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# Analysis of a ten-year (1997-2007) record of time-varying gravity in Strasbourg using absolute and superconducting gravimeters: new results on the calibration and comparison with GPS height changes and hydrology

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1 **Analysis of a ten-year (1997-2007) record of time-varying gravity in Strasbourg using**  
2 **absolute and superconducting gravimeters: new results on the calibration and comparison**  
3 **with GPS height changes and hydrology**

4  
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15

16

17 **Abstract**

18 This paper is devoted to a detailed investigation of a continuous record spanning more than 10 years  
19 (1997-2007) of the Strasbourg superconducting gravimeter (SG GWR C026). We will first show  
20 the results from various scale factor experiments using parallel registrations with an absolute  
21 gravimeter (AG FG5#206). These results will allow us to discuss the time stability of the calibration  
22 of the SG. Second, we will superimpose the AG and SG measurements to infer the long-term  
23 instrumental drift behavior of the SG but also the seasonal effects present at our station. These long-  
24 term effects will be discussed in terms of height changes by using collocated GPS measurements  
25 (since 1999) and in terms of hydrology (mainly with large scale hydrological models).

26 **Keywords:** SG calibration, inter-comparison of geodetic techniques, global hydrology model, GPS

27

28 **1. Introduction**

29 Since July 1996 the superconducting gravimeter (SG) GWR C026 is recording the time-  
30 varying gravity at the French J9 observatory in Strasbourg in the framework of the Global  
31 Geodynamics Project (GGP) (Crossley et al., 1999; Hinderer et al. 2004), although we are using  
32 here only gravity records since March 1997, after the upgrade of the acquisition system. In parallel  
33 to the SG measurements, absolute gravity (AG) measurements are performed routinely several

1 times per year using the ballistic instrument FG5 #206. It is well-established in the gravimetric  
2 community that parallel AG measurements with the continuous SG records are primordial to  
3 estimate and check the long-term stability of the SG instrumental drift. Besides, intensive AG  
4 recording during several days are regularly performed to estimate the calibration factor of the SG  
5 and to check its stability in time. The 10-year SG records now available at the J9 site highlight the  
6 presence of seasonal effects that we will interpret in terms of hydrology. Next, the long-term effects  
7 and the seasonal variations are investigated in the vertical displacement given by GPS data. The  
8 permanent GPS that belongs to the French geodetic network has been recorded since 1999 right on  
9 the top of the building of the gravity station. The collocated GPS height changes help in separating  
10 the gravity variation due to the vertical motion of the station from the variation due to the mass  
11 redistribution.

12

## 13 **2. SG calibration**

14 The scale factor calibration of a relative SG can be done in several ways: 1/ by monitoring  
15 the tides for a long period (2-3 years) and then use a well-known tidal amplitude (e.g. the diurnal  
16 wave  $O_1$ ) to calibrate the SG (Melchior, 1994); 2/ the use of a calibration platform (Falk et al.,  
17 2001); 3/ by moving an external mass (Achilli et al., 1995); 4/ by comparison with a reference  
18 instrument, especially an absolute gravimeter (Hinderer et al., 1991). Comparison with an absolute  
19 gravimeter is the most widely used method (e.g. Imanishi et al. 2002, Fukuda et al. 2005) to  
20 calibrate a relative gravimeter as it does not disturb the observational series of the SG and it also  
21 enables the investigation of the long-term drift of the SG (Francis et al., 1998). Since 1997, several  
22 calibration campaigns were performed at the J9 site. The time-length of the parallel registrations  
23 must be long enough (at least 5 days) to reach a reasonable accuracy on the scale factor estimate  
24 (Francis and van Dam, 2002). Therefore only the intensive campaigns, meaning at least 5 days of  
25 continuous AG measurements, are considered as useful for the scale-factor determination. The

1 usual procedure to estimate the calibration factor is by least-squares fitting of the SG records to the  
2 AG data points according to:

$$3 \quad y_i = a + bx_i, \quad (1)$$

4 where  $y_i$  stands for the AG data and is expressed in  $\text{nm/s}^2$ ,  $x_i$  for the SG feedback output in volt (V),  
5  $b$  is the scale-factor expressed in  $\text{nm/s}^2/\text{V}$  and  $a$  is the offset in  $\text{nm/s}^2$ . As the fit is better on high  
6 gravity signals, the tides are not removed from the signals. We use the set gravity values of the AG  
7 resulting from a statistical processing of the drop gravity values; a rejection criterion of outlier sets  
8 is applied at  $1\sigma$  (standard deviation), prior to the calibration. From the 1-min sampled SG records,  
9 we derive the SG value corresponding to the central time of the AG set before applying the linear  
10 least-squares method is applied. The raw SG records must have been corrected for any earthquake  
11 occurring at the time of calibration. AG set values are not perfect but contain some errors that we  
12 computed from the drop scatter. These standard deviations are used in the least-squares inversion in  
13 order to take into account the AG measurement errors; some clock problems can occur during the  
14 calibration experiments for instance that generate an error around  $1 \text{ nm/s}^2$  (Van Camp et al. 2005).

