Influence of different processing methods on the retrieval of gravity signals from GGP data

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Abstract

This study is devoted to the investigation of different processing methods of superconducting gravimeter (SG) data as available from the GGP network. We will use two different periods for our investigation: the first is a test period from March to December 1997 where we compare the impact on residual noise levels of 3 different processing procedures and the second is an interval going from March 1997 to February 2002 where we focus on the impact of instrumental drift and on the superposition with absolute gravimeter (AG) data.

1. Introduction

We intend to investigate here different processing methods of SG data as available from the GGP network since July 1997 (Crossley et al. 1999). Of course, any gravity set has to be pre-processed because there is a need for correcting the disturbances (spikes, steps, gaps) which would degrade any further treatment such as tidal analysis or spectral estimation. The problem of data gaps is in fact different from spikes and steps because the information is missing rather than corrupted leading to unevenly spaced data sets with all the inherent restrictions in using standard codes such as ETERNA (Wenzel 1998) or simply an FFT.
The main reason for this investigation is to measure the impact of any specific treatment in terms of noise levels of the gravity data. Another reason is to test the possibility of using a fully automatic method (or at least a semi-automatic treatment with final manual step adjustments) which could be extremely helpful in the pre-processing of a large number of SG data sets as available in the GGP data base. It is quite obvious that the work presented here, on a limited period (9 months in 1997) for only one station (Strasbourg), is time consuming and cannot be extended without tremendous effort to all the GGP stations.

Many different processing methods are available and in fact any SG group has its own strategy to pre-process the data. Even when using the same processing tool, there are however often personal factors that enter the treatment. For example, if some of the corrections can be set automatically by introducing a specific threshold for spike detection and removal, other problems such as small amplitude steps (offsets) need a visual inspection and a personal decision whether to correct or not.
Usually the classical preliminary step is to compute the residual gravity data using the following sequence:

- correction for local pressure effects using a standard barometric admittance – 3 nm s^{-2} /hPa, (see Crossley et al. 1995), or any other fitted value from a previous tidal analysis;
- correction for (solid Earth and ocean) tides by subtracting a so-called local tide computed from the luni-solar tidal potential with tidal gravimetric amplitude and phase factors originating from a previous tidal analysis at the same station. If such an analysis is not available, then one can use nominal factors for the solid Earth (e.g. Dehant et al. 1999) and ocean loading contributions (e.g. Scherneck 1991).

These two steps lead to the gravity residuals which are usually small amplitude signals which permit an easier detection of problems than the full gravity series.

We list hereafter some of the available methods for dealing with further problems:

- the slew rate method (Crossley et al. 1993) which is based on the application of a specific threshold to the time-derivative of the gravity residuals in order to detect non-physical samples. Rejected values can then be replaced by zero values which means that the gravity signal is replaced by the local theoretical tide;
- the PRETERNA pre-processing program by Wenzel (1994) using a threshold directly on the gravity residuals;
- the TSOFT program by Vauterin (1998) which consists in an automatic and/or manual corrections for spikes, gaps and steps applied on the gravity residuals;
- the least squares spectral analysis method by Pagiatakis (1999, 2000) which relies on a completely different philosophy namely that there is no need to interpolate bad data (samples can be unevenly spaced) and that there is a statistical estimate on the steps.

2. Test period: Strasbourg data from March 1997 to December 1997

We have tried here to compare 4 different methods applied to the gravity residuals:

1. a slew rate detection approach (Crossley et al. 1993) on 1 min samples but with manual correction for steps (data set provided by Jean-Paul Boy and method named JPB); the threshold was fixed to 2 nm s^{-2}/min to reject gravity data;
2. a semi-automatic treatment on raw data (2 sec) day by day (data set provided by David Crossley and method named DC); step 1 (DC 1) is essential cleaning to remove major disturbances and step 2 (DC 2) is final cleaning correcting smaller offsets and disturbances; data are then decimated to 1 min with the J9 filter which is the low-pass decimation filter we are using in Strasbourg;
3. a TSOFT-based method (data set provided by Séverine Rosat and method named SR) applied to 2 sec samples and further decimated to 1 min with J9 filter;
4. a TSOFT-based method either on 2 sec or 1 min samples and in a fully automatic or semi-automatic way (threshold of 10 nm s^{-2}) using the TSOFT tools (data set provided by Jacques Hinderer and method named JH); 2 sec samples are decimated to 1 min using a TSOFT decimation filter.

The evolution of the gravity residuals due to these four different pre-processing methods is shown in Figure 1. We began the time series by superposing the data and, because of different assumptions about the subsequent offset corrections, one sees that there is a cumulative divergence of the residuals at the end of the series.

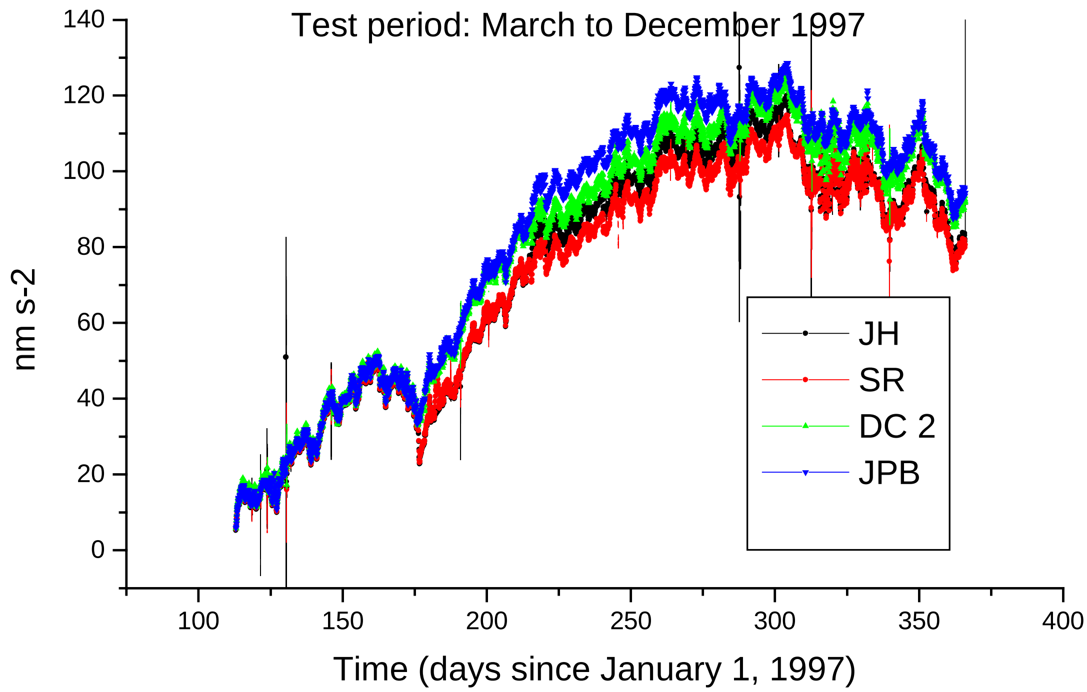

Figure 1. Gravity residuals during the test period in Strasbourg according to the 4 different pre-processing methods (JH, SR, DC 2, JPB).

