# GGP Ground Truth for Satellite Gravity Missions

by

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## Abstract

The launch of the satellite GRACE heralds a new era of high precision, time-varying, satellite measurements of the Earth's gravity field. An important aspect of the mission is to consider how the predicted high-accuracy gravity data might be validated. Two kinds of validation have been proposed; the first is internal, whereby the data are modeled for self – consistency to verify the internal accuracy of the spherical harmonic coefficients. The second is external validation using data from independent measurements, for example ocean bottom pressure gauges or continental land surface gravity measurements. Here we consider the latter possibility using the European sub-array of the Global Geodynamics Project (GGP) as 'ground truth' for comparison with GRACE. As a pilot study, we use 190 days of 1-hour data from the beginning of GGP (1 July 1997), at 8 European stations. We remove local tides, polar motion and local air pressure and filter the data to 6-hour samples and find that there are large variations between some stations, but also some stations show high correlations over periods of several weeks. For each time sample, the 8 stations are used to interpolate a minimum curvature (gridded) surface that extends over the geographical region. Although promising, no conclusions can yet be made on the accuracy that might be achieved in future comparisons with GRACE.

## Introduction

In preparation for the new generation of satellite gravity missions, Wahr et al. (1998) published an analysis of the expected accuracy of GRACE data. In it they carefully simulated the corrections required to interpret the new data for small time-varying signals such as variations in continental water storage. This was one of the papers that prompted us first to think about the possibility of combining satellite data and ground-based data from the Global Geodynamics Project (GGP). The GGP superconducting gravimeter (SG) network is far too sparse geographically to be suitable as a global gravity field, but there are sub-arrays of instruments, particularly in Asia and Europe, that warrant closer consideration. A preliminary look at the data was presented at the last IUGG meeting (Crossley and Hinderer, 1999).

Here we complete this initial study and develop a method to produce surface maps of the gravity over central Europe. Further developments have since been reported by us at the recent EGS meeting (Crossley et al., 2002) and a more detailed publication is in preparation.

## Review of GRACE Mission

The GRACE (Gravity Recovery and Climate Experiment) is a joint venture of NASA (USA), DLR (Germany), UTCSR (Texas), and GFZ (Potsdam). The spacecraft was launched on

March 16, 2002 from Pletesk Cosmodrome in Russia. The orbit is almost polar and has an initial altitude of about 485 km, giving a short orbital period of 1.5 hr. There are two satellites 250 km apart, linked to each other by microwave and to other satellites and ground-based stations by GPS positioning.

Satellite gravity missions traditionally have targeted the largest sources of variability in the Earth's gravity field: atmospheric mass redistribution, long period ocean and solid Earth tides, post glacial rebound, large scale vertical tectonics, and changes in Arctic / Antarctic ice volumes. With the very high accuracy anticipated of GRACE data, it is hoped that other effects can be determined, i.e. changes in continental water storage, the variability of ocean bottom pressure, and the redistribution of snow and ice. These changes will be monitored down to ground distances of 100-200 km and intervals of 2-4 weeks.

The methodology follows the following sequence (for details, see Wahr et al., 1998):

- assume a density change $\Delta\rho$ in a layer of thickness H (10 -15 km) surrounding the Earth's surface (i.e. the lower atmosphere and upper hydrosphere).
- convert $\Delta\rho$ to a surface density distribution $\Delta\sigma$ by integrating over H.
- expand $\Delta\sigma$ in spherical harmonics, with coefficients ($\hat{C}_\ell^m$, $\hat{S}_\ell^m$)
- relate these harmonics to the harmonics ($C_\ell^m$ , $S_\ell^m$) of the gravity field, determined from the satellite orbit, approximately every 14 days.
- deduce $\Delta\sigma$ from ($\hat{C}_\ell^m$ , $\hat{S}_\ell^m$), and thus infer $\Delta\rho$ by assuming H.

Note that in $\Delta\sigma$ we cannot distinguish between the type of source, e.g. water, ice, or snow. It is also evident that the GRACE data will be time-aliased if there is any unmodeled variation of gravity on time scales less than 2 weeks (as seems probable for the atmosphere and oceans).