15 The estimated scale factors for the various calibration campaigns are plotted in Fig. 1 for the  
16 period September 2002 – May 2008. As expected, the scale factor is stable in time, as there should  
17 be no changes in the magnetic fields of the upper and lower coils inducing the levitation of the  
18 niobium sphere inside the SG.

19 Note that because of the low instrumental drift of the SG (less than  $15 \text{ nm/s}^2$  per year; see  
20 next part) and the short duration of each calibration campaign (the longest one was 12 days), this  
21 instrumental drift does not need to be removed for the linear regression fitting. The induced error  
22 lies within the error bars of the scale factors.

23 The weighted mean value leads to a scale factor of  $-790.7 \pm 2.6 \text{ nm/s}^2/\text{V}$ , corresponding to  
24 a relative precision of 0.3 %. We have checked the decrease of the relative calibration error with the  
25 number of days of parallel AG measurements in Fig. 2 for the December 2004 campaign. Note that  
26 this calibration campaign was performed before the occurrence of the Sumatra earthquake. After 7

1 days of parallel measurements, the uncertainty merely does not decrease any more and tends to 0.7  
2 % for this specific campaign.

3 If we do not take into account the AG drop standard deviations, we obtain a value of -791.5  
4 +/- 0.5 nm/s<sup>2</sup>/V for the calibration factor which corresponds to a relative uncertainty of 0.06 %. In  
5 the past, Amalvict et al. (2001) performed estimates of the SG scale factor for the period March  
6 1997 – April 2000. By combining their values with ours, we obtain the scale factors plotted in Fig.  
7 1 (b) and the averaged value for the 10 years is -791.8 +/- 0.25 nm/s<sup>2</sup>/V. This relative uncertainty is  
8 smaller than the 0.1 % accuracy required for a number of geophysical studies (nearly diurnal free  
9 wobble, ocean and atmospheric loading, polar motion, anelasticity and tides...) as stated by Francis  
10 et al. (1998) and Baker and Bos (2003).

11

### 12 **3. SG instrumental drift**

13 The SGs are known to be stable in time, as confirmed by the previous session, and to have a  
14 low drift. They are therefore useful instruments to record long-period geophysical signals (e.g.  
15 Richter et al., 1995). By superposition with AG measurements, we can retrieve the purely  
16 instrumental part of the observed SG trend. This instrumental drift is defined as the total SG trend  
17 minus the observed trend in AG measurements. The AG trend is interpreted as a geophysical signal  
18 that could correspond to some long term deformations. Amalvict et al. (2004) have shown that the  
19 gravity was increasing in time at a rate of about 15.7 nm/s<sup>2</sup>/yr from the beginning of 1997 to the end  
20 of 2002. In this paper, our data are spanning from the beginning of 1997 to the end of 2007, and the  
21 gravity increase observed in AG measurements is about 13.3 nm/s<sup>2</sup>/yr, while the SG instrumental  
22 drift is deduced to be 13.9 nm/s<sup>2</sup>/yr. In Fig. 3 we show the superposition of AG measurements with  
23 the SG record at Strasbourg from 1997 to 2007 before and after removal of the SG instrumental  
24 drift. Both AG and SG records have been corrected for the local tides, local atmospheric pressure  
25 using a barometric admittance of -3 nm/s<sup>2</sup>/hPa and for the polar motion effect. The pole tide,  
26 induced by polar motion and length-of-day variations, is modeled using daily Earth orientation

1 parameters provided by the International Earth Rotation Service (EOPC04 series). The same  
2 processes must be applied to both datasets for a rigorous comparison. The SG data were calibrated  
3 using a scale factor of  $-792 \text{ nm/s}^2/\text{V}$ , based on the previous AG calibration campaigns and were first  
4 corrected for major instrumental perturbations such as gaps, spikes or offsets following the classical  
5 procedure (Crossley et al. 1993) and were decimated to hourly samples using a low-pass filter with  
6 a cut-off frequency of 12 cycles per day.