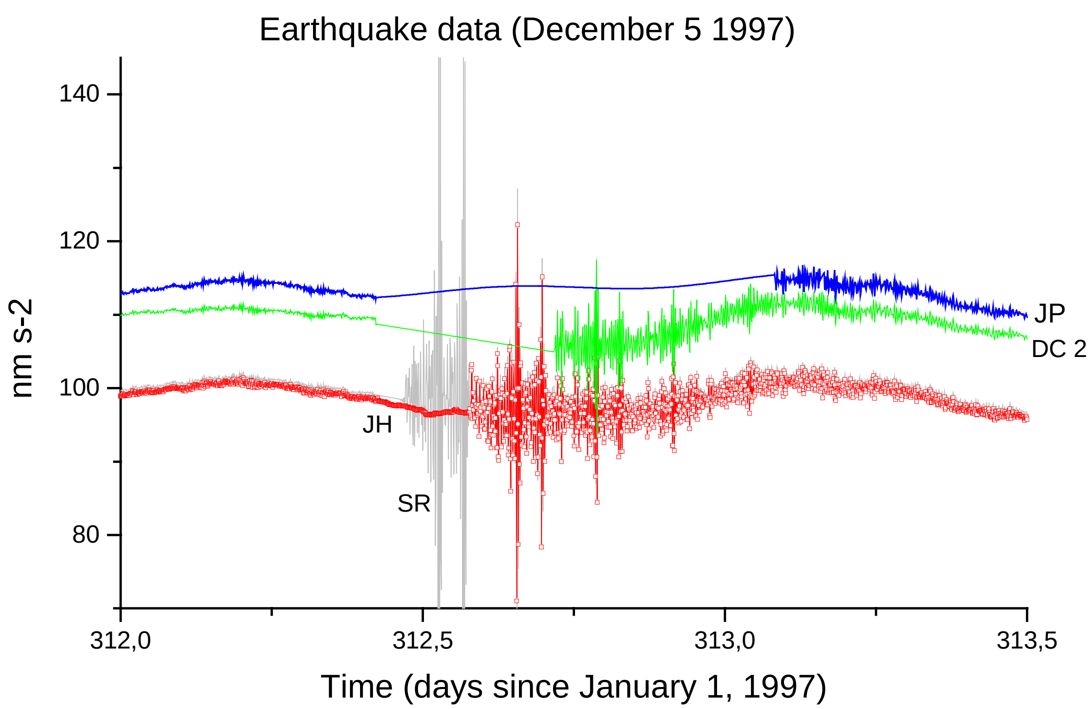

Figure 2. Different corrections of the gravity data during an earthquake (December 5, 1997).

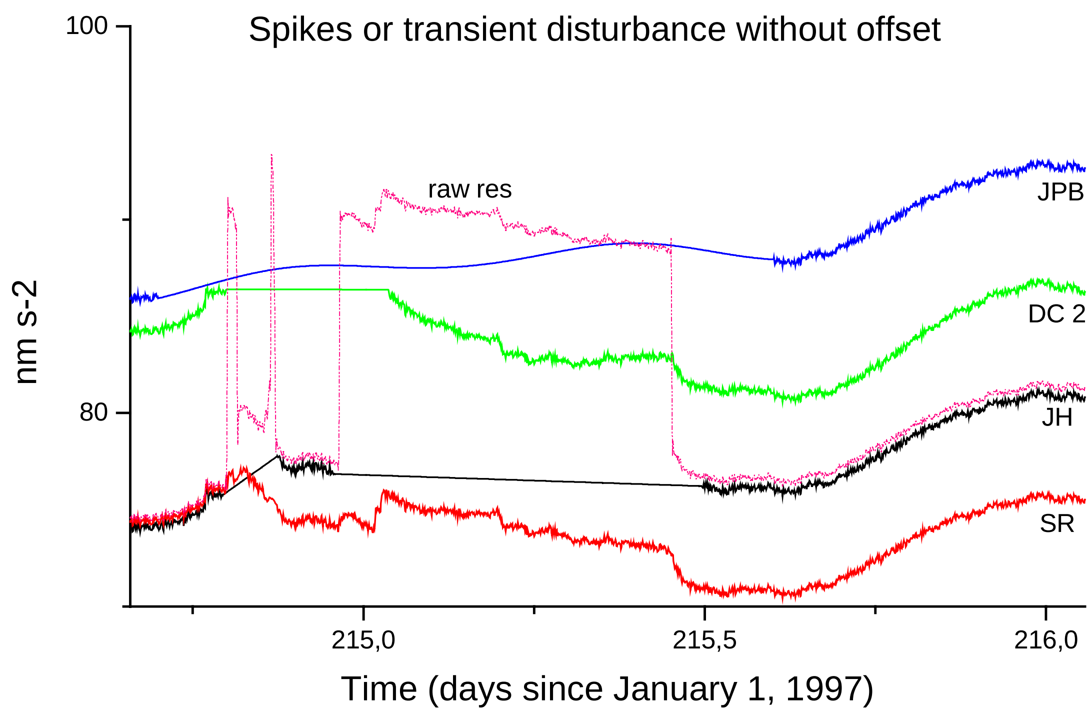

Figure 3. Corrections of spikes or transient disturbances without cumulative offset.

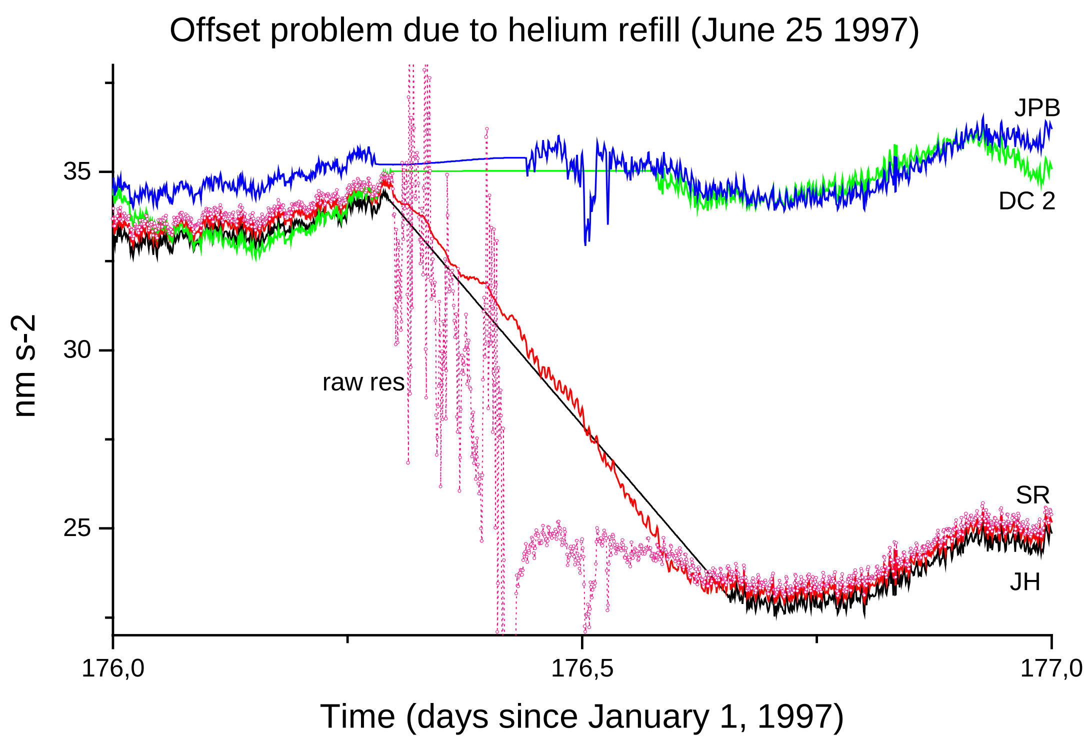

Figure 4 . Corrections of gravity data during a transfer of liquid helium in June 1997.

