5. Conclusion

In summary, we believe that in addition to other methods based on theoretical modeling, ocean bottom pressure or GPS vertical displacement, the validation of space-born gravity data with surface gravity observations is in progress. It appears clearly possible in Europe with the dense GGP sub-network available and using the annual signal of moderate amplitude due to continental hydrology (mainly soil moisture). However this method requires first to estimate the vertical motion from GPS in order to extract the gravity contribution arising from the motion in the existing gravity field (free air term). Second, since the gravity transfer function for surface measurements involves a Newtonian attraction term highly dependent on the location of the masses near the gravimeter, it is also required to model local hydrology in a very precise way. Another excellent opportunity to validate satellite gravity data is to perform new measurements in Africa with SG and AG focusing on two specific regions: the Sahara where a null test can be achieved and the monsoon region in the equatorial part where large signals are predicted from hydrology.

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