7 As we can observe on these plots, the gravity is smoothly increasing during the year 2001  
8 and the observed drift seems to be different before and after 2001. This kind of feature could  
9 suggest that the SG instrumental drift would be better modeled by an exponential function of time  
10 as suggested previously by Van Camp and Francis (2006). However, when looking at the observed  
11 gravity increase in the AG data, we can notice that the gravity rate is also different before and after  
12 April 2001.

13 Before April 2001, the observed gravity increase from the AG measurements is  $11.7$   
14  $\text{nm/s}^2/\text{yr}$  leading to an SG linear instrumental drift of  $13.1 \text{ nm/s}^2/\text{yr}$ . From the beginning of 2002 to  
15 the end of 2007, the observed gravity increase is only  $1 \text{ nm/s}^2/\text{yr}$  and the SG instrumental drift is  $8.4$   
16  $\text{nm/s}^2/\text{yr}$ . From before and after 2001, the gravity increase rate has dropped by a factor 10. The  
17 reason for this change of behavior has not been explained yet. Some local effects have to be  
18 investigated like, for instance, the local hydrology impact in 2001.

19

#### 20 **4. Seasonal effects**

21 Besides the long-term drift of the time-varying gravity, the seasonal effects clearly appear in  
22 the SG residuals plotted in Fig. 4 (a) and (b). These seasonal effects can mostly be explained by the  
23 global hydrology loading as the contribution of the continental water storage changes (soil-moisture  
24 and snow) to gravity variations is one of the largest signal at seasonal timescales (Boy and  
25 Hinderer, 2006). Contrary to the part 3 when comparing SG with AG with the use of a constant  
26 barometric admittance, here we correct gravity variations for global atmospheric and induced non-

1 tidal oceanic loading effects (Boy et al., 2002; Boy and Lyard, 2008) using global surface pressure  
2 field provided by the European Centre for Medium-range Weather Forecasts (ECMWF), and sea-  
3 surface height from the Toulouse Hydrodynamic Unstructured Grid Ocean model (HUGO-m)  
4 barotropic ocean model (Carrere and Lyard, 2003) with a resolution of 0.5 degree and a temporal  
5 sampling of 6 hours. In Fig. 5 we have superimposed the obtained SG residuals with the global  
6 hydrology effects estimated from two different global models: ECMWF with temporal sampling of  
7 6 hours and changing spatial sampling with the upgrades of the model (from 1.125 degree in 1997  
8 to less than 0.25 after 2006), and GLDAS/Noah (Global Land Data Assimilation System) (Rodell et  
9 al., 2004) with spatial sampling of 0.25 degree and temporal sampling of 3 hours. The outputs of  
10 these models consist in soil moisture content, in equivalent snow height, and to a smaller extend  
11 canopy water for GLDAS model. The hydrology effect is modeled as a thin-layer process acting on  
12 a spherical Earth surface for which we model the direct Newtonian attraction and the elastic  
13 loading. The local Newtonian contribution will have a sign different whether the station is buried in  
14 the ground or if the station is located at the surface. In the case of the J9 SG site, the station is  
15 below the ground, so an excess of water mass will decrease the gravity. Note that the local  
16 Newtonian attraction could be improved by taking into account the local topography of the site  
17 (Longuevergne, 2008).

18       There is a correlation between our SG residuals and these estimated continental water  
19 storage loading effects. The correlation with the ECMWF model is of 42 % for the period March  
20 1997 - April 2001 and is of 64 % for the period November 2001 – November 2007. The correlation  
21 with GLDAS model is 46 % for the period March 2000 - April 2001 and 37 % for the period  
22 November 2001 – December 2006. The ECMWF hydrological model better fits the SG residuals  
23 than GLDAS model. The difference between both hydrology models is as large as the difference  
24 between the computed hydrological effect and the gravity residuals. These discrepancies may be  
25 associated with local hydrology effects (see Longuevergne et al., 2008), which are not taken into  
26 account in global models. The atmospheric loading contribution should also be modeled using a



1 three-dimensional model (Neumeyer et al., 2004) of air masses attraction in the neighborhood of the  
2 gravimeter and a two-dimensional model of air masses attraction (Boy et al., 2002) far from the  
3 station.

4

## 5 **5. GPS height changes**

6 We can explain most of the observed seasonal effects in gravity using a global hydrology  
7 model. Besides the purely Newtonian attraction, the global water masses contribute to elastically  
8 deform the Earth's surface. Such a vertical displacement should be visible by GPS. Above the SG  
9 instrument at Strasbourg J9 site, a GPS antenna has been recorded since 1999.

10 Generally, the hydrological loading caused by an excess in the soil water content leads to a decrease  
11 in height (subsidence) observable by GPS and to an increase in gravity observable by SGs. Hence  
12 the ratio of gravity change versus height change is always negative for this type of load (de Linage  
13 et al. 2007).