Other examples of problems we are facing with gravity data are shown in accompanying figures. The corrections of the data during an earthquake (December 5, 1997) are shown in Figure 2 and one sees clearly that the amount of rejected data, depending on the philosophy of dealing with earthquakes, is highly variable from one author to the other.

The case of spikes or transient disturbances (mechanical or electrical) is shown in Figure 3 and again the changes differ according to the method (the raw residuals are also shown with a dotted line).

The final example is given in Figure 4 and concerns a possible offset problem related to a transfer of liquid helium. It is evident that two methods (JH and SR) do not correct for an offset, whereas the two other authors consider an offset to have occurred.

We have used the different time series in order to compute power spectral densities (PSD) (expressed in $(nm\ s^{-2})^2\ Hz^{-1}$) for inter-comparing the noise levels in various frequency bands. A general view of these noise levels is given in Figure 5 for the 5 different processing methods (DC 1 and DC 2, JH, SR, JPB); the legend is labelled according to decreasing power levels (e.g. DC 1 is the most noisy signal and the least noisy is JPB).

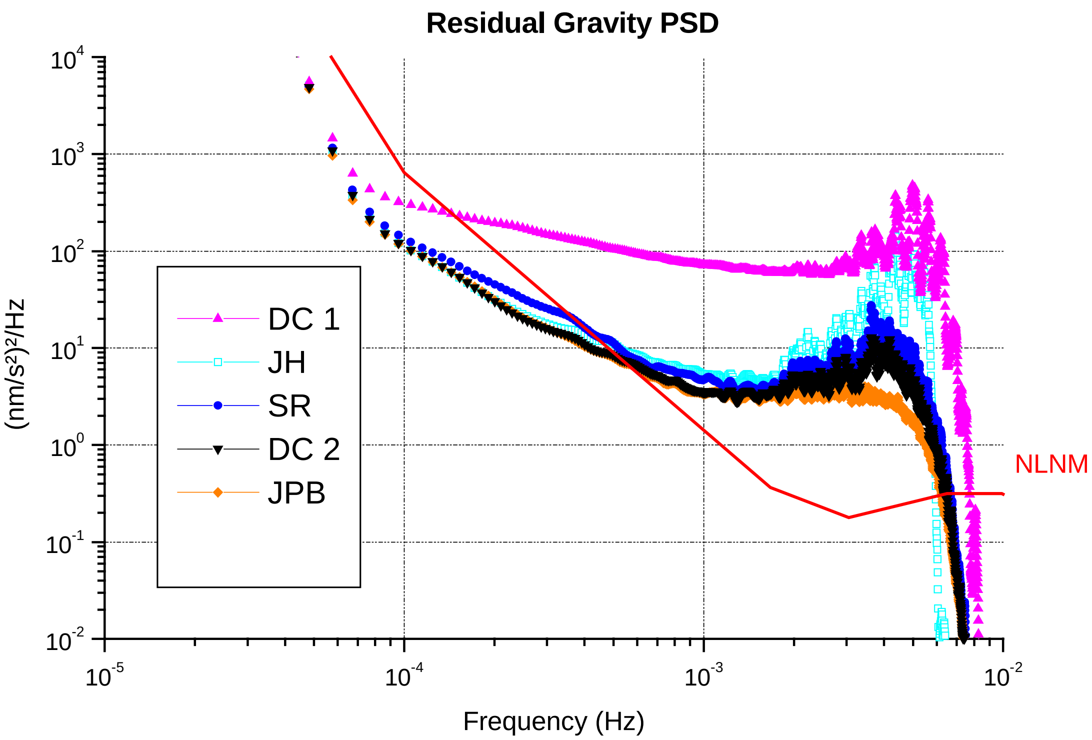

Figure 5. Power spectral densities of 5 residual gravity series, according to different methods of processing the data.

The continuous line is the New Low Noise Model (NLNM) of Peterson (1993) inferred from all the seismological records worldwide. For a more general discussion on the noise levels of the various GGP stations, we refer to Banka & Crossley (1999) and to Rosat et al. (2002). The decrease at the right end (high frequencies) is entirely caused by the decimation filters from 2 sec

to 1 min data. The left end shows that there is a convergence in the noise levels (for frequencies below 5. 10^{-5} Hz) which means that the tidal analysis of the corrected data would lead to almost the same results whatever the correction method. In the intermediate part, between 10^{-4} and 6. 10^{-3} Hz concerning the seismic and subseismic bands, the levels vary according to the method; DC 1 is much higher (by a factor 10) in PSD but this is not surprising because only the major gaps and offsets have been treated. The four other methods lead to similar noise levels for low frequencies but to different levels in the high frequency part mostly because of different amount of rejected data after earthquakes. This is why the lowest noise curve (JPB) corresponding to the highest number of rejected seismic data (see Figure 2) is also the one exhibiting almost no normal modes in the seismic band.
A zoom of Figure 5 focussing on the band (10^{-3} - 10^{-2} Hz) is given in Figure 6.

