Environmental loading effects on GPS time series

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Metsähovi is a permanent GPS-station in Finland. It is situated on the south coast, with the distance to the Baltic Sea being only 15 km. The effect of tidal loading is small since its distance to the ocean is 800-1000 km, therefore the other loading effects can be seen more clearly. We have studied the effects of non-tidal loading of the Baltic Sea and loading caused by atmospheric pressure and water storages on solid Earth in the height time series of GPS. When all known factors are taken into account, the variance in the GPS height time series diminishes up to 31%. Regression coefficients for the different factors were found to be –0.2 mm/hPa for the local air pressure, -9 mm/m for the nearby tide gauge recording and -0.05 mm/mm for the total water storage of Finland. The effect of local aquifers and global soil moisture need to be studied more carefully, because all the water storages correlate and give therefore similar results.

1 Introduction

The geographic distribution of atmospheric, hydrologic and oceanic masses varies in time and this in turn loads and deforms the surface of the Earth. The interactions between the solid Earth and the changing masses can be seen in gravity but also in vertical motion observed by GPS. There are several studies on the topic in both gravity and vertical motions. Combination of different loading factors has been studied (Van Dam and Wahr, 1998, Dong et al., 1996), as well as loading by single factors, such as continental water (van Dam et al., 2001, Llubes et al., 2004) or atmospheric loading (Boy et al., 1998, Van Dam et al. 1994). There is also a recent study in non-tidal loading by storm surges (Fratepietro et al., 2006). The loading phenomenon especially in gravity at Metsähovi has been studied before by Virtanen and Mäkinen (2003), Virtanen (2004) and Virtanen (2006). Studies of watersheds with gravity can be found in Virtanen et al. (2006).

We have studied the three best known and most significant loading factors in Finland, namely loading caused by air pressure, by non-tidal sea level changes and by changes in the watersheds. These loading factors are compared and correlated with the vertical motion observed by GPS for a time period of 8 years.

2 Methods

To see different factors and their effects on the vertical movements we have used two approaches. The first one is simple regression, which was used for the loading factor time series with the GPS time series. The second approach was to use Green's function formalism and coefficients to calculate and model the loading and create loading time series. After that the loading was reduced from the vertical movements. The flow chart for the data processing can be seen in figure 1.

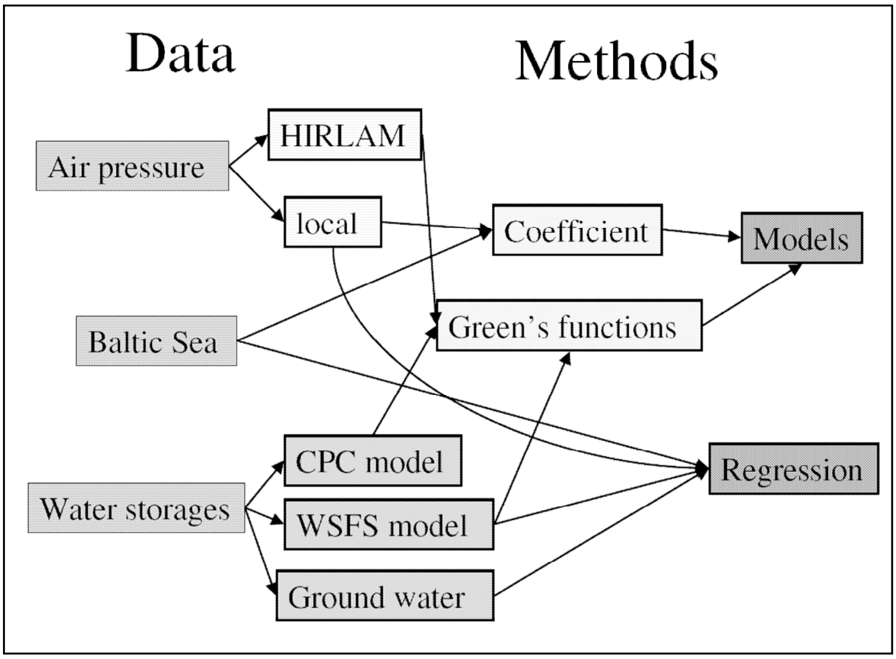

Figure 1. *The flow chart for the data processing, on left the different datasets and on right the processing methods used for them. Data will be explained more thoroughly in chapter 3.*

3 Data

The GPS time series has been calculated by the IGS process center at Jet Propulsion Laboratory (JPL) (available at http://sideshow.jpl.nasa.gov/mbh/series.html). It is shown in figure 2. The time series has been calculated using the GIPSY software and precise point positioning strategy. We used the radial component from here on referred to as height or vertical motion. The only correction to the data was the removal of the trend mainly caused by post-glacial rebound.