One of the examples considered by Wahr et al., is for Manaus, Brazil, in the Amazon River Basin. The accuracy of the GRACE recovery should be equivalent to 2 mm of water at wavelengths longer than 400 km. The errors rise rapidly; from about 10 cm water equivalent at 200 km to more than 100 cm at 100 km. This suggests that to be competitive and useful, ground-based gravity measurements will have to satisfy two criteria (a) to cover wavelengths between 100 and 1000 km and (b) reach accuracies of less than 0.4 μgal at wavelengths between 200 and 300 km. If both conditions are satisfied, then the errors of ground-based gravity and projected satellite gravity will overlap, and we can claim that ground-based (in this case GGP) gravity can be used to 'validate' satellite measurements.

**European GGP Data Sets**

The stations used in this study are shown in Figure 1; they are BR (Brasimone), BE (Brussels), MB (Membach), ME (Metsahovi), PO (Potsdam), ST (Strasbourg), VI (Vienna), and WE (Wettzell). Most of these are relatively evenly spaced in the middle of the European landmass, while Metsahovi is somewhat isolated at a distance from the others. Some stations are no longer operating; BE has been retired and PO was moved to Sutherland, South Africa. Also the instrument at Wettzell has been replaced with a newer model and a new station, Moxa, was started in 2000.

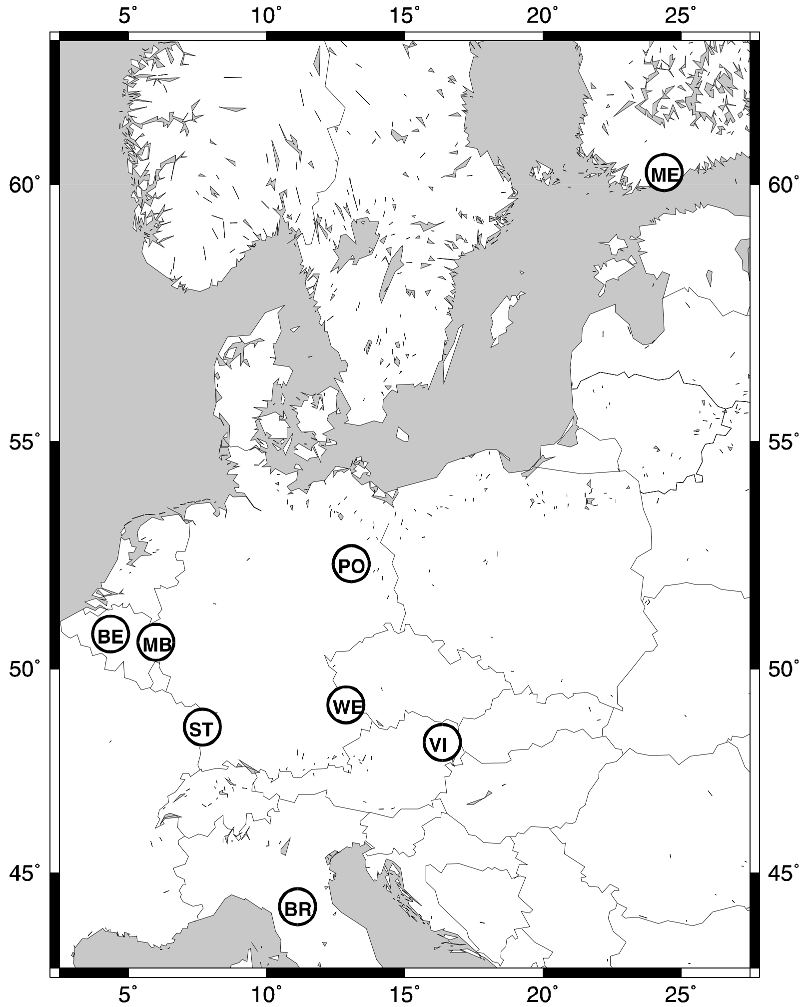



Figure 1. GGP stations from July 1997 – January 1998.

The distribution, or spacing, of the 8 stations taken in pairs, is plotted as a histogram in Figure 2. The distance range of 200 – 1000 km is well covered, but the inclusion of a single distant station (ME) extends the coverage up to 2000 km. Bernard Ducarme (personal communication, 1999), supplied the original series through the International Center for Earth Tides (ICET). They had been corrected for major problems and decimated to 1 hour (Figure 3).