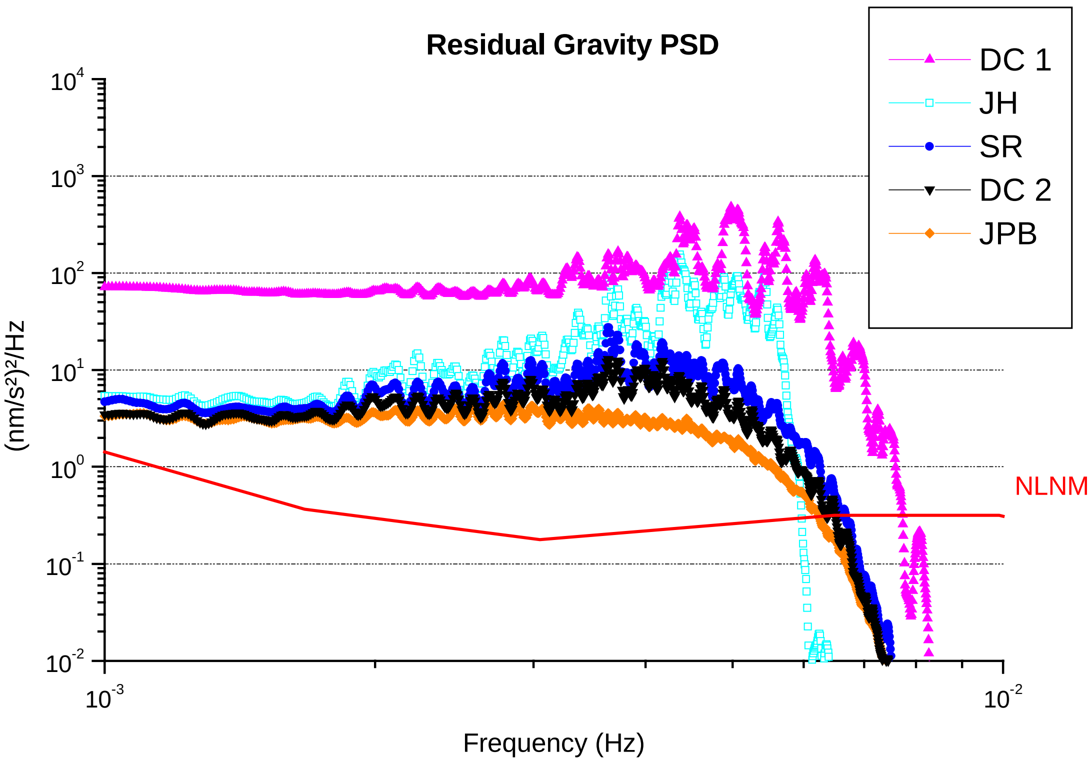

Figure 6. A zoom of Figure 5 for frequencies between 10^{-3} and 10^{-2} Hz. Note that there is a factor of 10 between the lowest and highest noise levels.

We will now show more specific results on the effects of some steps in the pre-processing. In all the remaining figures in this section, the different residual gravity PSD are computed with data from the JH method based on TSOFT. First, the role played by the decimation filter (from 2 sec to 1 min) is illustrated in Figure 7 where we compare the J9 filter (our own low-pass filter) to the filter implemented in TSOFT. The major difference is in the high frequency attenuation before the Nyquist frequency which is 8.33 10^{-3} Hz (for 1 min sampling); the different cut-off frequency also slightly alters the seismic band. Clearly the TSOFT filter is superior to the J9 one but one has to keep in mind that the length of these filters also differs.

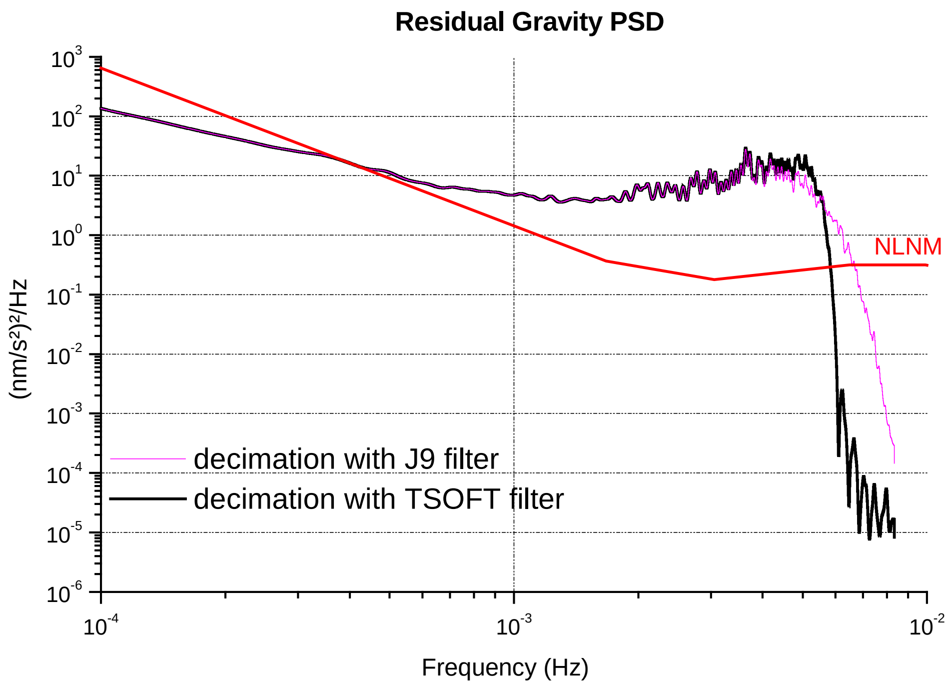

Figure 7. Residual gravity PSD of manually corrected 2 sec samples, one decimated with TSOFT and the other using the J9 digital decimation filter.

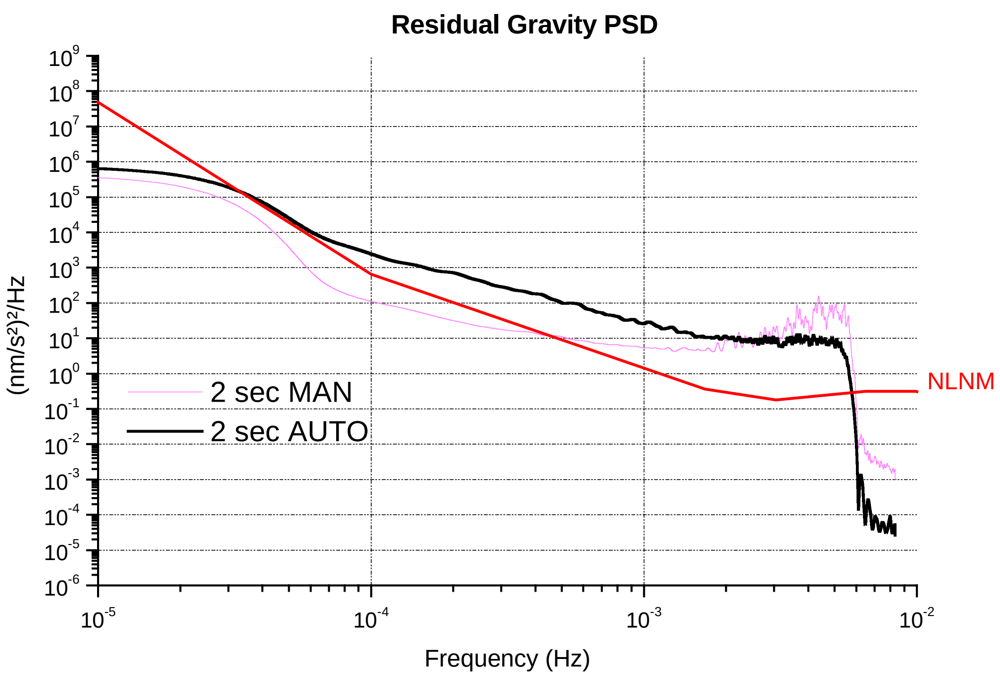

Figure 8. Residual gravity PSD according to automatic or manual corrections on 2 sec samples before 1 min decimation (both using the TSOFT filter).

The impact of using automatic or manual corrections on the 2 sec data is shown in Figure 8 and points out the rather large noise level changes which can arise in the seismic and subseismic bands; clearly this figure shows only one possible outcome because there is a specific threshold (in our case 10 nm s^{-2}) that can be used for the automatic spike rejection and that the manual corrections are depending on the author (in this case JH).