There are two sources of air pressure data. The local air pressure (fig. 3) was measured in Metsähovi next to GPS antenna. The numerical weather model data (High Resolution Limited Area Model, HIRLAM) were provided by the Finnish Meteorological Institute. The HIRLAM model has 6-hourly values and for this study we have used a subgrid that covers about 10° around Metsähovi. The grid size is 44 km $\times$ 44 km.

The Baltic Sea level time series is the hourly sea level at the Helsinki tide gauge (fig. 3), measured by Finnish Institute of Marine Research. The tide gauge is about 30 km from Metsähovi, but open sea is only 15 km from the station.

For the water storages there were three different datasets. The local aquifer was observed in a groundwater well at Metsähovi, some tens of meters from the GPS antenna. The regional watershed time series and grids (Watershed Simulation and Forecasting System, WSFS, Vehviläinen and Huttunen, 2002) were provided by the Finnish Environmental Institute, the time series can be seen in figure 3. The WSFS grids were originally daily 1 km $\times$ 1 km datasets and they were smoothed to 0.5° $\times$ 0.5° grids in this study. The global grid data were taken from the Climate Prediction Center (CPC, Fan and van den Dool, 2004). It is a monthly soil moisture data set with 0.5° resolution. CPC model was chosen because, despite its simplicity, it simulates the interannual variability of soil moisture reasonably well (Dirmeyer et al., 2004)

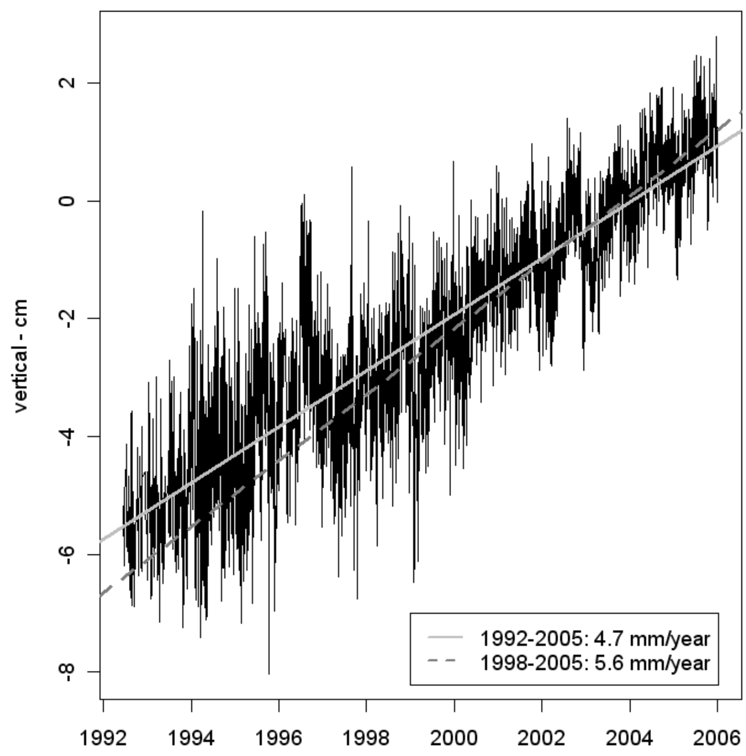

Figure 2. *The radial component of Metsähovi IGS time series 04/1994 – 12/2005, computed by JPL.*