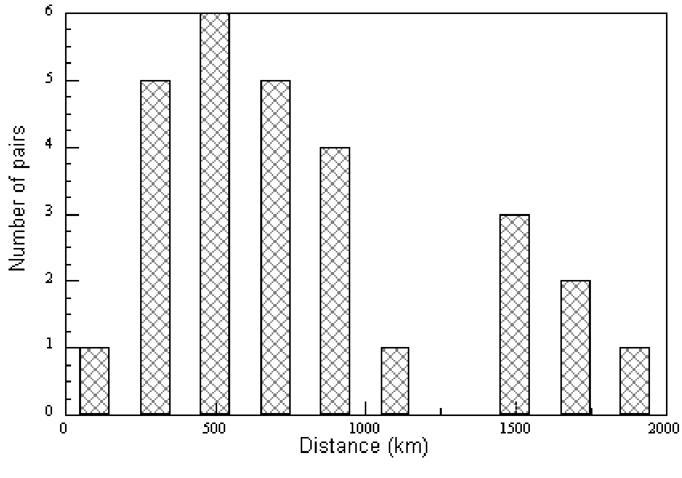



Figure 2. Station distribution, by pairs.

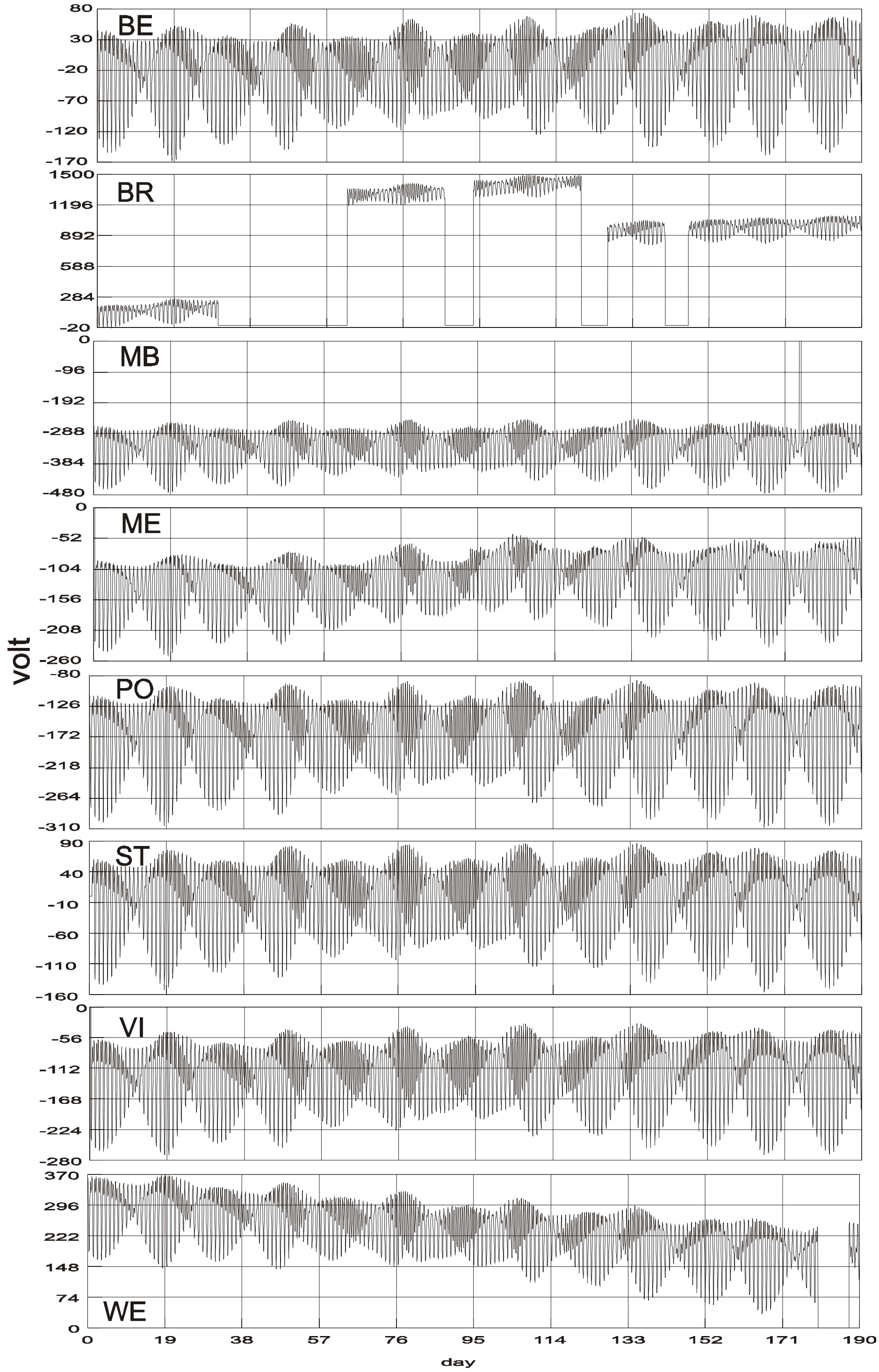



Figure 3. Initial 1-hour gravity data for 8 GGP stations, July 1997 – January 1998.

The first step is to remove a synthetic, or modeled, tide from each station. We do this using local tidal gravimetric factors (δ,κ) obtained from independent analyses for all waves with periods up to, and including, a month. For semi-annual and longer periods we use nominal values of (1.16, 0) to avoid minimizing the residual annual signals. We also remove the effect of local atmospheric pressure using a nominal admittance of –0.3 μgal $mbar^{-1}$. The residual series are displayed in Figure 4. It is clear that two stations, Brasimone and Wettzell, have special problems: BR has large data gaps and offsets and WE has a large negative drift that appears almost linear.

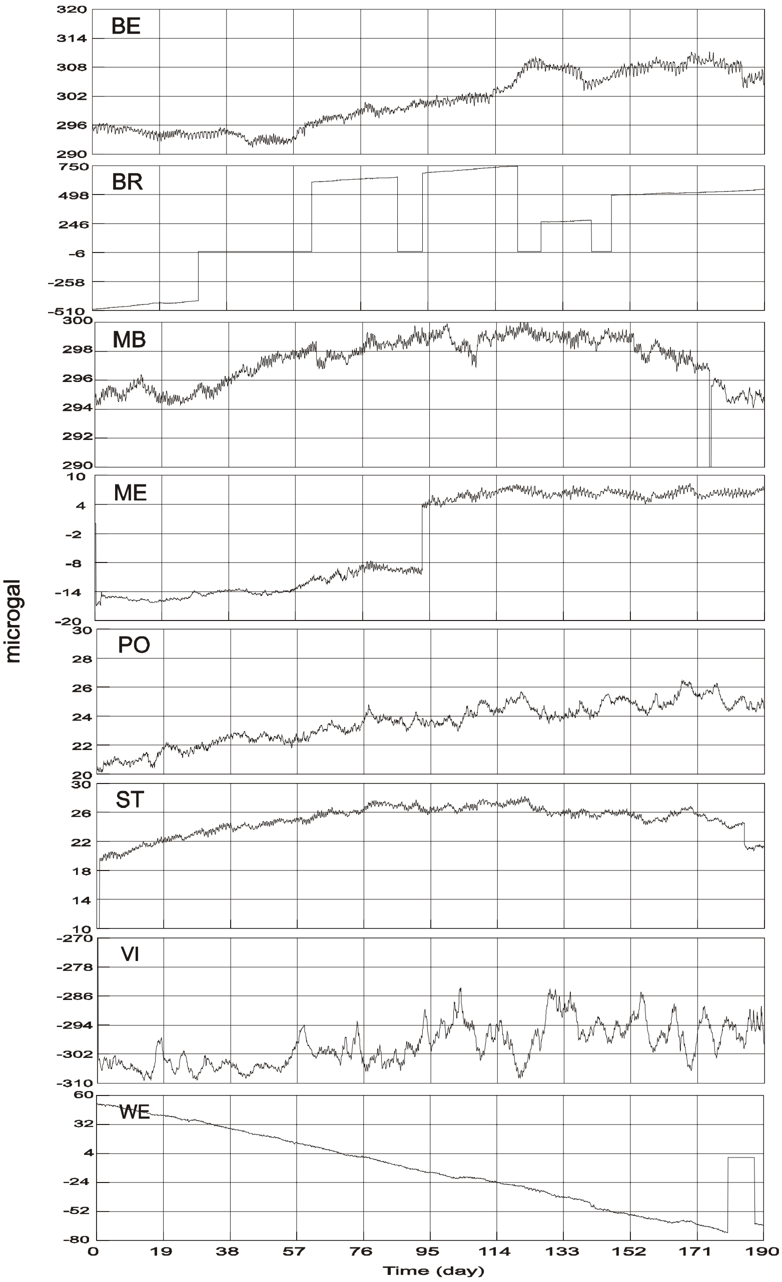



Figure 4. Gravity residuals after removal of tides and local pressure.