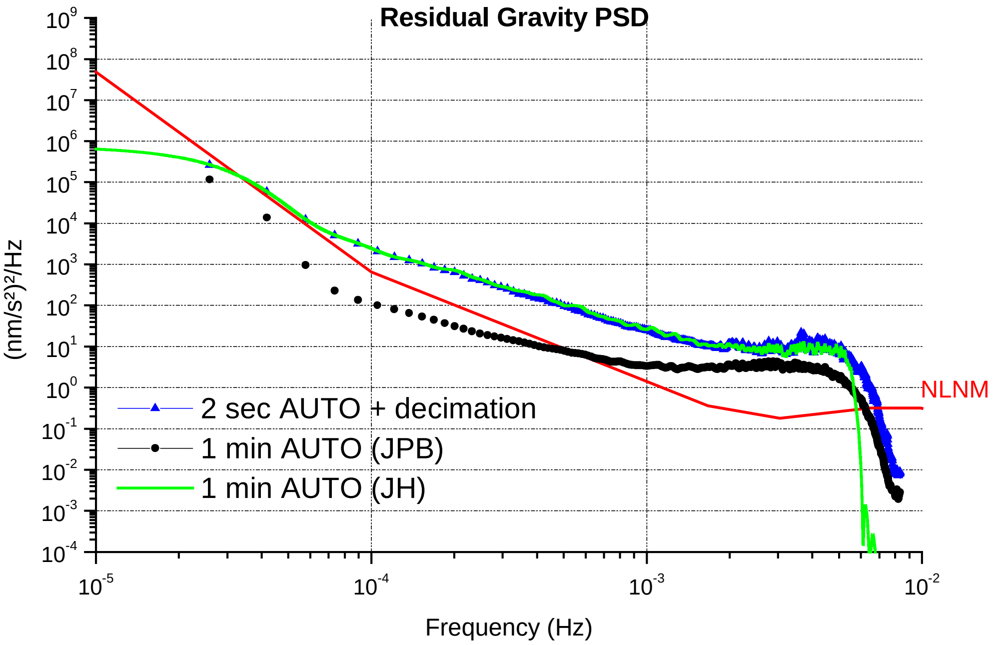

Figure 9. Residual gravity PSD for 3 different automatic correction procedures. One uses 2 sec samples before decimation, and the other two use 1 min samples from two different authors.

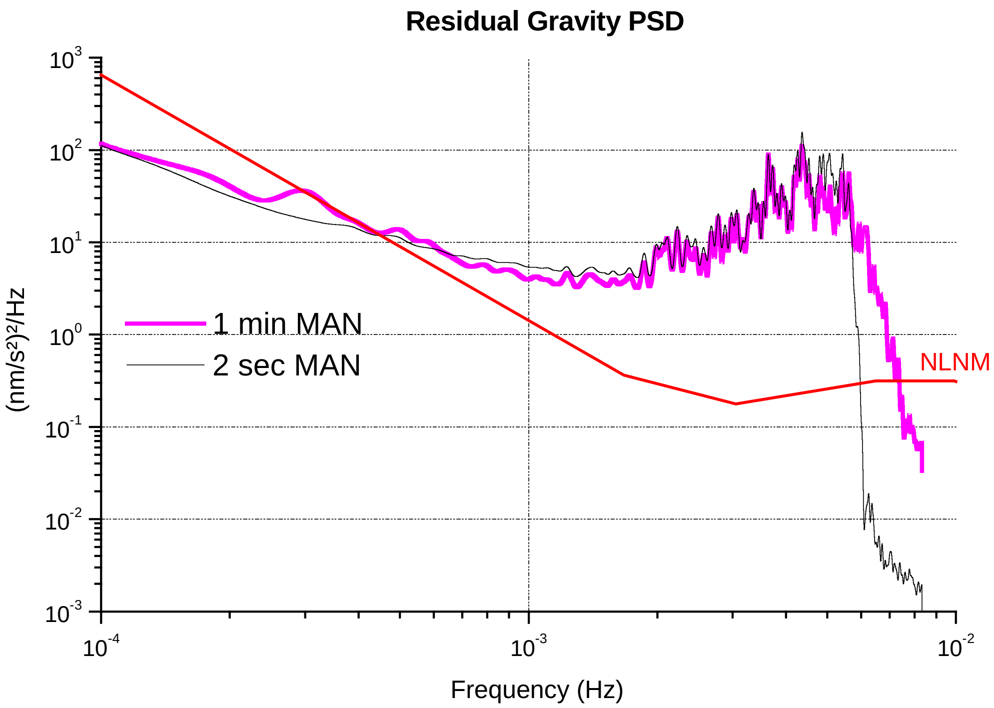

Figure 10. Residual gravity PSD according to manual corrections either on raw 2 sec data (further decimated using TSOFT filter) or on 1 min data.

The question of dealing automatically with raw samples (2 sec) or 1 min data is answered by Figure 9 where one sees that the dominant effect is the choice of the threshold rather than the sampling rate of the data in the automatic correction procedure; indeed JPB method with its lower threshold rejects more data than JH method and this leads to significantly lower noise level whereas the level difference between the two automatic methods (on raw or 1 min samples) (JH) is much weaker.

The use of different sampling rates in the manual correction procedure leads to Figure 10 where one can see that the low frequency levels are almost similar on the contrary to the band close to the Nyquist (because of different decimation filters).

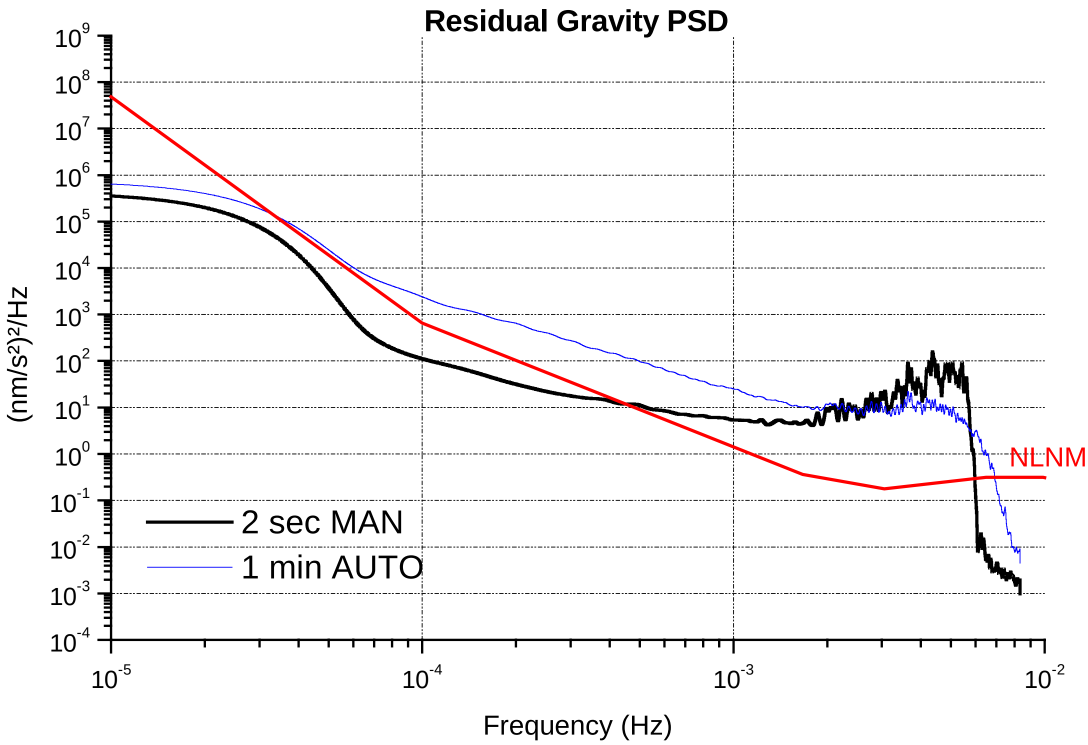

Figure 11. Residual gravity PSD according to two extreme cases: manual corrections on 2 sec samples and automatic corrections on 1 min samples.

