

Comparison of superconducting gravimeter observations with hydrological models of various spatial extents

H. Virtanen, M. Tervo, M. Bilker-Koivula,
Finnish Geodetic Institute
P.O.Box 15, FIN-02431 Masala, Finland
heikki.virtanen@fgi.fi

We have compared temporal gravity variations of the superconducting gravimeter T020 with various water storage models and observations at Metsähovi, Finland. We have used local data, regional and global hydrological models. The regional model is a highly accurate model for Finland, called the Watershed Simulation and Forecasting System (WSFS). The global model is the Climate Prediction Center global soil moisture data set (CPC), which correlates well with WSFS. We have exploited both regression methods and loading calculations using Green's function formalism to calculate gravity effects of these sources.

Gravity residuals are strongly correlated with local groundwater level, which clearly seems to correlate with the regional water storage. The important question is how to separate the effect of the near-field water storage from the loading effect of the regional or of the global water storage. Using regression methods exclusively, it is not possible to separate the various factors. Though, the local hydrological conditions have slowly altered and it offers a possibility to separate these phenomena.

Introduction

The superconducting gravimeter GWR T020 has been recording in Metsähovi almost continuously since August 1994. The gravity data correlates well with the local groundwater level (Fig. 1). In the gravity studies local hydrology has been conventionally corrected with regression on water level, observed by nearby borehole (Virtanen, 2000; 2001; 2006). Regression coefficients vary from 25 to 28 $\text{nms}^{-2}\text{m}^{-1}$. In addition, we have corrected the effect of the Baltic Sea loading (Virtanen, 2004).

We have treated only the local hydrology and the Newtonian attraction due to it. We have recently extended these studies to include regional and global water storage and its loading effect i.e. both the vertical deformation and the Newtonian attraction. We can crudely divide hydrological effect on gravity into three parts, depending on a distance. First is the local scale up to few kilometers, next, the regional scale up to several 100 km and then the continental or global scale. Theoretical studies show, that we are capable to detect gravity effect of local and global scale with superconducting gravimeter. However, the regional scale should be practically below the observational limit (Llubes et al., 2004).

We used two hydrological models: The Climate Prediction Center global soil moisture data set (Fan and Van den Dool, 2004) and the Watershed Simulation and Forecasting System (WSFS) of the Finnish Environment Institute (Vehviläinen and Huttunen, 2002). We have compared (Virtanen et al. 2005a; 2005b) the time series of T020 with both models, using regression methods and loading calculations. A key question is the separation of the attraction of near-field water storage from the loading effect of the regional water storage, as these two are strongly correlated. It seems, that using only regression methods it is not possible to separate the various factors and we will need stepwise modeling methods.

Hydrological phenomena appear to be a main cause for the regional gravity variation detected by

the gravity satellites CHAMP and GRACE. In several studies (Crossley and Hinderer, 2002; Crossley et al., 2004; 2005; Neumeyer et al. 2004; 2006; Virtanen et al. 2005a; 2005b) a correlation between regional gravity variation detected by the satellites and point gravity variation detected by the SGs has been pointed out. The question is again, which part of the SG response is driven by the regional hydrological loading and which part by the local hydrological attraction.

Data and processing

We have used hourly gravity data of superconducting gravimeter T020 at Metsähovi. The data set starts on December 1994 and ends on December 2005, being over 11 years. The data is almost continuous, except the one longer data gap (4 four months in 2003) due to failure of the data acquisition system (DAS). We have removed from refined and drift corrected gravity data tides, pole tide and effect of air pressure. The procedures of data processing are described in detail by Virtanen (2004; 2006). The gravity residuals are shown top in Fig. 5, including all hydrological effects and non-tidal loading of the Baltic Sea. All data used in the calculations were sampled to hourly values regardless of original sampling rate. Hourly values are interpolated from monthly values using near rigid splines. The grid loading calculations were done using a slightly modified programme NLOADF (Agnew, 1997). In other calculations we have applied the program TSOFT (Van Camp and Vauterin, 2005)

At a distance of 3 m from the T020 there is a 33 m deep borehole in the bedrock, with a diameter of 11 cm, for monitoring the groundwater (GW). The level has been measured manually since November 1994. In March 1998 a pressure sensor for the level measurements was installed in the borehole and connected to the DAS. The range of GW is 2.6 m (-4.5 m – 7.1m below surface). The low pass filtering (0.25 d) was applied on the data (Fig. 5 [B]).