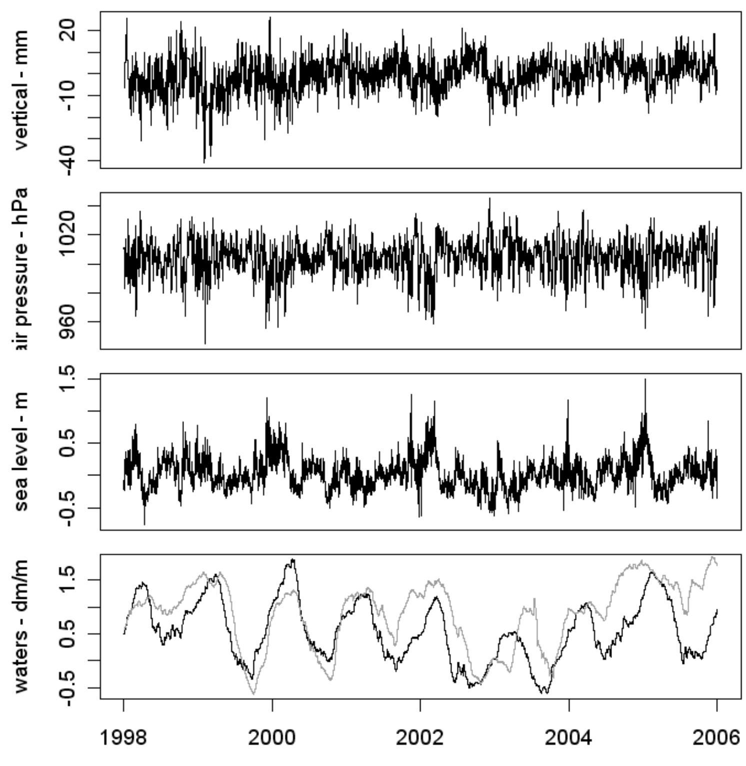

Figure 3. *The time series data 01/1998 – 12/2005. On top the GPS height (standard deviation 7.4 mm) of Metsähovi corrected for land uplift, second from top is the local atmospheric pressure, second from bottom the sea level time series of Helsinki tide gauge and at the bottom the total water storage of Finland (black, in dm) and local groundwater in Metsähovi (grey, in m).*

4 Loadings

The air pressure and watershed grids were processed to loading time series using Green's function formalism. The watershed calculations were done with the program NLOADF (Agnew, 1997) using the Gutenberg-Bullen Earth model. The CPC grid was used for the whole time span and a mixed model of CPC and WSFS was used when it was available, starting from June 2003. The sea level time series was transformed to loading by using a simple coefficient (-9 mm/m). For reference, a simple coefficient was also used for the air pressure (-0.23 mm/hPa). The coefficients were taken from previous study with superconducting gravimeter (Virtanen, 2004). To correct the apparent annual variation in the GPS time series a fitted sine function has been used at the institute. We have used it as a reference and to be able to compare our results with previous ones. The maximum of the sine is in September and the amplitude is 3.7 mm. Amplitude of the height change due to CPC loading is 3.8 mm and maximum is also in September, meaning that watersheds (and loading caused by them) are at minimum in the autumn. The calculated loadings for the whole time series can be seen in figure 4 and in figure 5 for the year 2004.

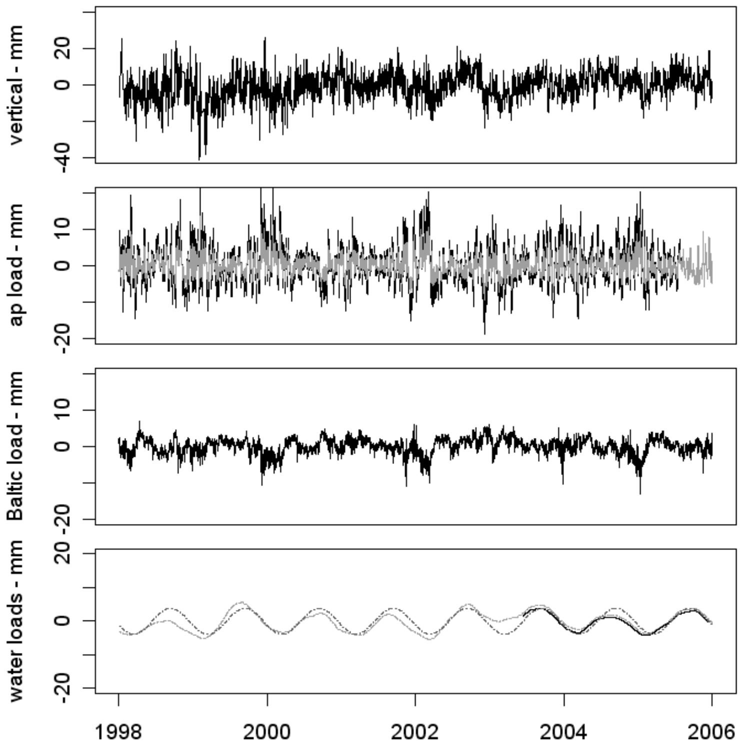

__Figure 4.__ The calculated loadings for the different factor 1998 – 2005. On top the GPS time series, second from top the atmospheric pressure loads from HIRLAM (black) and using coefficient (grey), second from bottom the load caused by Baltic Sea and on bottom the calculated watershed loads (CPC model on grey, mixed model on black, starting 06/2003) and a sine function (grey, dashed line). All the loading factors have the same scale (40 mm).