The final comparison (Figure 11) is showing two extreme cases: on the one hand, a very time consuming procedure where the 2 sec samples are all manually corrected and then decimated to 1 min; on the other hand, a very fast treatment where the 1 min samples are automatically corrected. One sees clearly the benefits of doing manual corrections on the gravity data after visual inspection rather than using an automatic procedure:

- the PSD (2 sec MAN) crosses the NLNM at a much higher frequency than the PSD (1 min AUTO) and hence has a lower noise level in the subseismic band;
- the PSD (2 sec MAN) exhibits more seismic normal modes than the other PSD and is therefore more appropriate in studies related to the hum or others.

3. Full period: Strasbourg data from March 1997 to February 2002

After having tested these different methods for pre-processing the gravity data on a limited time span in 1997, we investigate now the full available period for our instrument in Strasbourg, namely from March 1997 to February 2002 (almost 5 years). We keep only three methods, all of them being applied to 1 min samples:

1. a semi-automatic method (REPAIR) based on the slew rate detection (JPB) and using a threshold of 2 nm s^{-2} /min to reject gravity data;
2. the same method but with a different treatment of the pressure signal (SR). There is a barometer change (instrument failure) during the analysed period; JPB introduces a drift correction in the barometric pressure (~ 1.66 hPa/year) in order to have the same absolute levels when substituting one meter by the other while SR makes an offset correction in the pressure to adjust the levels (and hence in the gravity);
3. a semi-automatic method using TSOFT (JH) (as discussed in section 2).

The consequences on the evolution of the gravity residuals from March 1997 to February 2002 due to these 3 treatments are shown in Figure 12 which shows only slight overall differences.

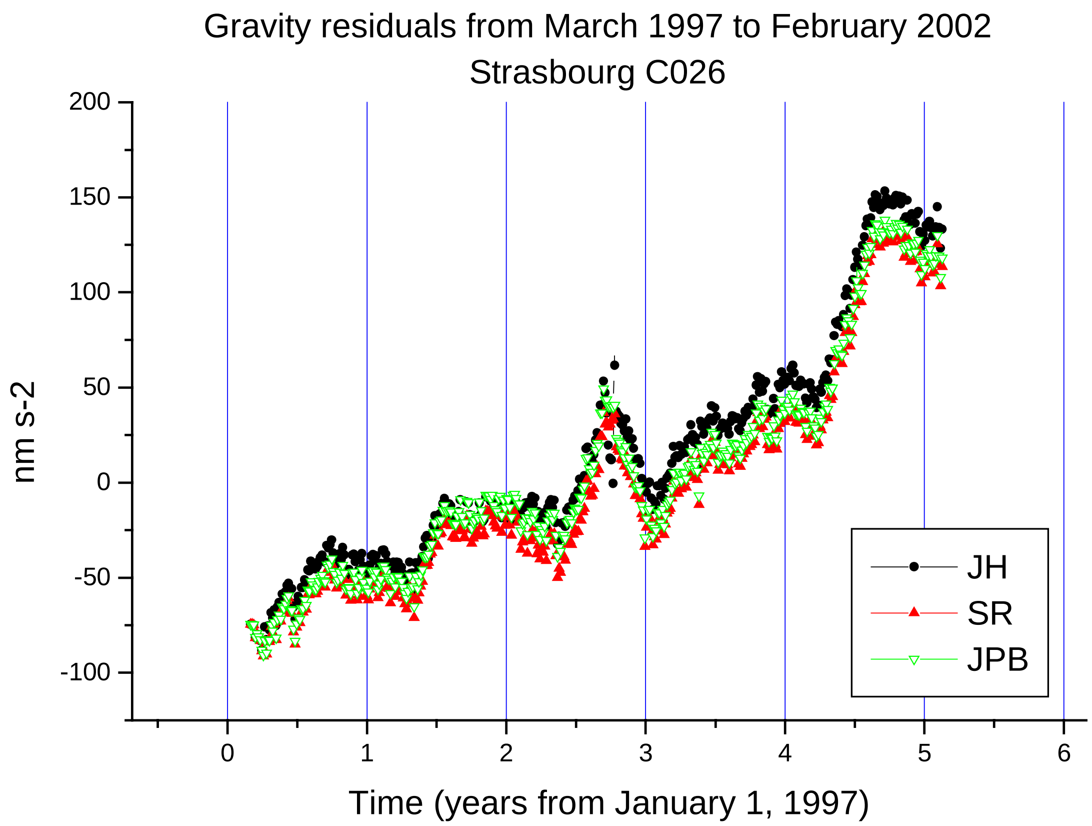

Figure 12. Time evolution of gravity residuals in Strasbourg from March 1997 to February 2002.

The differences in the gravity residuals between the JH and SR treatments are shown on Figure 13 exhibiting clearly the various offset corrections with different amplitudes.

A zoom of this difference covering several days is shown on Figure 14 and indicates a typical case of a different treatment of an offset; the oscillations are tidal constituents which originate from the use of (slightly) different tidal parameters in building up the residual signals.