For both stations BR and WE, we fit simultaneously a linear drift function and a series of offsets at fixed time locations; this is done iteratively to arrive at the correcting functions shown in Figure 5. None of the other stations had drifts removed, but the other offsets in Figure 4 were corrected. IERS-derived polar motion was also subtracted from each data set. The final 1-hour residuals are shown below in Figure 6.

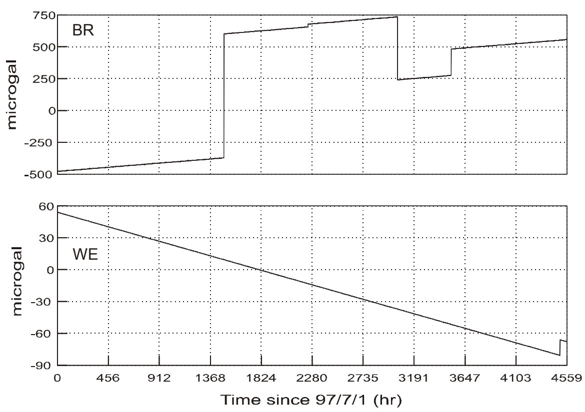



Figure 5. Corrections removed from 2 stations.

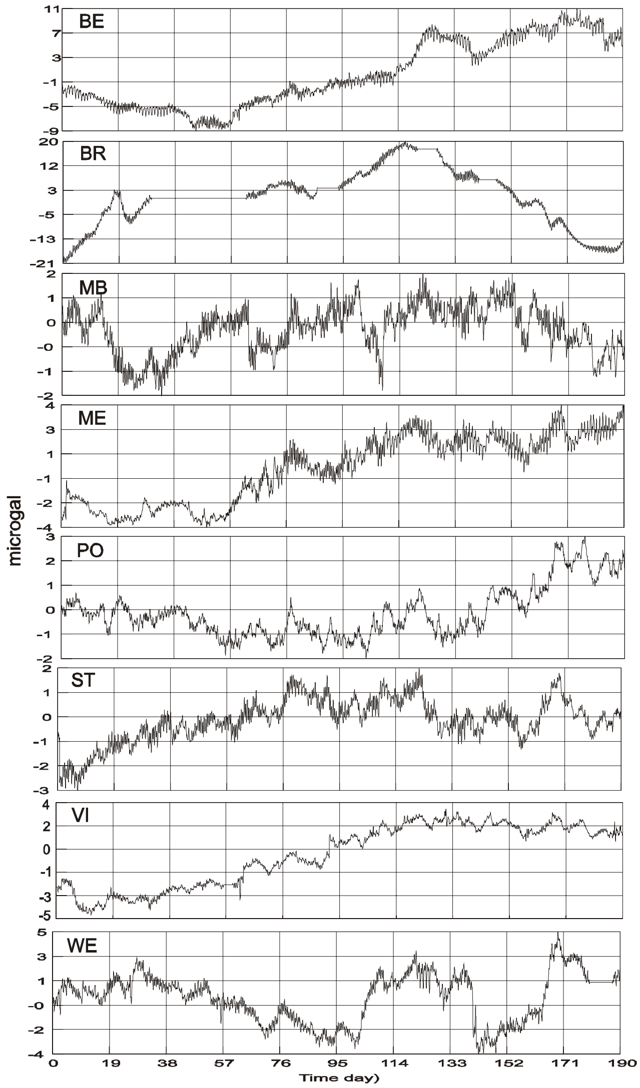
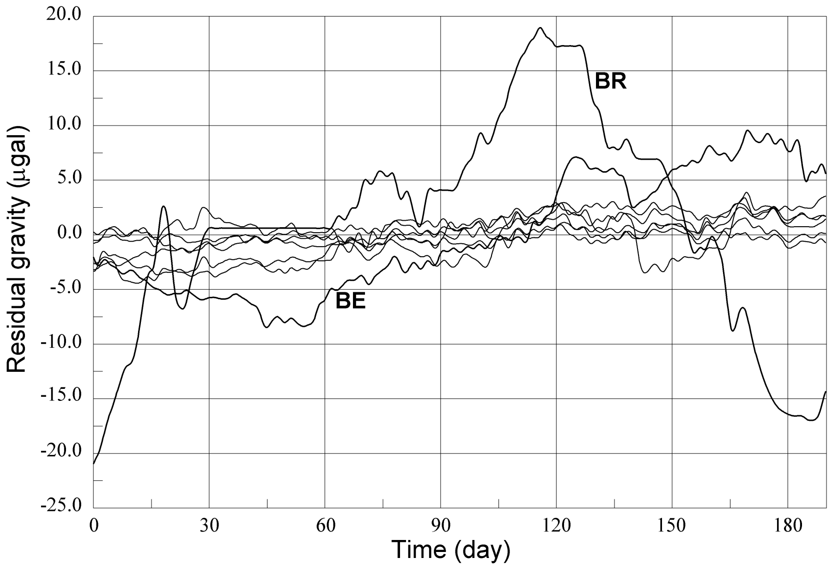