14 However since the Strasbourg SG station is below the ground, any excess of local water mass due  
15 to rain for instance will in fact decrease the gravity since the Newtonian local contribution  
16 dominates (see Boy & Hinderer 2006; Longuevergne et al. 2008). This is why the signs of height  
17 and gravity are expected to be the same for our station (see Fig. 6).

18 We analyzed the GPS data from J9 site as well as other French (RENAG,  
19 webrenag.unice.fr) sites and European stations from the International Global Navigation Satellite  
20 System Service (IGS) network. We analyzed the GPS vertical displacement using the version 10.33  
21 of GAMIT software. GPS Daily solutions are then combined using GLOBK software (Herring et  
22 al., 2006) to obtain times series of positions in an International reference frame, ITRF2005  
23 (Altamimi et al., 2007). We have not applied any loading correction in order to compare the  
24 obtained displacements with our gravity residuals as obtained in section 3.

25 Before 2001, the GPS vertical displacement is very noisy, so we compare the GPS height  
26 changes with the SG residuals from 2002 only. They are superimposed in Fig. 6 where the daily

1 GPS solutions were smoothed using an FFT filtering method. As expected, the seasonal effects are  
2 also observed in the GPS height changes with a positive correlation between vertical displacement  
3 and gravity.

4 If the seasonal effects observed in GPS height changes are due to the global hydrology  
5 loading, there must be a correlation between the elastic loading effect in gravity and the vertical  
6 displacement. We have plotted both signals in Fig. 7. The gravity contribution due to elastic  
7 hydrology loading has been computed using GLDAS global model. This purely elastic gravity  
8 effect has been converted into vertical displacement based on the ratio  $-2 \text{ nm/s}^2/\text{mm}$  which is a  
9 mean value of the ratio over a large spectral range (see Fig. 5 of de Linage et al. 2007). The  
10 seasonal variations observed in the GPS height changes are hence mostly explained by the elastic  
11 loading of the continental water masses.

12

## 13 **6. Conclusion**

14 The calibration factor of SG C026 in Strasbourg is very stable in time and has been  
15 determined to be  $-791.8 \pm 0.25 \text{ nm/s}^2/V$  (0.03 % relative precision) for the period March 1997-  
16 May 2008. From the beginning of 1997 to the end of 2007, the SG instrumental drift is equal to  
17  $13.9 \text{ nm/s}^2/\text{yr}$ . The observed AG gravity trend is different before and after April 2001, respectively  
18 of  $11.7 \text{ nm/s}^2/\text{yr}$  and  $1 \text{ nm/s}^2/\text{yr}$ , suggesting that some unexplained local effects occurred during this  
19 period. In addition to long term trends, there are seasonal effects observed in the gravity residuals  
20 site which are mostly due to the local hydrological Newtonian effects, while the elastic effect of the  
21 continental water storage prevails in the observed seasonal GPS height changes at J9. The 2001  
22 gravity increase cannot be explained by the global hydrological effects. Some other local effects  
23 must be investigated.

24

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1 **Figure caption**

2 Fig. 1 Time stability of the calibration factor of the GWR C026 at Strasbourg (J9). (a) From  
3 September 2002 to May 2008. The column bars represent the number of sets used for the inter-  
4 comparison with the AG measurements and the number indicates the number of days the parallel  
5 registration with the AG was performed. The least-square fitting was made with the AG standard  
6 deviations as weights. (b) From March 1997 to May 2008. The averaged scale factor value is  $-791.8$   
7  $\pm 0.25 \text{ nm/s}^2/\text{V}$ . Each observation is considered having the same weight (equal to one) in the least-  
8 square adjustment.

9 Fig. 2 Relative precision on the scale factor of the C026 superconducting gravimeter at Strasbourg  
10 in function of the number of observation days of absolute gravity measurements with the FG5 #206  
11 during the December 2004 calibration campaign.

12 Fig. 3 Superposition of AG FG5#206 measurements and SG GWR-C026 time-varying gravity at  
13 Strasbourg from March 1997 to December 2007. The upper plot represents the SG time-varying  
14 gravity without correction of the SG instrumental drift and the lower plot represents the  
15 superposition after removing the instrumental part from the SG trend. The estimated linear  
16 instrumental drift between 1997 and 2007 has been estimated to  $13.9 \text{ nm/s}^2/\text{yr}$ .