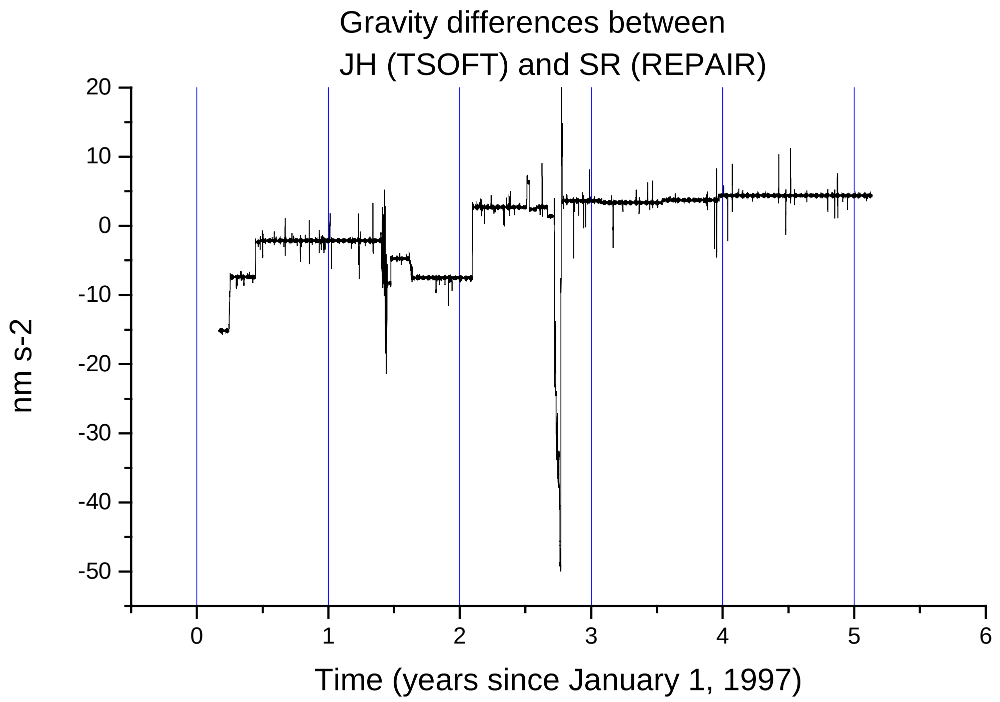

Figure 13. Difference in the gravity residuals due to two different treatments.

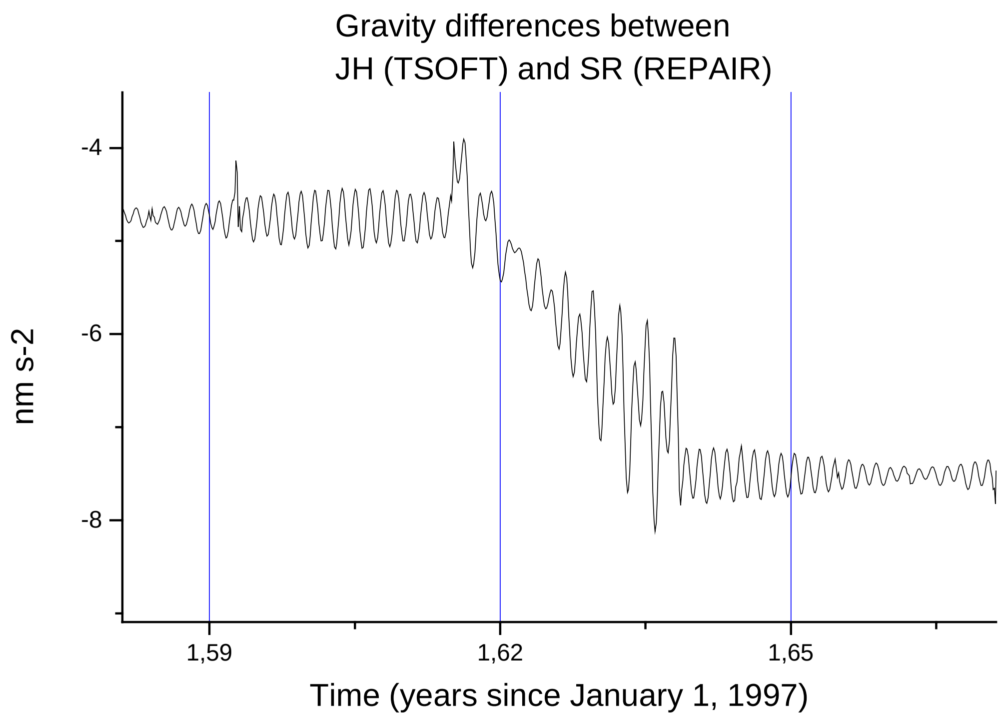

Figure 14. A zoom of figure 13 showing a probable offset over several days as well as small amplitude residual tides.

The question of removing offsets (especially the ones with small amplitudes of the order or less than 10 nm s^{-2}) has always been debated in the gravimetry community. Some can be instrumental (for instance mechanical when you touch the instrument), but many are geophysical and it is sometimes impossible to decide which is which without precise information on the auxiliary and environmental parameters (e.g. rain). The consequences are important for the study of the long term gravity changes because of the cumulative effect of the different offset corrections. In particular, the drift estimate of the SG will be affected by this effect. One constraint can be introduced by repeated absolute gravity measurements at the same site which will clearly help in determining the physical long term gravity evolution.

Figure 15 shows the superposition of AG and SG observations (following the TSOFT (JH) and REPAIR (SR) processing methods) at our station. Previous analysis on the same station but with shorter records can be found in Amalvict et al. (1998, 1999, 2001) and Boy et al. (2001).

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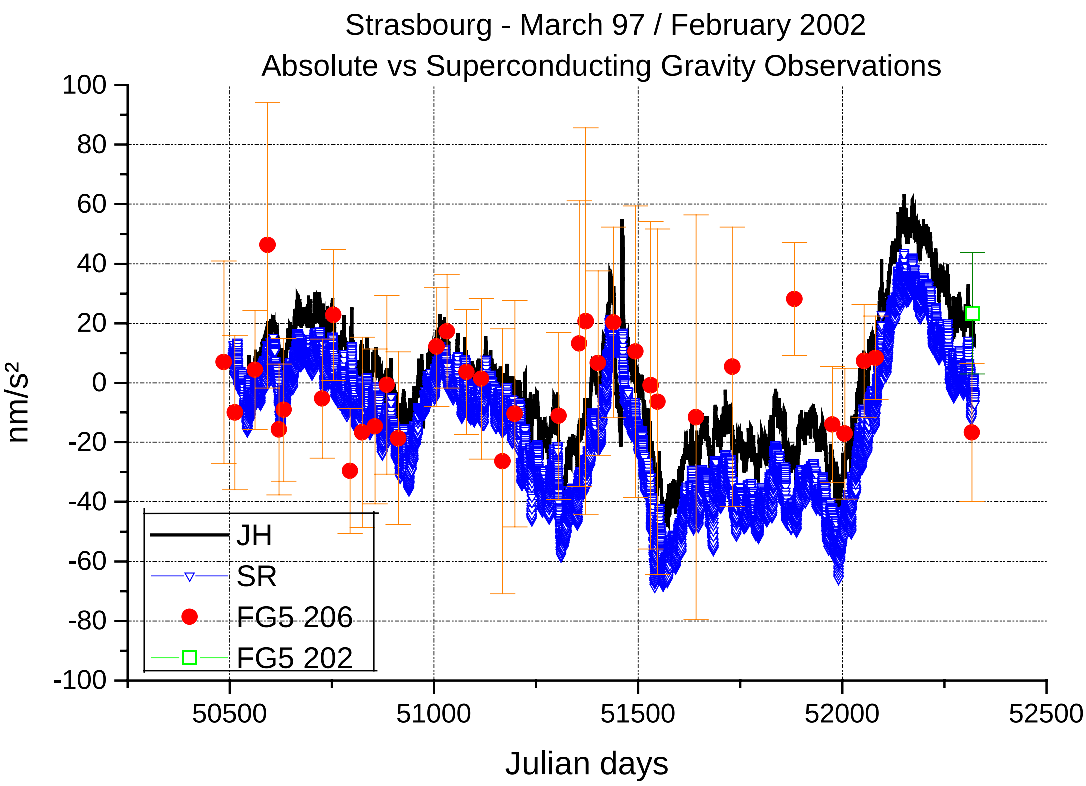

Figure 15. Superposition of absolute and superconducting gravimeter observations at Strasbourg during a 5 year time span (February 21, 1997 corresponds to Julian day 50500).