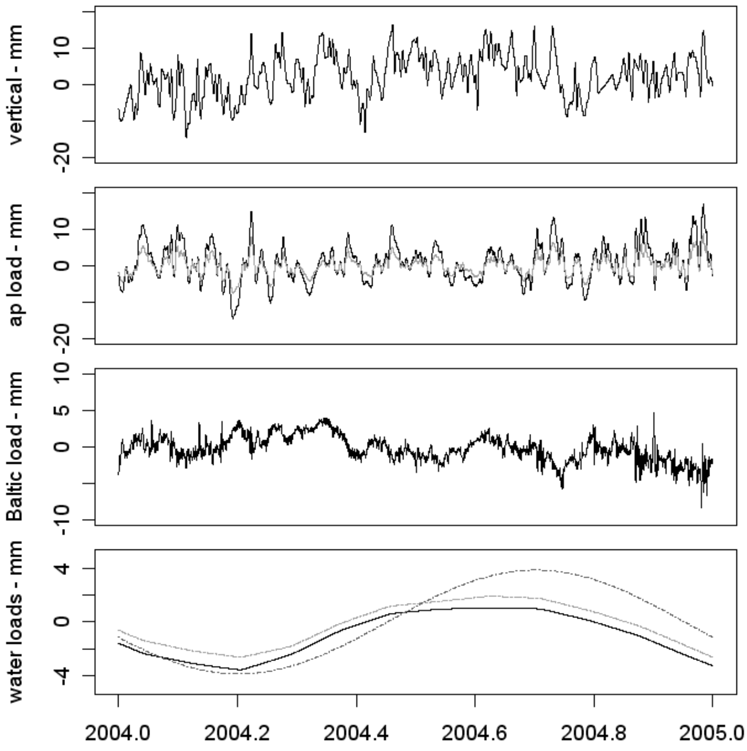

Figure 5. *The same as fig. 4, but for a shorter stretch of time, only year 2004. Note that the scales vary.*

5 Results

Results of the calculations can be seen in table 1. In table 2 the same results are shown for time period of one year. First, the regression was calculated (referred to as "Regression" in tables 1 and 2), starting with the air pressure alone, then with air pressure and sea level and so forth using the time series of figure 3. Second, the time series from the loading calculations (fig. 4) were reduced from the GPS time series (referred to as "Models" in tables 1 and 2). The best result (reduction in variance 31%) is achieved using a simple regression for GPS time series together with air pressure, sea level height and total water storage of Finland.

Table 1. *Results for 1998-2005. The "Regression" –part shows the results of the regression analysis, the different constants, correlation coefficients, standard deviations and reduction in the standard deviation respect to the original time series. The "Models" –part shows the standard deviations when the different loading models were reduced. Abbreviations are explained below the tables.*

1998 - 2005

REGRESSION		**ap** mm/hPa	**sea** mm/m	**gw** mm/m	**tw** mm/mm	**corr**	**std** mm	**%**
	vertical						7,3540	
	ap	-0,2132				0,3352	6,9284	5,8
	ap+sea	-0,2767	-6,8576			0,3854	6,7857	7,7
	ap+sea+tw	-0,2933	-5,2908		-0,047	0,5243	6,2620	14,8
	ap+sea+gw	-0,2763	-6,028	-1,3285		0,4003	6,7392	8,4
	vertical - cpc						6,8523	6,8
	ap	-0,2283				0,3853	6,3232	14,0
	ap+sea	-0,3028	-8,0512			0,4538	6,1061	17,0
MODELS								
	ap	-0,23					6,9311	5,8
	ap+sea	-0,23	-9				6,8431	6,9
	ap+sea+cpc	-0,23	-9				6,4157	12,8
	ap+sea+sinus	-0,23	-9				6,1817	15,9
	ap+sea+tw	-0,23	-9		-0,05		6,4162	12,8
	hrl+sea+cpc	HRL	-9				6,4605	12,1