17 Fig. 4 Superposition of AG FG5#206 measurements and SG GWR-C026 time-varying gravity at  
18 Strasbourg (a) before April 2001 and (b) after 2001. The left-hand plots represent the SG time-  
19 varying gravity without correction of the SG instrumental drift and the right-hand plots represent  
20 the superposition after removing the instrumental part from the SG trend. The estimated linear  
21 instrumental drift of the SG between 1997 and April 2001 is  $13.1 \text{ nm/s}^2/\text{yr}$ , and between 2002 and  
22 end of 2007 it is  $8.4 \text{ nm/s}^2/\text{yr}$ . The observed gravity increase rate before April 2001 is  $11.7 \text{ nm/s}^2/\text{yr}$   
23 and after 2001 it is  $1 \text{ nm/s}^2/\text{yr}$ .

24 Fig. 5 SG gravity residuals and global hydrology effects at Strasbourg, J9 site before (left-hand) and  
25 after (right-hand) 2001. In blue we have represented the continent water content effect using  
26 GLDAS global model and in red using the ECMWF model of soil moisture and snow.

- 1 Fig. 6 SG gravity residuals (in black) and GPS height changes (in blue) observed at Strasbourg, J9  
2 site from 2002 to late 2007. Note the positive correlation between both signals due to the fact that  
3 the local hydrological masses dominate and are located above the SG.
- 4 Fig. 7 GPS height changes (in blue) and elastic loading effect from the global GLDAS hydrology  
5 model (in black). The hydrology elastic loading has been multiplied by  $-0.5 \text{ mm/nm/s}^2$  in order to  
6 convert the elastic gravity effect into vertical displacement.



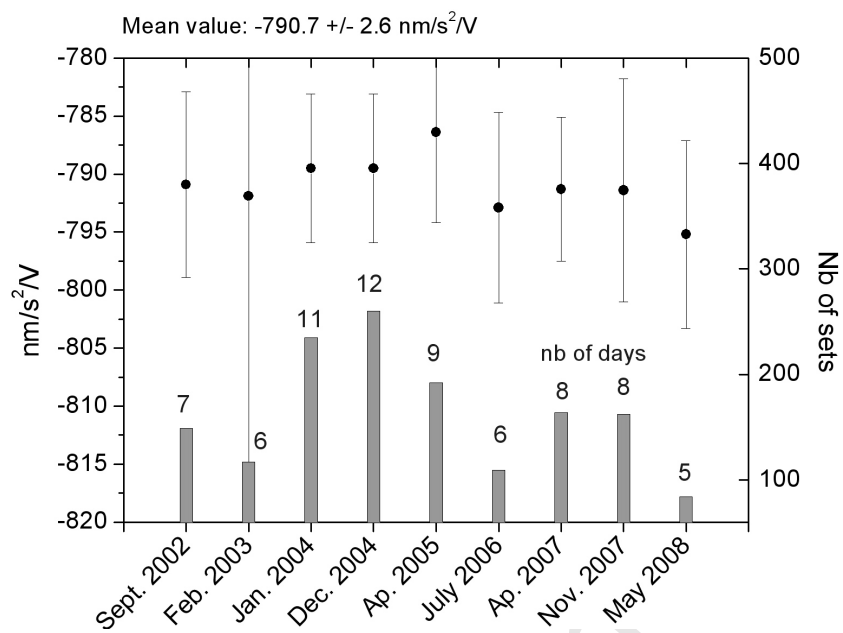


Fig.1 (a)

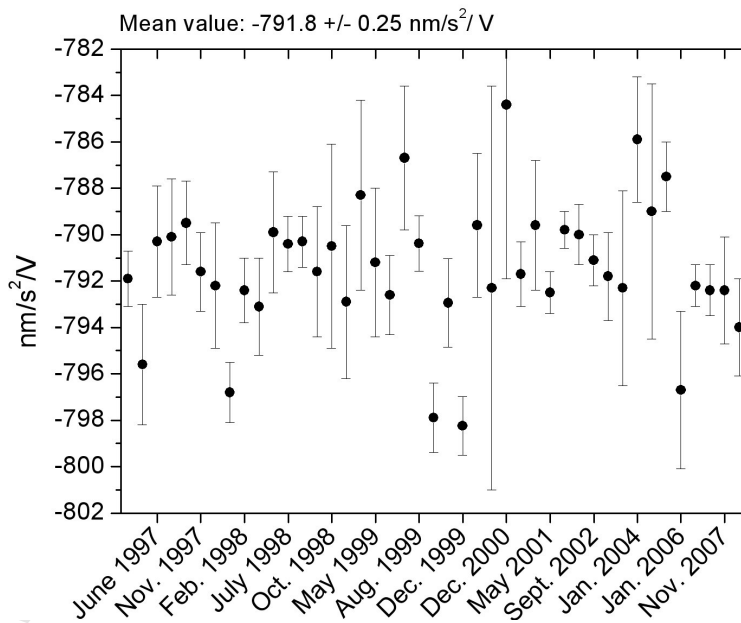


Fig. 1 (b)