We have used a very-high class regional hydrological model for Finland, Watershed and Forecasting System (WSFS) shown in Fig. 3 (Vehviläinen and Huttunen, 2002). Original data is in 1×1 km grids and includes all components of hydrological cycle. The data in this study is as daily average values (mm) of total Finnish water storage. We have water storage in mm for whole span of the analysis. The range is 250 mm. We have original grid data from June 2003 to December 2005, totally 31 months. We have averaged daily grids (664 km×1214 km) to monthly values of 0.5°×0.5° grid to calculate actual loading effect to gravity using Green's functions formalism (Tervo et al., 2006). Daily values in gravity unit (nms^{-2}) are regressed on the total water in units of mm. The results are shown in Fig. 4. The correlation is very good and we get coefficient: $0.058 \text{ nms}^{-2}\text{mm}^{-1}$. Thus, the regional water storage should give about 15 nms^{-2} effect on gravity.

There are several global hydrological models available. In this study we have used Climate Prediction Center global soil moisture data (Fan and Van den Dool, 2004). This data set (CPC) are given in monthly 0.5°×0.5° grid of water in mm. This model was selected because it gives rather good data of snow (Dirmeyer et al., 2004). We have modified this global grid to preserve mass balance (MB). The model gives soil moisture in land areas only. We have smoothed increasing/decreasing water to even layer on oceans. Global yearly rainfall is about 35 mm.

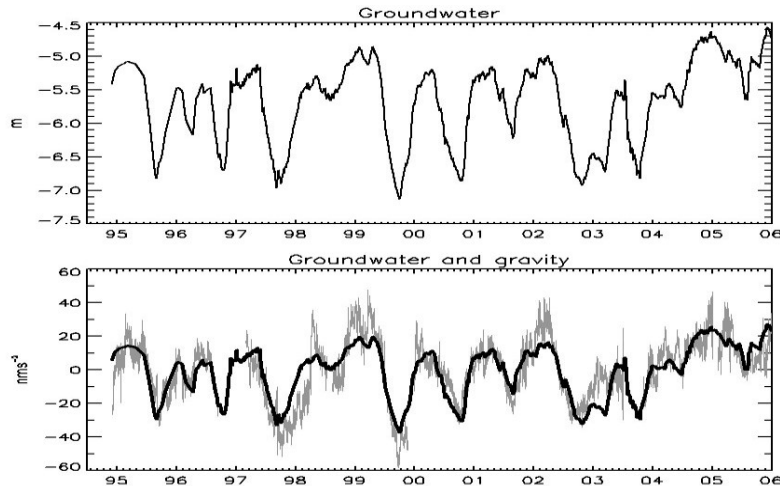


Fig. 1. The classical treatment of gravity data. Top: groundwater level at Metsähovi from 1 December 1994 to 31 Decemb 2005. Bottom: Gravity residuals with fitted groundwater level. The regression coefficient varies from 25 to 28 nms^{-2} depending on the correction of the Baltic Sea. Correlation coefficient is 0.83.

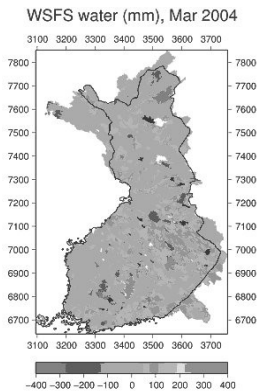


Fig. 2. The region of WSFS consist of Finland and connected watersheds

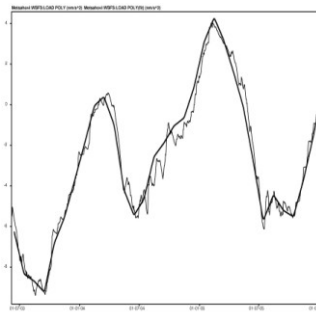


Fig. 3. The regression of loading gravity to mean value of total water storage in Finland ($0.058 \text{ nms}^{-2} \text{ mm}^{-1}$) 15.6.2003 – 15.12.2005.

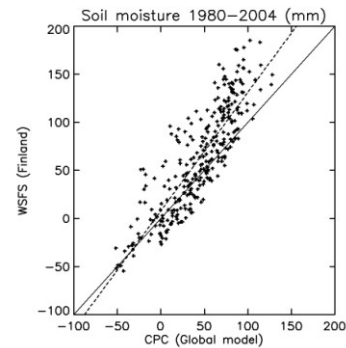


Fig. 4. WSFS vs. global model CPS, which is masked to the same area as WSFS

Next, we have calculated loading gravity effect using Green's function formalism. Monthly global gravity loading was then interpolated to hourly values (Fig. 5 [D]). The range of gravity variations is 30 nms^{-2} . For comparison we calculated the gravity load from CPC grid for the same area as WSFS and we found the maximum gravity effect of 5 nms^{-2} (Fig. 5 [E]). As additional data set we have data from snow water equivalence (Fig. 5 [F]) from station in distance about 40 km (MHR, 1994). We have used precipitation data (Fig. 5 [G]), too. The data is from Helsinki-Vantaa airport, at distance of 30 km (Meteorological Yearbook of Finland, 1994-; Ilmastokatsaus, 1999-). The data correlates well with local measurements, which do not work in winter.