Figure 6. Gravity residuals after removal of offsets and polar motion.




We now decimate the series to 6 hour samples using a filter with a cut-off period of 1 day (this is legal), thus removing the small residual tidal fluctuations (Figure 7). The 6-hour sampling was chosen because we intend to do a second step of adding global pressure effects from 6-hour meteorological data (but this is not done here).

Figure 7. Filtered gravity residuals superimposed

Thes residuals in Figure 7 are displayed at the same scale and we can see that 2 stations, BE and BR, account for the largest variability in the data. This is clear in Figure 8 where the root mean square values of the residuals are shown together. We refer to the stations VI, ME, WE, ST, PO and MB as as the 6 'best stations'. This division is clearly consistent with what we know of the stations themselves. Station BE was one of the first stations to be installed and it has experienced a variety of problems during its long installation at the Royal Observatory in Brussels. The long term gravity residuals are probably less reliable than at most of the other stations. Also, as mentioned above, station BR had many problems due to the data gaps, drift and offsets that are not completely correctable after the fact. Therefore we do not have a lot of confidence in the BR residuals in Figure 6.

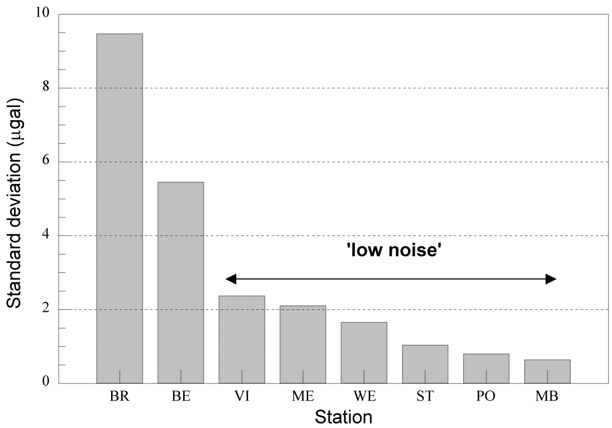



Figure 8. Station variability

If therefore we restrict attention to the 6 'low-noise' stations, we can plot their residuals on a scale of –5 to +4 μgal (Figure 9). Stations WE and ME now show greater variability than the other central stations MB, PO, ST, and VI.