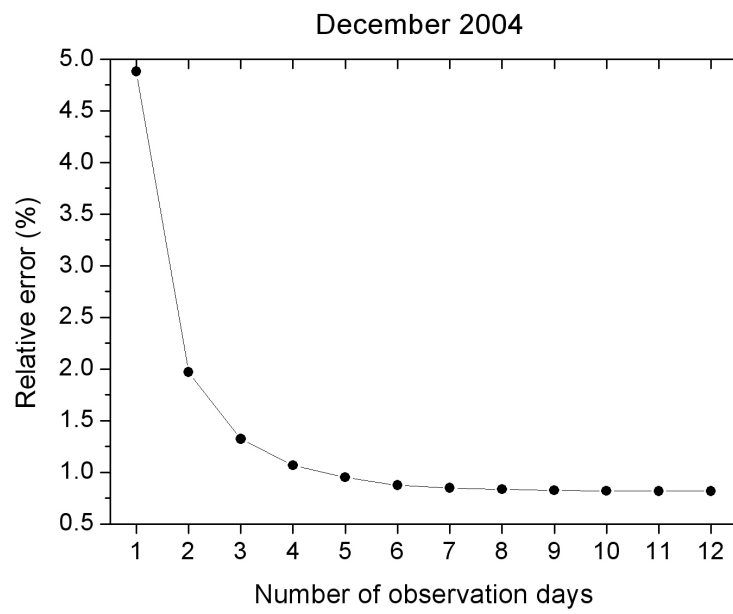


Fig. 2

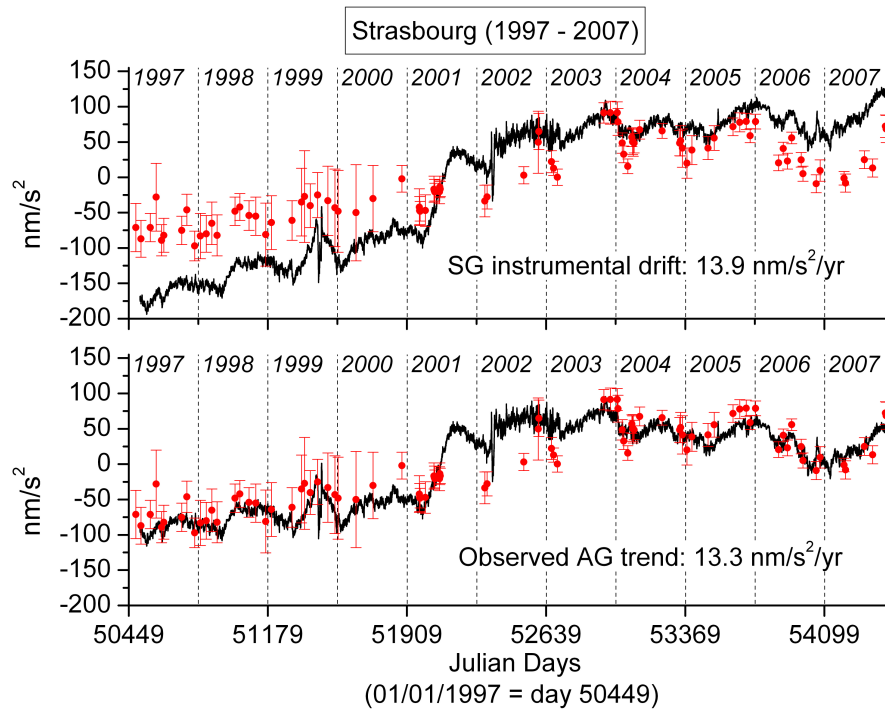


Fig. 3