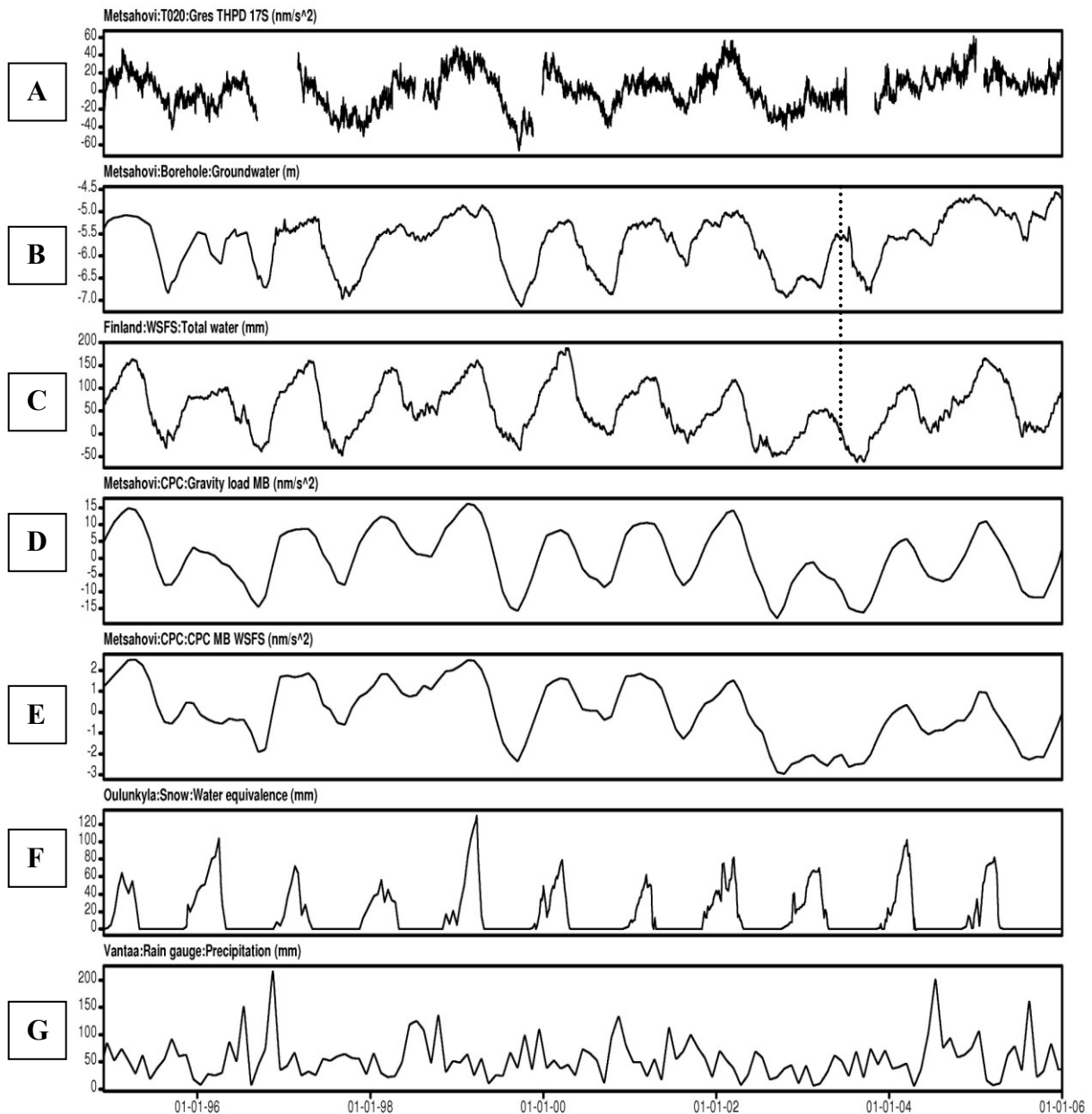


Fig. 5. From top to bottom: [A] Gravity residuals, [B] groundwater level at Metsähovi, [C] WSFS model for Finland, [D] CPC gravity load, [E] CPC gravity load for the region of WSFS, [F] Water equivalence of snow, [G] Precipitation at Helsinki-Vantaa airport. The dotted line in panels [B] and [C] shows approximately the time of change of local hydrological conditions.

Table 1
Results of gravity data of SG T020 vs. different hydrological models.