Both data sets have been corrected for the polar motion contribution using a nominal gravimetric factor 1.16; a fitted linear drift of 39.6 nm s^{-2}/year is subtracted from the SG while a fitted drift of 12.4 nm s^{-2}/year is removed from the AG. There are about 30 AG determinations with FG5#206 leading to mean g values obtained from about a week of continuous measurements for each mean value. The superposition is quite satisfying and almost all values overlap within the error bars (1 standard deviation in the case of AG). We have also indicated the February 2002 measurement with FG5#202 (done by M. Van Camp from ROB, Belgium) when our instrument came back from a factory maintenance and upgrade. A zoom of Figure 15 on the last 320 days of our gravity series is given in Figure 16. One can notice that:

1. the two processing techniques (REPAIR and TSOFT) lead to a 20 nm s^{-2} cumulative offset over the 5 year period (integrated effect of positive and negative offset corrections);

2. there is also a 30-40 nm s^{-2} gravity difference between FG5#202 and FG5#206 during the intercomparison test at the end of the record in February 2002 (with identical processing).

Because both residual curves show no offset correction during this time span, the TSOFT residual curve which is coincident with the three AG determinations in 2001 before the upgrade of the instrument favours the FG5#202 determination with respect to FG5#206 in February 2002 (after the upgrade). This example also shows the importance of having regularly AG measurements to follow the long term continuous evolution in gravity at an SG station. However there is a mutual advantage of using both types of measurements (AG versus SG) because the continuous SG monitoring can also help to reject extreme AG values (provided the drift of the SG is accurately known). In practise a proper treatment of both data sets requires simultaneous determinations of the offsets and the long term drift of the SG.

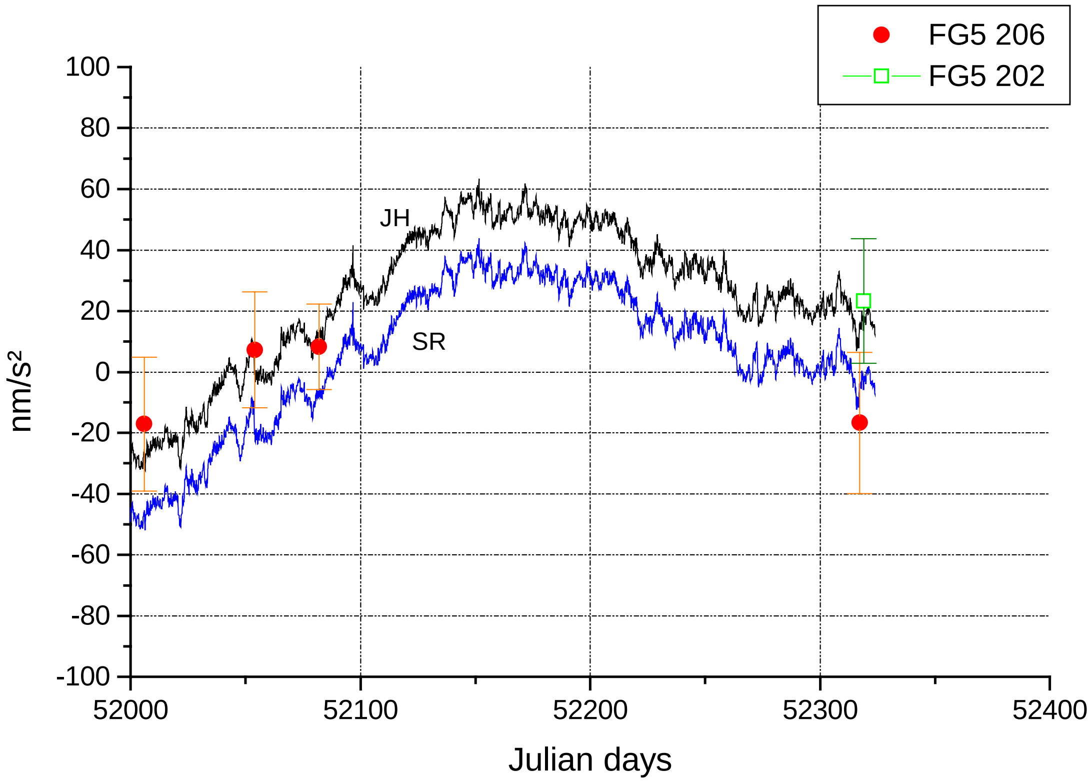

Figure 16. A zoom of Figure 15 showing the AG/SG superposition during the last 320 days of the 5 year period in Strasbourg.

4. Conclusion

This paper is devoted to the impact of different pre-processing methods on GGP gravity data. In the first part, we used a data set from March to December 1997 to test 5 different methods based either on 2 sec raw samples or 1 min data as provided in a standard form to the GGP data base. All the methods are based on a treatment of the disturbances left in the gravity residuals (observed gravity – local synthetic tide including solid and ocean loading tides – local pressure correction). Some of the methods are fully automatic with the help of the TSOFT pre-processing package and are able to remove spikes and offsets and to fill up gaps. Some other methods use the same TSOFT software to detect the problems but need a manual decision for applying the suggested corrections.

One method uses the slew rate detection algorithm (time derivative of gravity residuals) to point out the disturbances left in the signal. We assembled the gravity residual curves according to these various processing techniques and also computed the PSD to show the remaining noise levels in various frequency bands.

We could therefore address the problem of the importance of correcting raw data (in our case 2sec) or standard 1 min data and we could point out the role played by the decimation filters. The manual inspection of the data reveals the differences according to the author and we could also evaluate the price to pay when using a fully automatic method based on a specific threshold for spikes. No automatic offset correction was done in this study and we emphasize the difficulty of correcting small amplitude (less than 10 nm s^{-2}) apparent offsets. One important impact of offset corrections is that there is a cumulative effect with time.

We did then a similar analysis on a 5 year data set from March 1997 to February 2002. Again the importance of the cumulative offset corrections appears and reaches 20 nm s^{-2} at the end of the investigated period. There is a subsequent consequence in the drift estimate of the SG therefore possibly altering the retrieval of polar motion and seasonal contributions. Because of these offsets, there is a difficulty in using SG data to check AG data to better than several tens of nm s^{-2} (typically 20 to 30); we provide an example with FG5#202 and FG5#206 differences in February 2002.

The pre-processing of the GGP data is important in almost every frequency band of interest. The noise levels in the long period seismic and sub-seismic bands are strongly depending on the chosen procedure. It is less clear in the tidal bands where apparently only small differences are expected. Finally, the long term gravity time series retrieved from SG observations are crucially depending on the amount of corrected offsets, for the determination of the polar motion and the seasonal components.

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