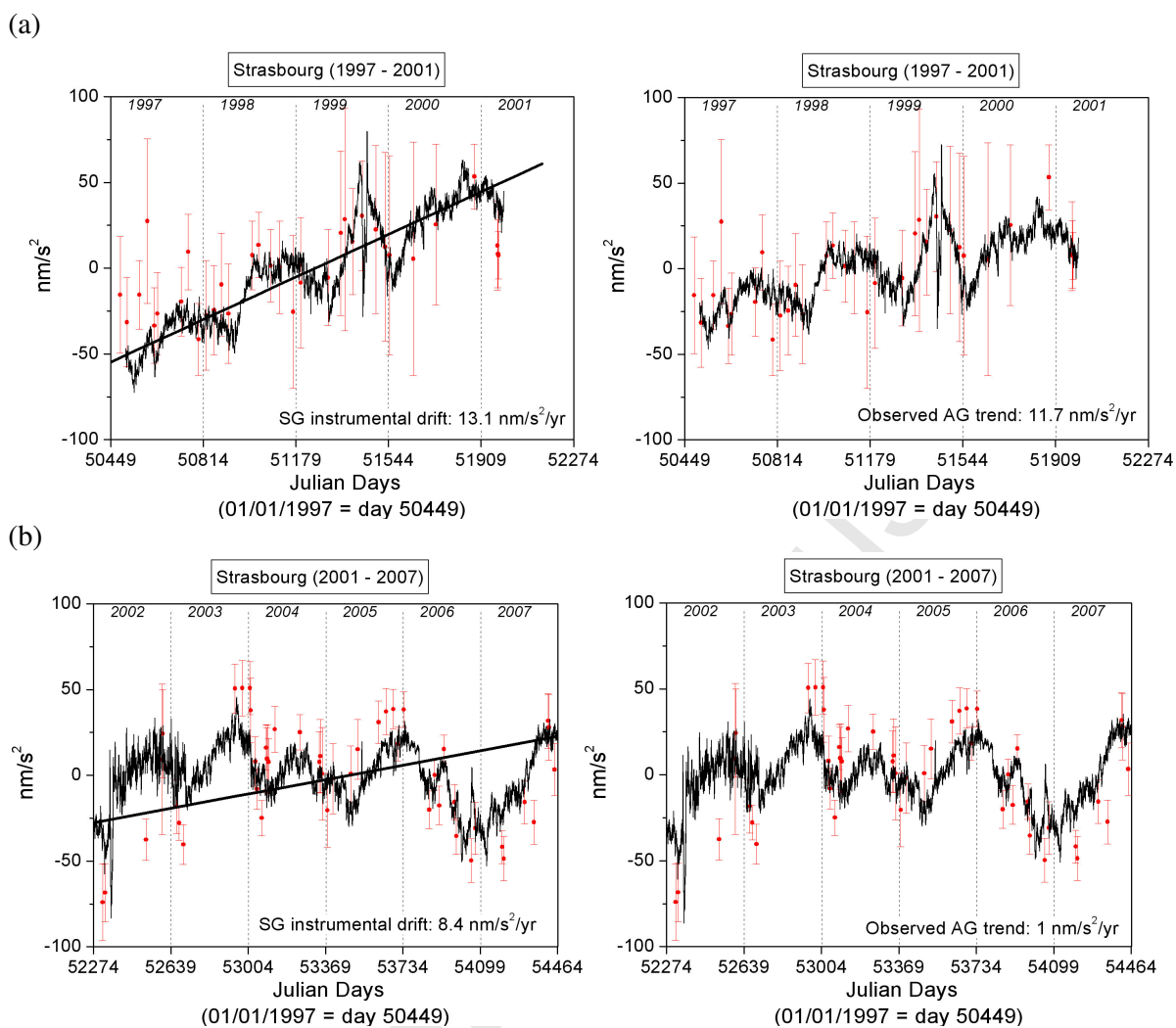


Fig. 4

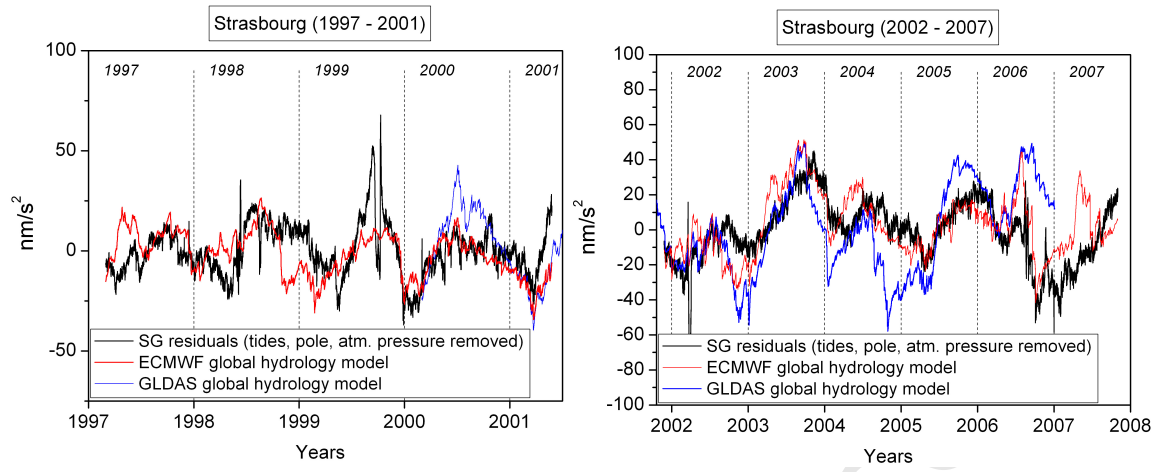


Fig. 5