Table 2. *Same as table 1, but for year 2004.*

2004

REGRESSION		**ap** mm/hPa	**sea** mm/m	**gw** mm/m	**tw** mm/mm	**corr**	**std** mm	**%**
	vertical						5,6048	
	ap	-0,2773				0,5325	4,7438	15,4
	ap+sea	-0,3261	-7,2132			0,5848	4,5463	18,9
	ap+sea+tw	-0,3244	-6,5816		-0,051	0,6496	4,2610	24,0
	ap+sea+gw	-0,3292	-8,9954	2,072		0,5977	4,4935	19,8
MODELS								
	ap	-0,23					4,7548	15,2
	ap+sea	-0,23	-9				4,7098	16,0
	ap+sea+cpc	-0,23	-9				4,3442	22,5
	ap+sea+wsfs	-0,23	-9				4,2950	23,4
	ap+sea+sinus	-0,23	-9				4,4177	21,2
	ap+sea+tw	-0,23	-9		-0,05		4,6982	16,2
	hrl+sea+cpc	HRL	-9				4,3144	23,0
	hrl+sea+wsfs	HRL	-9				4,4757	20,1

vertical	gps radial	*ap*	air pressure	*tw*	total water of Finland
corr	correlation	*hrl*	HIRLAM load	*gw*	ground water
std	standard deviation	*sea*	Baltic Sea	*cpc*	CPC model load
%	reduction of std in %	*sinus*	sine function	*wsfs*	WSFS model load

6 Discussion

The results show that environmental factors can be seen in the GPS vertical time series. The different watershed time series and grids correlate, so the different models give quite similar results. When using loading results for the period of eight years, the fitted sine function gives the best result. For a period of one year, the sine is not the best. We assume that for longer periods the sine is a mean for the process and therefore fits better, averaging out the small variation. For shorter time periods the averaging does not work and therefore the more realistic CPC or WSFS model give the best results.

Van Dam and Wahr (1998) have calculated coefficients for different loading effects in their review paper. They find a difference in loading of coastal and non-coastal sites. For Metsähovi the admittance of air pressure was found to be –0.129 mm/hPa and for Onsala in Sweden –0.122 mm/hPa. We found –0.21 mm/hPa for Metsähovi, this could be due to more detailed and local data. The amplitude of annual sine amplitude due to hydrologic variability was 2.1414 mm for Onsala in Van Dam and Wahr. The hydrologic effect has been calculated using sparser grid and a shorter period of time than we have used and that probably explains the over 1.5 mm difference.

The GPS time series we have used is coarse, we do not have much information about the processing. We assume it is quite standard processing, no corrections for snow on the radome or any other typical northern problems. There may also be a problem with aliased tidal signals due to 24-hour solutions (Penna and Stewart, 2003). Despite all this, the environmental factors diminish the variation.

Atmospheric pressure calculations give interesting results: the simple coefficient calculations gives better results than the complicated HIRLAM-calculation as can be seen in tables 1 and 2. For the longer time series the difference is small, only 0.05 mm in the standard deviation but for the one-year period the difference is 0.18 mm. This could be explained by the fact, that GPS does not see the mass movements in the atmosphere and therefore the local pressure gives adequate results. This has to be studied in more detail with more stations.

Local aquifer behaviour has changed in the past years. A swamp near Metsähovi has been dried and the variation in the groundwater well has diminished remarkably. We expect that in the future we can distinguish between the regional and local watersheds because of this changed situation using both GPS and superconducting gravimeter located nearby. The results of the vertical motion show so far only a weak signal of the difference.

In this study data from only one tide gauge was used to represent the level of the Baltic Sea. In the future, we hope to improve our calculations by using a grid model for the Baltic Sea level height. We presume it will give better results than the time series of one point alone. We are also planning to calculate PPP time series for all the Finnish permanent GPS stations to get more accurate knowledge of the loading processes in Finland.

7 Conclusions

Environmental loading effects can be found in GPS time series. Different factors need to be observed. For example, the loading caused by nearby sea cannot be corrected properly without knowledge of air pressure. The periodic fluctuation found in the time series can be traced back to the fluctuations in the water storages, but it is not fully explained by it. In some cases, e.g. Metsähovi, groundwater correlates well with total water storage and therefore can be used for the water storage correction if no other information is available. The reduction of all the known factors diminishes the variance in the GPS height up to 31 %. With shorter time spans the reduction is even greater.

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