Treatment	Classical	Coeff.	Unit	Corr.	RMS	- %
1	GTPHD		nms^{-2}		20.07	0
2	GTPHD/GW	27.72	$\text{nms}^{-2}\text{m}^{-1}$	0.824	11.23	44
3	[2]/HSL	21.42	$\text{nms}^{-2}\text{m}^{-1}$	0.436	10.24	49
	New					
4	GTPHD-CPCMB		nms^{-2}		16.73	17
5	[4]/GW	19.49	$\text{nms}^{-2}\text{m}^{-1}$	0.695	12.03	40
6	[5]/HSL	19.24	$\text{nms}^{-2}\text{m}^{-1}$	0.371	11.17	45
7	[1]-[5]*GW-[6]*HSL		nms^{-2}		10.88	46
8	[7]/WSFS	0.070	$\text{nms}^{-2}/\text{mm}$	0.355	10.17	49
9	[7]/SNOW	0.127	$\text{nms}^{-2}/\text{mm}$	0.303	10.37	48
10	[7]/PREC	-0.006	$\text{nms}^{-2}/\text{mm}$	0.015	10.88	46
11	[7]/CPC(WSFS)	1.691	$\text{nms}^{-2}/\text{nms}^{-2}$	0.216	10.62	47
12	[8]/SNOW	0.045	$\text{nms}^{-2}/\text{mm}$	0.114	10.10	50
13	[8]/PREC	0.024	$\text{nms}^{-2}/\text{mm}$	0.069	10.15	49
14	[7]/WSFS/SNOW	0.053	$\text{nms}^{-2}/\text{nms}^{-2}$			
		0.064	$\text{nms}^{-2}/\text{mm}$	0.377	10.07	50

GTPHD: Edited gravity residuals, where effects of tide, pole tide, air pressure and drift were removed, GW: local groundwater, HSL: Baltic Sea level in Helsinki, CPCMB: Modified CPC model, WSFS: Total water storage for Finland, CPC(WSFS): Global model masked for WSFS area, SNOW: Water equivalence of snow, PREC: Precipitation.

Results and comparisons

We can see directly that hydrological data are strongly correlated (Fig. 5. [B-E] and Fig. 4.) In addition, water equivalence of snow correlates with WSFS. Using only regression methods it is not possible to separate the various factors and we need stepwise modelling. Results are given in the table 1. In classical treatments (hereafter TR) we have not used regional or global hydrological data. We compare results of all calculations to TR 1 (-%), where no reduction has been done. First we have calculated regression with local groundwater (TR2) and further with the Baltic Sea level. In the new treatment (TR4 - TR15) we have taken into account regional and global hydrology. First, we have deducted from gravity data the global effect (TR4) and then we have repeated TR2 and TR3. We have used coefficient from TR5 and TR6 and subtracted GW and HLS effect from gravity data (TR7). Next, we have calculated regressions on regional data of WSFS (TR8), snow (TR9), precipitation (TR10) and CPC model masked for WSFS area (TR11). With residuals of TR8 we have done regressions on snow (TR12) and precipitation (TR13). Finally, we have used data of TR7 and a simultaneous regression on snow/precipitation (TR14) have been done.

Summary and conclusions

The classical treatments show that both local groundwater and the Baltic Sea level are important in the data processing. After removing the global hydrological effect the regression coefficient of GW diminished about 30% and change of coefficient for sea level is small (TR2,3,5 and 6). Therefore, we get an important result: 2/3 of hydrological effects are due to local factors. Another interest result is: The effect of Finnish water storage (WSFS) is observable (TR8). The regression gives $0.070 \text{ nms}^{-2}/\text{mm}$, which is comparable to the result shown in Fig. 3. The correlation coefficient of snow is lower, which is understandable due to lack of data in summer. Regression on precipitation seems to be insignificant (TR10). Results using global model CPC(WSFS) show (TR11) that WSFS gives better results as expected. The best result is achieved using gravity data, which is corrected for local factors and simultaneous regression on WSFS and snow.

As conclusion we can say that separation between local and regional hydrology factors seems to be possible, which is remarkably due to high accurate watershed model WSFS. The SG T020 at Metsähovi is capable to monitor regional water storage. Global contribution must be taken into account in the data processing. We have used in this study only one global monthly hydrological model. In future, we continue studies with other global models, which are preferably given more frequently (e.g. Rodell et al., 2004).

However, the most effective hydrological effects are local. The level of local groundwater has been a conventional tool to correct this effect (Virtanen, 2001). Hydrological conditions have slowly changed at Metsähovi since 2003 (Fig. 5 [B,C]). Storms have destroyed the forest around gravity laboratory and a nearby swamp has been dried up. The change of level of groundwater is smaller than before. However, it correlates well with WSFS and with gravity still. In the future, the SG might observe changes in regional water storage more sensitively. The accurate modelling of local hydrology will play an important role in studies of hydrological effects on gravity. Modelling includes soil moisture measurements in wider area, observing weather parameters and detailed studies of structure of bedrock near SG. It means developing complete 3-D hydrogeological-meteorological model for a local hydrological cycle.

We can use gravity methods to improve hydrological models of different spatial extensions, local, regional and global, nationally and internationally.

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