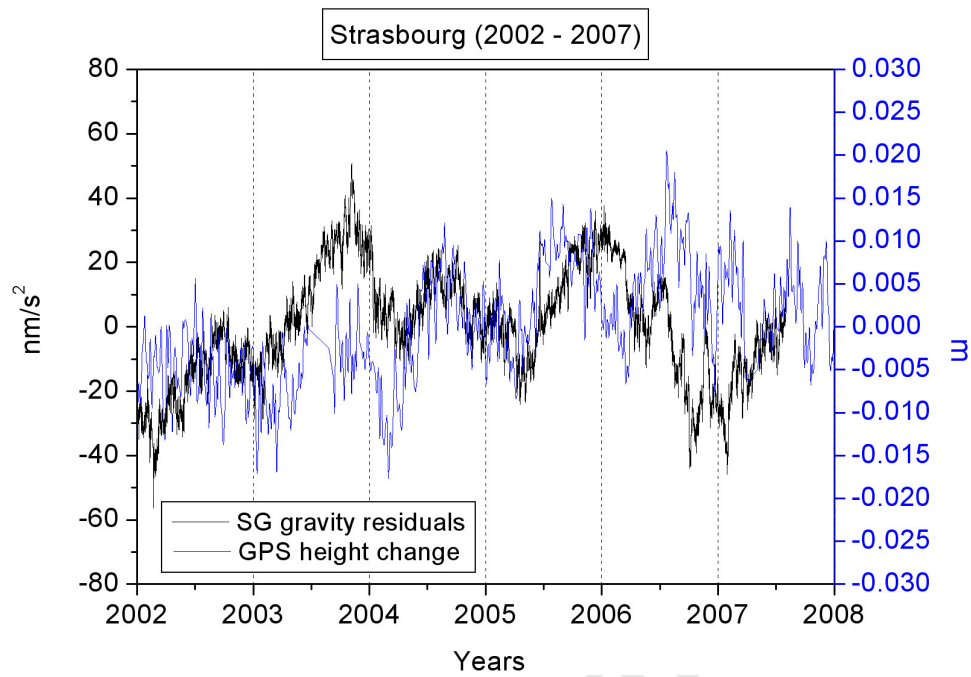


Fig. 6

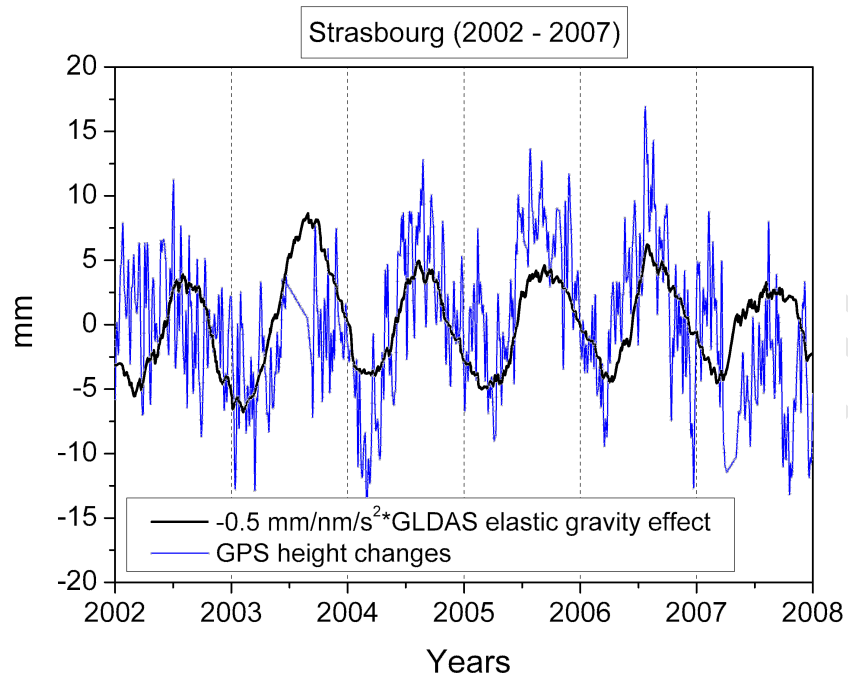


Fig. 7