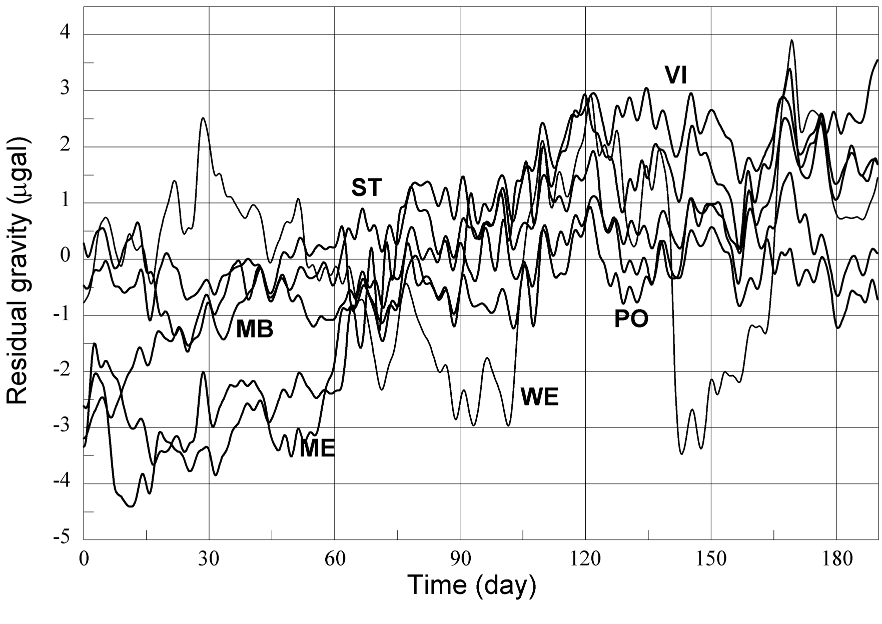



Figure 9. Six best stations, July 97 – Jan 98.

Despite the clear variability between sites, there are also significant similarities. For example, if we consider the data between days 70 and 100 (a month), and remove the local means for this month from each station, the coherence in the residuals can be quite striking (Figure 10). These stations reflect common variations with periods of several days, and this coherence persists for several weeks. The origin of these coherent signals is not known at this time, but the atmosphere must be considered the most likely source.

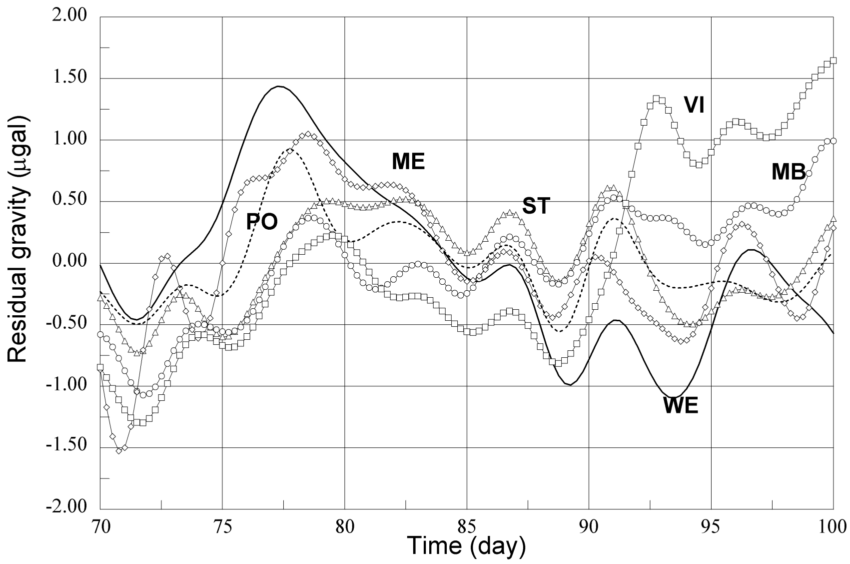



Figure 10. Six best stations over 1 month, local means removed.

**Discussion and Conclusions**

In the oral presentation of this paper, the data was taken one stage further. For each 1 day interval, the residuals at each station were interpolated to a uniform grid using a minimum curvature algorithm. This surface was then color coded and presented as an animation of bitmap images in the form of a movie. Space does not permit this movie to be show here, but it gives an idea of the time evolution of each station's gravity. Many things are yet to be done:

(1) Smooth the gravity surface to simulate the wavelengths that GRACE would be able to see in the European network of 8 stations. Smoothing can be as simple as fitting a polynomial surface, or as complicated as generating spherical harmonic coefficients and the pretending GRACE is trying to see this surface from 485 km.
(2) Remove instrument drift at all the stations, in addition to the 2 stations in Figure 5.
(3) Include the effect of global atmospheric pressure changes, in addition to the local correction.
(4) Consider other local signals, such as hydrology, that might not be seen by GRACE.
(5) Compare GGP data from 2000-2002 with actual gravity field models from CHAMP, which is now producing similar data to GRACE, but at a lower accuracy.

Our conclusion is necessarily tentative, but we believe that there are some promising features of GGP data that may be relevant to GRACE once a more sophisticated analysis is done.

**Acknowledgments**

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